Revolutionizing Electricity Trading: Blockchain-Enabled Game Theory Approach for Distributed Generation

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Abstract: The rapid growth of distributed generation (DG) systems, coupled with advancements in blockchain technology, has spurred interest in innovative approaches to electricity trading within decentralized energy networks. This research project presents an in-depth exploration of electricity trading for distributed generations using a game theory approach, facilitated by blockchain technology. By leveraging the principles of game theory, this study aims to analyze the dynamics of electricity trading among various participants in a distributed energy ecosystem and design efficient trading strategies that enhance market efficiency, participant collaboration, and grid stability.

The project focuses on developing a comprehensive framework that integrates blockchain - based smart contracts to automate and secure peer-to-peer electricity transactions. Through the application of game theory models, the interactions among various stakeholders, including prosumers (producer-consumers), consumers, and utility companies, are examined. The proposed approach seeks to address challenges related to market power, uncertainty, risk, and fairness while optimizing economic benefits for participants.

This research project provides broader understanding of blockchain's potential in reshaping electricity trading paradigms for distributed energy resources. Additionally, the application of game theory models offers insights into optimal strategies that participants can adopt to maximize their benefits while contributing to overall grid efficiency. As the world moves towards a more decentralized and sustainable energy landscape, this research project provides valuable insights into the role of blockchain and game theory in enabling efficient and collaborative electricity trading within distributed generation system.

1. Introduction

The late 19$^{\text{th}}$ century advent of electrification marked a pivotal moment in shaping the trajectory of the 20$^{\text{th}}$ century electricity system. Initially, a single electrical grid sufficed to connect power-generating utilities with consumers, leading regional utility companies to establish themselves as natural monopolies, firmly entrenched in every aspect of the electricity supply chain. This monopolistic landscape necessitated stringent regulatory oversight.

However, beginning in the 1990s, a significant transformation unfolded in both Europe and North America. A gradual process of unbundling dismantled the monopolistic structure, and the electrical grid was opened up to broader access. This ushered in an era of heightened competition, with the introduction of wholesale and retail markets further reshaping the landscape. Consequently, the market design of the electricity sector became considerably more intricate.

More recently, the imperative of addressing climate change has emerged as a driving force, propelling the widespread adoption of renewable energy sources (RES). This evolution, while environmentally crucial, has

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compounded the complexity of the sector. The intermittent nature of most RES sources introduces unpredictable fluctuations that are challenging to manage. Moreover, the expansion of renewable energy sources places significant strain on established utilities and poses challenges to grid infrastructure investment.

1.1. Relevance of Research Topic

A potentially major force for disruption to the way of doing business appeared in 2009. A person or group unknown to the public, called Satoshi Nakamoto, implemented a peer-to- peer (P2P) electronic cash system which runs on a publicly distributed ledger. The technology is commonly referred to as the blockchain and was introduced together with the cryptocurrency Bitcoin. In essence, blockchain technology allows P2P transactions within a network without relying on an intermediary or a central institution.

The first widely known project was the Brooklyn Microgrid[1], launched in a neighbourhood in Brooklyn, New York. The project successfully implemented a P2P electricity trading platform based on the blockchain in a microgrid setting. Around the world, several blockchain have been introduced by start-ups and utility companies such as Vattenfall in the Netherlands, Innogy in Germany, Wien Energie in Austria and Power Ledger in Australia.

Even though the blockchain has already been successfully implemented on a microgrid level, many uncertainties remain at the large-scale implementation level regarding how the technology fits into the current electricity market design. The unanswered questions include the required characteristics of the blockchain, its consequences for existing and new market actors, its impact on electricity market design as well as economic and regulatory issues.

As these trends allow for new business models to thrive, small enterprises will continue to enter the electricity value chain to offer services and solutions along the smart-grid value chain.

1.2. Research Question & Scope

Blockchain-based applications within the electricity market are not only new to the energy business but also a young field within academic research. Researchers so far have analysed how blockchain technology can support the energy management of the distribution grid and within residential microgrids while integrating distributed RES (Danzi et al., 2017). Furthermore, Mihaylov and Van Moffaert have introduced a digital currency that allows prosumers on the smart grid to trade their produced renewable energy (Mihaylov et al., 2014).

While the academic research mentioned analyses how blockchain technology can be used to solve some of the open questions and issues concerning the electricity market, it does not address business cases and opportunities. Research covers business models involving the smart grid or explores business models that encourage the flexibility of distributed energy resources (DER). Hence, there is a research gap regarding business models based on the blockchain within the electricity market.

The objective of the thesis is to identify blockchain-based business models within the electricity market and to analyse the applicable business models' value proposition for prosumers and consumers. The research further investigates the application of game theory to electricity trading. It proposes an alternate market making structure for efficient trading in the electricity trading sector. The said structure also investigates how the blockchain can

[1] More on this: https://www.brooklyn.energy

be implemented to facilitate a climate-friendly and distributed energy system. Hence, the following questions are raised and addressed in this research:

Clarifying Questions
What are electricity markets?
What are distributed ledger technologies and the blockchain?
What game-theoretic concepts are applicable to trading?

Table 1. Clarifying Questions

Research Questions
What are the existing blockchain-based business models within the electricity market?
How can game-theory and blockchain assimilate to give a stable market structure?

Table 2. Research Questions

1.3. Structure of the report

The core of this report is structured into six key sections, each contributing to the comprehensive exploration of the research topic. Following the introduction in Section 1, Sections 2 and 3 lay the foundational groundwork for the report by addressing key questions outlined in Section 1.2. Section 2 provides an in-depth analysis of current trends in the electricity market, examining both global and local perspectives to offer a holistic view of this dynamic sector. In Section 3, we delve into critical technological and economic developments, with a particular focus on the sharing economy and the transformative potential of blockchain technology. Section 3.2 further elaborates on the intricacies of blockchain technology. Moving forward, Section 4 delves into the realm of game theory, explicating essential concepts such as the Nash equilibrium, leader-follower games, and other pertinent ideas with direct applications to electricity trading.

Sections 5 and 6 directly address the research questions outlined in Section 1.2. Section 5 scrutinizes emerging blockchain-based business models within the electricity market, subjecting them to thorough analysis and evaluation. Following this, in Section 6, we put forth innovative and stable market structures that seamlessly integrate both blockchain technology and game theory, proposing potential solutions for enhanced efficiency in electricity trading.

Finally, Section 7 synthesizes the report's main findings and offers insights into the study's limitations, providing a cohesive conclusion to this comprehensive exploration of blockchain's role in shaping the future of the electricity market.

1.4. Literature Review

The integration of blockchain technology within the energy and electricity market context has become a prominent subject of inquiry in both academic literature and practical applications. This comprehensive literature review draws upon an extensive range of sources, utilizing databases and search engines such as Elsevier Discovery, IEEE database[2] as well as Google Scholar and Google. The primary objective of this research was to provide a comprehensive overview of blockchain's evolving role within the energy market and to forecast its potential future impact. To accomplish this, our inquiry centered around specific keywords, including '*energy blockchain*,' '*electricity blockchain,*' '*blockchain in the energy sector,*' and '*blockchain and game theory in the electricity market.*' This focused approach allowed us to capture a broad spectrum of relevant information, providing valuable insights into the dynamic developments within this emerging intersection of energy and blockchain technology.

Author	**Type**	**Research Area**	**Method**
Mihaylov et al. (2014)	Conference	Electricity trading; digital currency	Theoretical concept
Danzi et al. (2017)	Journal article	Electricity trading; smart contract	Simulation
Merz (2016)	Book chapter	Electricity trading; blockchain properties	Conceptualisation
PwC (2016)	Report	Energy trading; blockchain use cases	Qualitative discussion
Wencong Su. et al. (2014)	Journal article	Electricity Market; Game Theory	Simulation
Chen S. et al. (2021)	Journal article	Distributed Generations; Trading	Theoretical concept
Roman Gayduk (2017)	Thesis	Game Theory; Market Modeling	Interviews discussion
Burgwinkel et al. (2016)	Book chapter	Blockchain Business Models	Conceptualisation
Dai T. & Ciao W. (2013)	Journal article	Bidding Strategy; Game Theory	Proof-of-concept
CGI Group (2017)	Report	Energy trading; blockchain use cases	Qualitative evaluation

Table 3. Literature Overview of Blockchain in the electricity market

The synthesis of the literature review underscores several key observations regarding the intersection of blockchain and the energy market. First and foremost, the prevalent focus within this realm predominantly revolves around three core themes: energy trading (Mihaylov et al., 2014), peer-to-peer (P2P) transactions (Gayduk, 2017), and the utilization of smart contracts (Danzi et al., 2017). These themes collectively represent the driving forces shaping the application of blockchain technology in the energy sector, followed closely by discussions elucidating the inherent properties of blockchain and its diverse range of use cases.

Secondly, it is notable that a significant proportion of literature on this subject originates from non-academic sources, primarily emanating from management consultancies like PwC (Dutsch and Steinecke, 2017; CGI, 2017) and other non-academic institutions, including startups that have articulated their insights through white papers. Notably, PricewaterhouseCoopers (PwC) stands out as a prominent contributor in this regard, offering concise publications that effectively map out blockchain applications and use cases across the entire electricity value chain.

Thirdly, the review reveals that only a limited number of journal articles delve into the technical intricacies of blockchain applications specifically tailored to electricity trading or energy management (Chen et al., 2021). This suggests a potential gap in the academic literature, with an opportunity for further research to explore the technical underpinnings of blockchain's implementation within the context of the energy sector.

The analysis, while valuable at a technical level, currently lacks the critical dimension of practical implementation

[2] accessed via Shiv Nadar IoE

from a business perspective. It has yet to provide clear guidance on how blockchain technology should be effectively integrated into the energy sector's business framework. Furthermore, it leaves open questions about which precise business cases and opportunities can effectively tackle the unique challenges posed by this technology.

One conspicuous gap in the existing body of research is the absence of comprehensive exploration and development of business models grounded in blockchain technology within the electricity market. This research void stands at the intersection of technical, academic research and real-world, use-case-oriented publications by companies operating in the field.

This thesis endeavors to bridge this significant research gap by offering a nuanced and holistic perspective that not only delves into the technical aspects of blockchain but also navigates the intricate landscape of business implementation within the electricity market. Through a meticulous examination of blockchain's potential business applications, this research aims to provide valuable insights into how the technology can be harnessed to address the industry's unique challenges and opportunities, thereby facilitating a more seamless transition from theory to practice.

2. Trends in the Electricity Sector

This section provides a comprehensive overview of the structural components of the electricity system. Initially, we introduce and elucidate the fundamental elements that constitute the electricity system. Building upon this foundational understanding, we offer both a localized and a global perspective on the subject. Within this context, we delve into the intricacies of the electricity market, shedding light on the diverse array of stakeholders and entities that actively participate in this dynamic ecosystem. Furthermore, we embark on an in-depth exploration of power exchanges, pivotal institutions within the electricity market. To illustrate the practical application of these concepts, we showcase a selection of sample products that are traded on these power exchanges.

2.0.1. Electricity Grid

The electricity grid serves as the essential link between power generation at plants and end-user consumption. Initially, electricity is generated at power plants, then converted from low voltage to high voltage for efficient long-distance transmission through high-voltage lines. Subsequently, high-voltage electricity is transformed back to low voltage at substations to enable safe and compatible distribution for industrial, commercial, and residential applications. High voltage optimizes efficiency and cost-effectiveness during extended transmission, while low voltage prioritizes safety and compatibility, ensuring the electricity grid's reliable and efficient operation.

2.0.2. Electricity Market

In the conventional electricity industry market structure, power supply operated through a vertically integrated system operator (SO) overseeing the entirety of the supply chain. This setup designated transmission and distribution of electricity as natural monopolies. Essentially, a single company reaped the advantages of economies of scale because a singular transmission and distribution grid proved sufficient. This differed from a scenario where multiple companies managed parallel grids, which would be less efficient (Wangensteen, 2012).

To enhance efficiency and promote the well-being of the public, Europe embarked on a power market restructuring initiative in the early 1990s. While public ownership continued to be widespread, integrated operators were deliberately separated along vertical lines. Consequently, the power generation sector transformed into a fully competitive arena, while stringent regulations were imposed on the transmission system (TSO) and distribution system operators (DSO) due to their inherent natural monopoly characteristics. Independent power producers now exclusively bear the responsibility for power generation. Furthermore, this liberalization opened the doors for new power producers to enter the market, fostering a notable increase in competition (Wangensteen, 2012).

Within the revamped electricity market structure, Transmission System Operators (TSOs) assume ownership and operation of the primary grids. Their extensive responsibilities encompass several critical facets:

1. Ensuring Uninterrupted Power Supply: TSOs are entrusted with the vital task of maintaining a consistent and uninterrupted electricity supply.
2. Balancing Power Generation: They play a pivotal role in balancing the electricity generation within the system, ensuring that supply meets demand effectively.
3. Managing Capacity Margins: TSOs are responsible for maintaining adequate capacity margins both in the power generation system and the grid itself, guaranteeing system reliability.
4. Monitoring and Controlling Parameters: They diligently monitor and control the frequency and voltage levels within the grid to ensure the stability of the power system.
5. Tariff-Based Compensation: TSOs receive compensation through tariffs whenever electricity is sold to end customers, reflecting their role in maintaining the grid's operational integrity.

Regulatory authorities play a vital role in overseeing the monopolistic activities of both the System Operator (SO) and grid companies within the electricity industry. Their primary objective is to promote market efficiency by enforcing policies that ensure third-party access and maintain control over these entities. Given the physical interconnection of power systems, a pivotal tool in achieving market equilibrium is the power exchange.

The power exchange serves as a central platform facilitating the intricate process of matching supply and demand within the electricity market. It effectively manages the submission of bids for the sale and purchase of electricity, leading to the determination of prices and quantity. This mechanism not only streamlines transactions but also contributes to the overall stability and competitiveness of the market.

Electricity demand or consumption exhibits price inelasticity in the short term due to the lack of viable substitutes for electricity. This demand can be visualized through a load-duration curve, reflecting the dynamic nature of individual consumers' electricity needs, which vary over time. Residential, commercial, and industrial consumers each demonstrate distinct load patterns, influenced to varying degrees by external factors. Broadly speaking, households experience peak demand in the morning and late afternoon/evening, while offices consume the most energy during typical business hours. Furthermore, both households and offices are susceptible to temperature fluctuations, impacting electricity demand for heating and air-conditioning purposes. On a broader scale, these individual load curves are aggregated to define the electricity demand, commonly categorized into peak, mid, and base load, reflecting different levels of demand throughout the day.

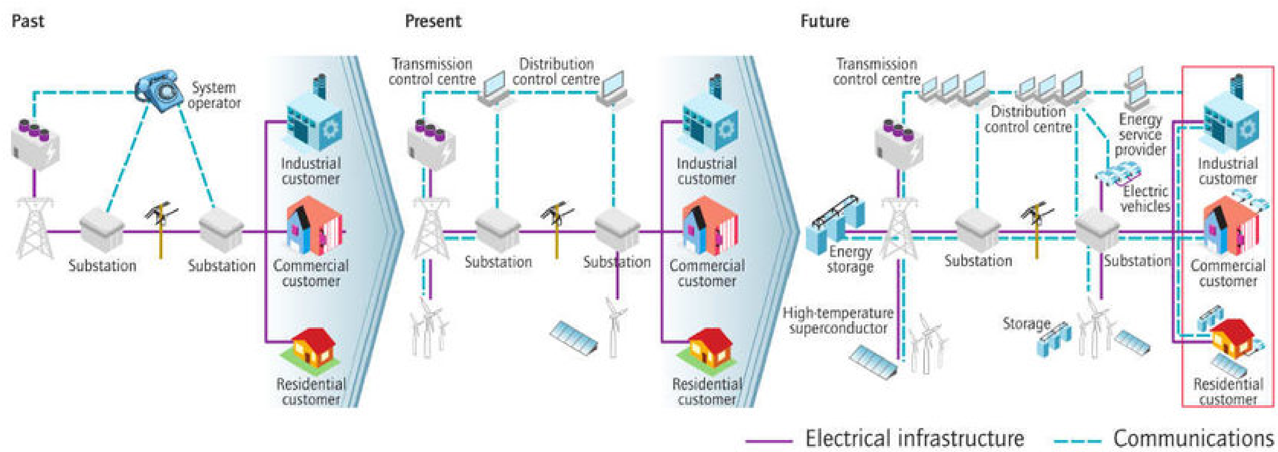

Figure 1. Depiction of the evolution of electricity grid; The past, present and the future

2.1. Market Design and Trading

There are generally two primary avenues for reducing energy and power costs: a) lowering the price of energy and power that consumers pay, and b) reducing overall energy and power consumption. Despite increased efforts to promote energy conservation and efficient generation, it remains challenging to reduce energy consumption significantly, mainly due to the expanding demands of modern living. Consequently, the current emphasis is on optimizing the price of energy and power for consumers. Achieving this goal hinges on efficient production methods and a well-structured procurement process. However, crafting the right procurement strategy can be intricate and overwhelming. Therefore, there arises a pressing need for a Power Exchange, providing a platform where both producers and buyers can access a competitive market.

The Power Exchange serves as a central hub where market prices are determined based on supply and demand dynamics, encompassing spot prices for short-term trading and forward prices for future dates. Key stakeholders in the Power Exchange include: a) power producers, b) power retailers, and c) large end-users. The significance of energy and power trading through exchanges has seen exponential growth in Europe and other regions due to the escalating energy consumption and the drive towards market integration. In today's interconnected world, few countries can solely rely on their indigenous energy and power sources to meet their needs. Engaging in energy and power trading through exchanges offers several advantages, including ensuring a steady supply of energy and power and safeguarding against supply shortages and price fluctuations.

Today, almost no country can address its energy/power needs from its own sources. Energy/power trading through exchange ensures: i) required supply and ii) protection from supply shortages and price fluctuations.

There are several regional or in-country energy and power exchanges that have been established in Europe, North America and Australia. Some major power exchanges are:

- Nord Pool Spot for Nordic countries (Sweden, Finland, Denmark and Norway) and Baltic States (Latvia, Lithuania and Estonia)

- EPEXSpot for France, Germany, Switzerland and Austria
- Nodal Exchange for North America (USA, Canada)
- Australian Energy Market Operator (AEMO) for Australia

3. Socio-Economic and technological developments

After the trends within the electricity markets have been discussed, the following chapter introduces technological and socio-economic developments that develop outside the electricity market: **the sharing economy** and the **blockchain technology.** This serves as a basis to analyse how a business model can utilize the blockchain and build upon existing trends to influence and address the challenges of the electricity market.

3.1. Sharing Economy

The sharing economy is a highly ambiguous term for a socio-economic concept which broadly describes organised resource sharing by individuals using a platform; or, as (Greenhouse, 2016) describes it:

"It's a hip, fast-growing sector of the economy, filled with headline-grabbing companies: Uber, Lyft, Airbnb, Task Rabbit. But there's a gnawing problem: People aren't sure what to call it. Many critics dislike the term most commonly used, the "sharing economy," because there often isn't much actual sharing going on. Others prefer to call it the on-demand economy, peer-to-peer economy, crowd-based economy, gig economy or collaborative economy. (Greenhouse, 2016)"

In summary, the sharing economy can be described as a socio-economic concept that summarizes social components, such as the willingness of consumers to become producers by sharing goods or offering service to other consumers, and economic concepts, such as online platforms that enable the exchange and interaction needed for these transactions. Although the sharing economy is a development that neither exclusively nor intensively focuses on the electricity market, it has three relevant influences on the electricity market's development.

Firstly, the sharing economy shows that alternative, collaborative-focused business models can be successful (Lombardi and Schwabe, 2016). From a conceptual perspective, this facilitates a transfer of these models to the electricity market. From an operational perspective, it eases the implementation of such models as investors are more willing to fund innovative, collaborative business models.

Second, the development of the sharing economy changes the overall perception and behaviour of customers. Consumers are becoming used to now owning an asset, but retrieving the needed service from another consumer. Similarly, the population is becoming more open to share the assets they own with other consumers (Rousselet, 2014). This facilitates the emergence of sharing-economy-based models in the electricity market, as their acceptance among end-consumers is already established through existing collaborative services.

Third, the rise of the sharing economy also increases acceptance of collaborative approaches among existing supply-sided market participants. (Valdman, 2016) points out that it is not the technical possibilities that prevent the electricity market from evolving further, but that instead it is the "sociology, not the physics, that stands in our way". Hence, it is important that existing experiences prevent over-regulation and facilitate an open approach to collaborative business models.

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