Implementation Framework of a Blockchain Based Infrastructure for Electricity Trading Within a Microgrid

Milan Todorović[1], Milica Knežević[1](✉), Domagoj Ševerdija[2], Slobodan Jelić[3], and Miodrag J. Mihaljević[1]

[1] Mathematical Institute of the Serbian Academy of Sciences and Arts, Kneza Mihaila 36, 11000 Belgrade, Serbia
{mtodorovic,mknezevic,miodragm}@mi.sanu.ac.rs

[2] Incepton, Vratnička 23, 31000 Osijek, Croatia
domagoj.severdija@incepton.hr

[3] Faculty of Civil Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, 11000 Belgrade, Serbia
sjelic@grf.bg.ac.rs

Abstract. Smart grid appears as a progression of a traditional electrical grid that ensures sustainable and economically efficient electricity system with enhanced quality, security and safety. The opportunity to produce electricity from renewable energy resources resulted with appearance of new type of participants within the smart grid. In order to provide fair trading environment for these participants significant research activities have been made in order to support the shift from centralized to distributed trading systems. The blockchain technology is recognized as a suitable backbone due to its inherent characteristics of decentralization and distributedness. This paper proposes a novel blockchain-based platform for electricity trading and provides implementation details of its constituting elements. The proposed infrastructure relies on the blockchain with enhanced, energy efficient consensus protocol, and assumes that prosumers of a micro-grid may also act as miners within a mining pool that validates trading transactions. Architecture of the system, employed smart contracts and monitoring of the system operations are described. The paper also points out to an alternative option for the pool mining that provides heavy reduction of the energy consumption in comparison with a traditional Proof-of-Work approach. Finally, a framework for an optimization of the pool manager and pool miners working strategies is given.

Keywords: Smart grid · Electricity trading · Blockchain · Consensus protocol · Smart contracts

Supported by the EU H2020 SMART4ALL #3 CTTE "BC4GRID" project.

H. Gao et al. (Eds.): CollaborateCom 2023, LNICST 561, pp. 38–53, 2024.
https://doi.org/10.1007/978-3-031-54521-4_3

1 Introduction

The concept of blockchain was introduced fifteen years ago as a basis for a decentralized digital currency Bitcoin [1]. Over the time, blockchain has surpassed the initial application which was exclusively related to cryptocurrencies and finance, and it is seen today as a general-purpose technology. Researchers and developers recognized that many other application domains can utilize the principal blockchain characteristics: decentralization, transparency, immutability and verifiability. One of the key enablers for the widespread adoption and usage of the blockchain technology were smart contracts, which introduced the programmability potential into blockchain. Smart contracts are programs that are stored on blockchain, and their code cannot be altered, similarly to any other blockchain data. They are executed in a decentralized manner by all blockchain nodes. Ethereum was the first, and still most popular, blockchain for smart contracts, with a rich ecosystem of decentralized applications (dApps) and tools for developing, testing, and deploying smart contracts. Some other platforms with smart contract functionality are, for example, Hyperledger Fabric, Solana, Chainlink, Algorand, Tezos, EOS, etc.

A vast amount of research and real-world projects focuses on building blockchain based systems. Blockchain applications include: supply chain management [2,3], electricity sector [4,5], healthcare and medicine [6–8], non-fungible tokens (NFTs) [9], Industry 4.0 [10], e-voting [11], etc. Regarding the electricity sector, a number of research studies as well as industry projects have been investigating the possibilities for integrating blockchain into existing infrastructures through different activities: metering and billing, P2P electricity trading, grid operations and management, renewable energy certificates, electric vehicle charging, etc. Some of the companies involved in the energy sector that initiated the projects based on blockchain are: LO3 Energy (USA) [12], PowerLedger (Australia) [13], TenneT (Netherlands and Germany), SunContract (Slovenia) [14].

This area of research remains highly active and is accompanied by ongoing challenges concerning the utilization of public blockchains to support decentralized electricity trading. Therefore, we propose the development of a decentralized platform based on an energy-efficient public blockchain, which enables secure, trustworthy, and safe decentralized electricity trading. The main contributions of the paper can be summarized as follows:

- A model of a decentralized infrastructure for electricity trading that enables fair participation of prosumers and consumers at the electricity market is proposed. The electricity prices are not dictated by an authority (power grid operator), but they can fluctuate according to supply and demand, and the electricity produced locally can be traded locally within the microgrid.
- The trading platform is blockchain based and it is implemented using smart contracts that provide all the functionalities necessary for user registration and trading activities. The source code of the smart contracts is made publicly available.

– A user-friendly interface that facilitates user interaction with the blockchain is developed. It servers as an entry point for the trading platform and makes calls to the smart contracts intuitive and easy to use. The source code of the trading platform interface is made publicly available.
– The energy-efficiency of the employed blockchain is addressed. In order to solve the problem of high energy consumption, which characterizes certain public blockchains, traditional Proof-of-Work consensus protocol is replaced with the one that allows two types of resources: energy and memory. In addition, since the prevalent mode of blockchain network organization are so call mining pools, the behaviour and certain optimizations regarding utility functions of the pool entities are analyzed.

The remainder of the paper is organized as follows. The model of the proposed infrastructure for blockchain-based energy trading is given in Sect. 2. Section 3 contains implementation details about the blockchain platform and the smart contracts for electricity trading. The developed user interface that facilitates access to the smart contracts and blockchain is described in Sect. 4. Section 5 addresses the energy-efficiency of the blockchain consensus protocol, discusses the roles of the actors in the blockchain network, and analyzes some optimization strategies of the actors. Conclusions are given in Sect. 6.

2 Framework for Energy Trading

Smart grid is an advanced transformation of a traditional electrical grid. It is a cyber-physical system that can efficiently integrate the activities of all participants (producers, consumers and prosumers) and ensure sustainable and economically efficient electricity system with low losses, high quality and supply security and safety [15]. Smart grid encompasses advanced technologies in order to monitor and control electricity and data flows. Microgrid is an important part of the smart grid concept. It contains almost all of components of the main grid, but in smaller scale [16]. Microgrids can operate autonomously in island-mode or connected and synchronized with the main grid [17]. The role of microgrids in energy systems become increasingly important. Microgrids support local generation and consumption of energy, thus reducing transmission and distribution losses [18]. In addition, microgrids facilitate the integration of renewable energy sources [19]. Microgrids can also improve security and resilience of the network, and provide ancillary services that facilitate the continuous energy flow in the system.

The natural next step in the evolution of power grids becomes the transition from the centralized model to a decentralized one. The centralized model is not the most fitted to deal with energy management, control and trading among distributed providers, consumers and prosumers. Monopoly of electricity prices that exist in the centralized model goes against the principles of a distributed market. An important role of smart grids is to support prosumers, which are both energy consumers and providers. In the centralized model, prosumers do not have the adequate access to the energy market due to a privileged role of the institutionalized, large-scale providers. The feed-in tariffs and similar incentives often do not apply for selling energy surplus back to the energy grid. This surplus is then usually sold to companies at lower prices and they sell it back at regular prices. Direct energy trading, without intermediaries, brings the potential for energy cost savings. This further promotes local generation of renewable energy. Prosumers can benefit from their investment while profits and value remain within the microgrid and local community [20].

Figure 1 shows a bird-view of the proposed blockchain-based infrastructure for electricity trading within a microgrid.

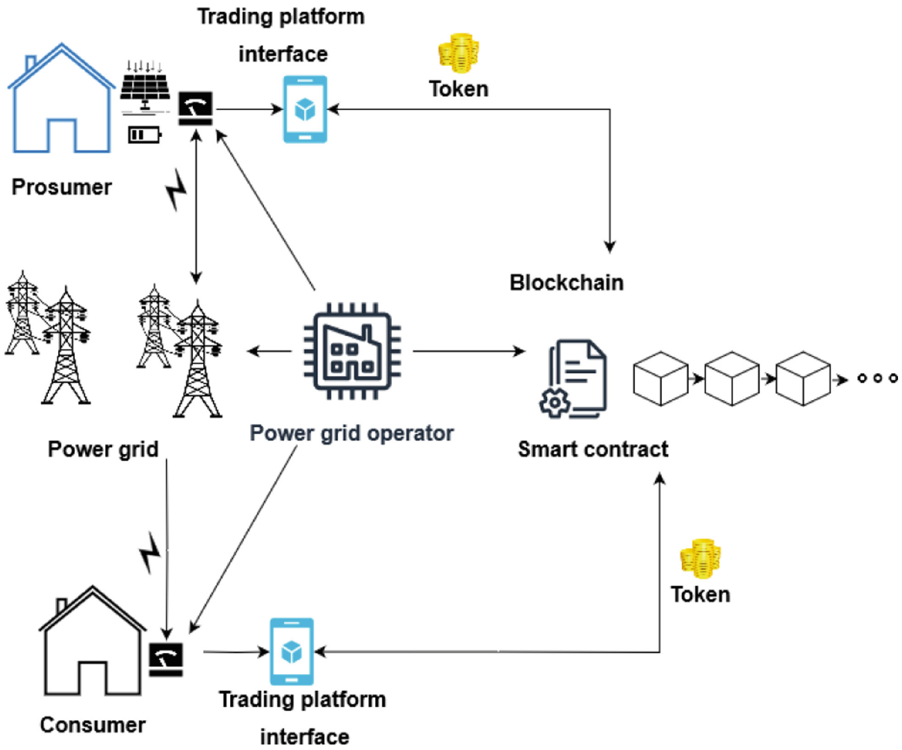


Fig. 1. Model for a blockchain-based electricity trading within a microgrid

The main components of the infrastructure are:

- **Consumer:** Users that are consuming the energy delivered through the power grid.
- **Prosumer:** Users that consume the energy and have capabilities to produce it, usually from renewable energy sources. The energy that prosumers generate is usually for their needs, but it can happen that they produce more that they can use, so they can feed the energy to the power grid.

- **Smart meters:** Digital devices that track all energy transfers between the consumers/prosumers and the power grid. The smart meters are registered to the blockchain network so that their owners (consumers/prosumers) can participate in energy trading.
- **Blockchain:** The underlying system for decentralized electricity trading. The blockchain hosts smart contracts that implement the functionalities necessary for smart meter registration, electricity token issuance, and trading. In addition, all trading records are stored in the blockchain in the form of blockchain transactions.
- **Trading platform interface:** GUI that facilitates access to the blockchain and the smart contracts. It enables users to create offers, buy electricity tokens, and monitor relevant blockchain activities.
- **Power grid:** An interconnected cyber-physical network for electricity delivery.
- **Power grid operator:** The entity entrusted with transporting energy through the power grid.

In the proposed infrastructure, blockchain facilitates direct energy trading within the grid and can incentivize end-user participation. For the energy they feed into the grid, prosumers receive the adequate number of blockchain tokens, where each token corresponds to a predefined amount of electricity. The tokens can be traded on the blockchain trading platform. The token price, and consequently the electricity price, is established based on supply and demand. Thus, the monopoly over the prices is suppressed.

It is important to note that energy-consuming blockchains are in contrast with the nature of P2P electricity trading aiming to increase energy efficiency. In order to solve this problem, the proposed infrastructure uses the blockchain consensus protocol that relies on two types of resources, energy and memory [28]. The protocol allows for the reduction of the amount of energy needed to maintain the blockchain by compensating it with the appropriate amount of memory resources. Section 5 discusses the details regarding functioning and maintenance of the underlying blockchain network, more specifically, the consensus protocol, as well as the roles that users (prosumers and consumers) can take.

3 Implementation of the Framework

3.1 Ethereum Blockchain Platform

Ethereum blockchain [21] was the first blockchain platform to support the creation and utilization of smart contracts, enabling the development of decentralized applications. This novel approach led to Ethereum becoming one of the most popular and enduring blockchain platforms. Ethereum remains an open and permissionless system, welcoming participation from anyone. Nevertheless, it's worth noting that one can also establish a private blockchain based on Ethereum, allowing it to operate in a permissioned manner when needed.

Within the Ethereum platform, each block consists of two main parts: the header and the body [22]. The block's body contains various crucial information regarding the transactions that are in the block. On the other hand, the header of the block contains several essential data fields used to execute the consensus protocol and maintain the security, immutability, and trustworthiness of the blockchain. One of the most noteworthy fields in the header is *ParentHash*, which holds the hash value of the preceding block in the chain. This plays a vital role in ensuring the immutability of the blockchain, as any attempt to modify a block would require modifying all the preceding blocks as well.

The consensus protocol is the primary mechanism that enables blockchain to function without the need for a trusted third party while ensuring the platform's consistency and security. Additionally, the consensus protocol establishes trust among the platform's users. Every miner who publishes a new block must execute the consensus protocol specific to that block. Typically, this protocol involves solving a challenging cryptographic puzzle, with the hash of the newly formed block as an input. Solving the puzzle requires a substantial amount of resources. The most well-known consensus protocol is Proof-of-Work, which relies on computational power as the required resource. However, there are other diverse protocols that utilize different resources such as memory, cryptocurrency, or even computational power for solving real-life problems [23].

In 2022, the official Ethereum platform successfully transitioned to the Proof-of-Stake consensus protocol, which is well-suited for large, established networks [24]. However, the latest implementation of Ethereum, known as *go-ethereum* and developed in the Go language, is designed in a modular manner that allows for the implementation of various new consensus protocols [25].

Another notable feature of the Ethereum platform that renders it adaptable for different applications is its support for smart contracts. These smart contracts represent computer programs executed on the Ethereum platform in a decentralized and distributed manner. They serve as the foundation for implementing decentralized applications based on blockchain systems [26].

3.2 Smart Contracts for Electricity Trading

The proposed infrastructure for decentralized electricity trading is based on the Ethereum's smart contract functionality. Through the utilization of the Solidity programming language, we have implemented two distinct smart contracts, which facilitate the realization of the intended decentralized energy platform. These two contracts, namely, *TokenDispenser* and *Trading*[1] are deployed by the Power grid operator.

The *TokenDispenser* contract encompasses functionalities for the prosumer registration within the trading platform. Additionally, it includes a set of methods that are specifically utilized by the prosumers' smart meters. These methods

[1] The source can be found at https://github.com/BSolutionsltd/BC4GRID/tree/main/smart-contracts.

are employed when prosumers generate electricity for the grid or receive electricity from it. Upon transmitting electricity to the grid, prosumers are rewarded with ERC20 [27] tokens, which serve as tangible evidence of the quantity of electricity that has been contributed. These ERC20 tokens are subsequently eligible for trading through the *Trading* contract. Furthermore, prosumers also have the option to exchange these tokens for additional electricity from the grid. The *TokenDispenser* contract incorporates the following methods:

- `RegisterSmartMeter`: This function allows registration of smart meters using their respective Ethereum addresses. After a successful registration, users gain access to the trading platform. It is important to emphasize that only the Power grid operator has the authority to register smart meters.
- `UnregisterSmartMeter`: Through this method, users can unregister their smart meters. Once completed, the user's access to the platform is revoked.
- `SendEnergy`: Smart meters associated with users utilize this method when transmitting electricity to the grid. As a result of this transmission, users are rewarded with freshly generated ERC20 tokens, which symbolize the amount of electricity sent.
- `ReceiveEnergy`: Whenever a user seeks to exchange their owned tokens for additional electricity from the grid, this function comes into play. The tokens spent in this exchange process are subsequently removed from circulation.

The *Trading* contract enables users to engage in the buying and selling of ERC20 tokens, that represent electricity units. Users aiming to sell tokens can create offers by specifying the token quantity, price, and offer's expiration time. Existing offers can also be modified. This contract enables users to view active offers, facilitating informed decisions on token purchases. Users are not obligated to purchase the full token quantity from an offer; instead, they can acquire the desired amount. Additionally, the *Trading* contract emits events indicating the creation of new offers, modifications to existing offers, and the conclusion of offers due to expiration. This contract's functionalities provide a mechanism for users to transact tokens representing actual electrical electricity within a decentralized context. The *Trading* contract implements the following methods:

- `CreateEnergyOffer`: Users intending to sell their ERC20 tokens can utilize this method to initiate an offer. This involves specifying the token quantity for sale, the corresponding price, and the offer's deadline. The method executes the transfer of the stipulated token quantity to the Trading smart contract to enable subsequent sales. Additionally, the created offer is recorded within the contract, and the emission of the `OfferCreated` event signifies its initiation.
- `BuyEnergyFromOffer`: This method allows users to purchase a defined quantity of tokens from a specific offer. Users provide the offer's identification, the desired token quantity, and the appropriate amount of the native cryptocurrency designated for payment. The method implements the transfer of the specified token quantity to the buyer and the corresponding cryptocurrency amount to the offer's seller. Furthermore, if tokens are still available for sale within the offer, the `OfferModified` event is triggered. Conversely, if

the offer's token inventory is depleted, the `OfferClosed` event is emitted to signal its completion.
- `ModifyOffer`: This method empowers users to adjust a previously created offer. By providing new values for the token quantity, token price, or offer deadline, users can refine the terms of their offer. This modification triggers an update to the offer, and as a result, the emission of the `OfferModified` event conveys the successful alteration. This functionality enhances user flexibility and responsiveness within the trading process.
- `RetrieveTokens`: This method enables users to reclaim the tokens from their expired offers that have not been sold. This action promotes a streamlined approach to managing unfulfilled offers, ensuring that users can readily reclaim their tokens when a transaction does not occur within the designated timeframe.
- `ListOffers`: This function provides a list of the IDs for all active offers within the system. Users can refer to this list to identify and select offers from which to purchase tokens.
- `GetOfferDetails`: This method retrieves comprehensive information about a specific offer using its ID. Details include the seller's address, the token quantity in the offer, the token price, and the offer's expiration deadline.

4 Monitoring of the Energy Trading

Our energy trading monitoring system is designed as a web service that uses the web3.js API to interact with the Ethereum Blockchain with user and administrator portals. This application seamlessly connects to the blockchain and provides access to the smart contract responsible for blockchain transactions and recording transaction data. Variables such as the electricity price are configured in a standard-compliant manner. The web application provides the functionality outlined in Fig. 2 and allows users to both generate and sell electricity (in the role of a producer) and buy and consume tokens (in the role of a consumer).

Smart meter data on electricity consumption and production is collected in a monitoring database used exclusively by the monitoring system to store user input data, while transaction data (smart contracts, tokens, etc.) is stored in a decentralized repository based on the blockchain technology implemented in the Etherium platform. We provide functionalities with two main roles: **administrator** and **prosumer**. The administrator role is used for system configuration, user account management, smart contract monitoring, security, and compliance. Administrators are responsible for configuring user account settings and restrictions, application settings, blockchain integration, and standards. User account management includes creating, modifying, and deleting user accounts, granting and revoking permissions, and security management. Administrators manage the deployment and maintenance of smart contracts for power transactions.

The prosumer role, on the other hand, allows prosumers to access their user profile, producer information, power purchases, surplus power sales, transaction history, and account statistics. The user profile includes personal

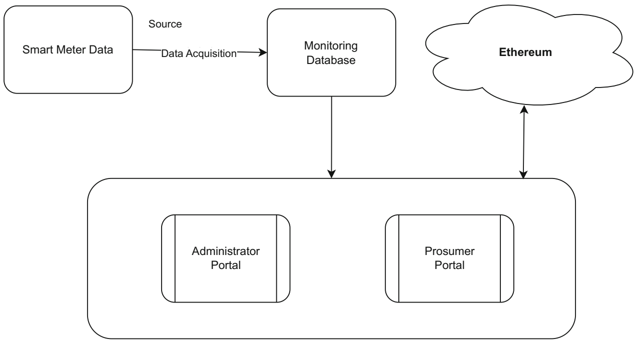


Fig. 2. Monitoring System architecture

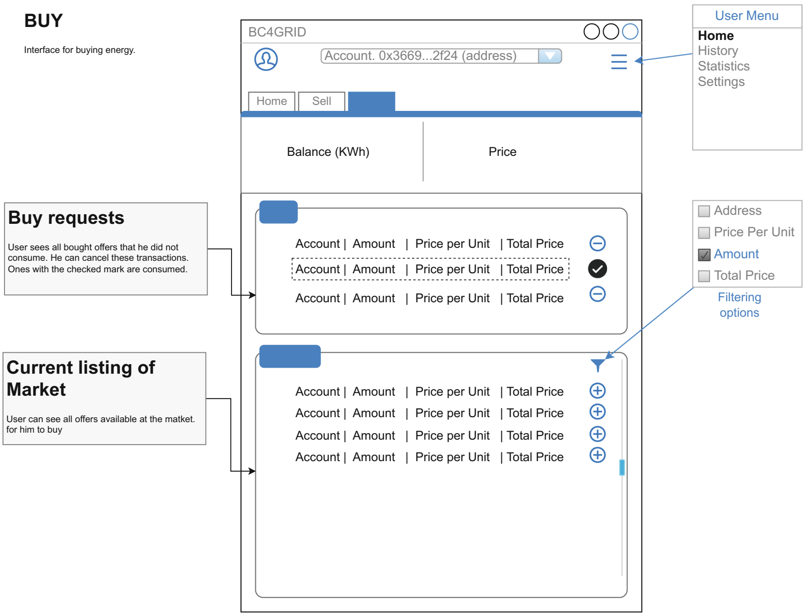
information, address, and account balance. This balance is divided into two categories: remaining energy in kilowatt hours (kWh) and the corresponding currency. Transactions are processed in kWh and tokens. If the user produces energy, the prosumer role allows access to details about his energy production facilities. For example, the interface can display the number of active solar panels and their daily output. The two main functions of the prosumer role are buying electricity (Fig. 3a) and selling surplus electricity (Fig. 3b). The platform will allow consumers to buy electricity through this application. They can buy electricity from a centralized (government) power source or from specific producers and prosumers on the open market. The platform will display available market offers and allow users to place purchase orders at existing prices or create their own purchase offers. Since users can also be producers of electrical energy, our platform allows them to create offers for all the energy they do not consume and sell it on the open market. Other features of the prosumer role include an overview of the user's transaction history (Fig. 4a) and user statistics (Fig. 4b). This includes information such as daily consumption, daily production (if the user is also a producer), and other relevant account-related data.

5 Optional Consensus Protocol and Pool Mining

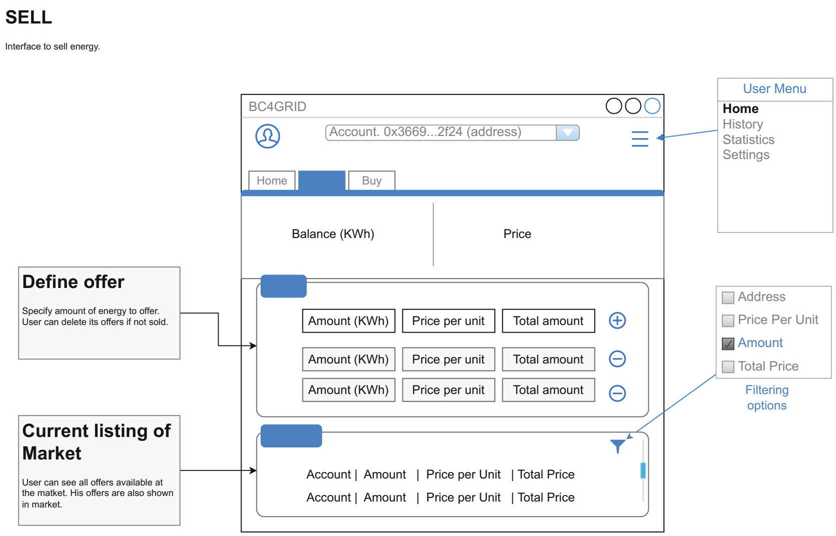
5.1 Summary of the Approach

Recently, an alternative approach to the traditional ones and the related pool mining have been reported and considered in [28–31].

We consider the following pool mining approach reported in [30]. Note that the considered architecture and the employed consensus protocol require two types of resources: energy and memory. The pool mining system consists of two entities: Pool Manager (PM) and pool miners. PM possess computational and memory resources. Computational resources of PM are for PM's evaluations and memory resources are for renting to the pool miners. Memory resources of PM contain certain in advances specified tables. Computational and memory

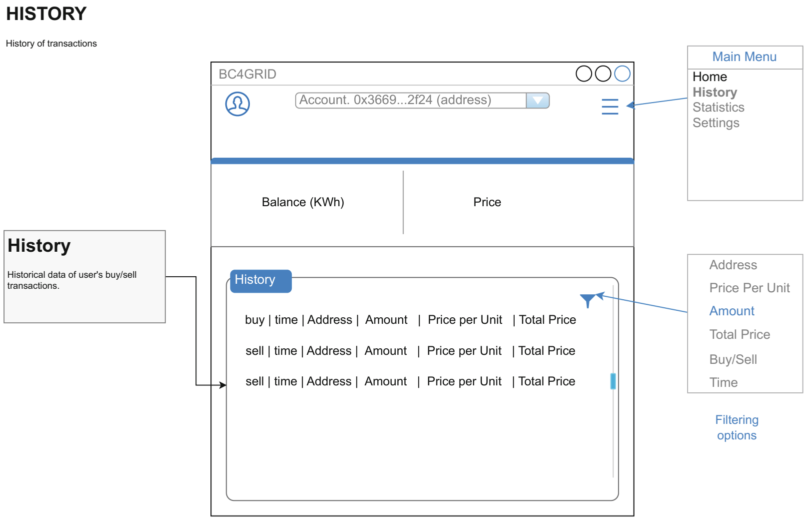


(a) Buy Mockup: Electricity Purchase



(b) Sell Mockup: Selling Excess Power

Fig. 3. Mockups of the Buy and Sell screens.



(a) Transaction History Mockup

(b) User Statistics Mockup

Fig. 4. Mockups of the Buy and Sell screens.

resources of PM could be considered as PM cloud. PM communicates with the pool miners through the dedicated gate. Main role of the pool miners is to perform certain evaluations required for solving the consensus protocol puzzle and considered pool mining setting assumes that only PM could complete puzzle solving. Accordingly, pool miners require only computational resources but, as the pool mining participants, they also should support PM by renting non overlapping parts memory resources of PM. The design setting assumes that certain miners could have own tables in order to perform malicious activities.

A mining pool is formed and initialized during the registration phase, when the pool manager registers all miners interested in joining and contributing their mining work to the pool. In this phase, each miner declares the size of the subtable he supports, i.e. rents it from the pool manager, and gets informed about the reward for pool mining contribution. The architectural framework is given in Fig. 5.

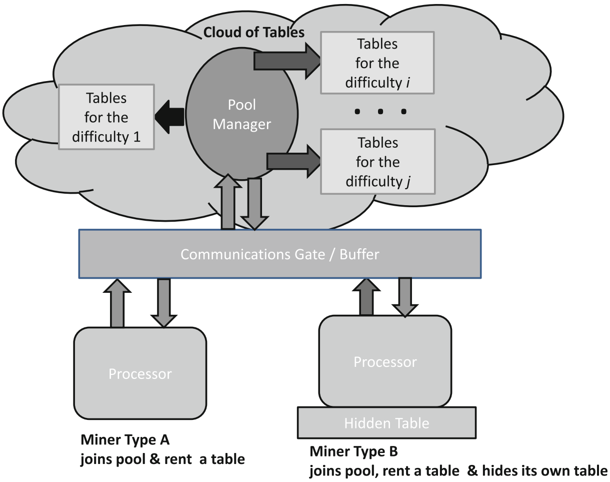


Fig. 5. Pool mining architectural framework, [30].

5.2 A Framework for the Strategies of the Blockchain Pool Manager and Miners

An Optimized Strategy of the Pool Manager. **Assumption 1**. Before beginning each mining round, the Pool Manager knows:
(i) a_t, because it is known when the mining block is given,
(ii) an upper bound on $E_t^{(PM)}$, because it is under control of PM,

Table 1. Notation

a_t	an award that the Pool Manager receives for inclusion of a block in the t-th mining round
$D_t^{(i)}$	number of candidates submitted to the Pool Manager by the i-th miner in the t-th mining round
$M_t^{(i)}$	the memory rented from the Pool Manager by the miner i in the t-th mining round
$E_t^{(PM)}$	energy spent by Pool Manager in the t-th mining round
α_t	the award rate granted by the Pool Manager in the t-th mining round
β_t	the energy cost rate in the t-th mining round
γ_t	the memory cost rate rented from the Pool Manager by a miner in the t-th mining round
I	number of miners in the mining pool
T	number of the mining rounds

(iii) the range of $M_t^{(i)}$, $M_{t,min}^{(i)} \leq M_t^{(i)} \leq M_{t,max}^{(i)}$ because each pool miner should declare it before the t-th round, $i = 1, 2, ..., I$, $t = 1, 2, ..., T$.
(iv) the range of $D_t^{(i)}$, $D_{t,min}^{(i)} \leq D_t^{(i)} \leq D_{t,max}^{(i)}$ because each pool miner should declare it before the t-th round, $i = 1, 2, ..., I$, $t = 1, 2, ..., T$ (Table 1).

The main goal of the Pool Manager is to manage pool mining and maximize its utility function $u(\cdot)$, by selection of the parameters α_t and γ_t according to Assumption 1.

We consider the following generic cost function and its instances that Pool Manager employs in order to maximize its profit regarding operation of the pool.

$$u(\cdot) = \sum_{t=1}^{T} a_t + \sum_{i=1}^{I}\sum_{t=1}^{T} u_1(\gamma_t, M_t^{(i)}) - \sum_{i=1}^{I}\sum_{t=1}^{T} u_2(\alpha_t, D_t^{(i)}, M_t^{(i)}) - \sum_{t=1}^{T} u_3(\beta_t, E_t^{(PM)}) \quad (1)$$

The main goal of the Pool Manager is to manage pool mining and maximize its cost function $u(\cdot)$, by selection of the parameters α_t and γ_t according to Assumption 1.

Optimization Scenario

- According to Assumptions 2 and 3, the Pool Manager optimizes α_t and γ_t in order to maximize the utility function $u(\cdot)$, before beginning of each mining round $t = 1, 2, ..., T$.
- According to the obtained α_t and γ_t, each miner i, optimizes $M_t^{(i)}$ and $E_t^{(i)}$ to be employed in the t-th mining round, $t = 1, 2, ..., T$, $i = 1, 2, ..., I$.

Table 2. Additional Notation.

$E_t^{(i,sell)}$	the energy a prosumer i sells in the t-th mining round
$E_t^{(i,purchase)}$	the energy a prosumer i purchase in the t-th mining round
$E_t^{(i)}$	the mining energy employed by the miner i in the t-th mining round
c	energy spending rate to obtain $D_t^{(i)}$ data employing $E_t^{(i)}$

An Optimized Strategy of the Prosumer. We consider the following generic cost function of a pool miner and its instantiates.

$$f^{(i)}(\cdot) = \sum_{t=1}^{T} f_1(\beta_t, E_t^{(i,sell)}) - \sum_{t=1}^{T} f_2(\beta_t, E_t^{(i,purchase)}) + \\ \sum_{t=1}^{T} f_3(\alpha_t, D_t^{(i)}, M_t^{(i)}) - \sum_{t=1}^{T} f_4(\beta_t, E_t^{(i)}) - \sum_{t=1}^{T} f_5(\gamma_t, M_t^{(i)}) \quad (2)$$

where

$$D_t^{(i)} = cE_t^{(i)} \ , \ t = 1, 2, ..., T \ .$$

The parameters $c, \alpha_t, \beta_t, \gamma_t$ in the basic consideration can be considered as independent from the variables $E_t^{(i,sell)}$, $E_t^{(i)}, M_t^{(i)}$, $t = 1, 2, ..., T$.

Optimization Goal. In the basic setting, the utility function $f^{(i)}$ should be maximized by selection of $E_t^{(i,sell)}$, $E_t^{(i,purchase)}$ $E_t^{(i)}$ and $M_t^{(i)}$ for the given $c, \alpha_t, \beta_t, \gamma_t$, $t = 1, 2, ..., T$ (Table 2).

6 Conclusions

This paper presents implementation details of a novel blockchain-based platform for electricity trading. Energy efficiency of the proposed solution is achieved through an advanced blockchain consensus protocol, that allows a trade-off between energy and memory resources necessary for blockchain maintenance. Theoretical analysis of different working strategies for the participants and the corresponding utility functions are given. All the primary functionalities of the trading system, necessary for user registration, electricity token issuance based on the amount of electricity fed into the grid, management of trading offers, etc. have been implemented. Source code of the smart contracts, which provide the aforementioned functionalities, is made publicly available. In addition, access to the trading platform is enabled via user interface developed to assist smooth interaction with the implemented functionalities.

References

1. Nakamoto, S.: Bitcoin: A Peer-to-Peer Electronic Cash System (2008). https://bitcoin.org/bitcoin.pdf
2. Queiroz, M.M., Telles, R., Bonilla, S.H.: Blockchain and supply chain management integration: a systematic review of the literature. Surg. Endosc. Other Interv. Tech. **25**(2), 241–254 (2020). https://doi.org/10.1108/SCM-03-2018-0143
3. Risso, L.A., Ganga, G.M.D., Godinho Filho, M., de Santa-Eulalia, L.A., Chikhi, T., Mosconi, E.: Present and future perspectives of blockchain in supply chain management: a review of reviews and research agenda. Comput. Ind. Eng., 109195 (2023)
4. Nour, M., Chaves-Ávila, J.P., Sánchez-Miralles, Á.: Review of blockchain potential applications in the electricity sector and challenges for large scale adoption. IEEE Access **10**, 47384–47418 (2022). https://doi.org/10.1109/ACCESS.2022.3171227
5. Uddin, S.S., et al.: Next-generation blockchain enabled smart grid: conceptual framework, key technologies and industry practices review. Energy AI, 100228 (2023)
6. Attaran, M.: Blockchain technology in healthcare: challenges and opportunities. Int. J. Healthcare Manag. **15**(1), 70–83 (2022). https://doi.org/10.1080/20479700.2020.1843887
7. Saeed, H., et al.: Blockchain technology in healthcare: a systematic review. PLoS ONE **17**(4) (2022). https://doi.org/10.1371/journal.pone.0266462
8. Mahajan, H.B.: Integration of healthcare 4.0 and blockchain into secure cloud-based electronic health records systems. Appl. Nanosci. (2022). https://doi.org/10.1007/s13204-021-02164-0
9. Kugler, L.: Non-fungible tokens and the future of art. Commun. ACM **64**(9), 19–20 (2021). https://doi.org/10.1145/3474355
10. Chen, Y., Lu, Y., Bulysheva, L., Kataev, M.Y.: Applications of blockchain in industry 4.0: a review. Inf. Syst. Front. (2022). https://doi.org/10.1007/s10796-022-10248-7
11. Huang, J., He, D., Obaidat, M.S., Vijayakumar, P., Luo, M., Choo, K.K.R.: The application of the blockchain technology in voting systems: a review. ACM Comput. Surv. **54**(3) (2021). https://doi.org/10.1145/3439725
12. Mengelkamp, E., Gärttner, J., Rock, K., Kessler, S., Orsini, L., Weinhardt, C.: Designing microgrid energy markets: a case study: The Brooklyn Microgrid. Appl. Energy **210**, 870–880 (2018)
13. PowerLedger: Whitepaper (2019). https://assets.website-files.com/612e1d86b8aa434030a7da5c/612e1d86b8aa434027a7dd6d_power-ledger-whitepaper.pdf
14. Suncontract: Whitepaper (2017). https://suncontract.org/wp-content/uploads/2020/12/whitepaper.pdf
15. EU Commission Task Force for Smart Grids - Expert Group 1: Functionalities of smart grids and smart meter (2010)
16. Yoldaş, Y., Önen, A., Muyeen, S.M., Vasilakos, A.V., Alan, I.: Enhancing smart grid with microgrids: challenges and opportunities. Renew. Sustain. Energy Rev. **72**, 205–214 (2017). https://doi.org/10.1016/j.rser.2017.01.064
17. Marnay, C., el al.: Microgrid evolution roadmap. In: Proceedings of the 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST), pp. 139–44. IEEE (2015)

18. Kamel, R.M., Chaouachi, A., Nagasaka, K.: Carbon emissions reduction and power losses saving besides voltage profiles improvement using microgrids. Low Carbon Econ. **1**(1), 1 (2010)
19. Mihaylov, M., et al.: SCANERGY: a scalable and modular system for energy trading between prosumers. In: Proceedings of the 2015 International Conference on Autonomous Agents and Multiagent Systems, IFAAMAS, pp. 1917–18 (2015)
20. Guoa, Y., Wanb, Z., Cheng, X.: When blockchain meets smart grids: a comprehensive survey. High-Confidence Comput. **2**(2), 100059 (2022)
21. Ethereum Whitepaper. https://ethereum.org/en/whitepaper/. Accessed 20 Sept 2023
22. Wood, G.: Ethereum: a secure decentralised generalised transaction ledger berlin version 2BCDB2D, 25 August 2023. https://ethereum.github.io/yellowpaper/paper.pdf. Accessed 18 Sept 2023
23. Bamakan, S.M.H., Motavali, A., Bondarti, A.B.: A survey of blockchain consensus algorithms performance evaluation criteria. Expert Syst. Appl. **154**, 113385 (2020)
24. Proof-of-Stake (POS). https://ethereum.org/en/developers/docs/consensus-mechanisms/pos/. Accessed 18 Sept 2023
25. go-ethereum: official go implementation of the Ethereum protocol. https://geth.ethereum.org/. Accessed 18 Sept 2023
26. Metcalfe, W.: Ethereum, smart contracts, dApps. In: Yano, M., Dai, C., Masuda, K., Kishimoto, Y. (eds.) Blockchain and Crypto Currency. ELIAP, pp. 77–93. Springer, Singapore (2020). https://doi.org/10.1007/978-981-15-3376-1_5
27. ERC-20 Token Standard. https://ethereum.org/en/developers/docs/standards/tokens/erc-20/. Accessed 19 Sept 2023
28. Mihaljević, M.J.: A blockchain consensus protocol based on dedicated time-memory-data trade-off. IEEE Access **8**, 141258–141268 (2020)
29. Mihaljević, M.J., Wang, L., Xu, S., Todorović, M.: An approach for blockchain pool mining employing the consensus protocol robust against block withholding and selfish mining attacks. Symmetry **14**(8), 1711, 28 (2022)
30. Mihaljević, M.J., Todorović, M., Knežević, M.: An evaluation of power consumption gain and security of flexible green pool mining in public blockchain systems. Symmetry **15**, 924 (2023). https://doi.org/10.3390/sym15040924
31. Mihaljević, M.J., Knežević, M., Urošević, D., Wang, L., Xu, S.: An approach for blockchain and symmetric keys broadcast encryption based access control in IoT. Symmetry **15**, 299 (2023). https://doi.org/10.3390/sym15020299