

Solar energy trading platform based on blockchain technology: A literature review and a case study

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Abstract: Solar energy, a vital renewable resource, requires efficient trading mechanisms, typically managed through Power Purchase Agreements (PPAs). However, current trading networks face significant challenges, including inadequate transaction tracking, limited data accessibility, and low transparency and trust. Blockchain technology offers a promising solution to these issues. This paper provides a comprehensive review of blockchain applications across various trading domains. We begin by introducing fundamental blockchain concepts and their role in enhancing solar energy trading security and functionality. Subsequently, we investigate existing blockchain-based platforms and conclude with a specific case study on solar energy. This study proposes a blockchain-based peer-to-peer (P2P) trading system designed to optimize solar energy exchanges. A comparative analysis between the proposed TBP platform and Power Ledger reveals key distinctions in architecture, data management, and pricing. Notably, the TBP platform offers a more integrated framework and flexible pricing, highlighting the vast research potential in blockchain-enabled solar trading and PPA implementation.

Keywords: Blockchain; Solar Energy Trading; Smart Contract; Token; Power Purchase Agreement (PPA).

1 Introduction

As solar energy becomes more widely adopted in various regions, developing effective methods for trading solar power has become a crucial challenge. Generally, solar energy trading can be classified into two categories: competitive and non-competitive. In the competitive approach, trading typically occurs between participants in the solar energy market.

In contrast, non-competitive trading usually involves transactions between the government and power plants. This form of trading may take place within a single organization or across a broader scope, aiming to minimize or eliminate competition in such markets.

In the competitive method, trading parties negotiate the price and contribute to the formation of a market. In contrast, in the non-competitive method, the price is predetermined—typically based on the terms of a PPA.

Despite these mechanisms, several challenges persist in solar energy trading. These include the need to track transactions, compensate for damages, provide users with access to past exchange data, enhance transparency and trust, and address both economic and security concerns. To overcome these issues, there is a growing need for a robust and reliable platform [1]. To address these challenges, researchers and designers have explored various solutions. Among the most promising technologies is blockchain, which provides a range of distinctive features for digital transactions. These features—including cryptography, transparency, decentralization, immutability, auditability, scalability, security, and privacy—make it particularly well suited for energy trading platforms [2]. Blockchain's use of encryption ensures high security, boosting users' confidence in the system. Moreover, operations within blockchain platforms follow strict rules and complex calculations, which are often difficult for the general public to analyze. A closer examination of blockchain properties highlights its potential in various applications, including solar energy trading. Some of these aspects will be further explained below [3].

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The first property is verifiability. This feature enables the distributed processing of verifiable and non-verifiable transactions. In general, this feature enables the ability to prove the accuracy of transactions in the blockchain. This feature can check users' transactions and approve or reject them without intermediaries. The possibility of approval or disapproval of transactions on the current platform without a blockchain is incorrect and can be arbitrary. This can be one of the drawbacks of the lack of a blockchain platform in different areas.

The second property is immutability. In many existing systems, it is possible to make changes to network information, which is a violation. While in the blockchain, this possibility is very difficult and it can be said that this probability is almost zero. The reason is the structure of blockchain networks, smart contracts, and their performance [4].

The third property is transparency. One of the most important properties of blockchain is transparency in blockchain networks. All transactions and operations within the network are transparent to participants while maintaining user privacy. In the event of incorrect information, the associated operations and transactions can be traced; however, invalid transactions cannot be validated or approved by the network. In conventional solar energy trading models, the details of PPAs are accessible only to the contracting parties. Other participants in the network do not have authorized access to information regarding solar energy transactions conducted in different locations, including their trading mechanisms and transaction volumes. For example, people in another country or city will not have access to information about other trading on this network.

The fourth property is programmability. One of the benefits of the Ethereum blockchain is that it can be defined intelligently, and this feature is only defined for some blockchain networks, such as Ethereum. It is also possible to make payments for trading in this network by using existing cryptocurrencies, which is certainly not easily possible to pay automatically in systems without blockchain.

The fifth property is anonymity. By using blockchain, you can monitor and track the performance of all users while maintaining your privacy. Therefore, in the current trading, this may be done without privacy.

The sixth characteristic is decentralization. Elimination of intermediaries is one of the main motivations for creating blockchain networks. By distributing all network operations within a unified blockchain framework, the system provides several advantages that are not achievable in conventional trading models. In traditional intermediary-based systems, third parties may exercise discretionary control over transactions and potentially introduce unintended modifications. Moreover, reliance

on manual oversight and centralized processing increases the likelihood of human error [5].

The seventh feature is accessibility and traceability. In Comparison with current trading, this possibility can only be provided to all members and users in blockchain networks. One of the main goals of this research is the possibility of tracking the source of traded solar energy, which can matter a lot to users. For instance, identifying the previous trading's buyers and sellers. What was the exchange price? And when did this exchange take place? However, having such information is impossible for current trading, or at least very complex.

The eighth property is security. High security is one of the main properties of blockchain networks. High security in such networks is due to the transparency of these types of networks.

The ninth property is distributivity. A complete copy of all network transactions in all complete nodes enables this feature, which can yield beneficial outcomes. Such as creating competition, innovation, quick agreements, public observation, and public benefit. While in the current trading method, it is not possible to view and access information for guaranteed purchase contracts.

The tenth characteristic is being online. The speed of transactions and payments for direct transactions in this network is faster than the PPA contract [6].

According to the characteristics of the blockchain, this platform can perform solar energy trading by using smart contracts on the blockchain network. The smart contract can make transactions automatically without the need for the intervention of an intermediary unit. The rules in each country for solar energy trading on the blockchain platform will be included in the PPA smart contract. The supervision of the relevant organizations will exist automatically. In another way, the relevant organizations will not be removed by the automation of trading, but their supervision will change.

Solar energy trading is typically conducted through PPAs. However, current solar energy trading systems face several challenges, including the lack of transaction tracking and payment mechanisms, limited user access to transaction data, and low levels of transparency and trust. In this context, blockchain emerges as a promising technology. It is a type of distributed ledger that offers key features such as transparency, privacy, security, decentralization, and immutability. These characteristics make blockchain well-suited to address the limitations of existing solar energy trading platforms. Thanks to its cryptographic structure, blockchain enables detailed tracking of transaction data by users, which helps overcome one of the major challenges in solar energy exchanges. One of the key issues in the electricity market—especially in our country—is related to financial

transactions. Blockchain can facilitate instant payments by defining digital tokens, a mechanism that has been implemented in our proposed platform.

This study provides a comprehensive review of blockchain-based solar energy trading platforms, identifying key challenges and research gaps in existing approaches. It explores how blockchain enhances transparency, security, and efficiency in peer-to-peer energy transactions. Furthermore, a case study is presented to demonstrate the feasibility of implementing blockchain-based PPAs for solar energy trading. The proposed TBP platform is compared with Power Ledger, highlighting differences in blockchain architecture, data management strategies, and pricing mechanisms. In summary, this study contributes to the literature by implementing a traditional PPA as a blockchain-based smart contract. To the best of the authors' knowledge, this represents one of the first implementations designed in accordance with the regulatory framework governing solar energy transactions in Iran, and tailored to the specific characteristics of the Iranian energy market. Additionally, defining the STC token for the solar energy trading platform, named BEST, can be introduced as the second contribution. This research contributes to the ongoing discourse on decentralized energy markets by offering insights into the practical implementation of blockchain technology for secure and efficient solar energy trading.

The rest of this study is structured as follows. Section 2 presents a review of related work. After describing the background of blockchain and PPA in Section 3, the experiment was conducted using a case study of PPA in solar energy trading in Section 4. This section also provides detailed descriptions of the proposed platform and implementation in subsections 4.1 and 4.2, respectively. Section 5 includes experimental results. Finally, Section 6 is the conclusion.

2 Related work

To address the challenges of centralized energy trading systems, particularly the reliance on trusted third parties and concerns about transaction security, blockchain technology offers a viable solution. In this regard, a token-based, private, and decentralized energy trading system has been implemented. This system uses the proof-of-work consensus mechanism along with multi-signature authentication and encrypted anonymous messaging streams, which enable peers to negotiate energy prices securely and anonymously. The proposed platform consists of three core components: the client interface, nodes within a peer-to-peer (P2P) network, and the blockchain infrastructure itself [7]. As described in [8], the electricity market trading model achieves a strong trade-off between data security and system utility, while also maintaining a balance between power supply and

demand. In this model, energy is stored and transferred using a private blockchain, whereas cross-regional energy trading is aggregated through a consortium blockchain, ensuring both scalability and collaborative management. Another peer-to-peer trading model is explained in [9]. This model has two algorithms: an auction model and a calculative data-dependent model that uses smart contracts. Synchronizing the scheduling of energy resources and accrediting fair payments does not require a centralized unit. Generating the energy EA, making a smart contract by the prosumer, selecting a miner based on POS, generating a purchase request transaction by the consumer, and energy released by the ESS are the scheme steps. The use of a blockchain-based platform to address issues such as energy imbalance, carbon reduction inconsistency, and residential privacy leakage in centralized trading markets is discussed in [10]. The authors propose a fully decentralized, blockchain-based peer-to-peer trading scheme that integrates both energy and carbon markets. The platform incorporates features such as pay-to-public-key-hash (P2PKH) and multi-signature mechanisms to enhance security and traceability. Compared to traditional centralized systems, this blockchain trading model offers notable benefits, including cost reduction and lower carbon emissions. In 2017, centralized power trading systems were highly complex and vulnerable to risks such as price tampering and cyberattacks. To address these issues, a blockchain-based platform involving administrator, producer, and consumer nodes was developed, as described in [11]. This platform—called Multichain—was one of the earliest implementations of blockchain in the energy trading sector. Experimental results demonstrated that key operations such as blockchain creation, node connectivity, asset issuance, and trading transactions were successfully managed. However, this early model faced several limitations, including slow performance in real-time conditions and inadequate support for partial transactions. Blockchain technology holds potential for providing regulatory transparency to both the public and private sectors, which may help resolve current management failures. As renewable electricity generation continues to expand and contribute a growing share to the total power supply, efficient energy distribution and the elimination of intermediaries are becoming critical, especially in the context of smart cities. Blockchain offers distributed and decentralized solutions to support secure and transparent energy transactions. A permissioned blockchain that uses Hyperledger Fabric to provide a localized peer-to-peer energy transacting network is explained in [12]. Decentralization, trust, security, and privacy in the renewable energy trading business are good characteristics of this platform. One of the main challenges in storing trading information on the blockchain is maintaining user privacy. Attackers can exploit data mining algorithms to infer sensitive user

information. To mitigate this risk, [13] proposes a consortium blockchain-based approach that enhances privacy without compromising trading functionality. This method specifically protects the privacy of energy trading participants in smart grids. It recognizes that variations in trading volumes can be analyzed to infer users' physical locations and energy usage patterns, thereby exposing private information. The proposed solution prevents such inferences, thereby strengthening the platform's privacy safeguards. With the emergence of technologies such as smart homes, the Internet of Things (IoT), and interconnected networks, new opportunities for efficient system management have arisen. In addition, the advent of blockchain technology has enabled innovative solutions for enhancing data security and protecting user privacy. A blockchain-based smart home that makes it impossible to forge data, called a transaction, is in [14]. The home miner centrally processes all the transactions that are generated in the information energy. In this research, a renewable energy trading platform using Ethereum's smart contract is used to ensure secure energy trading runs automatically without a middleman in a microgrid. The blockchain is the technology that is used in [15] to ensure delivery versus payment by linking transfers of assets with payments and also using a proof-of-work protocol. These platform benefits are faster and more flexible settlement. This user is to avoid settlement failures when participants fork the chain to get rid of trading losses. In the blockchain, to prevent forking needs to limit settlement speed through block size and block time to generate sufficient transaction fees and make mining costly. For regulators, three key themes emerge from this analysis. First, it links digital ledgers for asset ownership and payments together to support atomic trades. That is, providing a digital currency that could be used with securities settlement systems. The second and third are that blockchain-based settlement is feasible; sufficiently strong preferences for fast settlement and limited trade size and risk, and large enough trading volume are necessary conditions. Although mining is a heavy cost, in this research, based on the market for US corporate debt, the gains are in the range of 1 to 4 basis points relative to existing legacy settlement systems. With the ongoing evolution of the energy market, there is an increasing tendency to allow distributed energy agents and other multi-actor participants to engage in competitive trading. Blockchain technology offers a promising decentralized alternative to address several key challenges in the power sector. These challenges include inefficiencies in power market transactions, limitations of centralized power supply models, and shortcomings in public services and government management systems. Within the framework of transactive energy systems, a distributed energy trading mechanism based on blockchain smart contracts has been introduced. As outlined in [16], the smart contract structure includes

essential functional modules such as requirement publishing, qualification auditing, transaction confirmation, execution, and settlement. These features collectively support critical market operations such as auditing, bidding, clearing, and settlement, thereby enabling efficient and secure peer-to-peer (P2P) energy trading among prosumers. In [17], a decentralized platform is presented for implementing energy exchange mechanisms within a microgrid environment. This hybrid platform enables prosumers to trade energy without compromising system security or user privacy. The platform architecture combines smart contract-based validators with an external optimization engine, ensuring that energy offers are cleared both securely and efficiently. Furthermore, the platform includes resilience features that provide the robustness required for sustained and reliable operation, as demonstrated in the TRANSAX framework. The development of the Secure Private Blockchain (SPB) framework, as introduced in [18], is motivated by several critical challenges. These include the lack of privacy, excessive processing and packet overheads, and the reliance on a trusted third party (TTP) to secure transactions. This platform allows energy producers and consumers to negotiate energy prices directly, without intermediaries. A novel routing method is employed in which packets are routed based on the recipient's public key (PK). Furthermore, by introducing atomic meta-transactions, SPB eliminates the need for a TTP, ensuring that both parties fulfill their obligations. Two key transaction types are defined in this solution: the Commit to Pay (CTP) transaction, which facilitates energy payments, and the Energy Receipt Confirmation (ERC) transaction, which confirms the receipt of energy. Performance analysis indicates that SPB not only enhances resilience against various attack scenarios but also significantly reduces transaction costs and delays. The increasing need for new paradigms in distribution grid operation has become evident, particularly for approaches that leverage demand-side flexibility. At the same time, the lack of coordination among various actors limits both the efficiency and adaptability of the current power grid. To address these challenges, the study presented in [19] proposes a blockchain-based transactive energy platform. This platform introduces a market-oriented application designed specifically to balance renewable energy production by enabling decentralized energy exchange among households. The proposed solution incorporates auction mechanisms and dynamic transport pricing that incentivize prosumers to manage their energy consumption and generation in ways that align with both individual and grid-level objectives. By fostering autonomous local markets, the platform increases the renewable energy hosting capacity and enhances system flexibility. Compared to centralized implementations, it also improves security, transparency, and auditability. Further benefits, such as reduced voltage

deviations and mitigation of network imbalances, could be achieved if these mechanisms are fine-tuned and integrated into broader grid management systems. One of the peer-to-peer (P2P) energy transaction frameworks that offers both financial benefits to end users and enhanced energy security is discussed in [20]. This framework also enables greater flexibility for network operators in managing distributed renewable energy systems (DRES), including peak load shifting and the regulation of voltage and frequency. Furthermore, P2P transactions contribute to reducing the carbon footprint, shortening the payback period for renewable energy systems (RES), and encouraging the installation of DRES technologies. The study presents a comparative discussion of several distributed ledger technologies (DLTs) applicable to such frameworks, including Blockchain, Block Lattice, and the Directed Acyclic Graph (DAG) structure known as Tangle. To overcome key challenges in energy management, such as congestion pricing and non-optimal dispatch, the decentralization of the electricity market is proposed as a viable and effective strategy. A peer-to-peer (P2P) transactive microgrid model, in which prosumers can trade locally generated electricity with one another through a smart management system, is proposed in [21]. This model leverages blockchain technology to enable secure and efficient transactions. At the core of this system lies a smart contract-based auction model for energy trading, which facilitates automated and transparent negotiation processes. Unlike traditional electricity market designs, this approach allows for greater adaptability in handling varying inputs and outputs. Additionally, it supports dynamic modifications to the structure of the smart contracts themselves. Together, these features enable the system to more accurately replicate real-world market scenarios.

A key challenge in transactive energy networks is tracking transactions and ensuring fair compensation. Blockchain enables peer-to-peer (P2P) energy trading without a central authority. While most studies focus on business and legal aspects, [22] presents a technical, lab-scale implementation using the Hyperledger framework. It details setting up participants, assets, smart contracts, and infrastructure, offering a practical guide for researchers and engineers developing blockchain-based P2P solar trading platforms. With the widespread trading of surplus electricity, blockchain technology ensures both the immutability and transparency of energy transactions, as demonstrated in [23]. In addition, it enables the creation of ERC20 tokens through smart contracts, providing a flexible and secure mechanism for representing and exchanging energy assets. Transactions are executed automatically without the need for third-party intermediaries and can be customized to support a variety of transaction conditions. The system employs an Energy Storage System (ESS) to facilitate energy transfer between sellers and buyers, with payments conducted via

token transfers. By operating on a private blockchain network and utilizing smart contracts, the platform enhances both the security and transparency of energy exchanges. Moreover, since energy is circulated virtually, the platform contributes to improved energy use efficiency.

With the adoption of rooftop photovoltaic systems and small wind turbines, households are increasingly becoming prosumers, actively participating in localized peer-to-peer (P2P) electricity trading. In [24], a conceptual framework is introduced that enables households to autonomously exchange renewable energy with their neighbors using blockchain technology. This framework facilitates energy matching based on mutual benefit between supply and demand. However, further research is required to design efficient market systems and payment mechanisms. To mitigate the mismatch between energy supply and demand, the bidirectional trading capabilities of electric vehicles (EVs) offer a promising solution. A secure and efficient vehicle-to-grid (V2G) energy trading model based on consortium blockchain is proposed, which incorporates edge computing to enhance the success rate of block creation. The Stackelberg leader-follower game and the corresponding optimal strategies are modeled as a two-stage computational resource allocation problem, which is solved using a backward induction approach. The effectiveness of the proposed framework is validated through both numerical simulations and theoretical analysis [25]. Renewable energy distribution in microgrids represents a novel approach for facilitating energy exchanges between ledgers and prosumers, with blockchain technology demonstrating its capability to secure these transactions. In [26], a model for an energy ledger is presented to simulate electrical energy transactions within a microgrid, enabling energy trading between the ledger and prosumers. The proposed algorithm in this system is designed to enhance the efficiency of energy exchange operations. Simulation results indicate a significant reduction in the prosumers' monthly electricity bills, depending on the levels of solar cell and battery installations. The Power Ledger whitepaper [27] introduces a decentralized, blockchain-based energy trading platform designed to improve market efficiency and promote sustainability. It proposes a peer-to-peer (P2P) trading model that allows individuals and communities to directly exchange renewable energy, thereby reducing dependence on centralized systems. By leveraging blockchain technology, the platform ensures secure, transparent, and trustless transactions, aiming to create a cost-effective and low-carbon energy ecosystem. The whitepaper also presents a variety of applications within the Power Ledger ecosystem. These include microgrid management, electric vehicle integration, and wholesale market settlements. Collectively, these use

cases demonstrate the platform's potential to enhance both the resilience and sustainability of energy markets.

A comprehensive framework for designing sustainable microgrids integrated with blockchain-enabled peer-to-peer energy trading is proposed in [28]. This platform focuses on optimizing the placement, capacity, and interconnection of renewable energy sources to maximize profit and minimize environmental impact. By employing a multi-objective mixed-integer linear programming model that combines stochastic and fuzzy probabilistic programming, the approach effectively manages uncertainties in renewable generation and demand. The integration of blockchain-based smart contracts enables secure energy trading and dynamic pricing, resulting in a 15% increase in profit and a 13% reduction in environmental costs. This work fills key research gaps by addressing optimal interconnections among microgrids, handling renewable variability, and offering a decentralized, intelligent solution for sustainable energy management.

[29] Investigates blockchain technology (BCT) investment strategies in multi-stakeholder energy supply chains. It is conducted under hybrid carbon regulation frameworks that include both cap-and-trade systems and certified emission reductions (CERs). It applies a biform game-theoretic model to compare cooperative and non-cooperative investment behaviors of traditional and renewable energy firms. Cooperative investment among renewable energy firms promotes blockchain adoption and leads to higher overall supply chain profits. In contrast, traditional energy firms are less likely to invest when adopting cooperative strategies. The study also shows that collaboration reduces the negative effects of intense competition and supports long-term blockchain development in carbon trading.

A comprehensive review that explores the use of blockchain technology in transactive energy systems (TES) is presented in [30]. It highlighted blockchain's ability to improve trust, transparency, security, and transaction efficiency in decentralized energy trading among prosumers. The study compared different blockchain architectures, including traditional models and Directed Acyclic Graph (DAG)-based systems, to evaluate their performance in handling high-frequency micro-transactions. It also examined new communication standards such as IEEE 2030.5, the benefits of local energy generation, and the role of artificial intelligence in strengthening system resilience and security. Overall, the review highlighted the importance of blockchain in establishing secure, efficient, and sustainable decentralized energy markets.

A framework to evaluate the integration of blockchain technology into renewable energy supply chains is proposed in [31]. It analyzes key challenges such as high

costs, design complexity, and technological gaps. Using Iran's wind and solar sectors as a case study, the research shows how blockchain can improve transparency, efficiency, and trust. It also highlights the need for strategic planning and collaboration to address technical, financial, and regulatory barriers and to support broader adoption of blockchain in renewable energy systems.

A study that investigates the integration of Blockchain and Artificial Intelligence (AI) in business operations is in [32]. It emphasizes their complementary roles in improving transparency, efficiency, and security in sectors such as finance, healthcare, and supply chain management. The study uses qualitative methods, including case studies and expert interviews. It identifies several key challenges, including scalability issues, high implementation costs, data privacy concerns, and technological complexity. To address these challenges, the study proposes hybrid Blockchain models and ethical AI frameworks. It also highlights the need to overcome regulatory and resource constraints, especially for small and medium-sized enterprises, to fully realize the potential of Blockchain-AI integration.

The integration of artificial intelligence (AI) and blockchain analytics is presented in [33] to improve transaction analysis, with an emphasis on fraud detection and efficiency. The authors propose a transaction-hybrid classifier (THC) that combines SVM, KNN, and Random Forest algorithms using an XOR operation to enhance detection accuracy. Through detailed data preprocessing and feature engineering, the model achieves over 99% accuracy in identifying fraudulent transactions. This work advances AI-driven blockchain analytics by providing a scalable, efficient, and robust framework for fraud detection and transaction management.

Analyzing the use of blockchain technology to support additive symbiotic networks in industrial processes is explained in [34]. It focuses on recycling plastic waste into 3D printer filament using smart contracts and Hyperledger Fabric. The proposed architecture removes intermediaries and improves transparency. It also helps build trust among participants. Blockchain enables secure resource tracking and efficient transactions. However, the study identifies several challenges. These include technological immaturity, the need for staff training, infrastructure costs, and limited integration of off-chain transactions with payment systems. Overall, blockchain can support sustainable and collaborative industrial ecosystems.

Among the early real-world implementations of blockchain for peer-to-peer energy trading is the Brooklyn Microgrid project initiated in 2016 [35]. This study proposes a framework for designing microgrid energy markets with a focus on peer-to-peer renewable energy trading within local communities. Using the

Brooklyn Microgrid as a case study, it identifies seven key components for effective market operation and shows that blockchain can enable decentralized and secure transactions without central intermediaries. The results indicate that the Brooklyn Microgrid meets most of the proposed components, demonstrating the practicality of blockchain-based microgrid markets. However, regulatory barriers in many regions still limit large-scale adoption. Overall, the study highlights blockchain's potential to enhance local renewable energy use, strengthen community resilience, and encourage investment in green energy.

Some attributes of related work implemented on blockchain platforms are explained in Table 1 and Table 2.

3 Background

3.1 PPA

Getting a license and complying with the PPA process is crucial for setting up a solar power plant. Due to the suitable conditions that have been provided to expand the use of renewable energy by using PPA, the demand for the establishment of these power plants has increased. Since 2015, our country's government has agreed to buy power from subscribers for 20 years. This decision was made to increase the use of renewable energy in the country and to encourage the private sector to join this industry as much as possible. To get a license for a solar power plant with a capacity of up to 100 kilowatts, you need to branch off household or industrial electricity, and the second method is to build a solar farm with a capacity of more than 100 kilowatts. 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 Fig. 1. The amount of the contract, which is the price of solar energy exchanged, is obtained from a specific relationship that is explained in 4.2.1. The penetration date is the start time of the contract when the power plant is launched, and its solar energy trading with the government has started. Also, the duration of the contract is 20 years, during which only the PPA is valid. The customer's information must be approved by the Renewable Energy Organization (SATBA), and after that, each certified customer will have a valid ID, which is necessary to carry out transactions. The payment protocol is also one of the basic items that are explained in the PPA. The seller gets paid every two months, and the base rate according to the PPA drops by 30% from the 11th year onwards.

Table 1. Blockchain network attributes of related work.

Ref.	Platform	Network type	Prosumers	Tx. cost
[7]	blockchain	public	Not mentioned	token

[8]	blockchain	private	variable	Not mentioned
[9]	Ethereum	private	2	token
[10]	blockchain	public	7	token
[11]	blockchain	Not mentioned	Not mentioned	"Ecoin" token
[12]	Hyperledger fabric	permissioned	Not mentioned	token
[13]	Consortium blockchain	Private	variable	token
[14]	Ethereum	private	2	Ether
[15]	blockchain	permissioned	Not mentioned	digital currency
[16]	Ethereum	public	Not mentioned	Ether
[17]	Ethereum	private	97	Ether
[18]	blockchain	private	4	token
[19]	blockchain	Not mentioned	Not mentioned	Ecoin
[20]	Hyperledger fabric	private	20,50,200	
[21]	Ethereum	public	Variable (maximum =100)	Ether
[22]	Hyperledger fabric	private	5	
[23]	Ethereum	private	4	Ether
[24]	Ethereum	public	Not mentioned	Ether
[25]	consortium blockchain	private	Not mentioned	token
[26]	blockchain	Not mentioned	2	token
[27]	Ethereum	hybrid blockchain (public and private)	variable	POWR token

Table 2. Advantages and disadvantages of related work.

Ref.	advantage	disadvantage
[7]	A feasible and reliable approach to decentralized SG energy trading with enhanced privacy and security.	Large-scale data replication, requiring each node to maintain a complete copy of the blockchain ledger.

[8]	High operational efficiency and low computational costs, overhead, security risks, and privacy concerns.	Does not focus on improving the performance and scalability of the proposed scheme.	[21]	Security, real-time trade, minimal need for oversight	Prosumers have lower generation-to-demand ratios
[9]	Security, transparency, automation, flexibility, trust, and immutability.	Dependence on the main grid to balance supply and demand	[22]	Transparency and transaction traceability.	This implementation has high complexity in various sections.
[10]	Traceability, cost reduction, privacy, and security.	Lack of analysis of long-term low-carbon technology investments	[23]	Security through the private blockchain, transparency, and immutability	Limited scalability as the number of nodes increases
[11]	Fast and highly scalable, with efficient node connectivity, asset issuance, and transaction processing.	Scalability and transaction flexibility limitations	[24]	Decentralized, open-source, and transparent features, as well as security and privacy.	Further work is needed to design market mechanisms and transaction settlement.
[12]	Secure, privacy-preserving, and fault-tolerant with fast transaction finality	Not mentioned	[25]	Secure and efficient vehicles, improving the probability of successful block creation.	Lacks an efficient incentive mechanism design for V2G trading under information asymmetry
[13]	Enhanced privacy and faster performance than public blockchains	User ratings and distribution data are used without screening, raising privacy concerns.	[26]	A cost-effective, secure, privacy-preserving, and fault-tolerant decentralized system	The model implementation in the real microgrid system has not been tested.
[14]	Secure, automated, decentralized, and scalable via smart contracts	Not suitable for virtual microgrids	[27]	Trustless Trading, Transparency, Lower Costs and Interoperability	Regulatory, technical, and market challenges with price volatility and adoption barriers
[15]	Faster and more flexible settlement, with a feasible and secure approach.	Mining with limitations in speed is a high- cost approach.			
[16]	Transparent, fair, and decentralized automated trading via algorithms (no manual arbitration)	Not mentioned			
[17]	Privacy, trust, resilience, security	The application disk usage grows from 48MB to the disk limit of 50MB			
[18]	Secure, privacy-preserving, attack-resistant with reduced cost and latency	SPB implementation is not on real devices, and the benchmark			
[19]	Security, transparency, audibility	No consideration of voltage/current limit control mechanisms			
[20]	Effectively defend all assumed attacks, privacy	Not mentioned			

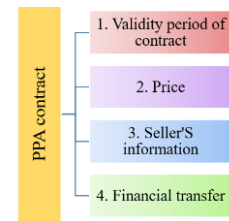


Fig 1. Important factors of PPA in solar energy Trading.

3.2 Blockchain

A blockchain is a type of distributed database designed to securely record and preserve information. This technology is built on a model that ensures the immutability and integrity of stored data, preventing unauthorized alterations or manipulations. Blockchain can be described as a comprehensive technical system resulting from the integration of three core technologies: asymmetric encryption algorithms, distributed data storage, and consensus mechanisms [36]. Through the combined use of cryptographic encryption and distributed architecture, the risks of hacking, data tampering, or deletion are significantly minimized. While the unique

characteristics that differentiate blockchain from other technologies are discussed in detail in the introduction, this section explores additional features that further highlight its advantages.

3.2.1 How blockchain works

In general, blockchain is responsible for registering transactions in the network. This process is done in several steps which are:

1. Sending transactions by users for all nodes on the network.

Any data entry operation can be considered a transaction. These transactions can be of any type. It could be a financial transaction such as transferring bitcoins or created by performing a function in a smart contract, and so on.

2. Placing unverified transactions in the blockchain network Mempool.

A Mempool is a space in a blockchain network where unverified transactions take place.

3. Select transactions for approval by users who are miners.

Users who play the role of a miner in the network, considering the fee of each transaction, select them to be in the new block and verify their transactions.

4. Trying to extract a new block containing the selected transactions.

Miners must be able to add new blocks to the blockchain by using the processing power of their systems and solving the mathematical equations governing the blockchain.

5. Add a new block to the blockchain that contains verified transactions.

The mining process is completed by the miners when a node can win the mining competition and receive the reward assigned to the operation.

6. Broadcasting new block information to all nodes.

All network nodes must have information about each block that is added to the end of the blockchain as quickly as possible. This process is done in a blockchain, and the network nodes will have the information about the previous block in their system memory before starting to compete for extracting the new block. The reason is that mining new blocks by users also needs to have information about the previous block such as the previous block hash.

7. Repeat this process as usual.

This operation will continue until all the cryptocurrencies that are defined in the various blockchains are extracted.

3.2.2 Types of blockchains

In general, blockchains can be divided into two categories: Permissioned and Permissionless. In a Permission-less blockchain, any quasi-anonymous user can log on to the network and become one of the nodes. In a permissioned blockchain, network access is allowed under certain rules for a limited number of nodes. The identity of users in a permissioned blockchain is known to all nodes in the network. Permissionless blockchains are more secure than Permissioned types because the number of nodes that approve transactions in the network is very high, and the possibility of collusion in the network is very low. On the other hand, the processing time and recording of transactions in the network for permissionless blockchains are relatively longer than for Permissioned types.

Based on the access level, four types of blockchains have been introduced so far, which are public, private, federated, and hybrid. The common feature of all these networks is that it is not possible to falsify or manipulate information in them. This means that it is impossible to delete or change the information. The most well-known type of public blockchain is a Permissionless distributed general ledger technology. There is no monopoly in this type of blockchain, and all information is recorded in the general ledger. Anyone can join the network, and all nodes have equal rights to access the blockchain, create new blocks, and validate them. These networks are completely decentralized, and their transactions are verified using the consensus mechanism. Public blockchains were originally used to exchange and store currencies, the most well-known of which are Bitcoin and Ethereum.

A private blockchain is a permissioned network that is controlled by a specific institution. In a private blockchain, a central power determines who can be one of the network nodes. This central power does not give all nodes equal rights to perform their duties. Therefore, the private blockchain lacks decentralization, since it limits public participation, and it may face consensus issues if the authorized nodes are corrupted. This type of blockchain is used in public or private organizations, and special individuals are selected to verify and view information.

Both public and private blockchain types have some advantages and disadvantages. Public blockchains have high processing time, and private blockchains are vulnerable to collusion. Federated and hybrid blockchains have been proposed to solve these problems.

A federated blockchain is a permissioned network operated by a group of organizations. Therefore, it has

higher decentralization and offers higher levels of security than a private blockchain run by a single entity. However, setting up collaborative networks between organizations can be difficult because it requires collaboration among them. Unlike the general blockchain, in which the consensus mechanism is defined by assuming complete distrust between nodes, in a federated blockchain, network nodes are known and they trust each other. To record information on this type of blockchain, the majority vote method is used. A hybrid blockchain is a combination of public and private networks. This type of blockchain is managed by an organization, but the level of oversight defined to validate specific transactions is the same as a general blockchain. This enables organizations to create a private and permissioned system next to a permissionless network. This lets approved people access data on the network and decide what information should be visible. Transactions and records in a hybrid blockchain are not usually public but can be verified if needed. The identity of users in such networks is anonymous, but if they enter into a transaction, their identity will be revealed to the other party [37].

3.2.3 Is blockchain needed?

When is the blockchain used? Using a blockchain can be useful when multiple distrustful entities want to interact with each other and are also reluctant to agree on a trusted third party online. The flow diagram in Fig. 2 is provided to examine the decision-making process. The flowchart in Fig. 2 can be a complete guide to the benefits of using a blockchain. This flowchart is designed to compare permissionless blockchains and a central database. Centralized systems usually outperform blockchain systems in latency and throughput because the blockchain structure has a complicated consensus mechanism. To compare centralized and decentralized systems, two systems, Bitcoin and Visa, can be considered. Visa can handle peaks of more than 50,000 transactions, while Bitcoin can only record about seven transactions per second. When deciding whether or not to use the blockchain system, this tradeoff should also be considered: whether decentralization is more important than throughput. The ability of a system to update over time is called throughput, and decentralization is how a system scales to a large number of authors without mutual trust. The tradeoff between these two features must be considered in deciding whether to use a blockchain in a particular application. In this case, one or more parties are considered to write the status of the system. If there is no need to store data in the system, there is no need for a database, and therefore, a blockchain, which is a type of database, is not applicable in this case. Also, using a shared database can be the best solution if all the authors trust each other and do not consider any participants to be malicious. But if none of the above conditions are true and members also do not trust each other, using a blockchain can be useful. In the next step, you must select the type of

blockchain, which is determined according to the type of access members have to the blockchain. There are three types of blockchains: public permissioned blockchain, private permissioned blockchain, and permissionless blockchain. If all members are allowed to read the status, a publicly permissioned blockchain will be used. If access is restricted to specific network participants, a privately permissioned blockchain can be employed. Conversely, if the authors are unknown to network members and there is no fixed authority—similar to Bitcoin—a permissionless blockchain represents an appropriate solution [38].

3.3 Ethereum

Ethereum is a universal computer (Vitalik Buterin). Ethereum was created so that we do not need any bank, company, or other institution to manage our lives except ourselves (Joseph Lubin). Ethereum is based on Bitcoin technology, but with great differences. What Bitcoin does to store data as distributed data, Ethereum also does to store as distributed data, plus calculations. Both Ethereum and Bitcoin allow users to use digital money without intermediaries or banks, but Ethereum allows programming. It means that Ethereum is programmable, so it can be a platform for smart contracts. Ethereum is the first public blockchain platform that is open-source and decentralized. The decentralized feature of Ethereum means that the system does not belong to anyone and is not controlled by any particular entity or person. The Ethereum network, similar to Bitcoin, inherits all the useful properties of blockchain, such as transparency, distribution, decentralization, peer-to-peer, cryptography, verifiability, and so on.

This platform allows developers to create and run decentralized applications called smart contracts. These programs run automatically without the need for centralized management on the Ethereum network [39], [40]. Ethereum can be described as a global computer built on a peer-to-peer network consisting of nodes. It also has all the features of a public blockchain such as public key and private key encryption, encrypted hash, Merkle tree, and more. Similar to all of the technologies, Ethereum has some disadvantages such as:

High energy consumption: Ethereum uses a proof-of-work method to ensure security and privacy, which is not cost-effective due to high energy consumption.

High-traffic network: Ethereum's network is so congested that it is not ideal for global use. The confirmation of transactions takes much longer because every node in the network has to verify them.

Ethereum 2.0 is a new project that aims to address the issues and enhance the Ethereum network. It was originally proposed to solve the problem of processing power limitation. This, also known as 2.0 ETH or Serenity, is a more advanced version of Ethereum that took a long time to run. Ethereum 2.0 was able to solve

the problem of network processing limitations by improving hardware and software, increasing efficiency,

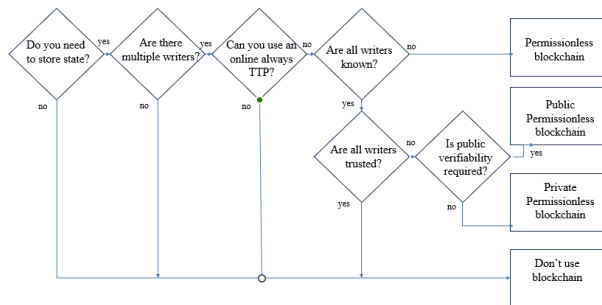


Fig 2. Flow chart to show how the blockchain works to solve a problem (whether it is appropriate or not?)

and increasing speed while maintaining the security and decentralization of the Ethereum network.

3.4 Smart contract

3.4.1 Ethereum Virtual Machine (EVM)

A virtual machine, or VM, is a software program that has specific code and acts as a processor that can run programs that are specific to the set of instructions in this set. The Java Virtual Machine (JVM) is one of the most widely used virtual machines today [41]. Ethereum's main innovation is its virtual machine called the Ethereum Virtual Machine. Instead of having to build a new blockchain for each application, it enables thousands of different applications to be built on a single platform. This feature provides users with an environment for executing Ethereum-based smart contracts. Although anyone can use EVM, no one can make counterfeit money on it. EVM controls line-by-line intelligent contract code written in high-level languages such as Python. There are two implementations for the EVM: VM bytecode (low-level code that conforms to VM instructions is called bytecode) and JIT-VM, and the Solidity code, which is the code for writing smart contracts, runs on bytecode [36]. The EVM is a complete Turing machine that operates on the Ethereum blockchain and acts as a single, universal, and 256-bit decentralized computer composed of constituent nodes. In addition, this machine uses algorithms to prevent denial-of-service attacks. These algorithms are widely seen in cryptocurrency markets and contain millions of executable objects, each with its own permanent data storage, and put all the smart contracts on it [41].

3.4.2 Smart contracts

The concept of smart contracts was first introduced in 1994 by Nikzabu [42]. A smart contract is a computer program that is executed automatically according to special conditions and instructions. They are given to it by the programmer without the intervention of a third party, provided that the transactions in this process are

traceable and irreversible [43]. Because these contracts are written on a blockchain platform, the existing data is encrypted with mathematical formulas and the information recorded on the network will be confidential. Smart contracts generally have two characteristics: "mode" and "value" [44]:

Mode: Smart contract manages relationships between organizations, institutions, and people. The contents of the contract are automatically executed when the conditions for compliance with the rights and obligations written in the smart contract codes are met.

Value: Smart contracts are written to carry out financial transactions between the parties to the transaction who have entered their assets into the contract. These assets remain locked within the contract until the specified terms and conditions are met. Once these conditions are fulfilled, the assets are distributed among the parties according to the allocations defined in the contract.

Today, the most widely used smart contract platform in this field is the Ethereum network. Based on the input data, the written contract determines whether there are performance requirements. If the rules and conditions were met, the nodes in the core network (commands written in the form of a computer program) would be executed by the EVM operating system by the commands written. After validation, a transaction is placed in the new block, and after the agreement of the whole network (according to the consensus algorithm), this new block is added to the blockchain network. If the smart contract executes successfully, the output will be a 64-bit known ID as the smart contract address. The blockchain network records all contract specifications and distributes them among the participating nodes. Once the smart contract code is deployed to the network, it becomes immutable and cannot be altered. Therefore, the smart contract must be programmed with a high degree of accuracy to ensure correct execution.

3.4.3 Smart contract features

It can be said that every smart contract contains three basic principles:

- **Subject of the contract:** According to the subject of the contract, the terms and conditions of allowing access to services for individuals are determined.
- **Terms of the contract:** The terms of the contract are written mathematically by using the programming language and stating all the details in the contract. Once the rules of the contract are in place, the parties to the contract are subject to rewards or penalties.
- **Digital signatures:** The contract's participants use a digital signature (private key) to express their consent or dissent with the specified conditions.

The smart contract has certain features. Among the features of smart contracts, the following can be mentioned [45].

- Smart contracts are independent and automated and do not require monitoring or intermediation.
- Smart contracts reduce costs and speed up transactions.
- Smart contracts are decentralized.
- Smart contracts are immutable or manipulative.
- Smart contracts have special terms and conditions under which the parties to the transaction are subject to rewards or fines.

3.4.4 Solidity

Solidity is a language that is based on a contract and is used for executing smart contracts and the EVM. It can be run on the server side with programming languages such as C++, Python, and JavaScript [46]. 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 [47]. The environment for executing Solidity programs without server-side components is called Remix, which is a browser-based software development environment (IDE) [46]. 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 of [48].

3.4.5 Gas

There is a charge for establishing smart contracts on the Ethereum Public Network. This means that every transaction is done by paying a fee in the Ethereum network. It should be noted that a transaction is a message sent from one account to another. This fee is determined by the Gas criterion. Gas can be called the fuel of the Ethereum network and is defined to prevent malicious attacks. The amount of gas is determined by the author of the smart contract. The author of the smart contract must pay for each step of the program that runs on the Ethereum network, such as calculating or storing in memory. To send the entire smart contract to the Ethereum network, he must pay the amount of gas required to execute the contract before sending the contract to the network. The unit of measurement is Gigawei, also known as "Gwei", and its value is 0.000000001 ether. Gas prices vary according to network performance because the capacity of the Ethereum network is limited, and not all transactions can be confirmed at the moment.

Ethereum certifiers, or miners, prefer to first approve transactions with higher fees (higher gas prices).

There are some key phrases to keep in mind when programming:

Gas limit: The highest gas fee you are willing to pay network miners for verifying a transaction. If the range is insufficient, it will lead to a failed transaction. The higher the range, the faster your transaction will be because it attracts more miners to prioritize your transaction over other transactions.

Gas price: The amount of ether that you are willing to pay for each unit of gas. As mentioned, its value is in terms of Gwei, which is a fraction of Wei. Wei is the smallest unit of ether, and Gwei is equivalent to 1000000000 Wei.

Gas cost: The computational work of a transaction is measured by the gas cost, which is a fixed value for a particular operation. It is calculated from the following Eq. (1).

$$\text{Ethereum Network Fee} = \text{Gas Limit} \times \text{Gas Price} \quad (1)$$

3.4.6 Token

The word token derives from tācen, which means a sign or symbol. It usually means privately issued coinlike items for specific purposes that have little inherent value, such as tokens for transportation, laundry, and arcade games. At this time, "tokens" executed on blockchains are redefining the word to mean blockchain-based abstractions that can be owned and represent assets, currency, or access rights. Limited use of the physical versions of tokens has a lot to do with the association between insignificant value and the word "token". Physical tokens are often restricted to specific businesses, organizations, or locations, and they typically have only one function and are not easily exchangeable. With the advent of blockchain tokens, these restrictions are removed, and their function is more accurate and completely redefinable. Many blockchain tokens can be traded for each other or other currencies on global liquid markets and serve multiple purposes globally.

4 Case study

4.1 Proposed platform

Fig. 3 shows the overview of the peer-to-peer solar energy trading platform, summarized as BSET. The main components in solar energy trading are buyers, sellers, and exchange platforms. Also, this designed platform has five main sections, which are: energy market, assigning tokens, defining rewards, validator unit for inputs, and validator unit for outputs. In this research, the main goal is to use the blockchain platform for solar energy trading.

The UML file related to solar energy trading is shown in Fig. 4. 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.

4.2 Implementation

4.2.1 Smart contract

In the proposed BSET platform, the smart contract defines all of the PPA sections that are needed for trading

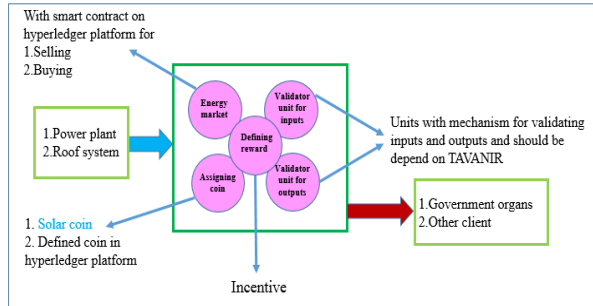


Fig 3. Blockchain Platform of Solar Energy Exchange "BSET".

solar energy. In this study, a PPA smart contract is defined between the government and solar power stations and is also implemented on the Ethereum blockchain and Binance Smart Chain (BNB). These different levels of PPA smart contracts are illustrated in Fig. 5.

There are some important points in the schedule section based on the PPA document. 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.

Fig. 6 shows the general schema of implementing a PPA smart contract on the blockchain platform.

In this figure, the three main roles and the cases that should be included in the smart PPA contract are mentioned. According to the rules that exist in PPA, sending a contract on the network is subject to entering the time, price, and total amount of the defined token. In the next step, executing the functions in the smart contract leads to recording the trading information on the blockchain, and finally, the trade finishes.

One of the main parts of a PPA smart contract is the determination of the price of traded energy. Pricing is determined according to Eq. (2). and Eq. (3).

$$\text{Price} = \text{Base Price} \times \text{Cofactor} \quad (2)$$

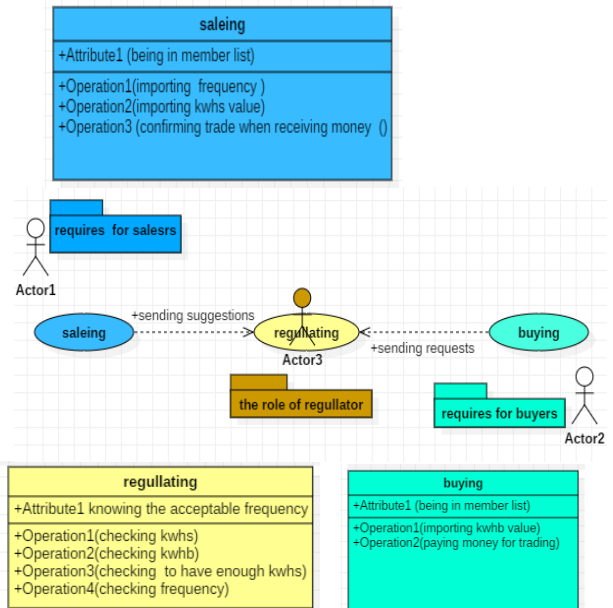


Fig 4. UML file related to the Solidity code of solar energy trading.

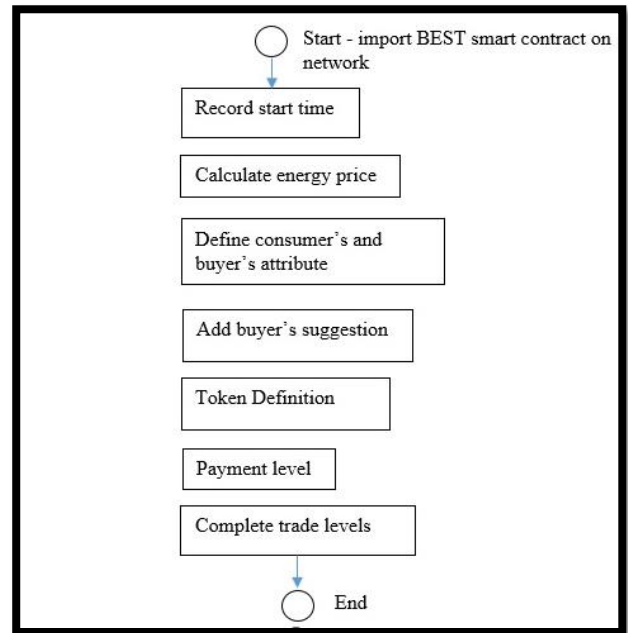


Fig 5. PPA smart contract flowchart.

$$\text{Cofactor} = \text{Inflation}^{\alpha} * \text{dollar price}^{1-\alpha} \quad (3)$$

In these relations, the price of energy is directly related to the two factors of inflation and the price of the dollar, which, as shown in Equation (3), is exponential if a function of the smart contract is allocated to pricing. Because the values of the inflation rate and the alpha number are decimal, the result of Equation (1) will be a decimal number. One of the limitations of the Solidity language is that it does not define a decimal number. As a result, it is impossible to define such a function and determine the price in the context of a smart contract.

4.2.2 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, or using the Trust Wallet website.

There are various standards for writing tokens, including REC standards, which stand for “Ethereum Request for Comment, and 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.

Fig. 7 is an interface contract declaring the required functions and events to meet the ERC20 standard:

The balance 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 the spender to spend. The transfer function is simple. It allows users to transfer a certain number of tokens to an address. So, when users use the transferFrom function, they can transfer tokens from the account of another person who has allowed users to use a certain number of tokens to an address. So, when users use the transferFrom function, they can transfer tokens from the account of another person who 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 transfer some tokens from one account to another, and 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.

4.3 Method

To evaluate the scenario presented above, we implement

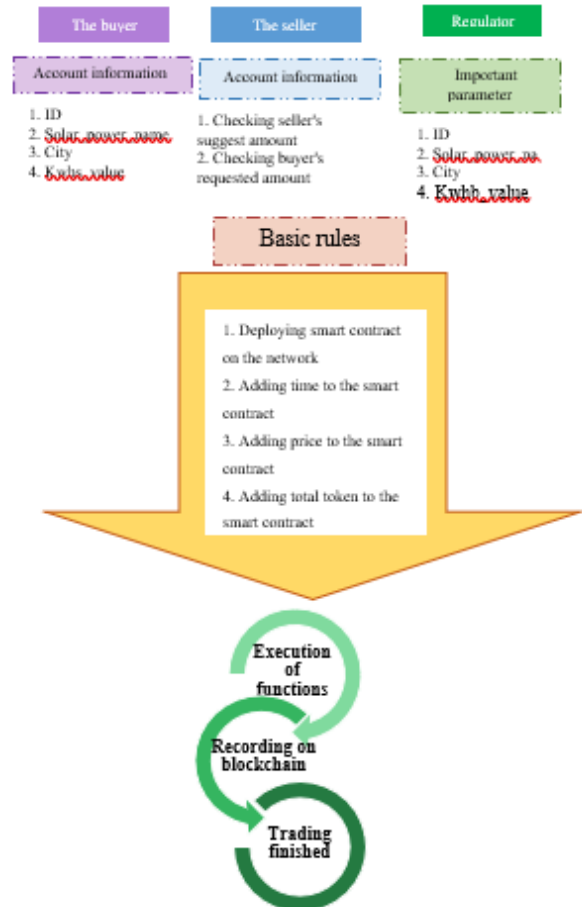


Fig 6. Smart contract deployment on blockchain

```
contract ERC20Interface {
    function totalSupply () public constant returns (uint);
    function balanceOf (address tokenowner) external view returns (uint);
    function allowance (address tokenowner, address spender) public constant returns (uint remaining);
    function transfer (address to, uint tokens) public returns (bool success);
    function approve (address spender, uint tokens) public returns (bool success);
    function transferFrom (address from, address to, uint tokens) external returns (bool success);

    event Transfer(address indexed from, address indexed to, uint tokens);
    event Approval(address indexed tokenOwner, address indexed spender, uint tokens);
}
```

Fig 7. The ERC20 Token Standard Interface

PPA on blockchain platforms by using smart contracts and the Solidity language. We configure two participants in the platform, the seller and the buyer, and perform various tests for the scenario. The role of the regulator is defined in the regulator function of the PPA smart contract. The tests are described in detail below: (1) deploying the PPA smart contract on blockchain platforms, which are 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. This is shown and explained in section 4.3.1. (2) To make financial payments in this smart contract, a token will be defined. (3) According to section 4.3.3, 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.

4.3.1 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, so the designer of the PPA smart contract who sends it on 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 & Unix Timestamp Conversion Tool. To design a smart contract in such a way that it will be active for a period of twenty years, this point is included in the form of a condition in the smart contract, whose pseudo-code is shown in Fig. 8. In this pseudo-code, duration = 630720000 is obtained from $20 * 365 * 24 * 60 * 60$.

_PRICE:

The price of the exchanged electricity must be entered manually as an input. This is because the pricing equation is exponential and depends on factors such as the dollar exchange rate and the inflation rate. In addition, due to the limitations of the Solidity programming language, automatic calculation within the PPA smart contract is not feasible.

```
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));
        _;
    }
    .....
}
```

Fig 8. Pseudo-code of time condition.

_TOTALSUPPLY:

Total Supply is related to the token defined in the PPA smart contract and represents the total number of issued or mined tokens.

The value of some parameters is given in Table 3, and in Fig. 9, the deployed smart contract with these values is shown.

Table 3. the value of PPA smart contract parameters

Parameters	Value
PRICE	1
STARTTIME	1678197442
TOTALSUPPLY	10000000000
decimals	0
symbol	STC
name	Solar Trading Coin

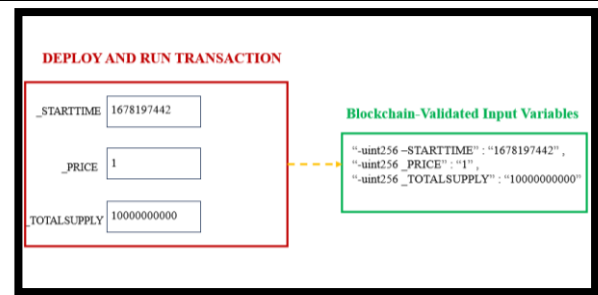


Fig 9. Smart contract inputs that are defined in the constructor function.

4.3.2 Token definition

At the same time as the PPA smart contract is deployed on the blockchain network, the smart contract of token definition will also be deployed on the network, and a token will be defined with the name and specifications. given in Table 3. This token is used for financial payments in 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.

4.3.3 Trading

After confirming the PPA smart contract on the blockchain network, users must enter their information to start the trading process. This information includes the name of the power plant, city, and ID, which are entered in the NationalCard function. This information will be stored on the blockchain, which is shown in Fig. 10.

In the next step, the value of the suggested amount and the required amount of solar energy are entered by the seller and buyer, and these values will be checked by the

regulator. Fig. 11 illustrates the suggested amount ($_kw\text{hs}$) and the required amount ($_kw\text{hb}$) of solar energy recorded on the blockchain platform.

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.

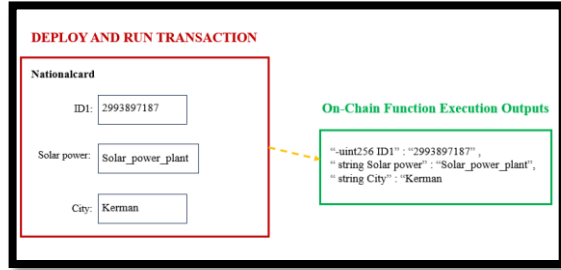


Fig 10. Storing Users' Information on the Blockchain.

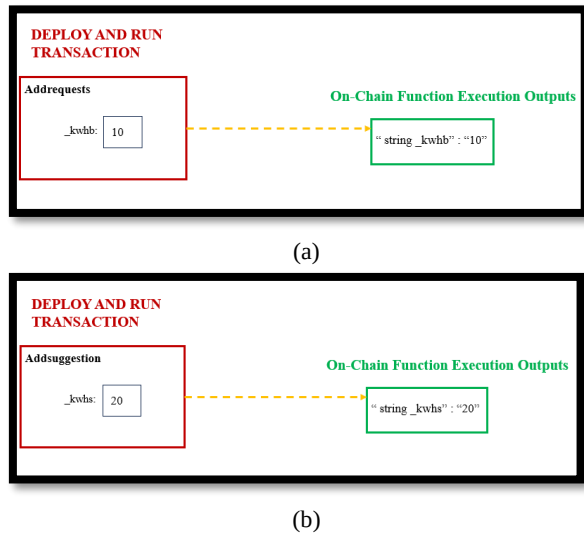


Fig 11. The value of (a) $_kw\text{hs}$, and (b) $_kw\text{hb}$.

4.3.4 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 Eq. (4).

$$\text{payment} = \text{price} * _kw\text{hs} \quad (4)$$

According to Table 3, in Test 1, the required amount of solar energy is 10 kW, and the suggested amount is 20 kW. Therefore, in this test, 10 kW of solar energy has been traded.

As a result, the amount is 20 kW. The buyer must deposit the 10 STC ($1*10$) into the seller's account. In Fig. 12, the balance of accounts before payment by the buyer

is shown, which is 1000 STC for account 1(12-a) and 0 STC (12-b) for account 2. In Fig. 13, after paying 10 STC to the seller, the values are also 990 STC (13-a) and 10 STC (13-b), respectively. Also, in these figures, account 1 is the buyer and account 2 is the seller.



Fig 12. The STC token balance of (a) account 1 (1000STC) and (b) account 2 (0 STC) before payment.

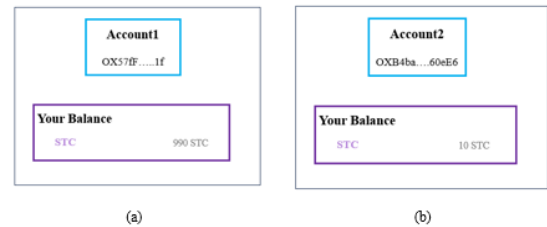


Fig 13. The STC token balance of (a) account 1 (990STC) and (b) account 2 (10 STC) after payment.

5 Results

By using this platform and a process with the mentioned steps, solar energy trading is tested 10 times on different days and hours. The value of the proposed amount and the required amount of solar energy in these 10 trades are given in Table 4.

In this implementation, which has been reported 10 times in Fig. 14 and Fig. 15, the amount of total gas consumed and the duration of transactions are shown.

According to Fig. 14, the gas cost includes the amount required to store the specifications of both the buyer and the seller on the blockchain. It also accounts for the storage of the proposed and requested solar energy quantities. In addition, the gas needed to transfer tokens from the buyer's account to the seller's account is included in the total cost.

Fig. 14 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 Fig. 14, trade number 3 and trade number 5 with a gas cost of 0.0019 TBNB have the lowest gas cost.

Fig. 15 is drawn based on the time duration of a transaction and is actually the time spent to perform the items mentioned in Fig. 14.

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

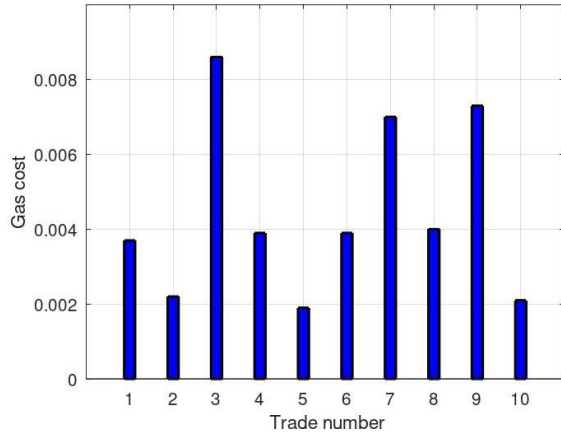


Fig 14. Gas cost in solar energy trading.

Table 4. The Value of the Proposed Amount and the Required Amount of Solar Energy.

Transaction number	The required amount of solar energy	The suggested amount of solar energy
1	10 sec	20
2	500 sec	600
3	100 sec	150
4	50	60
5	900	910
6	40	50
7	5	6
8	800	810
9	800	900
10	300	350

these values. Total time is 466 seconds, and total gas is 0.023.

The reason for the difference between the "total time" in Table 4 and the "time duration" in Fig. 15 of the 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 the trade also differ from each other.

Fig. 15 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 many transactions are waiting to be confirmed by the network, transactions are confirmed more slowly, and this amount increases; if it is quieter, transactions are confirmed faster, and this amount will be less. In this test, according to Fig. 15, trade number 5 with a duration of

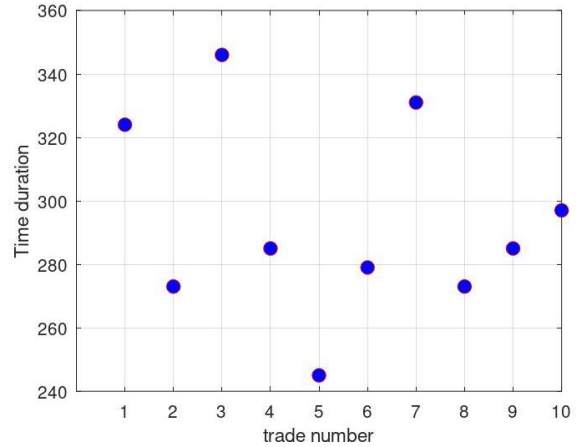


Fig 15. Time duration in solar energy trading.

245 seconds has the shortest duration, and trade number 3 with a duration of 346 seconds has the longest duration.

The proposed blockchain-based trading platform was tested through 10 independent runs, each involving approximately 15 transactions. The measured Transactions Per Second (TPS) ranged from 0.0429 to 0.0612, with an average TPS of 0.0516 and a standard deviation of 0.0054. Although the number of transactions was relatively low (reflecting real-world micro-trade scenarios), the results demonstrate consistent performance across repeated executions.

It is important to mention that at first, the Rinkeby network was used for implementation. But due to the protocol changes of Ethereum, the Rinkeby test network may not work as reliably and will be deprecated. For this reason, the implementation continued on other Ethereum test networks, including "Goerli" and "Sepolia", and also the Binance Smart Chain (BNB) test network. As a comparison, the gas cost and time duration of the trade for deploying the smart contract PPA on these three networks are given in Table 5.

Table 5. Comparison of Blockchain Networks.

Blockchain network	Time duration	Gas cost
BNB testnet	50sec	0.01
Goerli	57sec	0.00508
Sepolia	39sec	0.00502

Table 4 shows that the BNB test network had the highest gas cost, and the Sepolia test network had the lowest gas

cost. Of course, this point is important because getting the test token of TBNB is easier than Sepolia.

5.1 Comparison of the Performance of the Proposed Trading Platform and Existing Platforms

To compare the proposed trading platform with Power Ledger, several key metrics must be evaluated. The comparison can be divided into two categories: technical and functional.

a) Technical Comparison

Blockchain Architecture and Smart Contracts

The blockchain in the Power Ledger trading platform combines Ethereum and Ecochain blockchains. In contrast, the proposed platform uses BNB Smart Chain and Ethereum (Sepolia) test networks. Both platforms utilize smart contracts to regulate and automate transactions between producers and consumers. The payment system on both platforms involves tokens designed by the developers of these platforms. In Power Ledger, the relevant token is called "Power," while in the proposed, it is called "STC."

Data Management and Privacy

Power Ledger stores energy production and transaction data on the blockchain but processes sensitive information off-chain. On the other hand, the TBP platform stores all information on the blockchain.

b) Functional Comparison

Business Model and Use Cases

Power Ledger primarily targets regulated markets such as Australia and Thailand. In contrast, the TBP platform is designed for solar energy exchanges in the Iranian market. Additionally, the pricing model and transparency in Power Ledger are based on supply and demand, whereas in the proposed model, the price is determined in three different ways. In the first case, if technical knowledge for domestic equipment in power plant construction is not considered, the price is set based on inflation rates and dollar fluctuations by the relevant authority, and transactions are carried out accordingly. In the second case, if the local content and its impact on solar energy prices are considered, the price is determined by a smart contract that accounts for technical knowledge. To mitigate the effects of sudden dollar changes and inflation, a fuzzy system is used to calculate the price in the new versions.

In addition to the compared features, other technical characteristics have been reviewed and aligned in Table 6. Efforts were also made to access the test environment of this platform to complete the comparisons; however,

access was unfortunately not granted, and the task could not be accomplished.

For smart contract execution, the complexity is primarily dependent on the size and logic of the contract. In our case, the smart contract involves conditional checks and updates for pricing, incentives, and energy credits, which are executed in constant or linear time, i.e., $O(1)$ to $O(n)$, where n is the number of involved parameters or accounts.

Table 6. Comparative Table of the Proposed TBP Platform and Power Ledger.

P2P trading system	Gas cost	Consensus algorithm	Token name	Blockchain platform
Power ledger	POWER	POS, POSA	power	Private, public
TBP	TBNB, STC	POS	STC	Public

The consensus mechanism used in TBP is [e.g., Proof of Authority (PoA)], which is lightweight compared to Proof of Work (PoW) and has constant computational complexity $O(1)$ for each validator per block.

The overall computational complexity per transaction in the TBP is therefore $O(1)$ to $O(n)$, depending on the number of smart contract conditions and external data references. No expensive cryptographic computations (like mining or zero-knowledge proofs) are used. Compared to traditional public blockchains like Ethereum (with PoW or PoS), our TBP is optimized for low-complexity, high-efficiency operation suitable for micro-transactions in localized energy trading environments.

In practical blockchain-based applications for the energy and electric vehicle (EV) sectors, various challenges continue to hinder widespread adoption, particularly those related to cybersecurity and system integrity. Notable concerns include the risk of chain forks, selfish mining strategies, weaknesses in consensus protocols, anonymity-related complications, and vulnerabilities in smart contract design.

To address these challenges, the proposed Trading Blockchain Platform (TBP) has been developed using a permissioned blockchain architecture based on the Proof of Authority (PoA) consensus algorithm. This choice significantly improves system stability and security. Specifically, forks are minimized due to the deterministic nature of block production, which is handled exclusively by a trusted set of pre-approved validators.

Furthermore, because the TBP does not rely on mining or incentive-driven competition, the issue of selfish mining is effectively eliminated. The PoA consensus model also provides resistance against Sybil and majority attacks, which are common concerns in public and permissionless blockchain networks.

In terms of user identity and data transparency, TBP

diverges from fully anonymous blockchain models by adopting identity-linked accounts with role-based access control. This design ensures both transaction traceability and compliance with energy market regulations, which are crucial for real-world deployment in energy trading systems.

Additionally, the TBP utilizes modular and well-audited smart contracts, which are intentionally designed to be simple and secure. Best practices in smart contract development—such as gas optimization, reentrancy protection, and modular structure—have been followed to minimize potential vulnerabilities.

In summary, the architectural and security choices made in the design of TBP address many of the critical limitations of traditional public blockchains. As a result, the platform is better suited for secure, transparent, and efficient micro-transactions in decentralized renewable energy trading scenarios.

To provide a balanced context, a comparison between the proposed system and recent blockchain-based energy platforms such as WattCrop and EggBlock [49] is made. WattCrop employs a PoS mechanism to enable peer-to-peer energy exchange with reduced energy costs, but its scalability remains limited in high-load environments. EggBlock integrates a hybrid PoA/PoS structure for agricultural and solar microgrids, achieving rapid confirmation times but relying on semi-centralized validation. In comparison, the proposed platform adopts a PoA-based architecture that emphasizes efficient transaction validation, incentive-based pricing, and fair energy valuation via a fuzzy logic system. While it addresses several efficiency and fairness issues, scalability and gas cost optimization remain ongoing challenges requiring future refinement.

6 Limitations of Blockchain-Based Energy Trading

Despite its numerous advantages in enhancing transparency, traceability, and decentralization, blockchain technology is not without limitations when applied to energy trading systems.

6.1 Energy Consumption

One of the primary concerns is energy consumption, particularly in networks employing the Proof-of-Work consensus mechanism. Such networks require intensive computational resources to validate transactions, resulting in substantial energy use that contradicts the sustainability goals of renewable energy initiatives. Although newer consensus algorithms such as Proof-of-Stake (PoS) and Proof-of-Authority (PoA) have significantly reduced energy requirements, they still involve trade-offs between decentralization, security, and performance.

6.2 Scalability Constraints

Another critical challenge is scalability. Public blockchains often experience low transaction throughput

and high latency under heavy network load, making real-time energy trading and micro transactions impractical. High gas fees during congestion further restrict the economic feasibility of frequent small-scale transactions. Additionally, integrating blockchain with Internet of Things (IoT)-based smart meters and legacy energy management systems remains complex, requiring robust data synchronization and interoperability frameworks.

6.3 Privacy and regulatory

Privacy and regulatory compliance also present important considerations. While blockchain's transparency ensures accountability, it can inadvertently expose sensitive user or operational data. Moreover, the absence of unified regulatory frameworks for blockchain-based energy markets may hinder large-scale deployment and cross-border trading.

7 Conclusion

This study implements a PPA smart contract on a blockchain platform for trading solar energy. This platform implements four essential factors of the PPA contract, which include the duration of the contract validity, the price of solar energy, seller information, and financial payments. By using this platform, transaction information is stored in a secure, immutable, and distributed environment, and tracking it will be possible. The results of implementation for different transactions indicate the non-uniformity of time and gas costs on different days and hours. By using this platform, users in each city can also trade solar energy with each other. One of the main advantages of this platform is the possibility of financial payments using the token STC. This token has been designed for the BSET platform and can be transferred to the seller's account faster than the traditional method of transactions. Also, the comparison between the proposed TBP platform and Power Ledger reveals key differences in blockchain architecture, data management strategies, and pricing models. Significantly, TBP employs a more integrated blockchain approach and offers a flexible pricing system, setting it apart from Power Ledger.

Conflict of Interest

The authors declare no conflict of interest.

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Declaration of generative AI and AI-assisted technologies

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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