What blockchain can do for power grids?

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Abstract
An up-to-date comprehensive review for power engineers and practitioners.
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1. Introduction
Blockchain technology already counts at least two decades of existence. Nevertheless, we aim of this review paper is to present existing and emerging ways in which the energy industry can exploit the methodology and practice of the Blockchain technology.

In particular, we understand that the current as well as the emerging energy price generation environment leads to a substantial change in the whole energy industry, posing significant and diverse challenges. We believe that Blockchain, both as a concept and as a technological background, can be part of the solution to various challenges, helping both the companies to pursue their profitability in the energy market arena and the independent user communities to work towards common energy benefit. This article may be also considered as is a brief synopsis and annotation in principle of the possibilities of coupling energy with crypto-currencies and Blockchain in particular.

The basic value of the blockchain is directly related to the concept of trust. Blockchain is a decentralized database that allows people and organizations to trade without having to trust each other. They have the ability to trade with, for example, money without participating in these banks or any other brokerage organization, as is the case with conventional transactions.

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Because of this, the blockchain is expected to change the way we perform global value transactions. Therefore, it is important to explore what this new technology can offer in the energy sector. In other words, in this work we will focus on energy transactions instead of money transactions. Although, we almost exclusively consider the power grid, we believe that the facts presented and the lessons delivered as well as the concluding remarks apply to other energy sectors as well, with no particular difficulty.

The rest of this paper is organized as follows. In the next section we provide the basic concepts and develop the required background on Blockchain and the next generation power grids and the challenges they both pose. Section 3 contained a review of related papers that recently appeared in scientific journals after peer review. In section 4 briefly overview the associated EU funded projects and in section 5 other related major and promising efforts. Our concluding remarks together with selected research and development propositions can be found in sections 6 and 7 respectively.

2. Concepts and Background

In recent years we have been monitoring the evolution of power grids in intelligent networks and lastly what is called the grid edge.

The truly interesting changes that drive developments in the electricity sector occur at the edges of the network, where the consumer meets the grid, competes with it, disrupts it and generally acts in ways that test his traditional mode of operation.

The most important changes that are already happening on the network are:

- Production is more interrupted due to an increase in the share of renewable energy sources.
- Transmission and distribution become more controllable and fault tolerant due to network digitization.
- Consumers have the dual role of both producer and consumer.
- Loads become more interactive and dynamic.

These changes challenge the traditional way in which utility companies operate. These companies are called upon to respond to change and adapt.
Ignoring the largely unanswered questions on the rising price and not only Bitcoin, the cryptobonds, and especially the underlying technology of Blockchain begin to mature and seriously examine their impact on a number of technologically most important areas.

Although it is still early, it is worth asking ourselves whether the technology of Blockchain can play an interesting role in recent and emerging energy developments. The expected role will be of further interest due to the two-way relationship between energy trading and the energy cost of running the Blockchain algorithms. These algorithms are based on evidence (such as Proof-of-Work) which in turn requires the necessary energy use. By way of example, we report that in 2014 energy consumption was $240 kWh per bitcoin [2]. In addition, these energy costs are almost always paid in a non-cryptographic currency, introducing a steady downward pressure on the price. The energy cost of evidence of what modern crypt coins (like Proof-of-Stake and Proof-of-Capacity) is several thousand times smaller, but remains a very important parameter.

Blockchain is a distributed system that provides trust among counterparties. It allows the creation of distributed peer-to-peer networks, where members of no confidence can interact without a trusted intermediary in a verifiable way. Using Blockchain microgrids can be made more robust by using a distributed database, in the form of a common accounting book, to manage transactions. This resilience may also be related to the strengthening of these networks in the face of electronic attacks and the strengthening of them on the solidarity side. These transactions may include transactions in electricity, money transactions or even the recording of electron flow in the network [17].

It is also our deep conviction that Blockchain technology can make a significant contribution to the development of local energy communities [24]. The creation of these communities is a priority for the European Union.

3. Related peer-reviewed publications

Blockchain has been mainly considered in the gray literature. As graphically depicted in Figure 1, only recently blockchain studies have appeared in peer-review articles.

[23] is a review article, presenting blockchain based projects with application on microgrids. Authors focus on start-up approaches and attempt to technically compare them.
[31] and [39] are, to the best of our knowledge, the first papers that try to use blockchain for energy transactions validating them with a power flow solution.

[31] presents an architecture for the operation of a P2P energy market which respects the physical constraints placed by the grid while maximizing social welfare. Authors use blockchain to coordinate devices and facilitate the aggregation step of the decentralized optimal power flow algorithm they have used. Distributed energy resources perform a local optimization step and send the results of this step to a smart contract. This smart contract serves as a coordinator, executing the last step of the algorithm which is the aggregation of the local optima. They consider a day-ahead scheduling problem. The implementation is based on a smart contract deployed on a public test Ethereum network.

The goal of paper [39] is to use blockchain to attribute the energy losses to each P2P transaction, taking place at distribution level, between a generator and a load. Although the goal of this paper is to go beyond the economic aspects of energy transactions and use the blockchain to make distributed decisions for technical operations on the grid, it is clear that this was not fully achieved. Authors state that they have assigned the computation of energy losses in a central entity. This entity validates transactions, computes the power flow algorithm, provides energy losses and includes them to blockchain transaction segments. A fully-distributed approach where nodes run a distributed power flow algorithm is not explored in this paper.

In [37], a double auction energy market based on blockchain is presented. This energy market is a P2P market, where consumption bids are matched
with generation bids. The authors do not provide us with more details on the their implementation, and we do not know what software was used for the operation of the P2P blockchain network, if the market operation is based on a smart contract, if the use a public or a private blockchain. Different trading strategies that can be adopted by market participants are discussed but this is something implemented externally to blockchain.

In [30] a market design framework is introduced. This framework consists of seven fundamental components for the efficient operation of blockchain based microgrid energy markets. These seven components are: microgrid setup, grid connection, information system, market mechanism, pricing mechanism, energy management trading system and regulation. The Brooklyn Microgrid project was used as a case study and was evaluated according to the seven required components as they were introduced by the authors.

[32] and [33] is an attempt to explore the application of blockchain and smart contracts to improve smart grid cyber resiliency and secure transactive energy applications. Authors claim that the combination of PNNL’s Buildings-to-Grid Cyber Testbed and the connected campus is a realistic environment for the simulation of blockchain applications for transactive energy. The simulations in such a realistic environment will help improve the state of the art and use blockchain to create a more resilient grid.

[34] Data acquired from metering devices are stored as energy transactions on the blockchain. A smart contract is deployed for each DEP (distributed energy prosumer) enrolled in the demand response program proposed by the authors. These smart contracts check the compliance of each DEP to the desired energy profile, calculate the associated rewards and penalties and decide the definition of new demand response events. The validation of the proposed model was done through a simulation of a grid with 12 DEPs using energy traces of UK building datasets. Ethereum protocol was used for the operation of the P2P network and smart contracts were written in Solidity.

[26] is a non technical paper, a SWOT analysis on the use of blockchain technology on promoting photovoltaic in China.

[35] presents an M2M electricity market were two electricity producers and one electricity consumer are trading with each other over a blockchain. In the proof-of-concept implementation presented the physical machines were replaced with physical simulations of industrial processes and MultiChain was used for the creation and deployment of a private blockchain. Also this paper studies the research and application potential of blockchain technology
[21] begins with an overview of the transformation energy markets have gone through the last years in Europe. This transformation mainly consists of the liberalization of the energy markets and the Guarantees of Origin (GoO) for energy. Authors have developed an Energy Token Market using the Ethereum Blockchain and a Smart Contract deployed on it. The objective of the Smart Contract is to allow people trade crypto tokens that mimic GoOs. A cryptocurrency that also mimics GoOs is SolarCoin [16]. In SolarCoin every time one certified photovoltaic system generates 1MWh of electricity, one SolarCoin is awarded to its owner. SolarCoins can be sold later just like GoOs.

In [29] and [20] authors focus on the privacy preservation issue that comes with the use of the distributed ledger technology on the transactive grid. They claim that transaction level data provide greater insights into prosumer’s behavior compared to smart meters.

In [29] a trading workflow called PETra (Privacy-preserving Energy Transactions) is presented. PETra is build on distributed ledger technology and proven techniques for anonymity, such as mixing services, randomly generated anonymous addresses, anonymous communication identifiers and onion routing.

In [20] authors describe how the communication and transaction mechanisms of PETra can be extended to provide anonymity. The solution they propose is the use of garlic routing and ring signatures. The combination of the two methods provides anonymity on the whole chain of transactions both on the network communication layer and on the distributed ledger transaction layer.

4. Horizon 2020 Projects

The EU through Horizon 2020, its financial instrument coupling research and innovation, has been systematically supporting the penetration of the blockchain technology into the energy sector. This section is devoted to associated projects. In Table 1 we present the basic characteristic of these projects. We provide our brief description for each one of them right after.

P2P-SmartTest [11] is an already completed Horizon2020 innovation action project. In [38] authors, in the context of the project, present a review of the existing P2P Energy Trading Projects. The conclusions of the review
Table 1: List of EU supported projects.

| acronym          | blockchain | purpose                              | start | end     | refs |
|------------------|------------|--------------------------------------|-------|---------|------|
| P2P-SmartTest    | -          | P2P trading                          | 2015  | 2017    | [11] |
| CROSSBOW         | -          | Energy markets                       | 2017  | 2021    | [6]  |
| Future Flow      | -          | Balancing services                   | 2016  | 2019    | [10] |
| Defender         | -          | Security                             | 2017  | 2020    | [7]  |
| eDream           | -          | Community energy systems             | 2018  | 2020    | [9]  |
| SealedGRID       | -          | Security                             | 2018  | 2021    | [13] |
| SOFIE            | -          | IoT                                  | 2018  | 2020    | [28] |

include the belief that blockchain is considered to be a very promising technique which can simplify the metering and billing system of the P2P energy trading market.

CROSSBOW [6] stands for: CROSS BOrder management of variable renewable energies and storage units enabling a transnational Wholesale market. This Horizon2020 project’s main goal is the development and deployment of a set of technological solutions which will enable increasing the shared use of resources to foster transmission networks cross-border management of variable renewable energies and storage units. These solutions will enable a higher penetration of clean energies whilst reducing network operational costs and improving economic benefits of RES and storage units. In this project blockchain will be used in the implementation of the market platform. As it is mentioned in their web-page: a novel orchestrated multi-nodal market platform will be adapted and deployed, which will allow market players to integrate and interoperate on the distributed concepts with minimum set of harmonized technical data requirements for market participation.

Future Flow [10] is a horizon 2020 research project. The stated objective of this project is to design and pilot test comprehensive techno-economic models for open and non-discriminatory access of advanced consumers and distributed generators to a regional platform for balancing and redispachting services. Blockchain is used in pilots of this project to study if the use of blockchain could allow for trusted information, such as device features, and standard compliance information to be published in an elegant, safe, and low-cost way.

Defender [7], a horizon 2020 innovation project, studies critical energy infrastructures’ security, resilience and self-healing by design. Defender will adapt, integrate, upscale and validate a number of technologies and deploy
them within an integrated framework to address these issues. Blockchain is not at the center of this project, its technology will be leveraged for providing peer-to-peer trustworthiness.

eDream [9] is a research a horizon2020 project, with their first publication [34] discussed in previous section. eDream works on the redesign of traditional market approaches and smart grid operations. Their aim is the creation of novel decentralized and community-driven energy systems fully exploring local capacities, constraints and Virtual Power Plants-oriented optimization in terms of local and secure grid nodes stabilization.

SealedGRID (MSCA-RISE) studies security threats inherited to Smart Grid from the ICT sector, privacy issues and new vulnerabilities, related to the specific characteristics of the smart grid infrastructure. At the time of writing, no extra information related to this project is available.

SOFIE is based on the idea of using interconnected distributed ledgers as a cornerstone to build decentralized business platforms that support the interconnection of diverse IoT systems. The project promises to create three pilots in three different sectors: food chain, gaming, and energy market.

5. Entrepreneurial efforts

In Table 2 we have summarized the characteristics of the selected entrepreneurial efforts presented in this section.

Brooklyn Microgrid [4] is an energy project developed by LO3 energy and partners including Siemens AG and Centrica Innovations. This project is one of the first projects leveraging blockchain technology for P2P energy trading. The aim of this project is to study how the technology of blockchain can enable instant trading of solar energy between neighborhoods. More specifically, since April 2016, a pilot project runs in Brooklyn, which studies how buildings equipped with distributed energy resources can be integrated into a decentralized P2P electricity network. Five buildings, participating in the program, have installed photovoltaic systems on their top floor and produce energy. The amount of energy not consumed by these buildings is sold to five neighboring households. Buildings are connected through the conventional power network, while transactions are managed and stored by a central system based on blockchain.

Power Ledger [12] has developed a private Proof-of-Stake blockchain named EcoChain. EcoChain is currently in use in trials, while a transition to a modified fee-less Consortium Ethereum network is under development. Power
Ledger uses this private/consortium network to handle the transaction for P2P energy trading while public Ethereum blockchain is used to offer their POWR tokens to end users and exchanges. Power Ledger uses a second token named Sparkz, this token is issued against escrowed POWR tokens. Sparkz tokens are used by applications hosted on Power Ledger’s platform. These applications include P2P trading, wholesale market settlement, autonomous asset management, electric vehicles and more, with each level of development varying from conceptual design to operational.

Grid+[22] is building a hardware and a software stack. A smart agent that stores cryptocurrencies, processes payments and programmatically buys and sells electricity and a software stack making the payments. Short term plans include the operation of Grid+ as an energy retailer. Compared to current retailer Grid+ claims to lower variable costs, enable real-time payments and offer lower prices to consumers. Long term plans include enabling dynamic pricing computing real-time dynamic distribution costs, P2P markets and integration of wholesale market in the retail market. Grid+ has issued two cryptotokens, BOLT and GRID. BOLT is a stable currency with each BOLT being redeemable for $1 worth of energy on the Grid+ platform. GRID token were sold in a token sale, every GRID has the right to purchase 500 kWh of electricity at the wholesale price available to Grid+ platform. Grid+ plans to work on Ethereum future Raiden network.

WePower [19] introduces itself as a blockchain-based green energy trading platform. WePower enables energy tokenization, energy producers can issue energy tokens which represent energy they commit to produce and deliver. These tokens can be seen as a contract between energy producers and consumers. WePower platform wants to build through energy tokenization a global energy market and improve the currently existing investment ecosystem.

Verv[36] is developing a platform for trading at the grid edge. P2P trading will occur inside local communities. Trading will be executed on private blockchain networks, one for each community. Local community ledgers will publish a digest of all transactions to the public Ethereum ledger on a daily basis. All transactions taking place on Verv’s trading platform will be conducted using VLUX tokens, while the daily digest of data to Ethereum public ledger will include transaction fees paid in Ether. Verv wants to differentiate its self from other efforts by combining blockchain with data analytics, machine learning and IoT.

Irene [27] is not a trading platform but an electricity supplier. Irene
buys electricity from producers, at market prices or at the price they are entitled to, and sells it back to consumers at Irene’s retail tariff. Energy consumers can freely choose the energy producers from which they wish to energy from. Irene guarantees to the participating producers that all their available energy will be purchased. If the energy is not purchased by the participating consumers Irene sells the excess amount of energy back to the grid at wholesale price. The main difference between Irene and other efforts is the fact that Irene has used Stellar blockchain implementation. Tellus token is used inside Irene network and Stellar’s option to customize tokens so they can meet AML compliance regulation is used.

Share&Charge [14] is an open network developed by MotionWerk and its partners. It works on a decentralized digital protocol for electric vehicle charging. Share & Charge introduces a way for P2P car charging based on Ethereum BlockChain. Consumers will be able to control smart charging poles using an application without the intervention of an intermediary. Share&Charge goal is to offer a fully automated, global authentication, billing, and pricing solution without an intermediary. Share&Charge1.0 was based on Ethereum’s public blockchain network but due to challenges faced described in this post[18] Share&Charge2.0 will be based on a consortium blockchain network. Main obstacles faced on public network include transaction fees and pending transactions.

SolarCoin[16] is a digital currency. The owner of a solar system, when joining SolarCoin network is eligible to receive a 1 SolarCoin, from SolarCoin Foundation, for each 1 MWh of solar electricity produced. SolarCoins can be used as digital currency or they can be traded for government currencies (fiat) on global cryptocurrency exchanges. SolarCoin has its dedicated blockchain network. The implementation is based on a fork from LiteCoin source code.

Intelen, a Greek company, in cooperation with University of Piraeus, are currently implementing a system for peer-to-peer exchange of energy between prosumers, using blockchain technology. This system will be a part of Intelen’s digital platform, and will enable consumers to participate in real time energy markets. All peer-to-peer transactions will be certified through blockchain technology, and special digital wallets will also be used, which will be interconnected with the loyalty system of Intelen’s platform [5].
## Table 2: List of Entrepreneurial efforts

| Platform            | Platform          | Token            | ICO   | Market Cap       | refs |
|---------------------|-------------------|------------------|-------|------------------|------|
| Brooklyn Microgrid  | Ethereum          | Exergy           | -     | -                | [4]  |
| PowerLedger         | Ethereum          | POWR, Sparkz     | $34m  | $167.01m(POWR)   | [12] |
| Grid+               | Ethereum          | GRID, BOLT       | $40m  | $19.41m(GRID)    | [22] |
| WePower             | Ethereum          | WPR              | $40m  | $47.21m          | [19] |
| Verv VLUX           | Ethereum          | VLUX             | July 2018 | -       | [36] |
| Irene               | Stellar           | TLU              | Aug 2018 | -       | [27] |
| Share&Charge        | Share&Charge      | -                | -     | -                | [16] |
| SolarCoin           | Litecoin          | SLR              | -     | $14.71m         | [16] |
| Intele              | -                 | -                | -     | -                | [5]  |

### 6. Concluding remarks

Apart from a few first implementations, the applicability of bc to the power grid is still largely theoretical. At this stage, some early participants are designing power and device authentication systems. But for the most part, the scientific community is trying to find out how the technology of Blockchain could be implemented and how it can be started. In other words, the question must be answered, is the technology that will make a decisive contribution to the completion of the so-called energy transition? Some answers that the community of people working on Blockchain and Smart Grids has attempted to do is the following:

**Why Blockchain?**

- Fast, cheap, secure and transparent transactions between multiple members.
- Autonomous distributed trading markets with low operating costs and almost instantaneous conciliations and settlements.
- A "no confidence" system without the need for intervention or interpretation by any contractor.

**What are the benefits of using Blockchain in the energy sector?**

- Enhanced finance for photovoltaic systems and battery storage.
- Solve the spilt-incentive problem with multi-owner properties.
• Increases the value utilization and therefore the value of network assets.
• Easier access to low cost electricity.
• Reduces wastage of power in transmission.
• Provides a platform for generating or saving sharing power.

The fact that the needs of the electricity grid, such as those encountered with the entry of an increasing number of renewable sources, coincide with the possibilities offered by the technology of Blockchain makes us believe that its use in the energy sector has a lot to offers. One element that reinforces this view is the fact that over the last two years many new businesses have been created and consortia have been formed between big companies from the energy sector and newcomers to study these possibilities and create products. Primarily, these efforts focus on implementations that include peer-to-peer energy trading and pricing applications.

7. Research Propositions

We conclude this paper by presenting abstract propositions for further elaboration and research by the energy community. The first propositions are focusing more on the consumer perspective and the latter on.

Prop 1 Double auctions (see below)

Prop 2 Storage into markets, perhaps the easiest solution is through Blockchain.

Prop 2 Investigate the implementation of a distributed application with the technology of Blockchain and the use of smart contracts to operate a real-time energy markets at large scale, as these described in the models developed for the USA in [25].

A smart grid based on Blockchain coupled with real-time auctions and smart meters can be the key to the energy transition effort as advocated by several, including Siemens [15, 3]. As far as we know, to date there has been no organized effort to implement a Blockchain real time auctions mechanism.

There is an effort by DomRaider [8] to develop a technology solution for managing real-time auctions worldwide. According to its creators,
any kind of commodity, whether physical or virtual, can be sold using their Blockchain network.

Another effort comes from the distributed AuctionHouse [1] application. This application is based on an intelligent contract that is currently in the testing phase and runs the Ethereum Ropsten Testnet network public test. After the testing phase, its creators are aiming to run on the Ethereum public network. This smart contract will implement the auction of goods the property of which can be transferred using Blockchain. the needs of the power grid, as these are borne by the introduction of an increasing number of renewable sources, coincide with the possibilities offered by the technology of Blockchain makes us believe that its use in the energy sector has much to offer. One element that reinforces this view is the fact that over the last two years many new businesses have been created and consortia have been formed between big companies from the energy sector and newcomers to study these possibilities and create products. Primarily, these efforts focus on implementations that include peer-to-peer energy trading and pricing applications.

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