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Blockchain-based smart contracts for power purchase agreements: Trading solar energy with fuzzy pricing

M. Mirzasadeghi, [1] and H. Nezamabadi-pour, [2]

[1,2] *Department of Electrical Engineering, Shahid Bahonar University of Kerman, Kerman, Iran*

mehrzada.mirzasadeghi@eng.uk.ac.ir; nezam@uk.ac.ir

Abstract

Solar energy as a renewable energy, is widely used by many solar power plants to generate electricity. As production in this sector grows, conducting business in this area becomes increasingly important. Solar energy trading is facilitated through power purchase agreements (PPA), which outline the key elements for building a solar power plant and managing related transactions. However, the current trading system has several drawbacks. These challenges include the absence of transaction tracking and payment mechanisms, limited user access to transaction data, and low transparency, trust, and consistency in solar energy pricing. A new technology that has recently emerged and can be utilized for trading is blockchain technology. It is a continuously growing list of recordable items, called blocks that are linked together using encryption. By leveraging blockchain for solar energy trading, many existing challenges can be addressed. Essentially, blockchain functions as a decentralized shared ledger, enabling members to collaborate for specific purposes without depending on a central authority. One of the notable features of some blockchain networks, including Ethereum, is the ability to create smart contracts. A smart contract is a set of computer codes that automatically execute on a blockchain platform under predefined conditions, without the central authority need. Blockchain, through the use of smart contracts, can offer a secure, transparent, peer-to-peer, distributed, decentralized, verifiable, reliable, and traceable platform for solar energy transactions. Additionally, by defining national cryptocurrencies within this localized context, it is possible to prevent the outflow of currency from the country during international transactions. To address the issue of solar energy pricing, which depends on the inflation rate factor and the dollar rate factor, the use of a fuzzy system can be effective. Fuzzy logic is a computational approach used to model uncertainties and complexities in real-world systems. In the context of PPA, a fuzzy system can serve as an effective tool for pricing electricity generated by solar power plants. As a result, designing a platform with blockchain features for solar energy trading, implementing PPA contracts on the blockchain, and using a fuzzy system for solar energy pricing are extensive areas of focus for this research.

Keywords: Solar energy, power purchase agreements (PPA), blockchain, smart contract, fuzzy pricing, fuzzy system.

1 Introduction

As solar energy becomes increasingly prevalent, identifying diverse methods for trading solar power is essential. Solar energy trading can be categorized into two types: competitive and non-competitive. Competitive trading typically occurs among participants within the solar energy market. In contrast, non-competitive trading takes place between the government and power plants. This non-competitive approach can be implemented within a single organization or on a larger scale to eliminate competition in the market. In the competitive method, the trading parties negotiate a price for the transaction, creating a market dynamic. In the non-competitive method, the price is predetermined, typically based on the terms outlined in the Power Purchase Agreement (PPA). There are several challenges in trading within this field. To address these issues and achieve goals such as tracking transactions, compensating for damages,

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providing users access to information about past exchanges, creating transparency and trust in the exchange platform, and resolving economic and security concerns, a dedicated platform is necessary [29]. To address these challenges and create an effective platform, designers in this field have explored various solutions. Today, one of the promising options that can help design a suitable platform, achieve necessary goals, and tackle existing challenges is the blockchain network [4]. This platform, characterized by key features such as cryptography, transparency, decentralization, immutability, auditing, scalability, security, and privacy, can revolutionize the exchange process. These unique features of blockchain have facilitated its widespread adoption across various applications. For instance, the privacy-preserving capability of blockchain has successfully addressed related concerns in various use cases, including [15], [33], and [57]. The use of encryption in blockchain networks ensures high security, boosting user confidence in these systems. Additionally, all operations within this network adhere to specific rules and involve complex calculations that are challenging for the general public to decipher. A closer look at the properties of blockchain networks highlights their necessity across various fields, including solar energy exchanges. Some of these properties are such as verifiability [17], immutability [51], transparency, programmability, anonymity, decentralization [9], accessibility and traceability, security, distributive, being online [28]. Leveraging the unique features of blockchain, this platform facilitates solar energy trading through the use of smart contracts on the blockchain network. These smart contracts enable automatic transactions without the need for intermediary intervention. Country-specific regulations for solar energy trading will be embedded within the PPA smart contract. Supervision by relevant organizations will be inherently integrated. Thus, while automation streamlines trading, it does not eliminate regulatory oversight but rather transforms its nature. The application of fuzzy systems in pricing for solar energy trading introduces a various mechanism for dealing with the inherent uncertainties in solar power generation and market demand. Fuzzy logic enables the creation of pricing models that can accommodate the fluctuating nature of solar energy and the diverse factors influencing market prices. By utilizing fuzzy systems, pricing strategies can be more adaptive and responsive to real-time data, ensuring fair and competitive rates. This approach not only enhances the accuracy and reliability of pricing decisions but also promotes a more balanced and efficient solar energy market, benefiting both producers and consumers [19]. Moreover, utilizing fuzzy systems can be effective in addressing the issue of solar energy pricing, which depends on the two variable factors of the dollar rate factor and the inflation rate factor. Additionally, fuzzy systems can effectively address solar energy pricing by adapting to the two variable factors: the dollar exchange rate and inflation rate. Fuzzy systems are accurate and resilient pricing models. This approach not only helps in better reflecting the complex and dynamic nature of economic conditions but also aids in mitigating the risks associated with sudden fluctuations in these variables. This enables stakeholders in the solar energy market to make more informed decisions and ensure more stable and competitive long-term pricing. Additionally, by modeling uncertainties and inaccuracies in economic factors, it provides a flexible and adaptive framework for pricing strategies. By incorporating a range of possible values and scenarios for both the exchange rate and inflation, fuzzy systems can generate more. In this article, we present an innovative approach to trading solar energy using blockchain technology combined with fuzzy logic for pricing. This research explores the potential of blockchain-based smart contracts to streamline and secure power purchase agreements (PPAs) by automating transactions and ensuring transparency. Our key contributions include: a. Integration of Blockchain and Fuzzy Logic: We present a new framework that uses blockchain for secure and transparent solar energy trading while utilizing fuzzy logic to address pricing uncertainties. This integration ensures that the pricing model is adaptable to fluctuating market conditions and energy production variability. b. Smart Contract Design for PPAs: We develop and implement smart contracts tailored for PPAs. It automates the execution of agreements between solar energy producers and consumers. These smart contracts are designed to handle complex conditions and trigger transactions based on predefined rules and real-time data inputs. c. Fuzzy Pricing Model: We propose a fuzzy pricing model that accounts for various factors influencing solar energy prices, such as weather conditions, energy demand, and supply levels. The fuzzy logic approach provides a more flexible and realistic pricing mechanism compared to traditional fixed or linear models. d. Case Study and Simulation: To validate our framework, we conduct a case study and simulation. they demonstrate the practical application and benefits of using blockchain-based smart contracts with fuzzy pricing in real-world scenarios. Our results show improved efficiency, reduced transaction costs, and enhanced trust among stakeholders. By combining blockchain technology with fuzzy logic for pricing, this article contributes to advancing the state of the art in renewable energy trading. it offers a scalable solution for managing power purchase agreements in the rapidly evolving energy landscape. The rest of this study is structured as follows. Section 2 presents a review of related work. After describing the background of blockchain, PPA, and fuzzy system in section 3, the proposed platform is explained in section 4. Sections 5 and 6 provide detailed descriptions of the implementation and the experimental results, respectively. Section 7 discusses this proposed system. And finally, section 8 is the conclusion.

2 Related work

Blockchain technology addresses issues in centralized trading by ensuring transaction security without trusted third parties. A token-based private decentralized energy trading system uses proof of work, multi-signatures, and encrypted messaging. these mechanisms enable anonymous peer negotiation, with the software comprising a platform client, peer-to-peer network nodes, and the blockchain itself [1]. The electricity market trading model is described in [32]. strikes a favorable balance between data security and system utility, while effectively managing the balance between power supply and demand. This model facilitates energy storage and transfer within a private blockchain and facilitates aggregated cross-regional energy trading through a consortium blockchain. Another peer-to-peer trading model is detailed in [47]. This model uses an auction algorithm and a calculative data-dependent algorithm with smart contracts to coordinate energy scheduling and ensure equitable payments without a central authority. The process involves the prosumer generating energy, creating a smart contract, selecting a miner via POS, the consumer initiating a purchase, and the energy being released by the ESS. The use of a blockchain platform to address issues like energy imbalance, carbon reduction, and residential privacy leakage in centralized trading markets is discussed in [20]. A decentralized, blockchain-based peer-to-peer trading scheme integrating energy and carbon markets has been designed, featuring pay-to-public-key-hash and multiple signatures. This system reduces costs and carbon emissions compared to centralized systems, which in 2017 were complex and susceptible to price tampering and hacking. The blockchain platform described in [38], led to the development of Multichain. it effectively managed blockchain creation, node connectivity, asset issuance, and trading transactions, though it faced performance issues and was inadequate for partial transactions. Despite these challenges, blockchain technology can enhance management in both public and private sectors, particularly by facilitating renewable energy generation and enabling decentralized energy distribution in smart cities. A permission blockchain using Hyperledger Fabric to create a localized peer-to-peer energy trading network is detailed in [26]. This platform's strengths include decentralization, trust, security, and privacy in the renewable energy trading business. Maintaining privacy for trading information stored on the blockchain is a significant challenge. To protect user privacy from data mining attacks, researchers proposed a consortium blockchain method that enhances privacy without limiting trading functions [13]. This solution strengthens privacy in energy trading by addressing the detection of relationships between trading volumes, physical locations, and energy usage. It supports various applications for efficient system maintenance in smart homes and interconnected networks. A blockchain-based smart home, which ensures data integrity and prevents transaction forgery, is discussed in [25]. In this system, a home miner centrally processes all transactions generated in the information energy sector. The research utilizes a renewable energy trading platform based on Ethereum smart contracts, ensuring secure, automatic energy trading within a microgrid without the need for intermediaries. Regulatory considerations for blockchain in asset ownership and payments highlight the need for fast settlements, limited trade size and risk, and sufficient trading volume to ensure feasibility [7]. Despite high mining costs, blockchain offers modest gains over traditional systems. Its application in energy markets supports decentralized transactions and smart contracts, facilitating peer-to-peer energy trading and improving power market efficiency [59]. A decentralized platform described in [30] enables secure and private energy trading in a microgrid setting. It integrates smart contract-based validators with an external optimizer for efficient offer clearing and includes resilience features to ensure robustness for the TRANSAX system. The secure private blockchain (SPB) framework addresses privacy, processing overhead, and reliance on trusted third parties. It enables direct energy price negotiations and routing based on destination public keys. It eliminates the need for a third party through atomic meta-transactions, ensuring commitment fulfillment and resilience against attacks, while also reducing costs and delays [10]. The blockchain transactive platform in [18] improves distribution grid limitations by enabling demand-side flexibility and coordination. It achieves this through a market application for balancing renewable energy. It facilitates local energy management via auction mechanisms and dynamic fee rebates. This approach enhances renewable energy hosting, security, transparency, and auditability, while potentially reducing voltage deviations and network imbalances. The P2P energy transaction framework in [5] enhances network operator flexibility in managing Distributed Renewable Energy Systems (DRES) by enabling peak load shifting and voltage regulation. It also reduces carbon footprints, and encouraging DRES installation. It examines distributed ledger technologies like Blockchain, Block Lattice, and Directed Acyclic Graphs to address congestion pricing and improve energy dispatch through market decentralization. The P2P transactive microgrid model in [46] utilizes blockchain and smart contracts to enable local energy trading among prosumers through a smart management system. This approach offers flexible, adaptable contracts that reflect real-life scenarios, removes the need for a central market entity, and addresses challenges like transaction tracking and compensation. However, existing blockchain pilots often lack detailed implementation for P2P trading platforms. In [43], a laboratory-scale implementation of a blockchain network using Hyperledger for solar electricity exchange is detailed, involving smart contracts, participant identities, and wallets. The setup, which includes Hyperledger Composer and REST server, demonstrates a functional platform for prosumers to trade solar energy. It provides valuable insights for researchers and utility engineers developing blockchain-based

P2P solar trading systems. The blockchain-based platform described in [42]ensures immutability and transparency in surplus electricity trading by using ERC20 tokens and smart contracts for automatic, third-party-free transactions. It includes an Energy Storage System (ESS) for energy transfer and payments, enhancing security through a private blockchain and promoting efficiency by allowing households with renewable systems to engage in localized P2P trading. The framework proposed in [56] enables households to autonomously trade renewable energy with neighbors using blockchain technology, focusing on matching supply and demand for mutual benefit. It suggests further research for market systems and payment methods and proposes using bidirectional energy trading capabilities of electric vehicles (EVs). It also suggests a consortium blockchain-based secure mechanism for vehicle-to-grid (V2G) to address demand-supply mismatches, with edge computing to improve block creation success. The computational resource allocation problem is addressed in two stages: Stackelberg's leader-follower game and optimal strategies, obtained using the backward induction approach. The performance of the proposed framework is validated through numerical results and theoretical analysis in [61]. Research in [53] introduces a model for renewable energy distribution in microgrids using blockchain to secure transactions between ledgers and prosumers. The simulated system shows that the proposed algorithm significantly reduces prosumers' monthly electricity bills, with savings varying based on the extent of solar cell and battery installation. Fuzzy systems are used in numerous applications due to their unique capabilities in modeling uncertainty and inherent complexities. These systems are employed in fields such as industrial control, complex system management, medical diagnosis, and decision-making. For example, particle swarm optimization [11], Designing a model for the agricultural sector [44], fuzzy logic with engineering applications [45] economic dispatch problem [37], mobile robot navigation [39], modeling nonlinear MIMO systems [12], financial analysis [14], fuzzy control [41] and gold price prediction [58]. Fuzzy systems are used in various cases and applications of solar energy. Some of these applications are as follows: Globalization has heightened energy consumption, underscoring the importance of employing soft computing techniques like fuzzy logic in energy modeling. This approach optimizes renewable energy systems such as solar, wind, and bio-energy, promoting economic prosperity and environmental security. Renewable energy sources are crucial for economic prosperity and environmental security, with fuzzy logic playing a key role in decision-making and optimization models. Fuzzy logic is extensively used in assessing and evaluating renewable energy systems. Various studies have employed fuzzy logic in decision support systems, energy management planning, and optimization models for renewable energy utilization. Fuzzy logic helps handle uncertainties and complexities present in energy modeling, aiding decision-makers in selecting optimal renewable energy solutions. Researchers can adapt fuzzy-based modeling to enhance their studies and develop practical solutions for addressing energy-environment concerns [48]. A fuzzy expert system for managing energy in smart homes, microgrids, and renewable sources by utilizing input variables such as insolation, electricity price, wind speed, and load energy to optimize energy storage and maximize financial gain is presented in [60]. The system optimizes energy usage, storage, and production, reducing costs and improving efficiency. Input variables like insolation, electricity price, wind speed, and load energy are used for energy management. Fuzzification of input variables, rule specification, and de-fuzzification of output in the expert system. This system efficiently manages renewable energy resources, achieving high levels of battery charge and thermal energy utilization, and also the proposed controller was more effective in optimizing energy usage and reducing air emissions compared to existing approaches. Optimizing energy planning through inter-entity energy trading can yield economic benefits and reduce environmental impacts. This was demonstrated in a Malaysian case study that utilized a multi-period Peer-to-Peer (P2P) energy trading model with a fuzzy optimization approach. It emphasized the advantages of multi-period Peer-to-Peer (P2P) energy trading in lowering electricity bills and carbon emissions. It recommended using advanced data-driven tools such as artificial intelligence and blockchain technology for energy forecasting. Additionally, policy recommendations were made to promote renewable energy and P2P trading, emphasizing data protection regulations. It also used a fuzzy optimization approach to optimize conflicting objectives simultaneously [27]. [31] presents a novel method utilizing fuzzy inference systems to assist Florida prosumers in choosing between a peer-to-peer energy network and the traditional grid. The method considers changes in net metering rules and aims to maximize profit while accounting for cost, reliability, and environmental impact. Fuzzy logic control systems can help prosumers maximize profit by choosing between peer-to-peer energy trading and grid connections. In this proposed method the FIS solution can optimize profit compared to solely connecting to the P2P market or the grid. Also breaking up the FIS system into separate components simplifies decision-making for prosumers. It demonstrates the feasibility of the proposed model in decision-making for microgrid design, the impact of P2P trading on total profit, and the applicability of the solution approach in enhancing sustainability. Focusing on sustainable microgrid design with P2P energy trading using blockchain technology is in [50]. It enables secure and sustainable peer-to-peer energy trading. This research proposes a fuzzy multi-objective programming model to optimize sustainable microgrid design, considering economic and environmental objectives with social constraints. It demonstrates the feasibility of the proposed model in decision-making for microgrid design, the impact of P2P trading on total profit, and the applicability of the solution approach in enhancing sustainability. This method can enhance profitability and reduce CO2 emissions in smart microgrids connected to the main grid. The price

of solar energy is crucial for making efficient investment decisions. This study uses a Hesitant Fuzzy Cognitive Map (HFCM) model to define and represent the various factors that significantly impact long-term solar energy pricing. The research emphasizes the use of HFCMs to model the causal relationships in solar energy pricing, identifying key factors such as regulatory policies, fiscal incentives, and public financing. The findings indicate that these factors play a significant role in determining the price of solar energy. Through calculations with different initial state vectors, the solar energy price eventually reaches a constant equilibrium. This inertia state of the solar energy price influences the factors supporting and disrupting the solar energy system, causing them to also enter an inertia state [8]. Recent studies [11-30] reviewed in this section have focused on blockchain-based trading platforms with an emphasis on blockchain characteristics such as transparency and decentralization. None of them conducted solar energy transactions using a power purchase agreement (PPA) on the blockchain platform. Other studies [40-44] have utilized fuzzy systems for various applications, including energy management, maximum power point tracking in solar systems, reducing electricity consumption, compensating solar panel owner losses, and balancing energy supply and demand. However, these methods often lack the necessary mechanisms to manage pricing uncertainties arising from significant and sudden fluctuations in inflation rates and dollar change rates. In contrast, the proposed system effectively addresses pricing uncertainty by integrating fuzzy logic and blockchain smart contracts, ensuring secure and adaptable pricing. This dual approach not only overcomes the limitations of existing systems but also provides an efficient and scalable framework for decentralized energy trading. Unlike previous works that mainly focused on predefined pricing rules, the proposed system uses a fuzzy inference engine to dynamically adjust prices based on real-world conditions. This adaptability ensures fairer pricing for users while maintaining system reliability. By combining these innovations, the proposed system not only addresses existing challenges but also lays a strong foundation for future advancements in blockchain-based renewable energy markets.

3 Bachground

3.1 PPA

Obtaining a license and following the Power Purchase Agreement (PPA) process are essential steps for setting up a solar power plant. The government has facilitated conditions to promote renewable energy, increasing the demand for solar plants. Since 2015, the government has committed to purchasing power from solar producers for 20 years to encourage private sector participation. To set up a solar plant, there are two main approaches: Buying electricity for household or industrial use (up to 100 kW). Building a solar farm with a capacity of over 100 kW. Each PPA between the government and customers specifies key details, including the contract amount, effective date, duration, customer information, and payment terms. Contracts last 20 years, starting when the solar plant begins energy trading. Customer details must be approved by the Renewable Energy Organization (SATBA), providing a valid ID for transactions. Payments are made bi-monthly, with the base rate reducing by 30 percent from the 11th year onward. Each PPA that is concluded between the government and customers includes several basic items such as the contract amount, the effective date and duration of the contract, customer specifications, and how to pay customers, which are summarized in Figure 1.

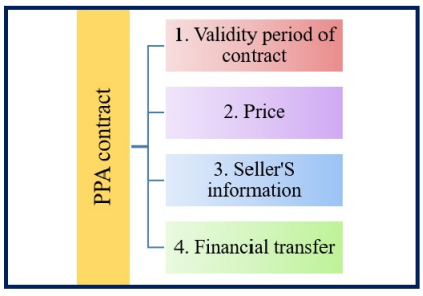


Figure 1: Important factors of PPA in solar energy trading.

3.2 Fuzzy system

Fuzzy Logic (FL) is based on Fuzzy Set Theory, established by Lofti A. Zadeh in 1965. Today, fuzzy sets have their mathematical foundations, rooted in set theory and multi-valued logic. These advancements have enriched classical two-

valued calculus with a profound and novel perspective. Unlike classical knowledge systems, Fuzzy Logic (FL) formalizes modes of reasoning that are approximate rather than exact (Kosko 1992). FL is more aligned with human thinking and natural language than traditional logical systems. Essentially, it offers an effective way to capture the world's approximate and inexact nature. In most practical applications, a key part of Fuzzy Logic (FL) focuses on using IF-THEN rules. This segment of FL includes concepts and methods for handling knowledge represented by systems of fuzzy IF-THEN rules. The essential part of this is a set of linguistic rules related to fuzzy implication and the compositional rule of inference. Essentially, FL provides an algorithm that transforms expert knowledge-based linguistic control strategies into automatic control strategies, with the advantage that fuzzy antecedents eliminate the need for precise input matching [3]. The fuzzy inference system is a widely used computational framework grounded in fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. It can process both fuzzy and crisp inputs, but it typically generates outputs as fuzzy sets. Therefore, a defuzzification method is required to convert a fuzzy set into a representative crisp value. The Mamdani fuzzy inference system was initially proposed to control a steam engine and boiler combination using linguistic control rules derived from experienced human operators [23].

3.3 Blockchain

A distributed database that is used to record information is called a blockchain. This technology is made from a model based on blockchain information that cannot be changed and manipulated. Blockchain can also be called a comprehensive technical system that is designed from the integration of the three basic technologies of asymmetric encryption algorithms, distributed data storage, and consensus algorithms [2]. By using the two features of encryption and data distribution the possibility of hacking, changing, and deleting recorded information is almost eliminated. Blockchain has unique features that distinguish it from other technologies, which are fully described in the introduction. In this section, other features are also discussed.

3.3.1 How blockchain works

Blockchain records transactions through a multi-step process: 1. Transaction Submission: Users send transactions to all network nodes. These can include financial transfers (e.g., sending cryptocurrencies) or executing functions in smart contracts. 2. Mempool Storage: Unverified transactions are stored in a Mempool, a waiting area within the network. 3. Transaction Selection: Miners select transactions for processing based on their fees and verify them. 4. Block Creation: Miners compete to solve complex mathematical problems, allowing them to create a new block containing verified transactions. 5. Block Addition: The winning miner adds the new block to the blockchain and receives a reward. 6. Broadcasting: Information about the new block is shared across all network nodes to maintain synchronization. Nodes also retain information about the previous block for future mining. 7. Repetition: This process repeats until all defined cryptocurrencies are mined.

3.3.2 Types of blockchains

Blockchains can be divided into Permissioned and Permissionless types. In Permissionless blockchains, anyone can join anonymously and become a node. It ensures higher security due to the large number of nodes verifying transactions, though at the cost of slower processing times. Permissioned blockchains restrict participation to authorized users with verified identities. While this allows for faster transactions, it can introduce potential security risks due to the smaller number of nodes. Based on access levels, blockchains are classified into public, private, federated, and hybrid. Public blockchains (like Bitcoin and Ethereum) are permissionless and decentralized, allowing anyone to join and verify transactions. Private blockchains are permissioned and managed by a single entity, with limited node participation, making them vulnerable to collusion. Federated blockchains are more decentralized than private ones, operated by multiple organizations that collaborate and use a majority vote for consensus. Hybrid blockchains combine public and private features, where organizations manage data visibility while maintaining privacy in transactions. In these networks, user identities remain anonymous unless they are directly involved in a transaction [35].

3.3.3 Consensus algorithm

The consensus mechanism is fundamental to establishing trust in blockchain networks, as it ensures that all participants agree on the validity of transactions. Various consensus algorithms, such as Proof of Work (PoW), Proof of Stake (PoS), and Proof of Authority (PoA), play crucial roles in this process, each with distinct features and implications for security and decentralization. Key Consensus Mechanisms are as follows: 1. Proof of Work (PoW): Requires computational effort to validate transactions, enhancing security but consuming significant energy. 2. Proof of Stake (PoS): Allows

validators to create new blocks based on their stake, promoting efficiency but risking centralization among wealthier nodes [21]. 3. Proof of Authority (PoA): Relies on a limited number of trusted nodes, which can improve transaction speed but may compromise decentralization [24]. The BNB Smart Chain (BSC) that is utilized in this study for implementation, uses a Proof of Staked Authority (PoSA) consensus mechanism. PoSA is a hybrid of two common mechanisms: Proof of Stake and Proof of Authority. BNB Smart Chain's PoSA consensus combines staking (like in PoS) with authority like in PoA. Validators are selected based on their staked BNB, and they rotate in producing blocks. This mechanism is designed to provide faster transaction processing while ensuring sufficient security for the network.

3.4 Ethereum

Ethereum, described by Vitalik Buterin as a "universal computer," is designed to enable individuals to manage their affairs independently, without intermediaries like banks. While based on Bitcoin's technology, Ethereum introduces key differences: it not only stores data but also supports distributed computations It also allowing for programmable transactions via smart contracts. As the first open-source, decentralized blockchain platform, Ethereum is not controlled by any single entity and offers features like transparency, cryptography, and peer-to-peer interactions [36]. Ethereum enables developers to build decentralized applications (dApps) that operate autonomously. Despite its advantages, Ethereum has some drawbacks, including high energy consumption due to its proof-of-work (PoW) method and network congestion, which causes transaction delays. To address these issues, Ethereum 2.0 (ETH 2.0 or Serenity) was introduced, improving efficiency, speed, and scalability while maintaining security and decentralization [16].

3.4.1 Ethereum Virtual Machine (EVM)

A virtual machine (VM) is a software program that executes code by following specific instructions, with the Java Virtual Machine (JVM) being a well-known example. Ethereum's key innovation is the Ethereum Virtual Machine (EVM) it allows multiple applications to be built on a single platform, enabling the execution of smart contracts. Unlike traditional blockchains, where each application requires a new blockchain, the EVM provides a unified environment for running Ethereum-based programs [16]. The EVM executes smart contract code line-by-line, written in high-level languages like Solidity, which compiles into bytecode. It is a Turing-complete machine, functioning as a universal, decentralized 256-bit computer made up of nodes. The EVM also includes algorithms to prevent denial-of-service attacks and manages numerous executable objects, each with its own permanent data storage, ensuring the secure operation of smart contracts [22].

3.4.2 Smart contract

The concept of smart contracts was first introduced by Nick Szabo in 1994 [49]. A smart contract is a computer program that executes automatically according to predefined conditions and instructions set by the programmer, without the need for third-party intervention [54]. Transactions conducted through smart contracts are traceable and irreversible. Since these contracts are written on a blockchain platform, the data is encrypted with mathematical formulas, ensuring the confidentiality of the information recorded on the network. Smart contracts have two main characteristics, Mode and Value. Mode manages relationships between parties (organizations, institutions, individuals), automatically executing agreements when conditions are met. Value handles financial transactions, holding assets until conditions are satisfied, after which assets are distributed according to the contract terms [52]. The Ethereum network is the most widely used platform for smart contracts. The Ethereum Virtual Machine (EVM) processes the contract's code, executing commands based on input data. If the contract's conditions are met, a transaction is added to a new block on the blockchain after network consensus. Each successful execution generates a unique 64-bit ID as the smart contract address. Once deployed, smart contract code is immutable, requiring precise programming from the outset. Smart contracts operate based on four key principles: 1. Subject of the Contract: Defines the terms and conditions for granting access to services. 2. Terms of the Contract: Written in a programming language, these rules outline all details, including rewards or penalties for compliance or violation. 3. Digital Signatures: Participants use digital signatures (private keys) to agree or disagree with the terms.4.Automation and Independence: Smart contracts are self-executing, reducing the need for monitoring or intermediaries. The smart contract has certain features. Among the features of smart contracts, the following can be mentioned [34]. 1. Automation without the need for oversight. 2. Cost reduction and faster transactions. 3. Decentralization. 4. Enforced rules with associated rewards or penalties

3.4.3 Solidity

Solidity is a language that is based on a contract and is used for executing smart contracts and EVM. It can be run on the server side with programming languages such as C ++, Python, and JavaScript [55]. Programs that are written using the Solidity language are distributed in the blockchain network between nodes, and everyone on the network will have a copy of it. These types of programs are called DAPP programs [6]. The environment for executing solidity programs without server-side components is called Remix, which is a browser-based software development environment (IDE) [54]. When the deploy button is clicked, the transaction is sent and the selected smart contract is executed. The criterion for this transaction is gas and all transactions are done with a gas limit [40].

3.4.4 Gas

Deploying smart contracts on the Ethereum network requires a fee, known as "gas," which is necessary for every transaction. The gas acts as the network's fuel and helps prevent malicious attacks. The contract author determines the gas amount needed to cover each program step, including computations and memory usage. Payment is required upfront in Gigawei (Gwei), with each Gwei equal to 0.000000001 ether. Gas prices fluctuate based on network congestion, and validators prioritize transactions with higher fees. Key terms include Gas Limit, which is the maximum gas fee you are willing to pay for transaction verification. Higher limits can speed up processing. Gas Price is the ether amount per unit of gas, measured in Gwei. Higher prices make transactions more likely to be prioritized. Gas Cost is the fixed amount of computational work needed for a transaction, determining the total gas consumed. This is calculated from the following Equation 1:

$$\text{Ethereum Network fee} = \text{Gas limit} \times \text{Gas Price}. \tag{1}$$

3.4.5 Token

The word "token" originates from the Old English word "tácen," meaning a sign or symbol. Traditionally, it refers to privately issued, coin-like items with minimal inherent value, such as tokens for transportation, laundry, and arcade games. Currently, blockchain technology is redefining "tokens" to mean blockchain-based abstractions that can be owned and represent assets, currency, or access rights. The limited use of physical tokens is linked to their association with low value. Physical tokens are typically confined to specific businesses, organizations, or locations, serve a single function, and are not easily exchangeable. Blockchain tokens, however, eliminate these restrictions, offering precise and re-definable functions. Many blockchain tokens can be traded for each other or other currencies on global liquid markets, serving multiple purposes worldwide.

4 Methods

In the proposed model to address the existing challenges in solar energy exchanges, two technologies are utilized in designing the proposed platform for solar energy exchanges. They are the "fuzzy system" and the "blockchain". The fuzzy system facilitates the pricing of solar energy based on the inflation rate factor and the dollar rate factor, both of which are variable. Blockchain, due to its structure, provides transparency and security for solar energy exchanges. Figure 2 presents the block diagram of the proposed model. This model comprises two main blocks: Block 1 is the fuzzy pricing system, and Block 2 is the blockchain platform for solar energy exchanges. In Block 1, the fuzzy system uses the inflation rate and dollar exchange rate as inputs to generate an output, which is the price of solar energy. The details related to this process are presented in Figure 3. The price derived from the fuzzy system is given as input to the blockchain platform for solar energy exchanges in Block 2. The details concerning the blockchain platform for solar energy exchanges are provided in Figure 4. The UML file related to solar energy trading is shown in Figure 5. The three main roles of buyer, seller, and regulator are shown in this figure. The requirements of each role and the operations they perform are also briefly mentioned.

4.1 Fuzzy system

Two methods have been employed for implementing the fuzzy system, both utilizing MATLAB software. The first method involves coding, which can be considered a direct approach, while the second method utilizes the MATLAB toolbox. Fuzzy Logic Toolbox enables the use of fuzzy systems for various applications. This method is much simpler and more comprehensible compared to direct coding methods. In the implementation of fuzzy systems using MATLAB's Fuzzy Logic Toolbox, various methods and logics are employed. One commonly used method is the Mamdani approach. This approach is one of the most well-known and oldest fuzzy methods, introduced by Mamdani. In this method, fuzzy

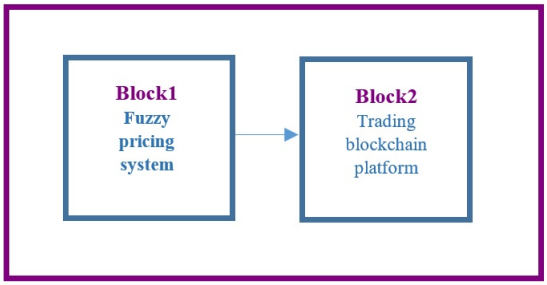


Figure 2: Proposed model for trading solar energy system.

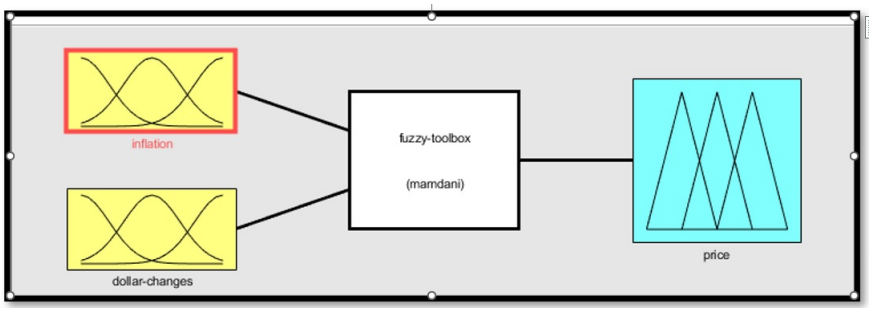


Figure 3: fuzzy pricing system.

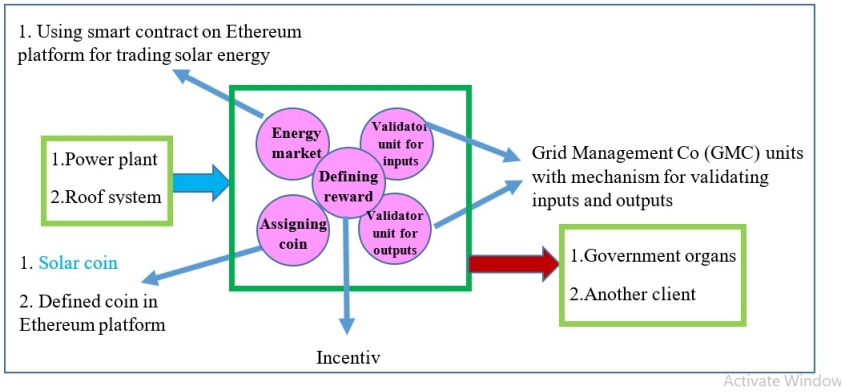


Figure 4: Trading blockchain platform: Blockchain Platform of Solar Energy Exchange "BSET".

rules are defined as "IF-THEN" statements and fuzzy outputs are combined using max-min operations. The centroid method is then used for defuzzification of the output. To avoid excessive elaboration, the explanations and results related to the implementation using MATLAB toolbox are presented in this research. Steps for Implementing a Fuzzy System in MATLAB are as bellow: 1. Defining Fuzzy Input and Output Variables: Determine linguistic variables and membership functions for each input and output. 2. Defining Fuzzy Rules: Create a set of "IF-THEN" rules that specify how inputs are combined to produce outputs. 3. Performing Fuzzification: Convert precise input values into fuzzy values using membership functions. 4. Performing Fuzzy Inference: Combine and evaluate fuzzy rules to generate fuzzy output. 5. Defuzzification: Convert fuzzy outputs into precise values using methods such as the centroid method.

4.2 Smart contract system

In the proposed BSET platform, the smart contract defines all PPA sections needed for trading solar energy. In this study, a PPA smart contract is defined between the government and solar power stations and also is implemented on the Ethereum blockchain and Binance Smart Chain (BNB). These different levels of PPA smart contracts are illustrated

in Fig 5. The schedule section has some important points based on the PPA document. At first, the smart contract should be run on a blockchain platform for twenty years since it has been deployed on the blockchain network. "How to consider PPA validity period in a smart contract?". The answer to this question is the next important point of this section. Therefore, there are two ways to consider the validity period of a PPA in a smart contract. The first method is to define a specific function in a smart contract, which will be executed by users to record the start time of the PPA contract in the blockchain. In this case, there is a possibility of fraud by users so they want to record the start time based on their interest. But in the second method, the organization that is sending smart contracts on the blockchain platform records the start time. To send a smart contract on the network, the organization must enter the initial values that are defined in the smart contract constructor functions by the organization. In this case, due to the supervision of the government organization on the start time, there is no possibility of any fraud compared to the first method. One of the main parts of a PPA smart contract is the determination of the price of traded energy. Pricing is determined according to Equation 2-4.

$$\text{Impact factor } = \text{Inflation rate factor } \times \text{dollar change rate factor}, \tag{2}$$

$$\text{Inflation rate factor} = \frac{\text{inflation rate}}{100} + 1, \tag{3}$$

$$\text{Dollar change rate factor} = \frac{\text{dollar change rate}}{100} + 1. \tag{4}$$

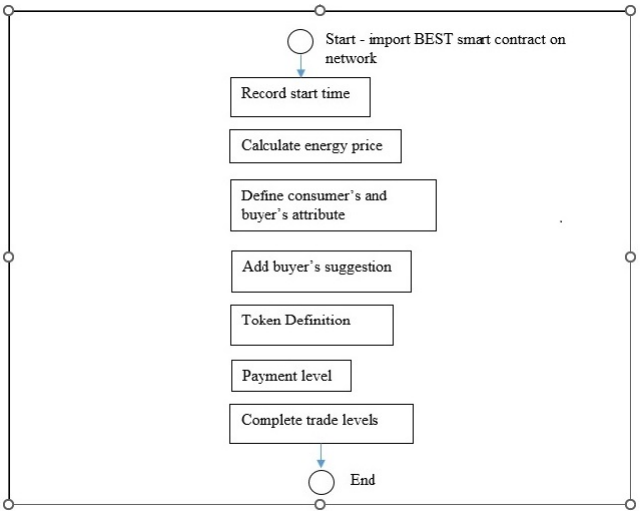


Figure 5: PPA smart contract flowchart

In these relations, the price of energy is directly related to the two factors of the inflation rate factor and the dollar rate factor, which, as shown in equation 3.

4.3 Token definition

One of the basic parts of the BSET platform is the definition of tokens for transactions and financial payments in this contract. For this purpose, we use a separate smart contract to define the token and name it the STC token. To write this token similar to the previous smart contract, we use REMIX and send it to the test networks. There are many ways to deploy token smart contracts on the network such as MetaMask wallet, using MyEtherWallet, using TrustWallet website. There are various standards for writing tokens. They include REC standards, which stand for "Ethereum Request for Comment, such as ERC-20, ERC-223, ERC-621, ERC-721, ERC-777, ERC-1155, and ERC-1400. In this platform, we use the ERC20 standard to write tokens. The balance of function should give us the balance of an address that we give it now allowance is an interesting one. In your ERC20 tokens, we can permit someone else to spend a certain amount of money from our wallet. this function is tightly coupled with the proof function. A proof is a function that allows a certain wallet address to spend X number of tokens from your wallet allowance. On the other hand, this will give users the remaining tokens that the token owner has allowed to spend by the spender. The function transfer

is simple. It allows users to transfer a certain number of tokens to an address. So, when users use the transfer from function they can transfer tokens from the account of another person. This has allowed users to use a certain number of tokens to another account. The immediate events should be obvious. We would emit a transfer event when we transferred some tokens from one account to another. The approval event will be triggered when someone has approved someone to spend money on their behalf. And this is the interface of the standard tokens if you have those functions inside your token, it will be accepted as an ERC20 token.

4.4 Smart contract technical details

Implementing a Power Purchase Agreement (PPA) on a blockchain platform requires designing a smart contract using the Solidity programming language. Once developed, the contract is deployed on the blockchain, enabling users to track solar energy transactions. Since smart contracts incur gas fees for operations, several optimizations were applied to enhance gas efficiency. Optimizations: Complex operations, such as loops, were minimized, and data storage was improved using mappings and structs to lower gas costs. Mappings store data in key-value pairs, while structs group related data, making data retrieval and storage more efficient. 2. Development and Testing: The contract was developed and tested on the BNB Smart Chain (BSC) test network using Remix IDE. Remix provides a user-friendly interface for compiling and deploying contracts. Developers can interact with the contract via API endpoints, facilitating integration with external systems, such as energy trading platforms. Events emitted by the contract allow real-time tracking of key activities, like pricing updates and transaction outcomes. 3. Security and Deployment: Blockchain's immutability, transparency, and auditability ensure data security, preventing unauthorized tampering. To mitigate the risk of denial-of-service (DoS) attacks, the contract was optimized by reducing loops and unnecessary storage writes, enhancing both cost-effectiveness and security. Thorough testing on the test network ensures efficiency and scalability before deployment to the BSC mainnet.

5 Implementation

To evaluate the scenario presented above, we implement two blocks: a fuzzy system for pricing solar energy and Power Purchase Assignments (PPA) on blockchain platforms. For pricing solar energy with the fuzzy system we use Matlab and for PPA on blockchain using smart contracts and solidity language. The implementation steps for the fuzzy pricing block in Figure 3 are as follows: The first step involves defining the inputs and outputs and specifying the numerical range. This system has two inputs, "Inflation rate factor " and "Dollar rate factor" and one output, "solar energy price." The numerical ranges for the inputs and output are provided in Table 1. The next step is to determine the

Variable name	Range
Inflation rate	[0-50]
Dollar price	[0-50]
Solar energy price	[3000-7000]

Table 1: Variable Range

type of membership function for the variables, which has been chosen to be Gaussian for all three variables. The next step is to define the if-then rules for the fuzzy system. These rules are presented in Figure 6. It shows the Rule Editor in MATLAB's fuzzy toolbox, used to define fuzzy "IF-THEN" rules. Each rule combines conditions, such as "If inflation is low and dollar-changes are low, then the price is low." The system defines three ranges—low, medium, and high—for both inputs and outputs. These rules form the foundation of the fuzzy system, which calculates the output (price) based on the input variables (inflation and dollar changes) in a fuzzy manner. The final step involves obtaining the output, the results of which are presented in Section 6. The implementation explanation of the trading blockchain platform block in Figure 2 is as follows: We configure two participants in the platform, the seller and the buyer, and perform various tests for the scenario. The regulator's role is defined in the regulator function of the PPA smart contract. The tests are described below: (1) deploying PPA smart contract on blockchain platforms Ethereum and BNB (Binance Smart Chain) in this test. PPA smart contract inputs should be filled by the user when the smart contract is deployed, which is shown and explained in section 5.1. (2) To make financial payments in this smart contract, a token will be defined. (3) According to section 5.3 users need to enter their information to start trading. (4) Finally, financial payments are made using a token that is defined for this smart contract (STC). The essential point in the PPA smart contract is that the buyer is generally defined in this contract but in fact, the buyer is always the government in our country. In this article, we initially stated that "the buyer is always the government in our country"

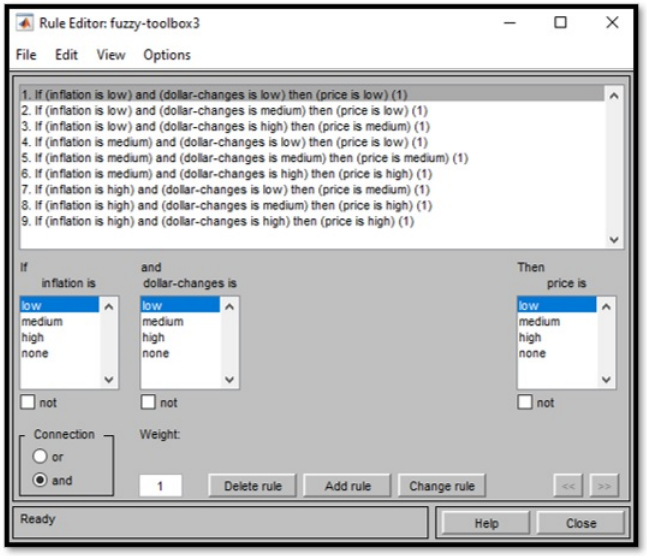


Figure 6: Fuzzy system pricing rules

to illustrate a specific case in a controlled energy market. The platform is designed to be flexible and adaptable. It accommodated various types of buyers beyond government entities, including individual consumers and businesses. As the energy market evolves, particularly with the increasing adoption of peer-to-peer (P2P) trading models, it is essential to recognize that the system can seamlessly integrate different buyer profiles. The platform uses smart contracts to let different participants trade energy easily. Consumers can buy directly from producers, and businesses can buy or sell energy as needed. This creates a flexible, open market, moving beyond traditional government-controlled agreements. The platform enables efficient, direct energy trading between users without central control. Blockchain ensures secure, transparent transactions and allows flexible agreements that can adjust to market changes and user needs. The platform uses smart contracts, dynamic pricing, and marketplace features to engage diverse buyers. It is also important to note that in power purchase agreements, the buyer is always defined as the government, which can be considered a specific case. However, in the platform developed in this research, according to the implementation steps outlined in Section 5, the buyer can be any individual. Additionally, all the options defined for the seller are also considered for the buyer.

5.1 Inputs

For deploying the smart contract on the network, the defined inputs in the constructor function must be set to start trades and execute smart contract functions. Which include:

- -STARTTIME: The PPA smart contract is active for twenty years. Therefore, the designer of the PPA smart contract who sends it to the network must enter the time based on the timestamp criterion as inputs of the smart contract in the constructor function. This can be done using various sites such as https://www.epochconverter.com, a type of Epoch and Unix Timestamp Conversion Tool. To design a smart contract in such a way that it will be active for twenty years, this point is included in the form of a condition in the smart contract, whose pseudo-code is shown in Figure 7. In this pseudo-code duration = 630720000 is obtained from 30 *20* 60* 60. The code in Figure 7 defines a “twentyyear” Modifier. It enforces a time constraint, ensuring that specific actions within the contract can only be executed within 20 years starting from a defined “starttime”. This is useful for limiting the duration of contract operations or token activities.

- -PRICE: The price of the solar energy trading must also be entered as an input. The price of solar energy is derived from the output of the fuzzy system. According to different values for the inflation rate factor and the dollar rate factor, one of these amounts is 48000. It has been considered as 48000 to obtain the outputs of this implementation. This amount serves as the input for the blockchain trading system, and 48000 has been set as the price of conducting the transactions. The values of some parameters are given in Table 2 and in Fig 8 The deployed smart contract with these values is shown. Figure 8 shows the inputs in the constructor function of the smart contract, including the start time and price per unit of solar energy. These inputs are initialized during

```
pragma solidity ^0.8.17;
 import 'ERC20.sol';
 contract trade is ERC20 {
 ..................
uint duration = 630720000;
modifier twentyyear () {
      require ( block.timestamp > starttime &&   block.timestamp < (starttime +
duration));
      _;
  }
.............
}
```

Figure 7: Pseudo-code for Time-based Execution Condition

deployment, entered on the left side of the interface, and stored on the blockchain after confirmation, as depicted on the right side.

Parameters	value
PRICE	48000
STARTTIME	1721802889
TOTALSUPPLY	1000000
Decimals	0
Symbol	STC
Name	Solar Trading Coin

Table 2: The value of PPA smart contract parameters

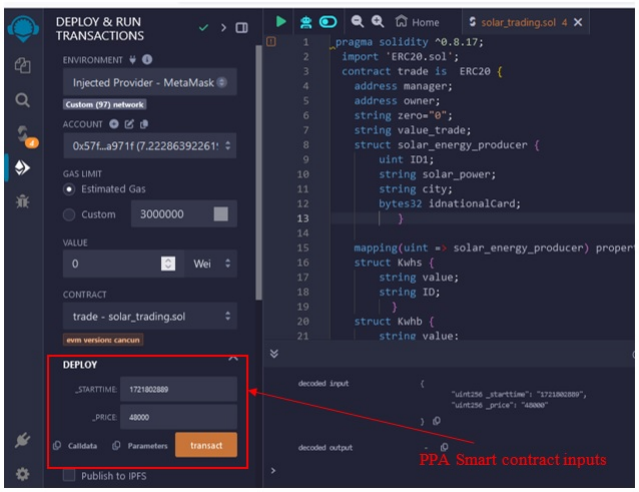


Figure 8: Smart Contract Inputs Defined and Initialized in the Constructor Function for Solar Energy Trading

5.2 Token definition

The PPA smart contract will be deployed on the blockchain network at the same time as the token definition smart contract. A token will be defined with the name and specifications provided in Table 2. This token is used for financial payments of solar energy trading. On the other hand, the defined token must be imported into the user's wallet. In this implementation, MetaMask is the wallet that is used. in more detail, the users run the transfer function which contains the "value" and the "address" of the seller, and the payment amount is deposited into the seller's wallet account.

5.3 Trading

After confirming the PPA smart contract by the blockchain network, users must enter their information to start the trading process as shown in Fig. This information includes the name of the power plant, city, and ID, that are entered in the NationalCard function. They are entered on the left side of the interface and stored on the right side after confirmation. In the next step, the seller and buyer enter the values for the suggested and required amounts

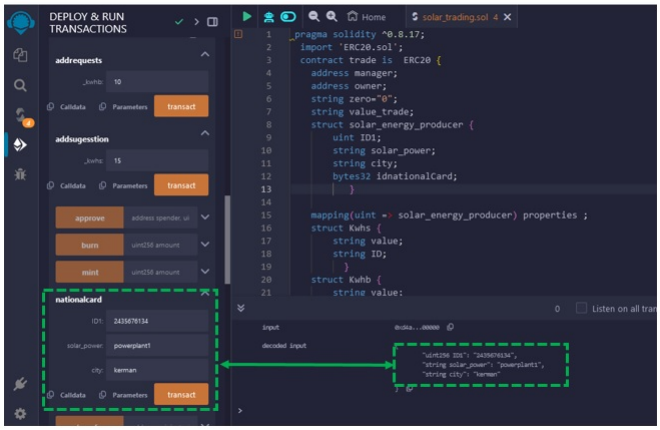


Figure 9: Storing User's Information on the Blockchain

of solar energy. These values will then be checked by the regulator. One of the ideas that can be raised about this implementation is that if the necessary infrastructure for transferring solar energy is available, this smart contract can also be used to conduct trade between two different cities.

5.4 Managing energy imbalances and intermittency

The intermittent nature of solar power, caused by factors such as weather conditions and time of day, presents a challenge for balancing supply and demand in energy markets. In the proposed in blockchain-based solar energy trading, these challenges can be mitigated by two mechanisms integrated into the smart contract design. 1. Peer-to-Peer Energy Trading: One of the key features of the blockchain platform is its ability to facilitate peer-to-peer (P2P) energy trading. When a producer is unable to meet the demand, the system can automatically search for other producers within the network who can sell their surplus energy. This decentralized approach enhances grid reliability and ensures that buyers can meet their energy needs even during periods of low production from their primary energy provider. 2. Definition of the Regulator Role: As mentioned in the article, this implementation defines three roles: buyer, seller, and regulator. The regulator is responsible for approving transactions and assessing the value of supply and demand. It also addresses scenarios where the seller is unable to deliver the agreed energy amount due to weather-related issues or when there are fluctuations in the buyer's demand. The regulator, as the relevant authority, will take action against the offending user in accordance with the existing regulations.

5.5 Financial payments

After the regulator's approval and in the final stage, the buyer must deposit enough money into the seller's account. The amount that must be deposited into the seller's account is calculated according to Equation 5:

$$\text{payment} = \text{price} \times \text{-kwhs}. \tag{5}$$

In test 1 according to Table 3, the value of the required amount of solar energy is 10 KW and the value of the suggested amount of solar energy is 20 KW So, in this test, 10 kW of solar energy has been traded. As a result, the buyer must deposit the 10 STC (48000*10) into the seller's account. In Figure 10, the balance of accounts before payment by the buyer is shown, which is 1000000 STC for account 1(10-a) and 0 STC (10-b) for account 2. In Fig 11 after paying 480000 STC to the seller, the values are also 520000 STC (11-a) and 10 STC (11-b) respectively. Also in these figures account 1 is the buyer and account 2 is the seller.

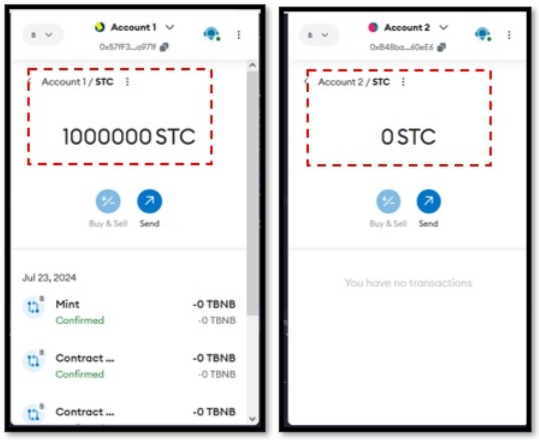


Figure 10: The STC token balance of (a) account 1 (1000000STC) and (b) account 2 (0 STC) before payment.

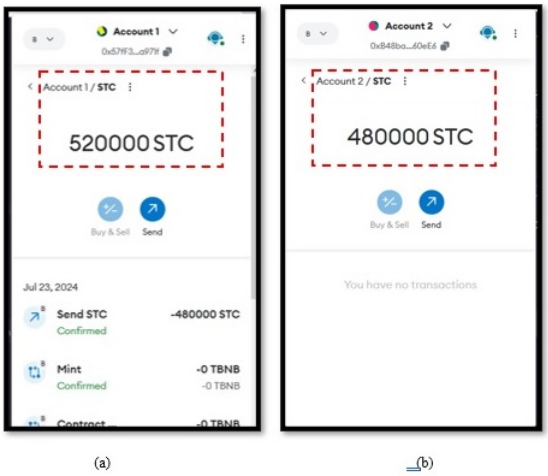


Figure 11: The STC token balance of (a) account 1 (520000STC) and (b) account 2 (480000 STC) after payment.

5.6 Data management and privacy in blockchain platforms

In a blockchain-based platform for solar energy trading, securing data and protecting privacy is crucial, particularly when handling sensitive information like solar trading data and transaction details. Although blockchain ensures transparency in trades, safeguarding the confidentiality of participants' data is vital to maintaining trust and confidence in the system. The platform utilizes robust encryption techniques to ensure the privacy of sensitive data, such as solar energy generation and trading records. All user data is encrypted before being recorded on the blockchain, and anonymization methods are applied to separate personal information from transaction details. This ensures user privacy is maintained, even in publicly accessible blockchain transactions. To optimize security and privacy, the platform stores sensitive information, such as user profiles and energy consumption data, off-chain in secure databases. Only the hashed references to these datasets are recorded on the blockchain, which ensures the immutability and transparency of the transaction without revealing personal data directly on the public ledger. The platform implements strict access controls through cryptographic keys. Only authorized participants, such as buyers, sellers, and regulators, can access sensitive information. Additionally, we can add multi-signature protocols to approve key transactions, ensuring that no single user can alter data or access private information without proper authorization. Despite the inherent security of blockchain technology, potential vulnerabilities, such as data breaches or unauthorized access, are addressed through advanced security measures. These include encrypted communication channels, strong consensus algorithms, regular security audits, and prompt updates to handle any emerging threats. The system ensures that data integrity and confidentiality are maintained at all times. By incorporating robust encryption, secure data storage, controlled access, and proactive security measures, the platform ensures a high level of privacy without compromising the transparency

of solar energy transactions. These features make the platform both secure and reliable for all participants.

6 Results

By applying the fuzzy system described in Section 5 for solar energy pricing, the results related to the fuzzy block mentioned in Figure 2 for two consecutive years are provided in Table 3. By using this platform and a process with the

Date	Inflation rate	Dollar price	Base price	Fuzzy price
2024 April 2	38.8	7.5	3000	48000
2023 April 3	41	48	3000	61000

Table 3: Fuzzy price

mentioned steps, solar energy trading is tested 10 times on different days and hours. In this implementation, which has been reported 10 times in Figures 12 and 13, the amount of total gas consumed and the duration of transactions are drawn. According to Figure 12, gas cost includes the gas required for storage of buyer and seller specifications on the

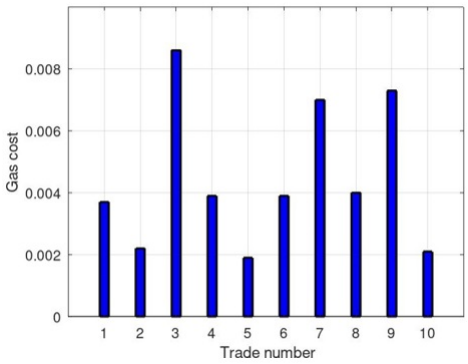


Figure 12: Gas cost in solar energy trading

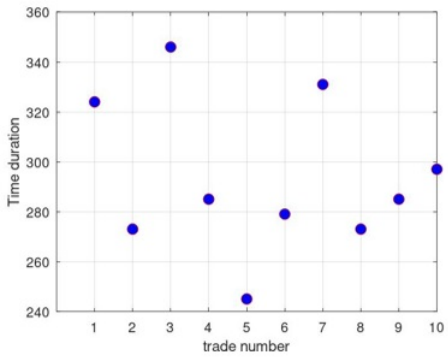


Figure 13: Time duration in solar energy trading

blockchain and also the amount of solar energy proposed and required, which will be added to the gas for transferring tokens from the buyer account to the seller account. Figure 12 shows that the gas cost for performing the trade was not the same at different times and depended on the blockchain network traffic. when the network is busy and many transactions are waiting to be confirmed by the network, this amount increases and if it is quieter, this amount will be less. In this test, according to Figure 12, trade number 3 with a gas cost of 0.0086 TBNB has the highest gas cost, and trade number 5 with a gas cost of 0.0019 TBNB has the lowest gas cost.

Figure 13 is drawn based on the time duration of a transaction and is the time spent to perform the items mentioned in Figure 12. The total gas cost and duration of a trade from the first step (deploying the contract on the blockchain)

to the final step (transferring tokens) have been different from these values. Total time is 466 seconds and total gas is 0.023. The reason for the difference between the "total time" and the "time duration" in Fig 13 of trade is two factors: the time duration of sending the PPA smart contract on the Blockchain and the time duration of defining the STC token. Similarly, the total gas consumption and gas consumption of trade also differ from each other. Figure 13 shows that the duration of trading varies at different times and is similar to gas cost depending on the network traffic. When the network is busy and there are many transactions waiting to be confirmed, transactions are confirmed more slowly, and this amount increases. However, if the network is quieter, transactions are confirmed faster, and this amount will be lower. In this test, according to Figure 13, trade number 5 with a duration of 245 seconds has the shortest duration, and trade number 3 with a duration of 346 seconds has the longest duration.

7 Discussion

7.1 Comparison with existing energy trading platforms

The proposed blockchain-based solar energy trading platform offers a comprehensive solution to the limitations observed in both traditional centralized systems and other decentralized platforms. Through the integration of Solar Trading Coin (STC) tokens and fuzzy pricing, the platform ensures cost-effectiveness, scalability, and regulatory compliance. 1. Token Definition and Cost-Effectiveness: In centralized energy trading platforms, intermediaries increase transaction costs and delays. By introducing the STC token, our platform enables peer-to-peer transactions, removing the need for intermediaries. The use of smart contracts ensures automated payments and reduces operational costs, providing a more cost-effective solution compared to traditional systems. 2. Scalability: The decentralized nature of blockchain and the use of tokens allow the platform to scale seamlessly. As more participants join the network, the platform automatically handles transactions without introducing bottlenecks. Fuzzy pricing further enhances scalability by adjusting prices dynamically based on real-time market data, making the platform adaptable to large-scale and cross-border transactions. 3. Regulatory Compliance: The STC token and smart contracts enable built-in regulatory compliance, ensuring that all transactions meet local and international energy trading regulations. Additionally, fuzzy pricing models are designed to comply with regulatory frameworks by incorporating relevant pricing laws into automated contracts. The transparency of blockchain provides real-time auditing capabilities, offering regulators complete visibility over the system without compromising user privacy.

7.2 Performance evaluation

This section will discuss the system's accuracy, robustness, biases, fairness, and efficiency compared to traditional pricing mechanisms. 1. To validate the accuracy and performance of the fuzzy logic pricing system, historical data on solar energy prices was collected for the period between [2020-2023]. This data included key economic factors, such as inflation rates and dollar exchange rates, which serve as input parameters for the fuzzy system. This dynamic pricing ability showcases the system's flexibility in adapting to fluctuations in inflation and currency exchange rates, providing a smoother and more responsive price prediction model compared to traditional pricing mechanisms. Moreover, the fuzzy logic system's ability to handle uncertainty in inputs, such as small variations in inflation rates or demand, demonstrates its advantage in avoiding sharp price changes, as typically seen in traditional pricing models. This flexibility ensures that both producers and consumers experience more stable pricing, contributing to a balanced and efficient market. 2.Regarding the robustness of the fuzzy system, if robustness is understood as the ability of a system to perform correctly and consistently in the face of variations or disturbances in inputs and different conditions, it can be stated that the output membership function (price) is defined as Gaussian. This modeling approach ensures smoother responses to input changes. As a result, the system performs well under various conditions and provides reasonable results. Additionally, by defining appropriate membership functions and ranges for the inputs, we can manage a wide range of inputs without failure or producing inconsistent results. However, the fuzzy pricing model has been validated by comparing its outputs against real market data over a set period. This validation confirms that the model produces stable and reasonable prices under varying conditions 3. Regarding the potential biases of the fuzzy system discussed in this paper, if we consider these biases as the tendency of a model to produce unfair or unreliable results due to assumptions, it can be stated that these biases may arise from the selection of input variables. Additionally, they may result from the design of membership functions. By defining the rules to closely reflect reality and utilizing historical trading data while appropriately selecting input variables, a more balanced pricing determination can be achieved, taking into account a broader range of variables compared to traditional systems. 4. The fuzzy system in this research promotes fairness because it dynamically adjusts solar energy prices based on real-time economic conditions such as inflation rate and dollar change rate. This system ensures that both producers (solar energy sellers) and consumers

(buyers) are treated equitably, avoiding the rigid and potentially biased outcomes of traditional pricing models. 5. The fuzzy pricing system's dynamic pricing capabilities significantly enhance market efficiency by ensuring better supply-demand matching. By adjusting prices in real-time based on market conditions, the system minimizes excess supply during low-demand periods, effectively reducing energy wastage.

8 Conclusion

In conclusion, the integration of blockchain technology and fuzzy logic into the solar energy trading sector offers a promising solution to the existing challenges. Blockchain provides a decentralized, secure, and transparent platform for conducting transactions, while smart contracts facilitate automated and reliable execution of Power Purchase Agreements (PPA). By addressing issues such as transaction tracking, payment mechanisms, and transparency in pricing, blockchain technology can significantly enhance the efficiency and trustworthiness of solar energy trading. Additionally, the application of fuzzy logic for pricing can effectively manage the complexities and uncertainties associated with inflation and exchange rate fluctuations. Therefore, this research highlights the potential of a blockchain-based platform combined with fuzzy logic to revolutionize solar energy trading, ensuring a more reliable, transparent, and efficient system for all stakeholders involved.

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References

[1] N. Z. Aitzhan, D. Svetinovic, *Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams*, IEEE Transactions on Dependable and Secure Computing, **15**(5) (2016), 840-852. https://doi.org/10.1109/TDSC.2016.2616861

[2] A. M. Antonopoulos, G. Wood, *Mastering ethereum: Building smart contracts and dapps*, O'reilly Media, 2018.

[3] L. A. Q. Aranibar, *Learning fuzzy logic from examples*, Master's thesis, Ohio University, 1994.

[4] J. Bao, D. He, M. Luo, K. K. R. Choo, *A survey of blockchain applications in the energy sector*, IEEE Systems Journal, **15**(3) (2020), 3370-3381. https://doi.org/10.1109/JSYST.2020.2998791

[5] Y. Besanger, Q. T. Tran, M. T. Le, *On the applicability of distributed ledger architectures to peer-to-peer energy trading framework*, In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, (2018), 1-5. https://doi.org/10.1109/EEEIC.2018.8494446

[6] P. Chapman, D. Xu, L. Deng, Y. Xiong, *Deviant: A mutation testing tool for solidity smart contracts*, In 2019 IEEE International Conference on Blockchain (Blockchain), (2019), 319-324. https://doi.org/10.1109/Blockchain.2019.00050

[7] J. Chiu, T. V. Koeppl, *Blockchain-based settlement for asset trading*, The Review of Financial Studies, **32**(5) (2019), 1716-1753. https://doi.org/10.1093/rfs/hhy122

[8] V. Çoban, S. Çevik Onar, *Strategic analysis of solar energy pricing process with hesitant fuzzy cognitive map*, Energy Management-Collective and Computational Intelligence with Theory and Applications, (2018), 195-227. https://doi.org/10.1007/978-3-319-75690-5_10

[9] T. T. A. Dinh, J. Wang, G. Chen, R. Liu, B. C. Ooi, K. L. Tan, *Blockbench: A framework for analyzing private blockchains*, In Proceedings of the 2017 ACM International Conference on Management of Data, (2017), 1085-1100. https://doi.org/10.1145/3035918.3064033

[10] A. Dorri, F. Luo, S. S. Kanhere, R. Jurdak, Z. Y. Dong, *SPB: A secure private blockchain-based solution for distributed energy trading*, IEEE Communications Magazine, **57**(7) (2019), 120-126. https://doi.org/10.1109/MCOM.2019.1800577

[11] M. B. Dowlatshahi, V. Derhami, H. Nezamabadi-Pour, *Fuzzy particle swarm optimization with nearest-better neighborhood for multimodal optimization*, Iranian Journal of Fuzzy Systems, **17**(4) (2020), 7-24. https://doi.org/10.22111/ijfs.2020.5403

[12] M. Eftekhari, M. Eftekhari, M. Majidi, H. Nezamabadi Pour, *Securing interpretability of fuzzy models for modeling nonlinear MIMO systems using a hybrid of evolutionary algorithms*, Iranian Journal of Fuzzy Systems, **9**(1) (2012), 61-77. https://doi.org/10.22111/IJFS.2012.226

[13] K. Gai, Y. Wu, L. Zhu, M. Qiu, M. Shen, *Privacy-preserving energy trading using consortium blockchain in smart grid*, IEEE Transactions on Industrial Informatics, **15**(6) (2019), 3548-3558. https://doi.org/10.1109/TII.2019.2893433

[14] A. M. Gil-Lafuente, *Fuzzy logic in financial analysis*, Berlin: Springer, **175** (2005). https://doi.org/10.1007/3-540-32368-6

[15] Y. Gong, H. Yao, Z. Xiong, C. P. Chen, D. Niyato, *Blockchain-aided digital twin offloading mechanism in space-air-ground networks*, IEEE Transactions on Mobile Computing, **24**(1) (2025), 183-197. https://doi.org/10.1109/TMC.2024.3455417

[16] M. Grincalaitis, *Mastering Ethereum: Implement advanced blockchain applications using Ethereum-supported tools, services, and protocols*, Packt Publishing Ltd, 2019.

[17] K. Hojckova, H. Ahlborg, G. M. Morrison, B. Sandén, *Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading*, Research Policy, **49**(8) (2020), 104046. https://doi.org/10.1016/j.respol.2020.104046

[18] J. Horta, D. Kofman, D. Menga, A. Silva, *Novel market approach for locally balancing renewable energy production and flexible demand*, In 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm), (2017), 533-539. https://doi.org/10.1109/SmartGridComm.2017.8340728

[19] E. Hossain, I. Khan, F. Un-Noor, S. S. Sikander, M. S. H. Sunny, *Application of big data and machine learning in smart grid, and associated security concerns: A review*, IEEE Access, **7** (2019), 13960-13988. https://doi.org/10.1109/ACCESS.2019.2894819

[20] W. Hua, H. Sun, *A blockchain-based peer-to-peer trading scheme coupling energy and carbon markets*, In 2019 International Conference on Smart Energy Systems and Technologies (SEST), (2019), 1-6. https://doi.org/10.1109/SEST.2019.8849111

[21] Z. Hussein, M. A. Salama, S. A. El-Rahman, *Evolution of blockchain consensus algorithms: A review on the latest milestones of blockchain consensus algorithms*, Cybersecurity, **6**(1) (2023), 30. https://doi.org/10.1186/s42400-023-00163-y

[22] K. Iyer, C. Dannen, *Building games with ethereum smart contracts*, New York: Apress., (2018), 19-36.

[23] J. S. R. Jang, C. T. Sun, E. Mizutani, *Neuro-fuzzy and soft computing-a computational approach to learning and machine intelligence*, [Book Review], IEEE Transactions on Automatic Control, **42**(10) (1997), 1482-1484. https://doi.org/10.1109/TAC.1997.633847

[24] Y. Jo, C. Park, *Enhancing ethereum PoA clique network with DAG-based BFT consensus*, In 2024 IEEE International Conference on Blockchain and Cryptocurrency (ICBC), (2024). https://doi.org/10.1109/ICBC59979.2024.10634410

[25] E. S. Kang, S. J. Pee, J. G. Song, J. W. Jang, *A blockchain-based energy trading platform for smart homes in a microgrid*, In 2018 3rd International Conference on Computer and Communication Systems (ICCCS), (2018), 472-476. https://doi.org/10.1109/CCOMS.2018.8463317

[26] R. K. Kodali, S. Yerroju, B. Y. K. Yogi, *Blockchain based energy trading*, In TENCON 2018-2018 IEEE Region 10 Conference, (2018), 1778-1783. https://doi.org/10.1109/TENCON.2018.8650447

[27] K. G. H. Kong, J. Y. Lim, W. D. Leong, W. P. Q. Ng, S. Y. Teng, J. Sunarso, B. S. How, *Fuzzy optimization for peer-to-peer (P2P) multi-period renewable energy trading planning*, Journal of Cleaner Production, **368** (2022), 133122. https://doi.org/10.1016/j.jclepro.2022.133122

[28] N. Kshetri, J. Voas, *Blockchain-enabled e-voting*, IEEE Software, **35**(4) (2018), 95-99. https://doi.org/10.1109/MS.2018.2801546

[29] A. Kumari, R. Gupta, S. Tanwar, S. Tyagi, N. Kumar, *When blockchain meets smart grid: Secure energy trading in demand response management*, IEEE Network, **34**(5) (2020), 299-305. https://doi.org/10.1109/MNET.001.1900660

[30] A. Laszka, S. Eisele, A. Dubey, G. Karsai, K. Kvaternik, *TRANSAX: A blockchain-based decentralized forward-trading energy exchanged for transactive microgrids*, In 2018 IEEE 24th International Conference on Parallel and Distributed Systems (ICPADS), **15**(3) (2018), 918-927. https://doi.org/10.1109/PADSW.2018.8645001

[31] H. Lopez, A. Zilouchian, *Peer-to-Peer energy trading for PV prosumers using fuzzy logic inference systems*, In 2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)), (2023), 1-4. https://doi.org/10.1109/PVSC48320.2023.10359770

[32] X. Lu, Z. Guan, X. Zhou, X. Du, L. Wu, M. Guizani, *A secure and efficient renewable energy trading scheme based on blockchain in smart grid*, In 2019 IEEE 21st International Conference on High Performance Computing and Communications; IEEE 17th International Conference on Smart City; IEEE 5th International Conference on Data Science and Systems (HPCC/SmartCity/DSS), (2019), 1839-1844. https://doi.org/10.1109/HPCC/SmartCity/DSS.2019.00253

[33] H. Luo, Q. Zhang, G. Sun, H. Yu, D. Niyato, *Symbiotic blockchain consensus: Cognitive backscatter communications-enabled wireless blockchain consensus*, IEEE/ACM Transactions on Networking, **32**(6) (2024), 5372-5387. https://doi.org/10.1109/TNET.2024.3462539

[34] B. K. Mohanta, S. S. Panda, D. Jena, *An overview of smart contract and use cases in blockchain technology*, In 2018 9th International Conference on Computing, Communication and Networking Technologies (ICCCNT), (2018), 1-4. https://doi.org/10.1109/ICCCNT.2018.8494045

[35] H. Nezamabadi-Pour, *The fundamental of blockchain and cryptocurrencies*, Shahid Bahonar University of Kerman Press. [In Farsi], 2023.

[36] H. Nezamabadi-Pour, *Advanced concepts of blockchain and smart contracts*, Shahid Bahonar University of Kerman Press. [In Farsi], 2023.

[37] H. Nezamabadi-Pour, S. Yazdani, M. M. Farsangi, M. Neyestani, *A solution to an economic dispatch problem by a fuzzy adaptive genetic algorithm*, Iranian Journal of Fuzzy Systems, **8**(5) (2011), 1-21. https://doi.org/10.22111/IJFS.2011.283

[38] S. C. Oh, M. S. Kim, Y. Park, G. T. Roh, C. W. Lee, *Implementation of blockchain-based energy trading system*, Asia Pacific Journal of Innovation and Entrepreneurship, **11**(3) (2017), 322-334. https://doi.org/10.1108/APJIE-12-2017-037

[39] H. Omrane, M. S. Masmoudi, M. Masmoudi, *Fuzzy logic based control for autonomous mobile robot navigation*, Computational Intelligence and Neuroscience, **2016**(1) (2016), 9548482. https://doi.org/10.1155/2016/9548482

[40] C. D. Parameswari, V. Mandadi, *Healthcare data protection based on blockchain using solidity*, In 2020 Fourth World Conference on Smart Trends in Systems, Security and Sustainability (WorldS4), (2020), 577-580. https://doi.org/10.1109/WorldS450073.2020.9210296

[41] W. Pedrycz, *Fuzzy control and fuzzy systems*, Research Studies Press Ltd, 1993. https://doi.org/10.5555/534143

[42] S. J. Pee, E. S. Kang, J. G. Song, J. W. Jang, *Blockchain-based smart energy trading platform using smart contract*, In 2019 International Conference on Artificial Intelligence in Information and Communication, (2019), 322-325. https://doi.org/10.1109/ICAIIC.2019.8668978

[43] M. Pipattanasomporn, M. Kuzlu, S. Rahman, *A blockchain-based platform for exchange of solar energy: Laboratory-scale implementation*, In 2018 International Conference and Utility Exhibition on Green Energy for Sustainable Development (ICUE), (2018), 1-9. https://doi.org/10.23919/ICUE-GESD.2018.8635679

[44] M. R. Rezaeifar, M. R. Zare Mehrjerdi, H. Nezamabadi-pour, H. Mehrabi Boshr Abadi, *Designing a sustainable development model for agricultural sector under critical circumstances (COVID-19 Pandemic): A fuzzy approach*, Iranian Journal of Fuzzy Systems, **20**(2) (2023), 173-200. https://doi.org/10.22111/ijfs.2023.7565

[45] T. J. Ross, *Fuzzy logic with engineering applications*, John Wiley and Sons, 2005.

[46] M. Sabounchi, J. Wei, *Towards resilient networked microgrids: Blockchain-enabled peer-to-peer electricity trading mechanism*, In 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), (2017), 1-5. https://doi.org/10.1109/EI2.2017.8245449

[47] A. Salian, S. Shah, J. Shah, K. Samdani, *Review of blockchain enabled decentralized energy trading mechanisms*, In 2019 IEEE International Conference on System, Computation, Automation and Networking (ICSCAN), (2019), 1-7. https://doi.org/10.1109/ICSCAN.2019.8878731

[48] L. Suganthi, S. Iniyan, A. A. Samuel, *Applications of fuzzy logic in renewable energy systems-a review*, Renewable and Sustainable Energy Reviews, **48** (2015), 585-607. https://doi.org/10.1016/j.rser.2015.04.037

[49] N. Szabo, *Smart contracts: Building blocks for digital markets*, EXTROPY: The Journal of Transhumanist Thought (16), **18**(2) (1996), 28.

[50] Y. C. Tsao, V. V. Thanh, *Toward sustainable microgrids with blockchain technology-based peer-to-peer energy trading mechanism: A fuzzy meta-heuristic approach*, Renewable and Sustainable Energy Reviews, **136** (2021), 110452. https://doi.org/10.1016/j.rser.2020.110452

[51] W. Viriyasitavat, D. Hoonsopon, *Blockchain characteristics and consensus in modern business processes*, Journal of Industrial Information Integration, **13** (2019), 32-39. https://doi.org/10.1016/j.jii.2018.07.004

[52] S. Wang, L. Ouyang, Y. Yuan, X. Ni, X. Han, F. Y. Wang, *Blockchain-enabled smart contracts: Architecture, applications, and future trends*, IEEE Transactions on Systems, Man, and Cybernetics: Systems, **49**(11) (2019), 2266-2277. https://doi.org/10.1109/TSMC.2019.2895123

[53] W. Warutai, P. S. W. Thongrod, C. Charoenlarpnopparut, *Optimal energy transaction ledger model for microgrid energy trading*, In 2019 IEEE 3rd International Conference on Circuits, Systems and Devices (ICCSD), (2019), 106-110. https://doi.org/10.1109/ICCSD.2019.8842999

[54] G. Wood, *Ethereum: A secure decentralised generalised transaction ledger*, Ethereum Project Yellow Paper, **151**(2014) (2014), 1-32.

[55] G. Wood, C. Reitwiessner, A. Beregszaszi, L. Husikyan, Y. Hirai, *Ethereum: A secure decentralised generalised transaction ledger*, Solidity Documentation. Ethereum Corp, 2016.

[56] P. Xie, W. Yan, P. Xuan, J. Zhu, Y. Wu, X. Li, J. Zou, *Conceptual framework of blockchain-based electricity trading for neighborhood renewable energy*, In 2018 2nd IEEE Conference on Energy Internet and Energy System Integration, (2023), 1-5. https://doi.org/10.1109/EI2.2018.8581887

[57] J. Yang, K. Yang, Z. Xiao, H. Jiang, S. Xu, S. Dustdar, *Improving commute experience for private car users via blockchain-enabled multitask learning*, IEEE Internet of Things Journal, **10**(24) (2023), 21656-21669. https://doi.org/10.1109/JIOT.2023.3317639

[58] A. Yazdani-Chamzini, S. H. Yakhchali, D. Volungevičiené, E. K. Zavadskas, *Forecasting gold price changes by using adaptive network fuzzy inference system*, Journal of Business Economics and Management, **13**(5) (2012), 994-1010. https://doi.org/10.3846/16111699.2012.683808

[59] S. Yu, S. Yang, Y. Li, J. Geng, *Distributed energy transaction mechanism design based on smart contract*, In 2018 China International Conference on Electricity Distribution (CICED), (2018), 3370-3381. https://doi.org/10.1109/CICED.2018.8592130

[60] R. Zhang, V. E. Sathishkumar, R. D. Jackson Samuel, *Fuzzy efficient energy smart home management system for renewable energy resources*, Sustainability, **12**(8) (2020), 3115. https://doi.org/10.3390/su12083115

[61] Z. Zhou, L. Tan, G. Xu, *Blockchain and edge computing based vehicle-to-grid energy trading in energy internet*, In 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), (2018), 1-5. https://doi.org/10.1109/EI2.2018.8582652