International Journal of Basic and Applied Sciences, 14 (8) (2025) 42-51

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/nky6ev75
Research paper

Blockchain-Driven Decentralized Green Energy Trading using Python and Ganache

Mr. R. Kavin [1] *, Dr. J. Jayakumar [2]

[1] Research Scholar, Department of Electrical and Electronics Engineering , Karunya Institute of Technology and Sciences, Coimbatore, India
[2] Professor, Department of Electrical and Electronics Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India
**Corresponding author E-mail: kavin882@gmail.com*

Received: October 15, 2025, Accepted: November 19, 2025, Published: December 4, 2025

Abstract

Efficient energy sharing among solar-based microgrids was crucial for enhancing grid reliability, scalability, and sustainability in modern energy systems. This research presents a novel blockchain-powered decentralized energy trading framework that integrates Raspberry Pi 4, IoT-driven real-time monitoring, and Ethereum-based smart contracts to facilitate seamless and secure peer-to-peer (P2P) energy exchange. The proposed system enables real-time data acquisition and transmission of critical energy parameters, including current, voltage, and power generation, from five interconnected solar microgrids. Raspberry Pi 4 serves as the centralized edge computing node, aggregating and transmitting real-time energy data to the ThingSpeak IoT platform, where advanced AI-driven analytics optimize grid efficiency. Blockchain technology, specifically Ethereum with Ganache, was employed to create a tamper-proof, transparent, and trustless energy marketplace, eliminating reliance on centralized energy intermediaries. The incorporation of Solidity-based smart contracts automates transactions, ensuring secure, immutable, and fair energy trading while enabling dynamic pricing models based on real-time demand-supply conditions. Python, integrated with Web3.py, facilitates seamless interaction between Raspberry Pi 4 and the blockchain network, ensuring low-latency transaction execution and verifiable trade settlements. Through the integration of IoT-enabled smart grids, blockchain-based energy transactions, and AI-driven predictive analytics, the proposed system offers a scalable, autonomous, and energy-efficient solution for decentralized energy management. Experimental validation confirms the system's effectiveness, demonstrating its ability to achieve real-time energy balancing, seamless P2P trading, and enhanced security through blockchain immutability. This cutting-edge approach significantly advances the adoption of renewable energy sources, optimizes microgrid autonomy, and reinforces the resilience of next-generation smart power networks, paving the way for a sustainable and decentralized energy economy.

Keywords: *Peer-to-Peer; Energy Trading; Ethereum; Blockchain; Python.*

1. Introduction

The increasing integration of distributed energy resources (DERs) has transformed power systems, making them more intelligent, flexible, and decentralized. Traditional centralized power systems, which rely on large-scale power plants for electricity generation and long-distance transmission, face several challenges, including inefficiencies, transmission losses, high operational costs, and dependency on fossil fuels. The rising adoption of renewable energy sources such as solar and wind power has created opportunities for decentralized energy generation at the consumer level. This shift was driven by the need for energy security, environmental sustainability, and the growing affordability of solar panels and energy storage technologies. As a result, individuals and small communities are evolving from passive consumers into active prosumers, entities that both produce and consume electricity. Integrating DERs into existing power systems requires efficient mechanisms for energy distribution, storage, and exchange, highlighting the need for P2P energy trading.

P2P energy trading was emerging as an innovative approach that allows direct energy exchange between consumers and prosumers without relying entirely on traditional utilities. By enabling decentralized transactions, P2P trading enhances energy utilization efficiency, reduces reliance on centralized power suppliers, and optimizes local energy consumption. Unlike conventional power systems, where energy flows in one direction from large power plants to consumers, P2P trading facilitates multi-directional energy exchanges. Consumers can purchase surplus energy directly from nearby prosumers, creating a local energy marketplace that fosters fair pricing, improved grid stability, and increased use of renewable energy. This decentralized approach enhances grid resilience, especially in microgrid settings where energy generation and consumption occur in close proximity. Despite its advantages, traditional P2P energy trading mechanisms face significant challenges, including a lack of transparency, trust issues, security vulnerabilities, and the complexity of transaction validation.

Blockchain technology presents a promising solution to address these challenges by offering a secure, transparent, and immutable platform for decentralized energy transactions. Blockchain, a distributed ledger technology, eliminates the need for intermediaries by enabling trustless transactions verified through cryptographic mechanisms. The key attributes of blockchain decentralization, immutability, transparency, and security align perfectly with the objectives of P2P energy trading. By leveraging Ethereum-based smart contracts, energy transactions can be automated, ensuring fairness, efficiency, and trust among participants. Smart contracts execute predefined conditions, enabling seamless energy exchanges between prosumers and consumers without manual intervention. This automation minimizes transaction delays, eliminates the need for third-party verification, and reduces operational costs. The use of blockchain technology enhances data integrity by preventing unauthorized alterations or tampering, ensuring that all energy exchanges are auditable and verifiable.

To facilitate real-time energy monitoring and seamless integration with blockchain, Internet of Things (IoT) technologies play a crucial role in the proposed system. The incorporation of Raspberry Pi 4, an affordable and efficient computing device, allows continuous data acquisition from multiple solar grids. Equipped with sensors, Raspberry Pi 4 collects critical parameters such as current, voltage, and power output, which are transmitted to the blockchain network and stored securely. The integration of the ThingSpeak IoT platform enables cloud-based data visualization, allowing users to monitor energy production, consumption, and transaction history in real time. The combination of IoT and blockchain creates a robust infrastructure for decentralized energy management, enhancing transparency and operational efficiency.

The proposed system utilizes Ganache, a local blockchain emulator, for Ethereum-based smart contract deployment. Ganache provides a controlled environment to test and validate blockchain transactions before implementing them on a live Ethereum network. The Python programming language, known for its versatility and rich ecosystem of libraries, was used to develop the blockchain application, interact with smart contracts, and process energy transaction requests. The system enables energy exchanges by defining a conversion mechanism, where one Ethereum coin corresponds to 1 kWh of energy. This innovative model ensures a standardized pricing structure, reducing price fluctuations and enabling predictable energy transactions between microgrid participants.

The significance of this research lies in its potential to revolutionize energy management by promoting local energy autonomy and reducing dependency on centralized power grids. By allowing prosumers to sell excess energy directly to their neighbours, this system fosters an economically and environmentally sustainable energy market. Encourages the adoption of renewable energy sources by providing financial incentives for surplus energy production. The decentralized energy trading framework enhances grid resilience by enabling energy balancing within microgrids, reducing the risk of power outages and transmission losses. The blockchain-based security mechanisms ensure data integrity, mitigate cyber threats, and eliminate fraudulent transactions, making the system highly secure and trustworthy.

The main objective of this study was to design, develop, and evaluate a blockchain-enabled P2P energy trading system that leverages IoT and smart contracts for decentralized energy exchanges. Specifically, this research aims to develop a framework using Raspberry Pi 4 for real-time monitoring of solar grids, implement Ethereum-based blockchain technology with Ganache for secure transactions, automate energy trading using smart contracts, and validate the system's feasibility and effectiveness through experimental testing. This study analyses the impact of decentralized energy trading on grid reliability, renewable energy adoption, and energy utilization efficiency.

This paper was structured as follows: Section 2 presents a comprehensive literature review, discussing previous research on P2P energy trading, blockchain integration in energy markets, and IoT-based energy monitoring. Section 3 details the system design and implementation, explaining the architectural components, blockchain integration, and transaction mechanisms. Section 4 elaborates on the operational aspects, including smart contract development, energy pricing models, and security features. Finally, Section 5 concludes the paper, summarizing the findings and highlighting future research directions.

IoT, blockchain, and smart contracts. This study presents a scalable, secure, and efficient approach to energy trading that has the potential to transform decentralized energy markets. The proposed framework not only optimizes local energy utilization but also fosters a sustainable and resilient energy ecosystem, addressing critical challenges in modern energy management.

2. Literature Review

The transition towards a sustainable energy future is heavily reliant on the proliferation of distributed energy resources (DERs), such as rooftop solar panels. This shift necessitates a move away from traditional, centralized energy management systems towards more flexible, transparent, and efficient peer-to-peer (P2P) energy trading models. Blockchain technology, with its inherent properties of decentralization, immutability, and transparency, has emerged as a foundational technology to enable such P2P markets. This review synthesizes existing research on blockchain-based energy trading, identifying key themes and critical gaps.

Kavin and Jayakumar conclude that a blockchain-based EMS is not just a theoretical concept but a necessary evolution for managing the future decentralized grid. Their primary contribution lies in proposing a specific, patent-aware system architecture that addresses the scalability and security limitations of earlier proposals. [1]

Kavin and Jayakumar conclude that the integration of IoT and Blockchain is a foundational paradigm shift for managing decentralized renewable energy. It transforms a collection of independent generators into an intelligent, self-organizing, and resilient energy network. [2]

Khan et al. conclusively argue that blockchain technology is a key enabler for sustainable development. In the context of sustainable cities, it empowers decentralized, efficient, and renewable energy-based smart grids. In healthcare, it builds the foundation for secure, transparent, and patient-centric systems that can improve health outcomes universally. [3]

Adeyemia et al. conclude that blockchain technology holds transformative potential for power distribution systems. It is positioned not as a standalone solution but as a critical enabling technology that can facilitate the transition to a more decentralized, democratized, and resilient grid. [4]

Du et al. (2021) conclude that the integration of blockchain technology is a promising pathway to modernize the smart grid. Their primary contribution lies in proposing a comprehensive and structured engineering framework that addresses the "how" of integration, not just the "why." [5]

Esmat et al. (2021) conclude that their novel decentralized platform is a viable and superior model for enabling P2P energy trading. The paper's major contribution is the successful integration of a well-established economic mechanism (the continuous double auction) with blockchain technology to create a scalable, efficient, and automated local energy market. [6]

Chen et al. (2021) conclude that a carefully designed hybrid blockchain architecture is essential for the practical realization of distributed P2P energy trading. The paper's primary contribution is this detailed technical blueprint that prioritizes scalability and privacy without sacrificing the core benefits of decentralization and security. [7]

Asfar's chapter concludes that blockchain technology is not merely an optional add-on but a fundamental component for building the secure, efficient, and sustainable smart cities of the future. Its primary contribution is its integrative vision. [8]

Manish's review concludes that blockchain technology holds disruptive potential for the energy sector, particularly in enabling P2P trading models that can accelerate the transition to a decentralized, democratized, and renewable-based energy system. However, this potential is currently constrained by significant technical, regulatory, and commercial challenges. [9]

Oliver et al. conclude that for blockchain to be successfully adopted in the energy sector, it must be designed within a comprehensive framework that prioritizes grid stability, security, and governance alongside market functionality. This paper's primary contribution is providing such a holistic blueprint. [10]

Arezoo et al. conclude that blockchain technology holds transformative potential for future smart grids, enabling new levels of decentralization, automation, and citizen participation. However, they stress that this potential is contingent upon overcoming significant technical and regulatory hurdles. The paper's monumental contribution is its role as a synthesizing and organizing force. [11]

Kavousi-Fard et al. conclude that a specifically designed, secure blockchain architecture is not just beneficial but essential for realizing the full potential of interconnected microgrids and creating a resilient, efficient, and democratic energy future. The paper's primary contribution is this novel architectural blueprint for a hierarchical, security-hardened blockchain system that can operate at the scale of the entire grid. [12]

Yapa's survey concludes that blockchain technology is a powerful disruptive force with the potential to redefine the architecture and operation of future smart grids, enabling a more decentralized, transparent, and efficient energy ecosystem. However, this potential is contingent upon a concerted, interdisciplinary effort to overcome the technical, regulatory, and commercial challenges detailed in the review. [13]

Francesco et al. conclude that Ethereum presents a viable and secure foundation for building P2P energy trading platforms, provided that architectural choices like hybrid processing and Layer-2 scaling are adopted to mitigate its inherent limitations. The paper's primary contribution is its practical, implementation-oriented perspective. [14]

Li et al. conclude that blockchain technology is a powerful enabler for innovative and decentralized energy trading models, which can increase market efficiency, promote renewable integration, and empower consumers. However, its adoption is contingent upon overcoming significant technical challenges related to scalability and cost, as well as navigating the complex landscape of energy market regulation. The paper's primary contribution is its focused synthesis of the energy trading domain. [15]

Harshal et al. conclude that a blockchain-based framework provides a secure and transparent foundation for implementing advanced energy optimization strategies in the smart grid. By ensuring data integrity and enabling automated, trustless execution of optimization decisions, blockchain can unlock significant efficiency gains and cost savings. The paper's primary contribution is its practical focus on the optimization value proposition. [16]

Anak and Rini conclude that blockchain technology is a transformative enabler for building a secure, transparent, and efficient smart grid. However, its success hinges on a meticulously designed architecture that prioritizes security, scalability, and seamless integration with existing grid infrastructure. [17]

Wang, Yao, and Wen conclude that blockchain technology holds significant potential to address key challenges in modern power systems, from enabling new market structures to enhancing cybersecurity. However, they stress that realizing this potential requires overcoming formidable technical, regulatory, and commercial barriers. [18]

Cantillo-Luna et al. conclude that blockchain technology is a critical enabler for the next phase of DER integration, moving from passive connection to active, valuable participation in grid operations. It provides the necessary trust, automation, and security to manage the complexity of a decentralized energy system. The paper's primary contribution is its detailed, engineering-focused framework for DER orchestration. It significantly advances the field beyond P2P trading and into the core domain of grid management and control. [19]

Hasan et al. conclude that while blockchain technology enhances security in many ways (immutability, transparency), its integration into the smart grid introduces a new class of cybersecurity challenges that must be proactively addressed. A security-by-design approach is non-negotiable for critical energy infrastructure. [20]

Juszczyk and Shahzad conclude that blockchain technology holds transformative potential for the renewable energy sector, offering solutions to critical challenges in integration, market creation, and transparency. However, they stress that realizing this potential requires a concerted effort to overcome technical limitations, evolve regulatory frameworks, and prove its value through large-scale demonstrations. [21]

Md Mahraj Murshalin AI Moti's paper presents a sophisticated and holistic framework that pushes the boundaries of P2P energy trading research. By successfully integrating the strategic foundations of game theory, the decentralized trust of blockchain, and the adaptive learning capabilities of reinforcement learning, it offers a powerful blueprint for intelligent and automated future energy markets. [22]

Baig concludes that a well-designed, user-friendly interface is not an optional add-on but a critical component for the successful adoption of blockchain-based P2P energy trading. The use of established web technologies like Angular and HTTP is a viable and effective strategy to achieve this. The paper's primary contribution is its practical, developer-centric perspective. [23]

Singh concludes that a Blockchain-Based Smart Energy Measurement System (BSEMS) provides a paradigm shift in how we trust and utilize the most fundamental data in the power sector. It moves metering from a system of record kept by a single authority to a system of verifiable truth maintained by a decentralized network. [24]

Ziqiang Xu's "Blockchain-Based Malicious Behaviour Management Scheme for Smart Grids" represents a valuable and timely contribution to the literature. It moves beyond conceptual uses of blockchain for energy trading and tackles the critical issue of security head-on. By proposing an integrated framework that combines a dynamic reputation model with an incentivized PBFT consensus, the paper offers a robust, transparent, and decentralized alternative to vulnerable centralized security models. [25]

Summary Table:

Table 1: Research Gaps and Contribution of this Work

Research Gap Identified in Literature	How This Work Addresses the Gap
The Simulation-to-Implementation Gap: Disconnect between simulated energy data and a functioning, on-chain trading system.	Provides an integrated Python-to-Ganache pipeline. We use Python to simulate prosumer/consumer meter data and directly feed this into smart contracts deployed on a local Ganache blockchain, creating a tangible link between simulation and execution.
Accessibility and Cost Transparency Gap: High gas fees on public networks and a lack of focus on cost-effective deployment for micro-trading.	Utilizes Ganache for a zero-cost, private blockchain environment. This allows for the demonstration of the core trading mechanism without the barrier of real cryptocurrency, while the code remains portable to cost-optimized Layer 2 solutions.
The Integrated Tooling Gap: Under-utilization of the Python ecosystem, combined with a local development blockchain for a seamless workflow.	Demonstrates a practical tech stack using Python, Web3.py, and Ganache. This work showcases how Python can be used for data generation, interaction with smart contracts (via Web3.py), and result analysis, all within a controllable Ganache environment.

Lack of a Cohesive, Lightweight Demonstration: Overly complex architectures that are difficult to replicate or use as a starting point.	Delivers a minimal viable product (MVP) with core functionality. The focus is on a clear, well-documented implementation of fundamental features: user registration, order book management, trade settlement, and transparent transaction history.

3. Materials and Methods

This paper introduces an advanced system for efficient energy sharing among solar-based microgrids by integrating Raspberry Pi 4, blockchain technology, and IoT-driven real-time monitoring. The proposed framework leverages Raspberry Pi 4 as a centralized data acquisition and processing unit, facilitating seamless real-time monitoring of critical parameters such as voltage, current, and power generation across multiple solar grids. The collected data was securely transmitted to the ThingSpeak IoT platform, ensuring real-time visualization and analytics for optimized energy management. To establish a trustless and decentralized energy trading mechanism, the system incorporates the Ethereum blockchain with Ganache, providing secure, immutable, and transparent transactions between prosumers and consumers. Ethereum smart contracts automate energy transactions, enabling autonomous energy trading with predefined conditions and eliminating the need for intermediaries. Python was utilized for blockchain development and system integration, leveraging Web3.py for seamless interaction between Raspberry Pi 4 and the Ethereum network. The proposed system enhances grid resilience, promotes decentralized energy trading, and supports a sustainable energy ecosystem by ensuring efficient utilization of renewable energy resources. The combination of IoT, blockchain, and real-time monitoring establishes a scalable, secure, and autonomous energy-sharing framework, paving the way for the future of intelligent, decentralized microgrids.

3.1. Microgrid

The distributed energy sharing framework leverages multiple interconnected solar-based microgrids, enabling real-time, autonomous energy exchange to maximize efficiency and sustainability. In this system, five solar grids are seamlessly integrated within a decentralized network, allowing for dynamic energy distribution and load balancing. Raspberry Pi 4 acts as the intelligent central controller, responsible for acquiring, processing, and transmitting real-time energy parameters, including current, voltage, and power generation, to the ThingSpeak IoT platform for continuous monitoring and data-driven decision-making. By integrating IoT-enabled sensors, blockchain-based smart contracts, and edge computing capabilities, the proposed system ensures secure, transparent, and optimized energy transactions among prosumers and consumers. This scalable microgrid architecture not only enhances energy reliability and grid resilience but also facilitates the seamless adoption of decentralized, peer-to-peer energy trading, promoting a sustainable and intelligent power distribution ecosystem. (Figure 1).

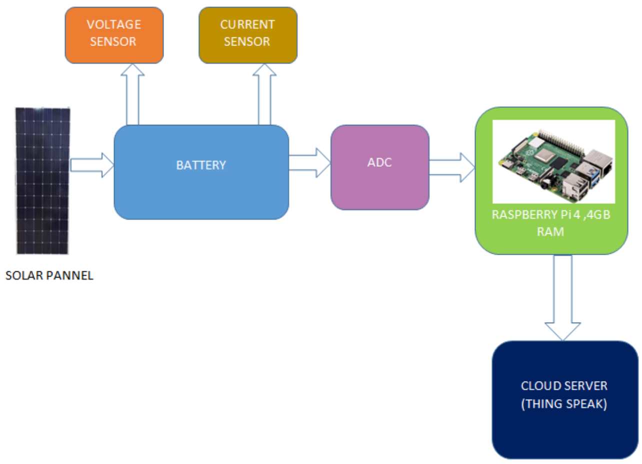

Fig. 1: Proposed Microgrid System.

Here was a detailed explanation of the procedure:

3.1.1. Solar-based 5-grid setup

The proposed system consists of five independent solar-powered microgrids, each integrated with high-efficiency PV panels to enable sustainable and decentralized energy generation (Figure 3). These microgrids function autonomously, capturing solar energy, converting it into electricity, and distributing it within their respective networks. By utilizing IoT-enabled sensors and Raspberry Pi 4, each microgrid continuously monitors key parameters such as voltage, current, and power generation, ensuring real-time tracking of energy production and consumption patterns. This approach not only enhances energy self-sufficiency but also reduces dependency on centralized grids, paving the way for a smart, resilient energy ecosystem.

Located in geographically dispersed areas, these microgrids are seamlessly interconnected through a blockchain-secured P2P energy trading network. This interconnection enables dynamic, real-time energy sharing, allowing microgrids with surplus energy to sell excess power to those experiencing shortages. By leveraging Ethereum blockchain technology with Ganache, the system ensures transparent, tamper-proof, and automated energy transactions, eliminating the need for traditional utility-based energy distribution. The use of smart contracts in Solidity facilitates secure, instant settlements, preventing manipulation, fraud, or centralized control in the trading process.

One of the key advantages of this setup was its ability to maintain optimal load balancing and grid stability through intelligent energy distribution. By analysing real-time demand-supply fluctuations using AI-driven analytics on the Thing Speak IoT platform, the system can predict and adjust energy flow dynamically, preventing overloading or energy wastage. Integrating battery storage solutions within each microgrid enhances energy resilience, allowing stored energy to be utilized during peak demand periods or low solar generation hours. This blockchain-integrated microgrid architecture not only optimizes energy efficiency but also fosters the development of a decentralized, sustainable, and community-driven energy marketplace. (Figure 2)

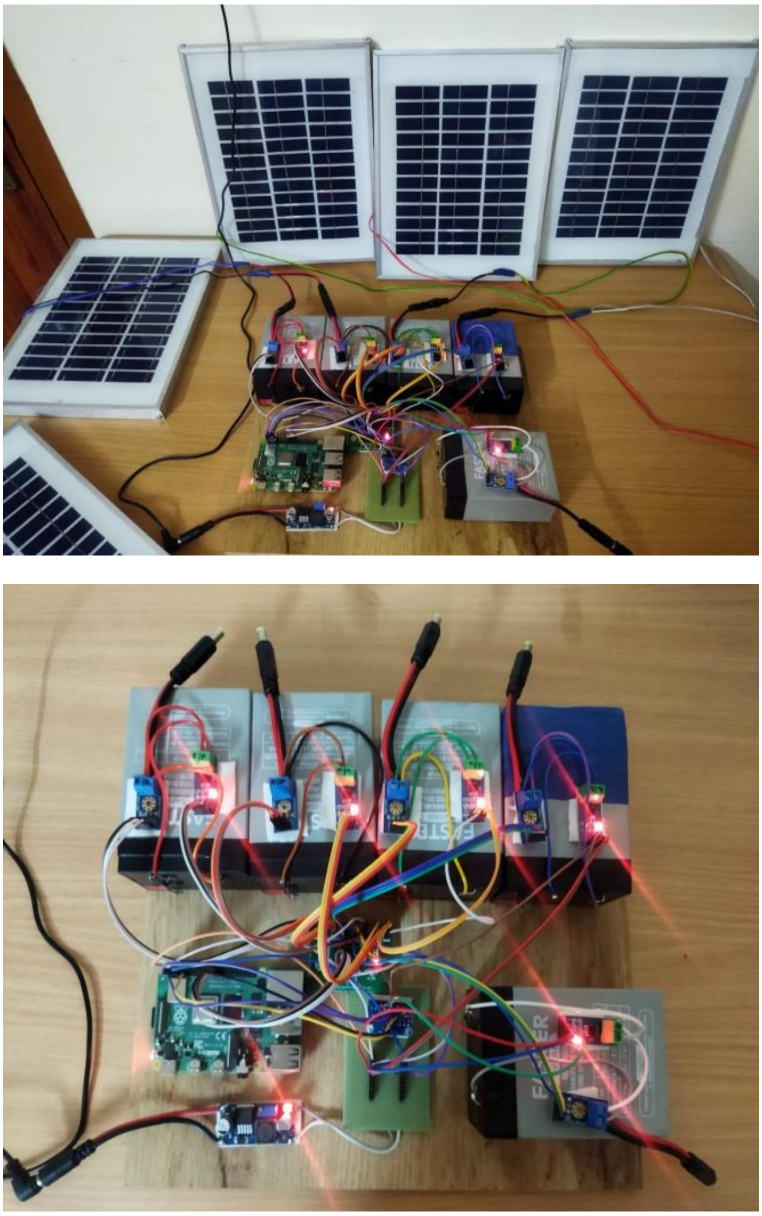

Fig. 2: Microgrid Using Solar PV.

3.1.2. Raspberry Pi 4 integration

The proposed blockchain-integrated energy trading system, Raspberry Pi 4, serves as the intelligent central node, enabling real-time energy monitoring, data processing, and secure communication across the interconnected microgrids. As a low-power yet high-performance computing device, Raspberry Pi 4 continuously gathers energy data from five solar grids, ensuring that the system remains responsive and efficient. Its ability to autonomously manage decentralized energy transactions allows microgrids to seamlessly share surplus energy while maintaining grid stability and optimized energy flow. By functioning as an edge computing device, Raspberry Pi 4 enhances the speed and reliability of data transmission, ensuring that energy trading decisions are executed in real time.

One of the critical functions of Raspberry Pi 4 was to acquire, analyse, and transmit key energy parameters, including current (Amperes), voltage (Volts), power consumption (kWh), and storage levels, from each solar grid. This data was processed locally and then transmitted securely to the ThingSpeak IoT platform, where AI-driven analytics facilitate real-time decision-making for energy allocation. By integrating IoT-based sensors with Raspberry Pi 4, the system ensures continuous data flow, enabling prosumers to track their energy usage and availability dynamically. This seamless data aggregation allows for automated blockchain-based energy trading, where smart contracts execute transactions based on real-time energy demand, supply, and pricing conditions.

Raspberry Pi 4 was chosen for its high computational power, low energy consumption, and superior interfacing capabilities, making it an ideal device for secure and decentralized energy management. Its ability to interface with IoT sensors, blockchain networks, and cloud-based platforms ensures that all components of the system operate harmoniously. Support for Python-based blockchain integration via Web3.py allows for direct interaction with Ethereum smart contracts, enabling tamper-proof and automated energy transactions. This edge computing architecture significantly enhances the efficiency of peer-to-peer energy trading, ensuring that the system remains scalable, cost-effective, and resilient in the evolving landscape of renewable energy distribution.

3.1.3. Data acquisition

The proposed blockchain-powered P2P energy trading system, Raspberry Pi 4, serves as the central data acquisition hub, continuously collecting real-time, high-frequency energy data from IoT-enabled sensors deployed across the five interconnected solar grids. These sensors monitor critical electrical parameters, allowing the system to assess energy availability, consumption patterns, and grid stability. By leveraging real-time data acquisition, the system ensures that energy surpluses and shortages are detected instantly, enabling automated blockchain transactions for efficient energy redistribution.

The IoT-enabled sensors integrated with Raspberry Pi 4 measure key energy parameters, including current (Amperes), voltage (Volts), and power generation (Watts), with high accuracy. This data was essential for monitoring microgrid performance, detecting faults, and optimizing energy flow. By continuously tracking these metrics, the system can identify fluctuations in energy production and consumption, ensuring that microgrids operate efficiently without overloads or underutilization. The seamless connectivity between Raspberry Pi 4, ThingSpeak IoT, and the blockchain network allows for real-time analytics, enabling the system to predict energy demand, optimize trading conditions, and enhance grid resilience.

Once collected, the acquired data was securely processed, logged, and stored within the Raspberry Pi 4's local memory, ensuring that all transactions and energy metrics remain tamper-proof and verifiable. This stored data was then seamlessly integrated with blockchain-based smart contracts, allowing for transparent and automated energy trading without human intervention. By utilizing the Ethereum blockchain with Ganache, each energy transaction was securely recorded on a decentralized ledger, preventing fraud and ensuring trust among prosumers. This real-time, automated energy trading mechanism enhances scalability, efficiency, and reliability, making blockchain-enabled microgrids a viable solution for decentralized renewable energy management.

3.1.4. Communication with ThingSpeak IoT platform

The blockchain-integrated P2P energy trading system, Raspberry Pi 4, acts as the central communication hub, transmitting real-time, high-resolution energy data to the ThingSpeak IoT platform. This ensures continuous monitoring and advanced analytics for optimizing microgrid performance, energy distribution, and trading efficiency. By collecting key energy parameters such as current, voltage, and power generation, Raspberry Pi 4 provides a real-time snapshot of energy availability across all interconnected microgrids. This data transmission was crucial for maintaining balance within the decentralized energy trading ecosystem, as it enables automated blockchain transactions based on live energy demand and supply conditions.

Thing Speak, a cloud-based IoT analytics platform, serves as a powerful tool for secure data aggregation, predictive analysis, and dynamic visualization. The energy data collected by Raspberry Pi 4 was processed in the ThingSpeak cloud environment, where AI-driven forecasting models predict consumption trends, detect inefficiencies, and optimize energy distribution. This allows for proactive decision-making, ensuring that energy surpluses are efficiently redirected to areas with higher demand. The interactive visualization dashboards within Thing Speak further empower prosumers and consumers by providing real-time insights into energy generation, storage levels, and transaction history, promoting transparency and trust in blockchain-enabled trading.

To guarantee secure and low-latency data transmission, Raspberry Pi 4 employs encrypted communication protocols such as MQTT, HTTPS, or Web Sockets, ensuring data integrity and protection against cyber threats. This secure transmission channel was essential for seamless interaction between the IoT-enabled microgrids, blockchain network, and AI-based analytics system. The energy metrics sent to ThingSpeak undergo AI-driven anomaly detection, allowing the system to identify unexpected power fluctuations, prevent fraudulent activities, and optimize automated smart contract execution. By integrating IoT, AI, and blockchain, the system not only enhances energy trading efficiency but also ensures a resilient, decentralized, and intelligent energy management infrastructure.

3.2. Blockchain

The decentralized energy sharing system was built on a hybrid Blockchain-IoT framework, integrating Raspberry Pi 4, Ethereum blockchain with Ganache, and a Python-based system automation to enable secure, transparent, and real-time energy transactions. Raspberry Pi 4 acts as an intelligent edge computing device, responsible for collecting, processing, and transmitting real-time energy data from five solar microgrids. This data was seamlessly integrated with blockchain-based smart contracts, ensuring that every transaction was validated, recorded, and executed autonomously. By leveraging IoT-enabled sensors and ThingSpeak cloud analytics, the system maintains real-time energy monitoring, allowing prosumers to track their energy surplus, consumption patterns, and trading history with complete transparency.

A trustless and tamper-resistant energy marketplace, the system deploys an Ethereum blockchain using Ganache, eliminating third-party intermediaries and centralized control over energy distribution. The Ethereum blockchain ensures that all transactions are immutable, meaning they cannot be altered, manipulated, or reversed, thereby enhancing security and trust among prosumers and consumers. Using Solidity smart contracts and Web3.py integration, the system automates energy transactions, dynamically adjusting energy pricing based on real-time supply-demand fluctuations. This self-regulating framework ensures that energy is distributed efficiently, preventing grid imbalances, inefficiencies, and unfair trading practices.

A tokenized energy trading model was implemented, where 1 Ethereum coin (ETH) corresponds to 1 kW of energy, allowing for automated, P2P transactions. When a solar microgrid generates excess energy, it can list this surplus on the blockchain network, where other microgrids or consumers experiencing an energy deficit can purchase it instantly. Smart contracts handle transaction validation, energy allocation, and payment settlement, ensuring low-latency, cost-effective, and verifiable energy trading. This Blockchain-IoT synergy guarantees a scalable, energy-efficient, and secure decentralized energy economy, enabling prosumers to actively participate in next-generation, self-sustaining smart grids while promoting the widespread adoption of renewable energy solutions.

3.2.1. Implementing blockchain technology with Ethereum and Ganache

A secure and decentralized energy trading environment, the system integrates Ganache, a private Ethereum blockchain, deployed on a local machine. Ganache serves as a controlled blockchain simulation environment, enabling low-cost and high-speed transaction processing while ensuring transparency, security, and immutability in P2P energy trading. By using a private blockchain, the system eliminates scalability concerns associated with public Ethereum networks, ensuring real-time execution of energy trades without incurring high gas fees. Raspberry Pi 4 interacts with this Ganache blockchain, continuously updating energy generation and consumption data, ensuring seamless smart contract execution for automated energy exchanges.

To facilitate secure and verifiable transactions, unique Ethereum accounts are generated for prosumers (energy producers) and consumers (energy buyers) within the blockchain network (Figure 4). These digital identities ensure that every transaction is cryptographically signed and permanently recorded, preventing fraud, double-spending, or unauthorized access. The blockchain ledger maintains a transparent record of energy generation, trading, and consumption, allowing all participants to verify transactions without relying on centralized authorities. The use of Web3.py, a Python-based blockchain interface, enables seamless connectivity between Raspberry Pi 4 and Ethereum, ensuring that each transaction is securely executed and validated in real-time. (Figure 3).

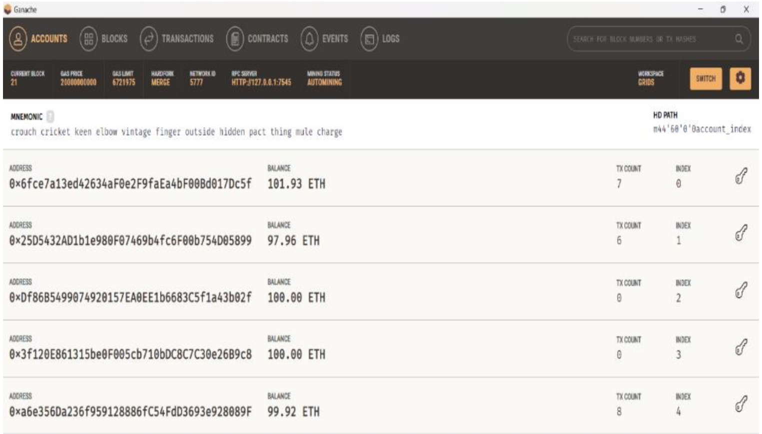

Fig. 3: Ganache.

The core functionality of the blockchain-enabled energy trading system was driven by smart contracts, which were developed, compiled, and deployed using Solidity in Remix IDE. These smart contracts automate the entire trading process, including energy pricing, transaction validation, and ownership transfer, thereby eliminating the need for third-party intermediaries. By embedding predefined conditions into the smart contracts, energy transactions are executed only when specified parameters, such as energy availability and pricing, are met. This self-executing and trustless system enhances grid efficiency, security, and reliability, ensuring a fully decentralized and autonomous peer-to-peer energy trading ecosystem.

3.2.2. Developing the energy sharing mechanism

Automated and decentralized P2P energy trading, the system utilizes Ethereum-based smart contracts developed in Solidity. These smart contracts act as self-executing agreements that regulate energy trading by incorporating secure and transparent exchange protocols. Energy ownership, trade execution, and pricing mechanisms, ensuring fair and efficient transactions between prosumers (energy producers) and consumers (energy buyers). By integrating dynamic pricing algorithms, the smart contracts calculate real-time energy costs based on Ethereum's market value, demand-supply fluctuations, and predefined exchange rates (1 Ethereum = 1 kW). This pricing mechanism ensures that energy trades remain cost-efficient and adaptable to market conditions, enhancing the scalability and economic feasibility of decentralized energy trading networks.

Secure and verifiable ownership transfers, the smart contract implements immutable energy transaction records. Every trade between prosumers and consumers was cryptographically signed and permanently stored on the blockchain, maintaining tamper-proof transaction logs. Once an energy transaction was validated, ownership of the energy unit was securely transferred, and the consumer's Ethereum balance was updated. This trustless and automated framework eliminates the need for third-party intermediaries, significantly reducing transaction costs and settlement delays. The smart contracts enable automated dispute resolution mechanisms, ensuring that all trades are conducted fairly and transparently while maintaining grid stability and optimized energy distribution.

Blockchain transactions with real-time IoT-based energy monitoring, the system utilizes Python middleware for seamless interaction between Raspberry Pi 4 and the Ethereum blockchain. The Web3.py library facilitates a secure connection between the Raspberry Pi 4 and the local Ganache blockchain, enabling efficient smart contract execution and real-time state updates. Custom Python scripts allow the system to query live energy prices, initiate Ethereum-based transactions for purchasing energy, and authenticate ownership transfers. This ensures that energy balances are updated in real time, securely recorded on the blockchain ledger, and readily auditable. By combining IoT, blockchain, and automated smart contract execution, the system achieves a highly scalable, transparent, and secure decentralized energy sharing ecosystem, optimizing renewable energy utilization and economic benefits for prosumers and consumers.

3.2.3. Energy sharing process

The energy sharing process begins with prosumers generating renewable energy using solar panels while IoT-enabled sensors continuously monitor energy output (kWh), voltage, and current in real time. Raspberry Pi 4 functions as the central data acquisition and processing unit, collecting and analysing key energy metrics before securely updating the blockchain-based smart contract with available surplus energy. Once the energy availability is confirmed, prosumers list their excess energy on the blockchain marketplace, where other microgrids or consumers can access and purchase it. The system enables prosumers to interact with the smart contract through a user-friendly graphical user interface (GUI) or command-line interface (CLI), ensuring secure, automated, and transparent transactions without intermediaries.

On the customer side, individuals or microgrids looking to purchase energy can access the decentralized blockchain platform to view the real-time availability of surplus energy from multiple prosumers. The system provides real-time pricing updates, allowing customers to select the desired amount of energy and initiate a smart contract-based transaction. This ensures that every energy exchange is recorded immutably on the blockchain, eliminating fraud and ensuring a trustless energy market. The payment process was handled using Ethereum (ETH) tokens, where the customer securely transfers the required amount of ETH to the smart contract. The smart contract automatically processes the transaction, verifying that the required funds have been received before confirming ownership transfer of the purchased energy units.

The energy exchange process was entirely autonomous and trustless, as Ethereum smart contracts validate and execute the transaction without human intervention. Upon successful verification, ownership of the specified energy amount was transferred from the prosumer to the customer, ensuring real-time settlement. Raspberry Pi 4 receives a blockchain event notification, updating the local energy balance of both the prosumer and customer, maintaining accurate transaction records across the microgrid network. The customer can now access and utilize the purchased energy directly from the prosumer's grid, benefiting from a secure, decentralized, and automated energy trading framework. This system optimizes renewable energy utilization, enhances grid resilience, and democratizes energy access, creating a sustainable and efficient peer-to-peer energy market.

3.2.4. Monitoring and visualization

Seamless monitoring and management of P2P energy trading, an interactive user interface (UI) or web-based dashboard was developed, enabling both prosumers and consumers to track real-time energy transactions, balances, and historical trading data. (Figure 4)

Fig. 4: User Interface.

The UI integrates visual analytics, transaction logs, and predictive insights, allowing users to make informed energy trading decisions based on real-time demand, supply, and pricing trends. By providing an intuitive and interactive experience, the dashboard empowers users to efficiently monitor their energy usage, assess blockchain-based settlements, and optimize energy-sharing strategies. This user-centric approach enhances transparency, usability, and engagement, making decentralized energy trading more accessible and efficient.
The Thing Speak IoT platform was leveraged for real-time energy data visualization, offering comprehensive insights into energy generation, consumption patterns, transaction history, and blockchain-based settlements. (Figure 5)

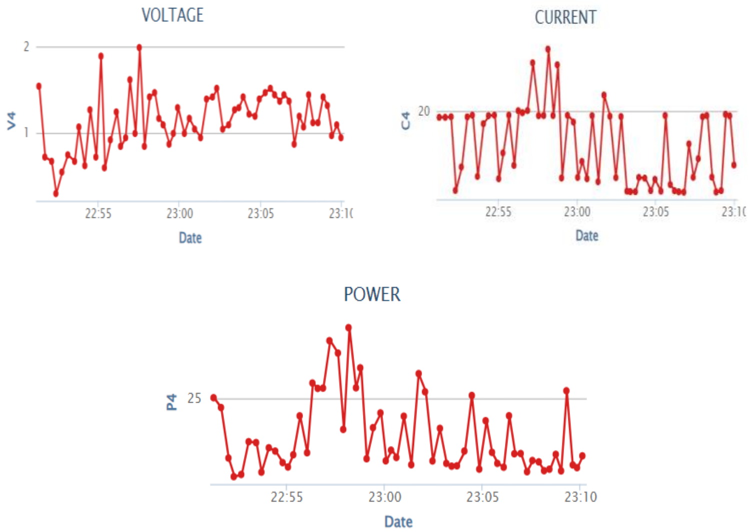

Fig. 5: Visualization of Realtime Energy Data.

The integration of IoT sensors with Raspberry Pi 4 ensures that key energy parameters are continuously monitored and updated on the ThingSpeak cloud platform, enabling dynamic and data-driven decision-making. The system provides customizable energy usage reports and trend analyses, allowing prosumers to adjust energy-sharing preferences, optimize storage utilization, and maximize trading benefits. By visualizing real-time blockchain transactions, the platform ensures that users have a clear, verifiable record of all energy exchanges, promoting trust in the decentralized energy trading framework.
Efficiency, security, and trading accuracy, AI-driven analytics, and anomaly detection are implemented within the monitoring and visualization system. These AI models analyse energy usage patterns, forecast demand-supply fluctuations, and optimize trading strategies to ensure equitable energy distribution and cost-effectiveness. Blockchain-based audit trails guarantee tamper-proof records of all energy transactions, ensuring compliance with regulatory standards and reinforcing trust among stakeholders. This secure, transparent, and AI-enhanced monitoring system ultimately transforms the traditional energy market by empowering users with real-time insights, predictive analytics, and decentralized control over their energy resources.

4. Results

The efficiency of a blockchain-integrated IoT energy management system was largely determined by its ability to acquire, process, and analyse real-time energy data from interconnected solar grids. Raspberry Pi 4 functions as an edge computing device, ensuring low-latency data acquisition from IoT-enabled sensors that measure energy generation, consumption, and storage levels. This real-time data collection was crucial for accurate energy trading and dynamic load balancing, allowing the system to identify surpluses and deficits and trigger automated smart contract transactions accordingly. The integration of ThingSpeak IoT cloud analytics further enhances the efficiency of energy monitoring, enabling predictive modelling and anomaly detection to improve system reliability.

A key factor in the system's operational performance was its blockchain transaction speed, which determines how quickly energy trades are executed. Ethereum smart contracts ensure instantaneous settlements, preventing delays in energy transfers that could disrupt grid stability. Since transactions are executed without human intervention, energy pricing, ownership transfers, and validation processes are fully automated, ensuring a trustless and highly reliable trading ecosystem. The system's smart contract efficiency eliminates traditional bureaucratic approval processes seen in centralized energy markets, providing a frictionless and cost-effective alternative. Tokenized energy pricing models (1 Ethereum = 1 kWh) ensure that energy transactions remain transparent, fair, and adaptable to market demand.

5. Discussion

The proposed blockchain-enabled P2P energy trading system presents a scalable, secure, and decentralized solution for efficient energy sharing among solar-based microgrids. By integrating IoT-based real-time monitoring, Raspberry Pi 4 for edge computing, and Ethereum blockchain with Ganache for transparent transactions, the system empowers prosumers to actively participate in a decentralized energy economy. The implementation of smart contracts automates energy exchanges, enforces trust less transactions, and eliminates third-party intermediaries, ensuring fair pricing, security, and transparency in energy trading. This approach enhances grid resilience, optimizes energy distribution, and promotes the widespread adoption of renewable energy resources, contributing to a sustainable and self-sufficient energy ecosystem.

Table 2: Comparison Framework

Feature	Traditional Centralized Grid	P2P Platforms (Centralized)	Proposed Blockchain System (Python/Ganache)
Architecture & Control	Top-down, utility-controlled. Unidirectional power flow.	Centralized platform (e.g., a company's server) mediates all transactions.	Fully Decentralized. No single intermediary; trust is established by the blockchain and smart contracts.
Role of Prosumer	Passive recipient of net metering policies. Limited market participation.	Active participant, but reliant on and subject to the rules of the platform operator.	Empowered Market Agent. Can set prices, choose trading partners, and engage in direct, automated contracts.
Transaction Transparency	Opaque. Consumers see only a final bill; pricing and energy sources are not granular.	Managed by the platform operator. Participants must trust the operator's records.	Fully Transparent & Auditable. Every trade is immutably recorded on a shared ledger, visible to all permissioned participants.
Transaction Costs	High overhead for metering, billing, and reconciliation is managed by the utility.	Platform fees are typically charged by the operator to maintain their service and profit.	Potentially Lower. Automates metering and settlement, reducing administrative overhead. (Note: Blockchain gas fees are a new cost to optimize.)
Settlement Speed	Monthly or bi-monthly billing cycles.	Can be faster (e.g., daily), but still batch-processed by the central operator.	Near Real-Time. Settlements can be programmed to execute instantly upon fulfillment of smart contract conditions.
Data Security & Integrity	Centralized databases are vulnerable to single-point-of-failure attacks and internal manipulation.	Similar centralized database risks. Privacy depends on the platform's policies.	Inherently Secure. Cryptographic hashing and distributed consensus make records tamper-proof. Users have greater control over their data.
Renewable Energy (RE) Tracking	Relies on cumbersome Renewable Energy Certificate (REC) markets, which are often decoupled from energy flow.	The platform can track and display RE, but this data is managed centrally and requires trust.	Granular & Inseparable Tracking. Each kWh of green energy can be cryptographically tokenized and tracked from its point of generation to consumption, ensuring provenance.
Grid Resilience	Vulnerable to cascading failures. Outages can be widespread.	Does not inherently change the grid architecture.	Enables Microgrids. Provides the transactional layer for communities to form self-sufficient, resilient microgrids that can operate during main grid failures.
Implementation & Maturity	Highly mature, globally deployed.	Emerging, with several successful pilots (e.g., LO3 Energy, Sonnen Community).	Early R&D / Prototype Stage. Our Python/Ganache implementation represents a foundational proof-of-concept, highlighting potential but requiring significant development for mass adoption.

6. Conclusion

The research highlights the transformative potential of emerging technologies, demonstrating how blockchain, IoT, and AI-driven analytics can revolutionize energy management, trading efficiency, and grid optimization. The proposed system ensures real-time tracking of energy generation, consumption, and transactions, enabling dynamic pricing adjustments, predictive analytics, and fraud-resistant energy settlements. By leveraging blockchain's immutability and IoT-enabled automation, this framework addresses key challenges in traditional energy distribution, such as inefficiency, security vulnerabilities, and dependency on centralized power grids.

As the global focus shifts towards sustainability, energy decentralization, and carbon neutrality, solutions like this play a crucial role in shaping the future of energy distribution and management. The successful implementation of this system underscores the feasibility of blockchain-integrated smart microgrids, paving the way for future advancements in decentralized energy networks, AI-driven demand forecasting, and cross-border energy trading. Ultimately, this research lays the foundation for a next-generation, self-sustaining, and community-driven energy infrastructure, accelerating the transition toward a more resilient, efficient, and eco-friendly energy ecosystem.

Acknowledgement

We would like to express our sincere gratitude to the IIT Palakkad Technology IHub Foundation (IPTIF) for their generous financial support and commitment to our blockchain-powered smart meter Project under the IMPACT Program of the IIT Palakkad Technology IHub Foundation (IPTIF). This project would not have been possible without their funding, which has enabled us to achieve significant advancements in energy consumption and monitoring systems.

References

[1] R. Kavin, Dr.J.Jayakumar, "Energy Management System for Distributed Energy Resources using Blockchain Technology" Recent Patents on Engineering, Vol 19, No.1, P.no-93-102 2025. https://doi.org/10.14419/xx1m2155.
[2] R.Kavin, Dr.J.Jayakumar, "Decentralized Renewable Power Generation Using IOT And Blockchain Technology," International Journal of Basic and Applied Sciences, 14 (2) (2025) 319-327. https://doi.org/10.14419/xx1m2155.
[3] F. Alam Khan, M. Asif, A. Ahmad, M. Alharbi, and H. Aljuaid, "Blockchain technology, improvement suggestions, security challenges on smart grid and its application in healthcare for sustainable development", Sustainable Society, vol.55, p. 102018, 2020. https://doi.org/10.1016/j.scs.2020.102018.
[4] Adetomike Adeyemia, Mingyu Yana, Mohammad Shahidehpoura, Cristina Boterob, Alba Valbuena Guerrab, Niroj Gurungb, Liuxi (Calvin) Zhangb, Aleksi Paasob "Blockchain technology applications in power distribution systems" The Electricity Journal Volume 33, Issue 8, October 2020, 106817. https://doi.org/10.1016/j.tej.2020.106817.
[5] Xiaomin Du, Ying Qi, Beibei Chen, Biaoan Shan, and Xinyu Liu "The Integration of Blockchain Technology and Smart Grid: Framework and Application" Hindawi Mathematical Problems in Engineering Volume 2021. https://doi.org/10.1155/2021/9956385.
[6] Ayman Esmat, Martijn de Vos, Yashar Ghiassi-Farrokhfal, Peter Palensky, Dick Epema "A novel decentralized platform for peer-to-peer energy trading market with blockchain technology" Applied Energy 116123, 2021. https://doi.org/10.1016/j.apenergy.2020.116123.
[7] Shuguo Chen, Weibin Ding, Zhongzheng Xiang and Yuanyuan Liu "Distributed Power Trading System Based on Blockchain Technology" Hindawi Complexity Volume 2021. https://doi.org/10.1155/2021/5538195.
[8] A.M. Asfar, "Blockchain implementation using smart grid-based smart city", In: Handbook of Research on Blockchain Technology, vol. 44. 2021, pp. 4666-4670. https://doi.org/10.1016/j.matpr.2020.11.013.
[9] K.T. Manish, "Emergence of blockchain-technology application in peer-to-peer electrical-energy trading: A review", Clean Energy, vol. 5, no. 1, pp. 104-123, 2021. https://doi.org/10.1093/ce/zkaa033.
[10] D. Oliver, M. Bessie, and S. Lindokhuhle, "Proposed framework for blockchain technology in a decentralised energy network", Protection and Control of Modern Power Systems., vol. 6, p. 3, 2021. https://doi.org/10.1186/s41601-021-00209-8.
[11] H.A. Arezoo, M.H. Seyed, M. Bisheh-Niasar, M. Shafie-khah, and A. Hasan, "Blockchain technology in the future smart grids: A comprehensive review and frameworks", International Journal of Electrical Power and Energy Systems, vol. 129, p. 106811, 2021. https://doi.org/10.1016/j.ijepes.2021.106811.
[12] A. Kavousi-Fard, A. Abdulaziz, A. Al-Sumaiti, A. Farughian, and S. Alyami, "An effective secured peer-to-peer energy market based on blockchain architecture for the interconnected microgrid and smart grid", International Journal of Electrical Power and Energy Systems, vol. 132, p. 107171, 2021. https://doi.org/10.1016/j.ijepes.2021.107171.
[13] Charithri Yapa "Survey on blockchain for future smart grids: Technical aspects, applications, integration challenges and future research", Energy Reports., vol. 7, pp. 6530-6564, 2021. https://doi.org/10.1016/j.egyr.2021.09.112.
[14] B. Francesco, L. Gianluca, M. Lorenzo, and R. Antonia, "An Ethereum-based solution for energy trading in smart grids", Digital
[15] Communication Networks., vol. 9, no. 1, pp. 194-202, 2021.
[16] H. Li, F. Xiao, L. Yin, and F. Wu, "Application of blockchain technology in energy trading: A review", Frontiers in Energy Research., vol. 9, p. 671133, 2021. https://doi.org/10.3389/fenrg.2021.671133.
[17] P. Harshal, S. Shilpa, and R. Linesh, "Study of blockchain based smart grid for energy optimization", Materials Today: Proceedings., vol. 44, no. 4666-4670 2021. https://doi.org/10.1016/j.matpr.2020.11.013.
[18] A.G.A. Anak, and H. Rini, "Blockchain for smart grid", Journal of King Saud University-Computer and Informatic Sciences., vol. 34, no. 3, pp. 666-6675, 2022. https://doi.org/10.1016/j.jksuci.2020.01.002.
[19] X. Wang, F. Yao, and F. Wen, "Applications of blockchain technology in modern power systems: A brief survey", Energies., vol. 15, p. 4516, 2022. https://doi.org/10.3390/en15134516.
[20] S. Cantillo-Luna, R. Moreno-Chuquen, and R.C. Harold, "Blockchain for distributed energy resources management and integration", IEEE Access, vol. 10, pp. 68598-68617, 2022. https://doi.org/10.1109/ACCESS.2022.3184704.
[21] M.K. Hasan, A. Alkhalifah, S. Islam, and N.B.M. Babiker, "Blockchain technology on smart grid, energy trading, and big data: Security issues, challenges, and recommendations", Wireless. Communication. Mobile. Computing., vol. 2022. https://doi.org/10.1155/2022/9065768.
[22] Oskar Juszczyk, and Khuram Shahzad "Blockchain Technology for Renewable Energy: Principles, Applications and Prospects" 2022, 15, 4603. https://doi.org/10.3390/en15134603.
[23] Md Mahraj Murshalin AI Moti "Blockchain Based Smart-Grid Stackelberg Model for Electricity Trading and Price Forecasting Using Reinforcement Learning" Applied Sciences 2022
[24] Mirza Jabbar Aziz Baig "Blockchain based Peer to Peer Energy Trading System Using Open-Source Angular Framework and Hypertext Transfer Protocol" Electronics, 2023
[25] Manmmet Singh "BSEMS-A Blockchain-Based Smart Energy Measurement System" Sensors 2023. https://doi.org/10.3390/s23198086.
[26] Ziqiang Xu "Blockchain-Based Malicious Behaviour Management Scheme for Smart Grids" Smart Cities 2023. https://doi.org/10.1155/2023/5794002.