Blockchain-Enabled Game Theory Approach for Distributed Generation (BEGT-DG)

EED497 Major Project I

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ABSTRACT

As we witness the ongoing shift towards a more decentralized and flexible energy landscape, the significance of blockchain-based smart contracts in the energy sector is gaining prominence. These smart contracts, known for their automatic execution, adaptability, and resistance to tampering, are emerging as a pivotal technology in facilitating the evolution towards a more efficient, open, and transaction-driven energy market. This paper explores the integration of blockchain and game theory in the context of distributed generation. It utilizes a cournot game model to simulate electricity trading with mergers, revealing insights into market dynamics and participant strategies. To offer a clear path for both researchers and practitioners interested in this technology, we introduce a structured model for the smart contract process. This model comprises a unique 6-layer architecture and includes the presentation of an illustrative energy contract in both pseudocode and open-source code formats. Our study primarily focuses on two key areas where smart contracts are applied: energy and flexibility trading through game theory, and decentralized control. The paper concludes with a detailed discussion highlighting the advantages and challenges that require consideration in the field of smart contracts and blockchain technology in the energy sector.

KEYWORDS

Electricity Trading, Game Theory, Blockchain, Distributed Generation, Smart Contracts, Energy Trading, Transactive Energy, Smart Grids, Decentralized Energy Systems

1 INTRODUCTION

Traditional energy trading has historically relied on centralized systems involving numerous intermediaries. Nevertheless, as the demand for energy consumption rises, particularly in growing urban areas, there is a pressing demand for novel solutions capable of addressing these issues more effectively. Decentralized models have demonstrated the potential to enhance efficiency and scalability by approximately 50% [1] in contrast to conventional centralized systems. The traditional boundary between energy producers and consumers is becoming increasingly blurred due to the emergence of distributed generation, primarily driven by commercial and residential Photovoltaic (PV) installations.Initially, the growing presence of distributed generators with advanced infrastructure empowers residential consumers to capture energy and feed it into the distribution network. This development introduces fresh participants to the grid and contributes to the increased decentralization of the smart grid. Additionally, the increased number of participants across a broader geographical area has improved the efficiency of energy trading systems. As a result, there is a shift in focus from the conventional role of a central entity, such as an auctioneer, to more efficient management of these systems. [27]

Ever since the release of Satoshi Nakamoto's influential whitepaper introducing the cryptocurrency Bitcoin in 2008 [5], blockchain technology has garnered significant attention [10]. This technology is frequently linked to cryptocurrencies, primarily due to the notable disruption it has caused in the banking and financial sectors. Cryptocurrency has become a popular subject in investment circles as a growing number of people acquire digital assets [7], including Ether, Litecoin, or the previously mentioned Bitcoin. With the increasing acceptance of cryptocurrencies as a form of payment by numerous businesses and services, it is becoming increasingly evident that their current and potential impact as an alternative to traditional fiat currency cannot be disregarded.

Wind and solar energy technologies have rapidly advanced in recent years as a result of supportive energy policies, economic incentives and changes in the sector, such as the establishment of energy communities and microgrids [19]. Creating energy communities involves active participation of consumers, which may involve engagement in energy trading, investment in renewables or partaking in initiatives for energy autonomy and/or self-sufficiency.

1.1 Relevance of the Research Topic

The decentralised nature of a blockchain- based environment allows for a trust-free energy market without a central mediator [17] (besides the trust put in the operation of the smart meter and the electrical installer). The dynamic nature of such a market allows for real-time distributed decisions [9], such as reacting to demand or fluc- tuating renewable generation. A P2P energy trading system has been successfully implemented on a microgrid level. A proof of concept and working example of such a P2P energy trading case is the Brooklyn Microgrid[1], operated by LO3 Energy in New York [20]. Involved parties were found to save significantly on their electricity bill, especially those who contributed generation to the marketplace. The project has seen considerable success, such that an addition project has been implemented on a larger scale in Vermont.

Even though the blockchain has already been successfully implemented on a microgrid level, many uncertainties remain at the

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

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. The major contributions of this paper include the following three aspects:

(1) Propose (via simulation) a novel electricity trading process incorporating Game Theoretic principles.
(2) Propose a systematic model of the smart contracting process, by developing a novel 6-layer architecture, as well as presenting a sample energy contract in pseudo-code form.

1.2 Literature Review

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 [8]. Furthermore, Mihaylov and Van Moffaert have introduced a digital currency that allows prosumers on the smart grid to trade their produced renewable energy [18].

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 database2 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.

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 [18], peer-to-peer (P2P) transactions [13], and the utilization of smart contracts [8]. 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 [11, 14] 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 [6]. 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. This paper aims to fill a notable research gap by presenting a comprehensive perspective that not only explores the technical intricacies of blockchain but also navigates the complex terrain of business implementation in the electricity market. By thoroughly examining blockchain's potential business applications, the research seeks to offer valuable insights into leveraging the technology to tackle the unique challenges and opportunities within the industry. In addition, it introduces the novelty of incorporating game theory into the context of electricity trading, contributing to a more seamless transition from theoretical understanding to practical implementation.

2 BACKGROUND

This section presents background information and fundamental principles regarding the definition of a blockchain, a smart contract, including an example of a generic energy smart contract as well as game theoretic principles that are applicable to electricity markets.

2.1 Blockchain Technology Overview

Intuitively defined, a blockchain is a chain of information blocks (usually, containing information about crypto-currency transactions or smart contract specifications), linked together through cryptographic methods. It has alternatively been described as an append-only log, or a distributed ledger of transactions [26]. Unlike a centralised database, this ledger is distributed, meaning no single party has control over writing information to the blockchain. In fact, a number of nodes or peers all have a copy of the whole blockchain (or the key information of the chain), and mutually agree on how the information can be written/added through a consensus protocol.

The next major evolution in the blockchain space came in the form of smart contracts. These were first conceptually proposed by Nick Szabo in 1997 [21] as immutable scripts that execute automatically under specific circumstances, without any third party involvement [22]. The first and most notable platform for actually implanting smart contracts comes in the form of Ethereum, a next-generation blockchain that functions as a Turing-complete world computer [25]. Smart contracts on the Ethereum blockchain process cryptographic assets strictly according to predefined rules. The aptness of the execution of these smart contracts is verified using similar principles that govern the verification of Bitcoin transactions. For this reason, the execution of a smart contract cannot be impeded or interfered with by any party.

2.2 Game Theoretic Principles

The application of game theoretic principles in electricity trading introduces a dynamic and strategic dimension to the conventional models. In this context, participants, including producers, consumers, and utility companies, are viewed as strategic decision-makers engaging in a competitive or cooperative game. Game theory provides a framework to analyze the interactions, strategies, and outcomes within the electricity market. By incorporating strategic thinking and anticipating the actions of others, game theory offers valuable insights into optimal decision-making strategies, market dynamics, and overall system efficiency. This introduction explores the pivotal role that game theoretic principles play in reshaping and optimizing electricity trading scenarios, providing a nuanced understanding of the strategic interplay within the evolving energy landscape.

Game theoretic principles in literature form a foundational framework for understanding strategic interactions among participants in various scenarios, including electricity trading. One notable model within this realm is the Cournot model, which has proven particularly appropriate for the nuanced dynamics of electricity trading. The Cournot model, originating in economic theory, captures the essence of strategic competition among firms that simultaneously set production quantities. In the context of electricity trading, where producers (generators) determine their output levels, the Cournot model aligns well with the decentralized nature of the market.

3 METHODOLOGY

The Cournot model's suitability lies in its ability to represent the strategic decision-making of individual market participants, such as power producers, who aim to maximize their profits by adjusting their output levels. It acknowledges the interdependence of producers, recognizing that each participant's decision affects the market price and, consequently, the profits of others. This mirrors the intricacies of electricity trading, where producers must strategically adjust their generation levels based on anticipated actions of others.

3.1 Defining the market

We assume a linear Inverse Demand Curve,

$$P = A - B * Q$$

where P is the Price and Q is the total demand.
We also assume that the first derivatives of the Cost Curves of our companies are:

$$MC_i = K_i \; M_i q_i$$

where **i** is the number of the company.

3.2 Calculating production levels

Since the companies are in a **Cournot market game**, each one of them is going to maximize its profits, by adjusting its production, according to the demand and its competitor's production.

$$max \Pi_i q_i => MR_i = MC_i \; 1$$

$$...$$

$$for\; i = 1,\; 1 \;=>\; M_1 \; 2 * B * q_1 \; B * q_2 \; B * q_3 = A - K_1$$

$$for\; i = 2,\; 1 \;=>\; B * q_1 \; M_2 \; 2 * B * q_2 \; B * q_3 = A - K_2$$

$$for\; i = 3,\; 1 \;=>\; B * q_1 \; B * q_2 \; M_3 \; 2 * B * q_3 = A - K_3$$

$$Or$$

$$\begin{bmatrix} M_1 \; 2 * B & B & B \\ B & M_2 \; 2 * B & B \\ B & B & M_3 \; 2 * B \end{bmatrix} * \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} A - K_1 \\ A - K_2 \\ A - K_3 \end{bmatrix}$$

3.3 Cournot Market Game for N companies

We observe that the matrix that solves for the production units of each company, follows a clear pattern.

On the left side, the diagonal, is

$$MC_i \; 2 * B,\; where\; i = 1, 2, 3...N,\; for\; N\; companies$$

On the right side,

$$A - K_i,\; where\; i = 1, 2, 3...N,\; for\; N\; companies$$

In order to create a function *(in Python)* to calculate the units of production for any number of companies we:

1. Create an N x N matrix, X, where every element is *B*, the slope of the inverse demand curve

2. Two N x 1 arrays that are composed of the elements mentioned above,

$$X : \begin{bmatrix} B\,B\,B\,...B \\ B\,B\,B\,...B \\ ...\,...\,... \\ B\,B\,B\,...B \end{bmatrix},\; D : \begin{bmatrix} MC_1 \; 2 * B \\ MC_2 \; 2 * B \\ MC_3 \; 2 * B \\ ... \\ MC_N \; 2 * B \end{bmatrix} \; and\; U : \begin{bmatrix} A - K_1 \\ A - K_2 \\ A - K_3 \\ ... \\ A - K_N \end{bmatrix}$$

3. Replace the diagonal of matrix X, with matrix D to create matrix H.

4. Finally, if we solve $H * q = U$ for q, we get the production units for every company competing in the market.

3.4 Implementation

The theoretical framework discussed above was translated into a practical implementation using Python. The implementation involved simulating a 3-player Cournot game, with subsequent incorporation of mergers to replicate the market-making process observed in real auctions. Each player underwent a merger in various combinations within the three-player game to assess the impact on market dynamics. The implementation code, derived from extensive literature reviews, has been tailored to suit the objectives of this paper. Available on GitHub, this code serves as an initial proof of concept, suggesting that, based on the simulation outcomes, players are better off competing in an auction rather than opting for mergers

4 CODE SIMULATION

This section presents the results of the python simulation for a 3 player Cournot game for simulating electricity trading.

4.1 Experimental setup

The experimentation was conducted within a Jupyter environment on a high-performance M1 Pro MacBook Pro, equipped with 16GB of unified memory. The source code is open-sourced and accessible on GitHub [GitHub Repo], while the complete notebook can be viewed at [Notebook Location]. This hardware configuration was chosen for its robust computational capabilities to ensure reliable and efficient code execution during the experimental phase.

4.2 Results

We simulated a dynamic 3-player Cournot game to model the strategic interactions among market participants. The resulting profit outcomes for each company are detailed in Table 1. The iterative process utilizes the inverse demand function as input, with the overarching objective of maximizing profits for every player.

	Company 1	Company 2	Company 3
Profits	€ 12643.9	€ 20817.69	€ 20563.02

Table 1: Profits of individual companies

After companies **i** and **j** merge, we add the two marginal cost curves horizontally:

$$q_m = q_{iMC_i} \;\; q_{jMC_j},$$

where q_{mMC_m} is the inverse marginal cost curve of the new company, named m.

The new company, has now the following marginal cost:

$$MC_m = \frac{M_j * K_i \;\; M_i * K_j}{M_i \;\; M_j} \; \frac{M_i * M_j}{M_i \;\; M_j} * q_m$$

$$Or$$

$$MC_m = K_m \;\; M_m * q_m$$

Discussed below are the observations for post merger profits in comparison to the company that did not merge. Alongside there is also the pre-merger price of the non-merged company.

	Merged	Non-merged	Pre-merger
C1 & C2	€ 33461.59	€ 31936.7	€ 20563.02
C2 & C3	€ 50556.27	€ 22294.05	€ 12643.9
C1 & C3	€ 37659.68	€ 32458.15	€ 20817.69

Table 2: Profit post one-way merger of companies

As we simulate the mergers of two companies, by adding their q_{mc} horizontally, we can observe that the resulting companies produce fewer units. The competing companies are now fewer. The new equilibrium is closer to the equilibrium of a monopoly. However, the profits of the newly created company are less than the sum of the profits of the companies that merged. None of the above mergers are profitable, and the companies would rather compete than merge. The company that benefits from the merger is the one that did not take part in it. This happens because both its market share, and the market price, increase.The conclusion is that neither the consumers, nor the companies that took part in the merger, benefit from the merger. The only beneficiary is the company that did not take part in the merger.

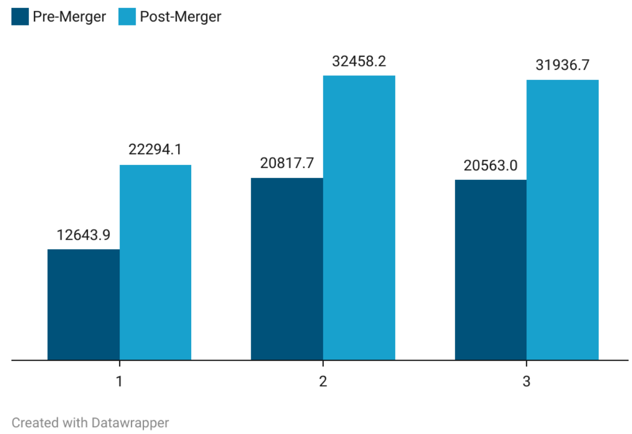

Figure 1: Profit analysis for non-merged company

5 ALGORITHM AND ARCHITECTURE

5.1 Flowchart

We present a sample smart contracting logic illustrated in Fig. 2, utilizing P2P energy trading as an illustrative example. The procedural flow begins with the contract's initialization, triggering the command to read the capacity and pricing information provided by the generators. It is assumed that the forecasting, estimation, and price selection processes occur at the generator's end. Subsequently, the generated offer is communicated to the potential buyers (consumers), initiating the bidding procedure.

Various techniques can be employed for price clearing, with the Double Auction being a commonly utilized method. This method involves ranking bids and offers in ascending and descending order, ultimately determining a clearing price. Notably, our contribution lies in the novel application of the Cournot Game Model to ascertain a clearing price. The initialization of an N-player Cournot game marks the beginning of the process. The system then simulates all the bids, aiming to maximize the profit for each producer while minimizing the overall production cost. This approach ensures a more competitive price for consumers, aligning with our objective to provide consumers with a favorable pricing structure for their power consumption.

The next step is to assess the physical feasibility of the allocations by inspecting the grid power flows. Then, the smart contract is updated with the outcome and the energy transaction is verified using the smart metre recording of the generator. Once verified, the total units and duration of generation are checked and any scaling and penalties are applied if necessary. Following this, the payment to the generators is authorised and the transaction is stored. This means that it is irreversible

5.2 Psuedocode

Algorithm 1 shows a brief pseudocode of a simplified smart contract for P2P energy balance update and transfer of funds. Separate data structures are created for consumers and prosumers as the information required from these agents are different. While the

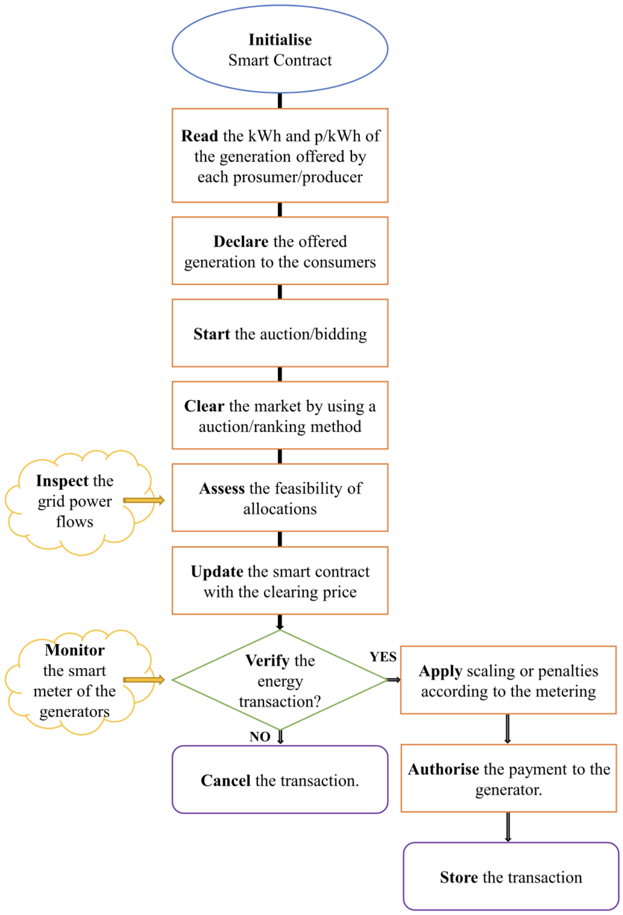

Figure 2: A sample smart contracting algorithm for P2P energy trading.

prosumer declares its hexadecimal identifier (i.e. address), *EnergyOffer* in KWh and e-wallet details, the consumer needs to input its ad- dress, *EnergyRequest* in kWh, the per-unit bid price and also their e-wallet details. The matched pairs for P2P trading would be input in the *LocalEnergyTransfer* which compares the requested and offered energy. If there is excess energy, the energy balances are updated accordingly and the total price is set as the product of the per-unit bid price and the energy requested by the consumer. On the other hand, if there is not enough local energy offered, the price is equal to the per-unit price multiplied by the energy offered by the prosumer.

5.3 Architecture

Encompassing various aspects from settlement mechanisms to cybersecurity, a multi-layered architecture is introduced to depict the information flow initiated by agent input. As illustrated in Figure 3, smart contract processing entails six layers that information traverses, spanning from user input to physical asset responses. These six layers are identified as follows: (1) Input from agents, devices, and the grid; (2) Energy management algorithms, encompassing

Algorithm 1 Pseudocode for a simplified P2P energy exchange balance update and transfer

```
Initialization
define PROSUMER(address, EnergyOffer, Wallet)
define CONSUMER(address, EnergyOffer, Wallet)
function LOCALENERGYTRANSFER(CONSUMER, PROSUMER)
    if prosumer.EnergyOffer > consumer.EnergyOffer then
        BalanceLocalEnergy ← consumer.BidPrice × consumer.EnergyRequest
        prosumer.EnergyOffer −= consumer.EnergyRequest
        consumer.EnergyRequest ← 0
    else
        BalanceLocalEnergy ← consumer.BidPrice × prosumer.EnergyOffer
        consumer.EnergyRequest −= prosumer.EnergyOffer
        prosumer.EnergyOffer ← 0
    prosumer.Wallet = BalanceLocalEnergy
    consumer.Wallet −= BalanceLocalEnergy
```

consensus and control algorithms; (3) Native smart contracting functions handling financial and gas transactions; (4) Blockchain functions responsible for verification, encryption, and other security measures; (5) Computational processes, including the various threads executed by the virtual environment (EVM); and (6) Communication layer facilitating the physical transfer of information between nodes.

Layer 1 serves as the data ingestion point, gathering information from various sources such as bids and offers from agents participating in peer-to-peer trading, availability signals from smart charging electric vehicles, and voltage levels from the grid to initiate automated demand-side adjustments. Layer 2, designed by energy researchers, utilizes the acquired data to implement energy management algorithms. This layer often incorporates novel optimization techniques, such as advanced settlement algorithms to reconcile discrepancies between contracted and delivered energy. Sophisticated decision-making processes, encompassing control algorithms and negotiations, also occur at this layer. To minimize computational expenses, these computations can be performed off-chain. Layer 3 involves smart contract programming, typically employing a dedicated smart contract language like Solidity. Instances of Layer 2 and Layer 3 being coded in different languages are common, necessitating their designation as distinct layers. This layer handles agent and device registration, financial transactions, gas usage calculations, and ultimately produces a digital contract comprising code and prose.

Layer 4 seamlessly integrates the smart contract onto a blockchain block, introducing the crucial aspects of verification and encryption. A widely used example is the Proof of Work mechanism employed by Bitcoin. Layer 5 handles the implementation and computation, interacting with virtual machines like the aforementioned EVM. Finally, Layer 6 facilitates information transfer through communication protocols, potentially involving machine-to-machine (M2M) communication via wired or wireless networks. For instance, the smart contract could initiate the transmission of information from a smart meter to a software application.

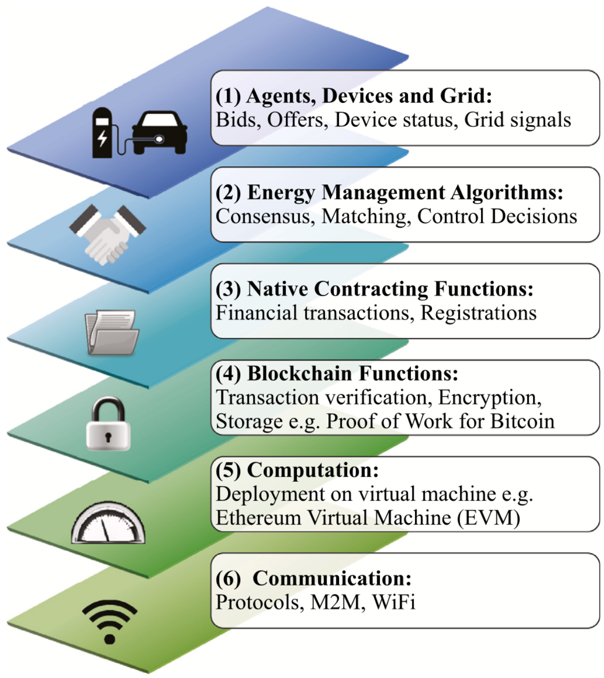

Figure 3: The 6-layer structure of smart contracting for electricity trading

6 FURTHER READING

In this section we provide a systematic review of reported applications in the energy area. Smart contracts have been proposed and used in many applications, ranging from energy trading to the coordination of distributed assets. The type of applications of smart contracts can be categorised into two main categories: *energy and flexibility trading* and *distributed control*. We follow these two main themes in this section and present all the different areas of energy applications.

6.1 Energy and flexibility trading

6.1.1 Peer-to-peer. Smart contracts are often employed for P2P trading applications. The smart contracts first receive the bids and offers from the different stakeholders (producers, prosumers and consumers), which usually also requires a deposit from the buyers. Different approaches are then used by smart contracts to match the buyers (consumers) with the sellers (producers). Approaches range from heuristic methods to more complex approaches that include double auctions and power flow validations. [24]

6.1.2 Peer-to-grid. Although the P2P area corresponds to the vast majority of smart contracts applications reported in published research, some works also use smart contracts for P2G transactions, as it is explained by Khalid et al. [16]. Indeed, after local P2P trades have been validated by a smart contract, remaining energy needs (or extra energy) can be traded between the consumers and the grid. In this case, the smart contract is used for billing purposes, but also to store and sign energy transactions between the prosumers and the grid [23], similar to the situation in the retail market category. When Peer-to-Grid transactions are required to compensate for energy shortage or surplus, the smart contract uses the grid electricity prices at the current hour in order to determine the amount of money required for the financial transaction.

6.2 Distributed Control

6.2.1 Electric Vehicle Management. In the field of electric vehicle (EV) charging systems, smart contracts can be used for different purposes. First, smart contracts can implement lighter optimisation algorithms such as limited neighbourhood search with memory to balance the distribution of EV users among parking spaces while achieving fair profits distribution among the owners of EV charging places [12]. One of the most popular application areas of smart contracting is smart charging for EVs [4]. Smart contracts are also used for peak load shifting and shaving by leveraging the flexibility of EV loads [28].

6.2.2 Virtual Power Plant. The concept of Virtual Power Plants (VPP) involves the operator that monitors the production or consumption of different assets in order to better coordinate and optimise the aggregated production [3] or reduce curtailment [2]. In this context, some authors [15] have proposed smart contracts to store and read data from distributed assets, in order to help for better synchronisation of the production.

7 CONCLUSION

Power trading systems represent a nonlinear and intricate domain with multifaceted functionalities and complex business processes. The integration of various data types and the sheer volume of data involved make these systems susceptible to challenges, particularly in ensuring the security of data and the reliability of transactions, especially when interacting with external business systems. This necessitates a focused approach to address these concerns.

This research centers on the core technology of a distributed power trading system, leveraging blockchain technology to achieve real-time power balance and establish the prerequisites for implementing smart contracts. The primary goal is to ensure the utmost reliability in power trading and data security. It also proposes a novel game theoretic order matching mechanism based on cournot games and mergers. It simulates the said mechanism using a 3 player game. The integration of blockchain technology and game theory principles presents a novel framework that addresses critical challenges in the domain of distributed generation. By leveraging decentralized consensus mechanisms and smart contracts, the proposed approach enhances the efficiency, transparency, and security of distributed generation systems.

However, it is essential to acknowledge that the implementation of blockchain-enabled game theory in distributed generation is not without challenges. Issues such as scalability, interoperability, and regulatory considerations need to be addressed for the widespread adoption of this innovative framework. Future research should delve deeper into these challenges and work towards practical solutions that pave the way for real-world applications. As the energy landscape continues to evolve, the integration of BEGT-DG holds promise for reshaping the dynamics of distributed energy systems, fostering a more sustainable, transparent, and collaborative energy future.

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