Journal of the Ghana Institution of Engineering (2024) 24:3
https//doi.org/10.56049/jghie.v24i3.173

ORIGINAL RESEARCH

# Decentralized energy trading systems for microgrids using blockchain and smart contract technologies

Ernest O. Ezugwu[1], Samuel O. Okozi[1], Okonkwo S. Hilary[1], Edet G. Godwin[1], Ezekiel G. Nwibo[1], Kufre E. Jack[2,*]

**Received:** 17th January, 2024 / **Accepted:** 29th October, 2024
**Published online:** 5th December, 2024

## Abstract

Blockchain technology, smart contract and microgrid systems have facilitated innovations and breakthroughs in the electricity industry. The once bundled electricity market dominated by a few key players is now gradually becoming unbundled to a more consumer-centric market due to these new technologies. To facilitate the use of community microgrids, this study develops a new trend in peer-to-peer energy trading. In this work, a model for a smart microgrid system, a decentralized energy trading platform based on blockchain, and smart contract technologies is proposed, considering an islanded community microgrid network of energy prosumers. Smart meters were used to ensure the bi-directional flow of data and power, thereby giving prosumers control over their power usage. Storage and validation of participants' data are stored on the blockchain network, which has a strong feature of decentralization, transparency, security and data immutability. The smart contract automatically executes power delivery and transfer of tokens from the buyer's wallet to the seller's energy wallet based on the transaction logic and protocol. A web-user interface was designed to enable the ease of transactions by market participants and the web-user interface was designed on React.Javascript while the smart contract codes were done on the solidity programming language. Algorithms were also developed for the market trade operations in real time and sets of mathematical equations were formulated for energy pricing based on the supply and demand philosophies to curtail over-pricing and underpricing of energy.

**Keywords:** Energy Management, Peer-to-Peer, Energy Trading, Blockchain, Smart Microgrid

## Introduction

With the increasing energy crisis and environmental issues, the renewable energy are considered a potential solution to realizing energy sustainability and a cleaner climate. For many years now, nations have continued to improve their energy policies to bring about the integration of Renewable Energy Sources (RESs) into their power systems to reduce fossil fuel consumption and embrace a cleaner and more sustainable energy system in both small and large-scale systems (Chanchangi *et al.*, 2022).

The traditional grid network was a centralized scheme in which energy/data flow was vertically unidirectional: generation; transmission; distribution and consumption (Zhou *et al.*, 2025). For centralized power system network, the whole system is linked together into a large grid, forming a complex network therefore leading to operational difficulties, high energy costs, environmental pollution, insecurity, inefficiency and energy unreliability (Omaji *et al.*, 2020).

In the current power system network, energy generation is centralized with a unidirectional power delivery system, implying that power is generated in bulk at the generating stations, transmitted through a transmission and distribution network and then delivered to end consumers (Sayed *et al.*, 2019). These stages are illustrated in Fig. 1. In a traditional power system network, electric power is generated by the rotation of turbines at the power plants mainly using hydro,

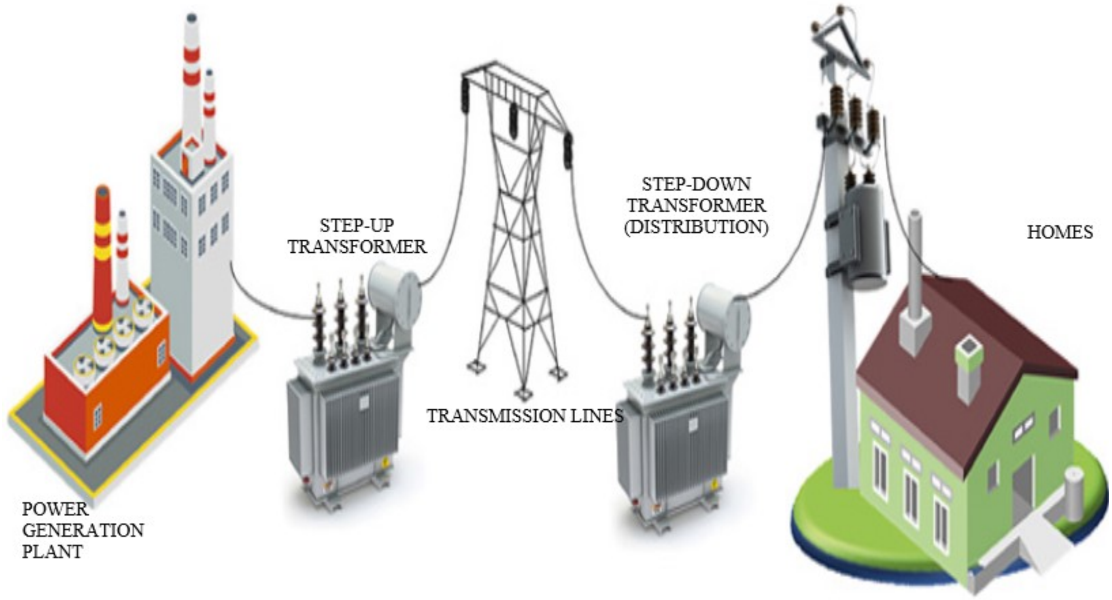


**Figure 1** Basic conventional power system network

coal, steam, nuclear etc. The pressure steam produced by boiling water with coal in massive boilers rotates turbines in most power plants (Bascom *et al.,* 2024).

The introduction of the distributed energy generation concept and more specifically, distributed energy resources (DER) results in the emergence of new energy individuals called energy prosumers and these are those who produce and consume energy at the same time. However, the development

*Corresponding author: kufre@futminna.edu.ng

[1]Department of Electrical/Electronic Engineering, School of Electrical System Engineering Technology, Federal University of Technology, Owerri, Imo State, Nigeria.

[2]Department of Mechatronics Engineering, School of Electrical Engineering and Technology, Federal University of Technology, Minna, Niger State, Nigeria.

*ISSN: 0855-0743/©GhIE 2024. All rights reserved*

of smart grids has made power systems more intelligent, and capable of communicating with adjacent systems (Beghi *et al*., 2012). Automated monitoring, data collection, information technologies, and processing systems in the smart grid are used to optimise power grid function and intelligently manage its various equipment. This results in increased energy efficiency, reduced infrastructure for energy production and transmission, and optimised equipment size (Mohammadi-Ivatloo and Jabari, 2018).

The growing number of distributed power generation and renewable energy sources gives rise to a new emerging electricity market in which prosumers and consumers can trade produced energy locally unlike traditionally where prosumers transact only with the energy network distributors (Zhou *et al*., 2015). Thus, the major challenge facing the integration of renewable energy generation at the distribution level is the lack of motivation on the side of the prosumers to feed-in their excess energy to the network because of the less pay it receives from the energy distributors as against the price paid for power consumption (Suthar and Pindoriya 2020). In recent times, the power grid network has undergone revolutionary transition to a decentralized, sustainable and intelligent system involving the creation of microgrids (Barakhtenko and Mayorov, 2023).

The conversion of bulk, one-way energy into distributed, multidirectional flows, or multilane highways, is known as decentralization (Lo and Ansari, 2013). A decentralised energy system minimises the use of fossil fuels and promotes environmental friendliness by placing energy producing facilities close to the region of energy consumption. It also enables more efficient use of renewable energy. There are numerous environmental and security advantages to the decentralised electric grid. Prior to this, the construction of massive central power plants and the delivery of the generated electricity to local users via extensive transmission and distribution networks were the main priorities of the power sector (Bascom *et al*., 2014). The goal of this system is to move power sources closer to the final consumer. Since the end consumers in this case are dispersed throughout an area, sourcing energy generation in a similarly decentralised manner can lower the associated economic and environmental costs as well as transmission and distribution inefficiencies.

Both the centralised energy trading system and the consumer-to-energy distributor trading can be replaced by peer -to-peer (P2P) energy trading through blockchain technology. A new generation trend in energy management is peer-to-peer energy trading, which enables prosumers to trade their excess energy. By allowing them to trade energy with their peers and creating new marketplaces for power systems, this has altered how energy consumers use their energy (Wongthongtham *et al*., 2020). The creation of such local markets provides the conditions for consumer active participation in electric energy trade operations thereby leading to the promotion of electricity cost reduction using renewable energy sources by the market participants (Perekalskiy *et al*., 2020). In summary, this study aims to create a decentralised, safe, and open energy trading system that promotes active consumer participation, empowering consumers in the energy industry and boosting energy independence.

To ensure energy security, reliability, sustainability and transparency of all energy transactions in a local P2P energy market, Blockchain technology can be deployed. Blockchain of recent has attracted significant attention not only in the financial sector but also in academics and the energy sector and has been applied in almost all fields, particularly in energy trading (Perekalskiy *et al*.,2020). Peer-to-peer networks are utilised by blockchain, a distributed ledger system, to store data and transactions. An open ledger that records all online transactions and permits users to connect, send, or verify transactions is a different way to think of blockchain. (Pee *et al.,*2019). In other words, Blockchain is a digitized system of accounting records based on a set of mathematical rules which record in detail all transactions to prevent illegal interference (Nguyen, 2016).

Blockchain can be thought of as the next digital revolution and has the potential for enormous impact just like the internet (Tatar and Burniske, 2018), (Kakavand *et al.,* 2017). The adoption of Blockchain technology for P2P energy trading has enabled a transition from the traditional centralized electricity market dominated by a few key players to a more decentralized market controlled by microgrids (Wongthongtham *et al*., 2020). Blockchain-based P2P energy trading enhances mutually beneficial transactions by enabling prosumers to sell their excess electricity to nearby customers directly, without the requirement for electricity merchants. The main advantage of this suggested approach is that consumers could pay less per kWh because batteries can be used to store untraded electricity, which would result in auctions for renewable electricity and create a market that benefits both consumers and prosumers. Prosumers would also earn more than they would through feed-in tariffs (Wongthongtham *et al.,* 2020).

In this paper, a P2P energy trading platform within a locality using blockchain model is proposed. This model is

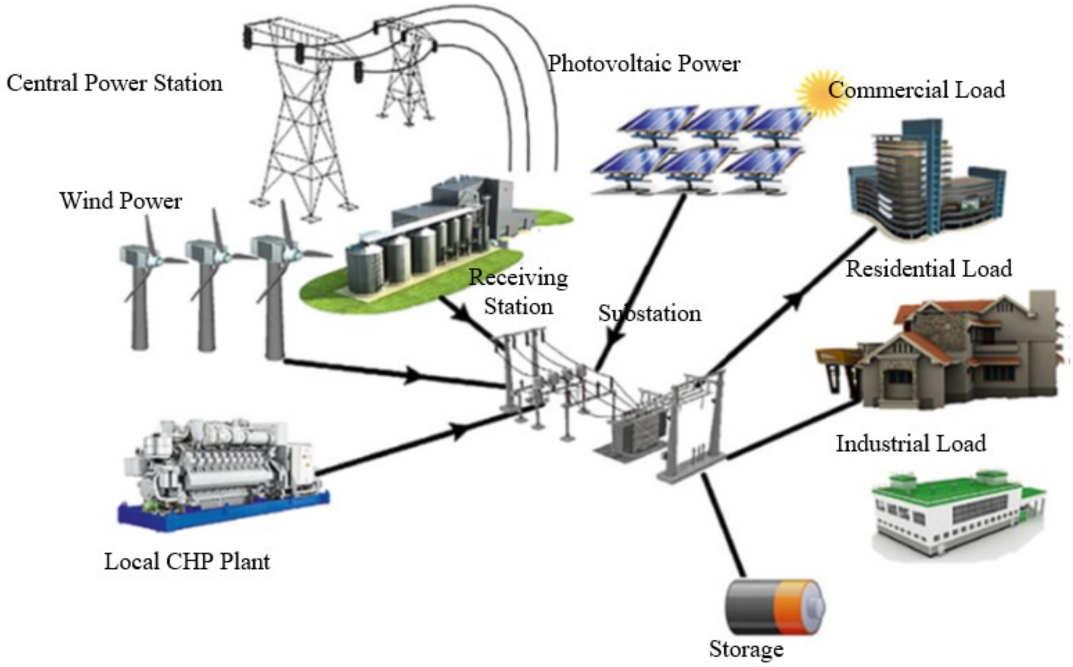


**Figure 2** Distributed energy resources paradigm in smart grid

made up of different nodes with each representing an individual/household or organization in a blockchain that can act as an energy prosumer with the ability to produce, sell and purchase energy, and can also trade energy through the P2P network without going through an energy intermediary and smart meter are connected to all the nodes. The smart meter serves to control all operations of receipt or transmission of electric power from the prosumers by analyzing the flow of energy thereby ensuring all switching operations based on the data flow of power (Perekalskiy *et al.,*2020). The prosumer covers the power needs with renewable energy sources, this is to say that its device is powered by what is generated around its domain. Detection of lack of power on any node triggers it to request for the purchase of energy from the network and ensures its receipt. A node in excess of energy are triggered to enter the network and sell the excess energy generated. Hence, a smart meter provides a bi-directional flow of energy between the participants and network (Perekalskiy *et al.,*2020).

The proposed model also incorporates smart contract algorithms that facilitate energy transactions based on predefined terms which are recorded on the smart meters. A smart contract was proposed in 1994 by An American scientist by name Nick Szabo and it was defined as a computerized transaction protocol that executes the terms of a contract (Sanitt, 2018). Smart contracts are self-enforced and does not require the involvement of a third party or mediator for its execution. An algorithm was also developed for trade operations based on the concept of energy supply and demand by means of pooling. Also, an interactive user-interface was developed using typescript and Solidity Programming Language to enable trade among the network participants. Long distance transmission line losses are avoided in this mode of arrangement and once organized in a web of smart microgrids, its design improves supply stability and reliability, and users are given more control (Smil, 2019). Microgrids coordinated with distributed energy generation gives systems with significantly enhanced grid efficiency and reliability (Refaat *et al.,* 2021). Decentralization of power generation enhances the reduction of power outages for critical facilities like hospitals or schools or any other facility in need of continuous power supply. Renewable Energy sources are preferable in this new approach; thus, decentralized grids are more energy-efficient than centralized grids (Alok and Mishra, 2016). The three main components of a decentralised energy system are demand response, energy storage, and distributed generation.

In a decentralised energy system, distributed generation is the primary characteristic. It is sometimes referred to as decentralised generation, embedded generation, distributed generation, or on-site generation. Distributed Energy Resources (DERs) are defined as small-scale decentralized power generation sites as shown in Figure 2 (Eskandari *et al*. 2020). DER systems are flexible and modular, usually located within the vicinity of the load. Renewable energy sources such as biomass, small hydro, solar, wind and geothermal are being utilized by DER systems. Smart grid can be deployed for the coordination and the controlling of such system. A bidirectional flow of power through the grid can be achieved using the distributed generation (Eskandari *et al.* 2020) . Potential benefits to the electric grid such as energy efficiency improvement, energy security enhancement and faster recovery of electricity services can be achieved using DERs (Refaat *et al.*, 2021).

A major drawback in the distribution of electricity has been the storage and generation of the needed amount of electrical energy. In a decentralized system, the addition of more generation sources has led to the difficulty of controlling supply to best match demand. Energy Storage Systems are essential technology used for obtaining effective utilization of renewable energy while ensuring continuous energy supply and grid support (Refaat *et al.,* 2021). These provide a settlement path to an end of disruptive electricity supply and to the peaks and valleys of supply. ESS is combined with advanced power electronics as the interface with the electrical grid (Barakhtenko and Mayorov, 2023). These can be installed at various number of points on and off the grid. Effective Storage System depends on storing and discharging electricity at the required time in such a way that relies on automatic and clear pricing signals transmitted to the smart storage systems. Solutions to challenges like power congestion at the distribution level, excess energy production at peak hours are being provided by the Energy Storage systems. Distributed Energy Storage System can be shown in Fig. 3.

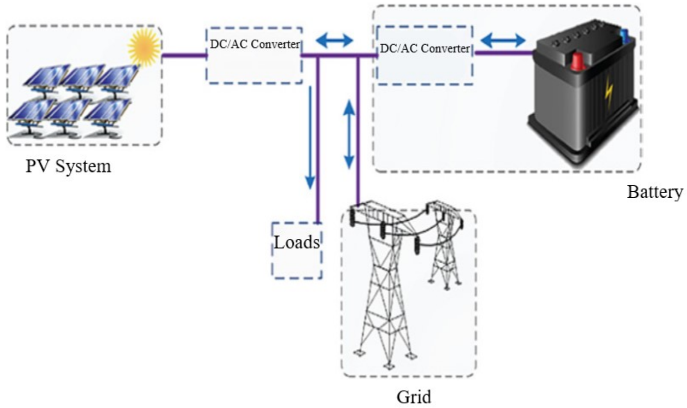


**Figure 3** Distributed energy storage system

If a buyer and a prosumer agree to transfer the penalty for deviating from the specified amount of power, the contract will automatically transfer the penalty to the buyer's account and record the transaction on the blockchain. As a result, the parties involved determine what words should be included in the smart contract; the final terms are then translated into computer programs using a particular programming language. A high-level object-oriented programming language with functions of state variables, events, declarations, modifiers etc. such as Solidity Programming language are used in Smart contract projects. Fig. 4 illustrates the complete life cycle of a smart contract with its explanation (Zheng *et al*., 2020).

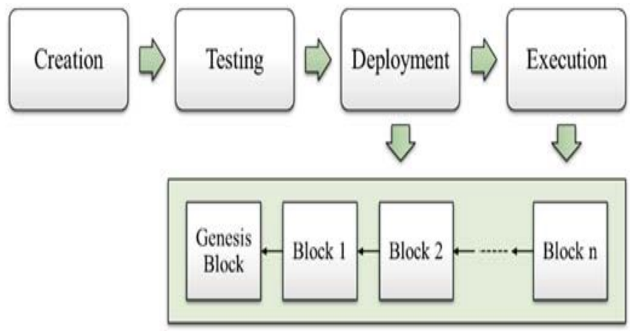


**Figure 4** Life cycle of a smart contract

The first step in this model is the formation of a smart contract, after which the parties and stakeholders concerned decide on the terms, limitations, clauses, and statements that will be included. It is transformed into a deployable computer program by a software engineer. Because the contract cannot be changed once it is deployed, it can be emulated on a blockchain network prior to its actual deployment. The bitcoin provided exclusively for testing is used to verify responses of the functionalities specified in the contract. A contract account is created, and the contract is saved on the blockchain upon successful validation. The deployed contract is accessible from every network node. During the contract's execution phase, the nodes can send messages, conduct transactions, or invoke the functionalities it provides. After the contract is successfully executed, digital assets are moved to the relevant accounts,

**Figure 5** Monocrystalline solar PV array

**Figure 6** Smart metering device (Ramón and Carou Álvarez, 2023)

state variables are modified, and the transaction is stored on the blockchain.

In a smart microgrid, loads and generators interact automatically in real time, giving users a significant say in how best to run the entire grid (Vahid-Ghavide *et al*., 2020). Over time, demand response improves the energy consumption profile by ensuring short-term load response. Smart grid (SG) plays a critical role in enabling the overall electric power sector objectives. The general goals of SG are to ensure the delivery of electric energy in an efficient, sustainable, resilient, and environmentally friendly manner (Refaat *et al.,* 2021).

The electricity market has for long been a solely centralized system, a one-way communication system with a single line transactional activity. Research efforts are currently ongoing on the decentralization of this market to a more flexible and consumer-centred system through modern technologies. Therefore, the justification for this paper on "Decentralized Energy Trading Systems for Microgrids Using Blockchain and Smart Contract Technologies" Following the current research trends in the electricity market, this paper develops a new trading pattern that facilitates the peer-to-peer energy trading systems for a community microgrid. It proposes a novel model for a decentralized energy trading platform deployed on the blockchain and smart contracts technologies for a stand-alone community microgrid (smart microgrid system) with due considerations for consumers and prosumers.

## Methodology

The approach utilized in this research work is a quantitative design, analysis and simulation aimed at providing a peer-to-peer energy trading platform based on blockchain technology within a local community of network participants. The methods are organized as follows: proposed model description, the energy market mode of operation, and description of the web-user interface. For the design, analysis, simulation and implementation of the proposed model decentralized energy trading system based on blockchain and smart microgrid technology, the following items are required: Solar Photovoltaic Modules; Inverters; Energy Storage Systems like Lithium-ion Batteries; Smart Meters; Smart Microgrid Controller/network; ETAP Simulation Software; Visual Studio Code; Web User Interface built on React and JavaScript programming languages and Smart Contract built on Solidity programming language.

### Solar photovoltaic modules

The solar voltaic modules convert the light energy captured from the sun into electric energy. Energy produced from the modules are used for residential and commercial loads. In the

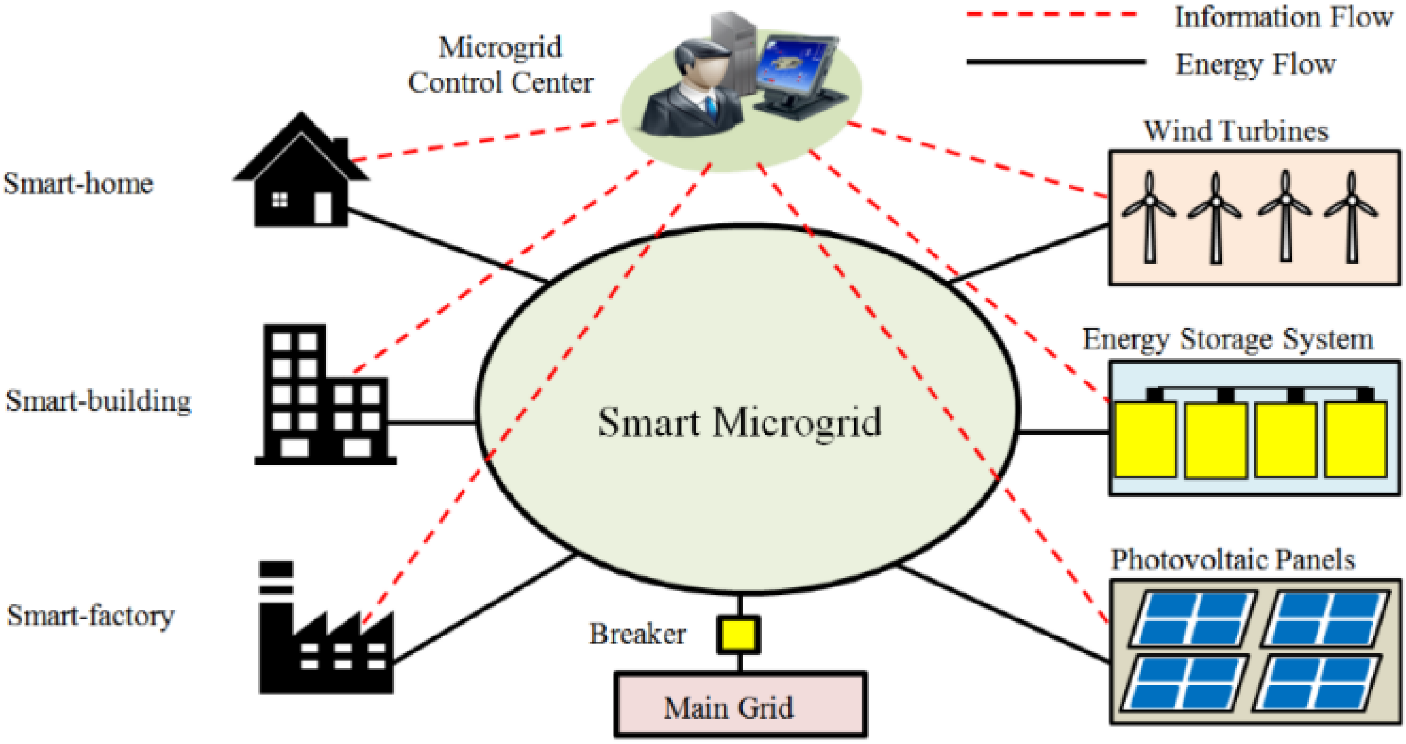


**Figure 7** Smart microgrid network with microgrid control center

proposed model, solar PV modules are used as source of distributed energy generation by the energy prosumers in the network. For efficiency and maximum utilization of renewable energy, monocrystalline solar PV cells are used in the PV array in Fig. 5.

***Inverters***

The primary function of an inverter, one of the most crucial components of a solar energy system, is to convert direct current (DC) electricity produced by solar photovoltaic arrays into alternating current (AC) for use by residential and commercial loads. Essentially, the inverter accomplishes DC-to -AC conversion by quickly changing the direction of a DC input, turning a DC.

***Energy storage system (ESS)***

Capturing energy produced at one point in time for use at a later time is the process of an energy storage system that reduces the imbalance between energy supply and demand. Any device that stores energy is referred to as an accumulator or battery. The process of converting energy from difficult-to-store forms to more manageable ones is known as energy storage. Lithium-ion batteries are the most effective battery type for use in an off-grid solar PV system, notwithstanding their high cost.

**Smart meter**

A two-way communication device like smart meters aids in building a link between the utilities and the end user. Smart meters, as opposed to conventional ones, have real-time sensor functionality, power outage notification, and power quality monitoring. Digitally operating smart meters allow for automatic and intricate data exchanges between utilities and customers.

***Smart microgrid/network***

The battery energy storage system, solar panels, and other generation assets are coordinated by the microgrid controller. Since there are no backup grid link in this setup, the Microgrid Controller runs all storage and generating assets concurrently as necessary to match energy demand with production as in Fig. 7.

**Etap simulation software**

Electrical transient analyzer program (etap) is an analytical engineering tool used by power systems engineers for the simulation, design, monitoring, control, operator training, optimizing and automation of power systems. the smart microgrid network in the proposed model is simulated using the etap.

**Web user interface**

A web-user interface was developed using React JavaScript library, it enables the ease of energy trading among the network participants. The sell and purchase options can be used by logged-in users to add requests for selling and purchasing power, respectively.

***Smart contract***

The business logic for blockchain transactions is stored in the smart contract which is the backend of the Web programmed in solidity programming language. The community manager chooses the criteria and reasoning to be included in a smart contract deploys, the contract to the blockchain network and creates a contract for decentralized energy trading. The contract is given a specific address and a wallet to hold cryptocurrency after a successful deployment. Additionally, it becomes immutable once distributed on the network because it cannot be changed. The decentralized energy trading platform described in this paper provides features for adding power-selling and power-buying requests, managing deviations, confirming power supply, and transferring money to and from the contract.

**The proposed model description**

The market model proposed incorporates the idea of smart contracts and recommends setting up blockchain nodes for each link to the electrical network in Fig. 8. Consumers will use intelligent metering devices (smart meters) as these nodes. A Seller is an entity that can consume and generate electricity. Each seller has his or her own means of generating electricity, such as using renewable energy sources, specifically a solar PV system.

A smart meter is installed at each node, and it will analyze power flows to regulate all transmission and reception operations of electric energy from sellers. All switching operations based on the data flow of power are also ensured by the smart meter. Once shortage of power is being detected by the smart meter for a particular node (household or network participant), notification are sent to the user's mobile device requesting for the purchase of power from the market and once authorized by the user, the smart meter makes a request for the purchase of power from the network and ensure its receipt provided that the user has enough tokens for the equivalent power purchase in his wallet.

Similarly, once the energy demand of the network participant are met by his own generation and thus, excess energy is being produced, the smart meter notifies the user as well through the mobile device and upon permission enters the market and sell the excess energy and the token is being saved in the user's wallet. The user can also make request for the purchase and sales of energy through the website.

The main function of the smart meter in this model is the provision of the bi-directional flow of energy and data between the buyer and the seller (Energy Prosumers) and information flow in the network. Fig. 8 shows a description of the proposed model, all the network participants are connected to Ethereum blockchain and, within every household is a smart meter that provides bi-directional flow of energy and information. All the network participants must be within the same vicinity. The model was built on Ethereum network using solidity programming language because Ethereum is a smart contract project. Given $P_G$ as the current generated power, $S_C$ as Storage Capacity, $P_{Req}$ as the Power consumption required, $P_{max}$ as the transmittable maximum Power, $P_d$ as the Power demand of the nodes, and T as time in seconds, the power demand required by each node can be calculated using equation 1:

$$P_d = (P_G \text{ x } T) - (P_{Req} \text{ x } T) + S_c P_d \leq P_{max} \quad (1)$$

For every value of positive $P_d$ at a particular time period T, the smart meter sends a notification to the mobile device of the user for a request to sell energy to the network. If request is granted by the user, the smart meter automatically sells energy to the network and ensures the credit of token to the seller's wallet and also the delivery of Power from the seller's energy storage system to the buyer. Also, for every negative value of $P_d$ at a time period T, the smart meter notifies the user for a request to purchase energy from the network and if granted, the smart meter makes purchase of the required power demand provided the amount of token in the user's wallet is enough for the transaction. Automatic buying and selling of energy in the network when excess or deficient energy is detected by the smart meter can also be carried out without permission of the user depending on the preferred settings of the smart meter. Figure 9 shows the algorithm for the proposed model Stages involved in decentralized energy Trading market includes:

***Smart contract implementation***

The business logic for transactions on the blockchain is stored in the smart contract. A smart contract for decentralized energy trading is created by the community manager, who also selects what conditions and logic to include in the contract before deploying it to the blockchain network. A unique address and token wallet are given to the contract after a successful deployment. Additionally, because it cannot be changed after it is deployed on the network, it becomes immutable.

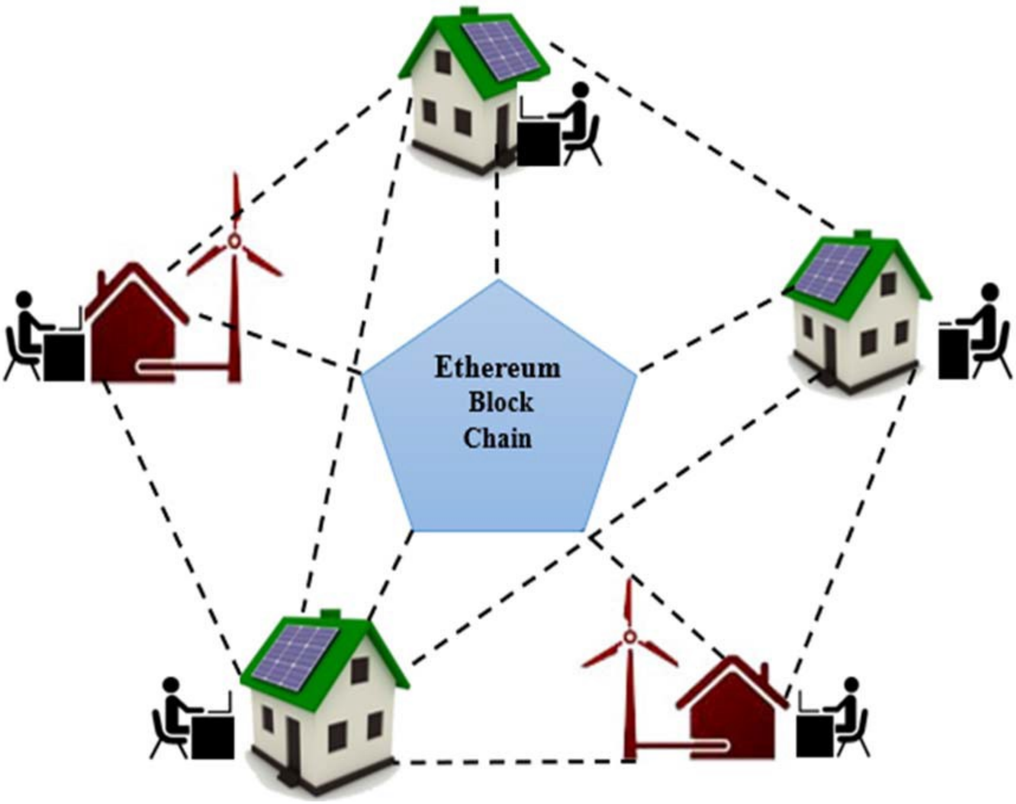


**Figure 8** Illustration diagram of the proposed model

***Power sell request by a prosumer***
The network participants with surplus power trade intention can initiate selling request by executing the power selling function of the contract. Information such as price, quantity and time delivery of power are also provided by the seller through the help of the smart meter. All requests are kept on the blockchain and can be accessed using smart contract

***Consumer makes a power purchase request***
Consumers interested in purchasing power can choose from the power selling requests submitted. Buying request once initiated by specifying the quantity of power required, a certain amount of cryptocurrency is being requested from the consumer to facilitate the transaction. The energy and network usage charges are included in the amount. The amount is automatically deducted from the consumer's wallet. Details of the trade are stored on the blockchain, and the respected power selling option is updated in order to avoid multiple requests for already traded power.

***Delivery of power***
Power is injected into the network by the seller within the timeframe and quantity negotiated with the consumer. Within same timeframe, the readings of the smart meter of both the prosumer and the consumer are validated and stored on the blockchain, the time-window readings at the end are also stored on the blockchain.

***Power delivery verification***
A function on the contract that ensures the delivery of power based on the agreed trade between the prosumer and the consumer is being carried out by the community manager. The smart meter readings of both the prosumer and the consumer are being accessed from the blockchain. The deviation between

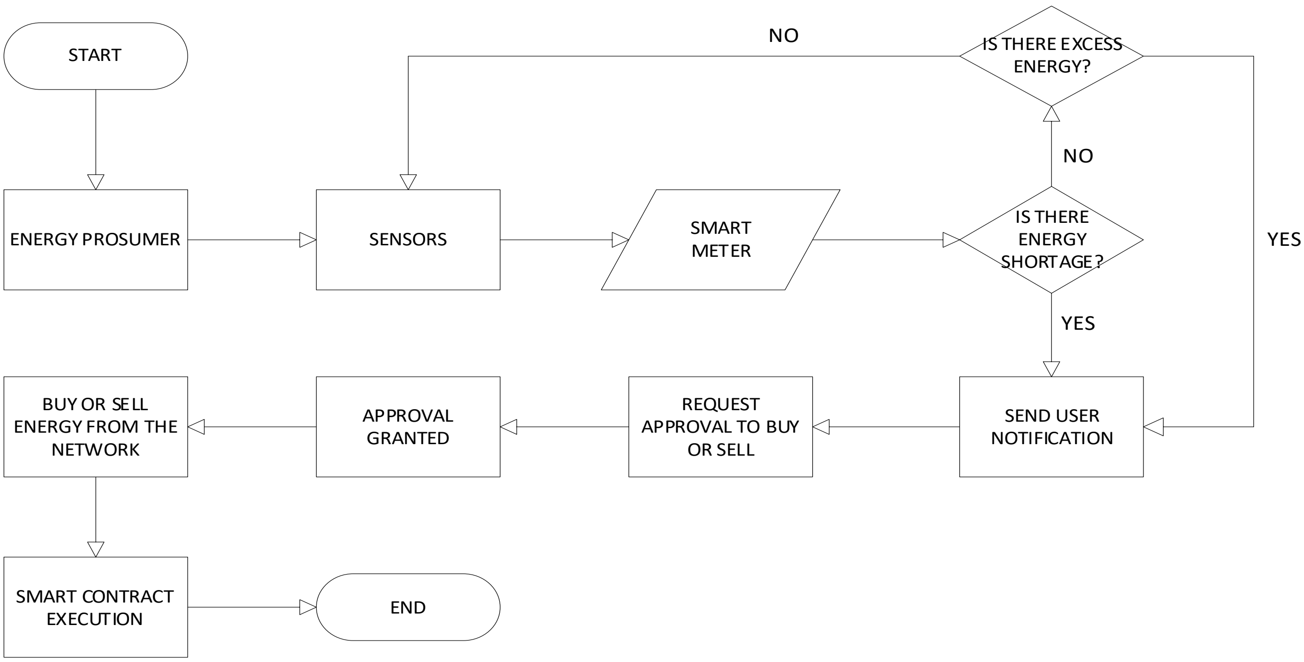


**Figure 9** Algorithm of the proposed model

the start and end of timeframe is calculated and compared with the power quantity of the trade details. A match in both quantities will lead to the execution of token settlement.

***Token transfer***
This entails the transfer of tokens in the form of cryptocurrency already deposited in the wallet of the consumer to the wallet address of the prosumer. After successful validation of delivery of power, the token is transferred to the prosumer's account after network charges have been deducted. The Smart Contract marks the transaction as completed and stores it in the blockchain for future purpose. Fig. 10 shows the steps involved in the decentralized Market model

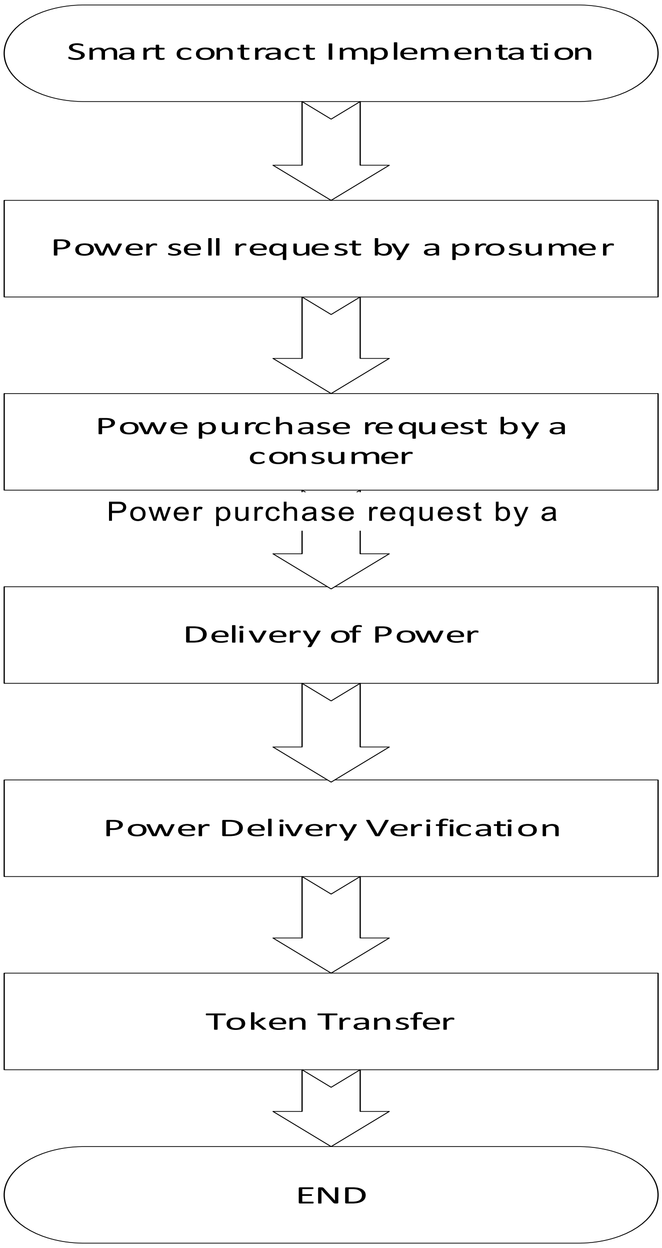


**Figure 10** Steps involved in a decentralized market model

**Development of price mechanism for the model**
Prosumer's extensive involvement in P2P trading and the impending benefits depend exclusively on the financing transactions among the participating sellers and buyers in the network. Hence, a need for an innovative pricing scheme is required in the decentralized energy trading system. The main aim of the pricing scheme is to effectively eliminate overpricing and underpricing at every point in time in the system leveraging on the concept of energy supply and demand. The Smart Contract makes provision for buying of electricity from a temporarily formed pool of Nodes (Prosumers) with excess energy, hence, the power available for meeting the household demands over a time period t. If $C_{i\,buy}$ denote the cost of purchase of power, $S_{i\,sell}$ denote the surplus power for sell, and $P_{i\,sell}$ denote the available power covering the household demand over the time period t, then the unique price for each seller's contract can be calculated as:

$$P_{i\,sell}\, S_{i\,sell} = \text{Generation Cost} + \mu . C_{i\,buy} \quad (2)$$

Where μ denotes the number of customers. From Eq. 2, it can be observed that an increase in the number of interested buyers leads to a corresponding increase in the selling price. Similarly for buyers, the estimated price can be calculated as:

$$P_{r\,sell}\, S_{i\,sell} = Consumer\ Price - \varepsilon . S_{i\,sell} \quad (3)$$

From Eqn. (3), the variable ε shows that more sellers in the pool will lead to a corresponding decrease in the price of energy. Hence, it can be deduced from Eqn. (2) and Eqn. (3) that more supply of energy in the network will lead to lesser price while more demand of energy maybe during summer and rainy periods will lead to higher price of power, thus, the trading mechanism is balanced.

**Proposed energy trading framework with functionalities**
The components of the proposed energy trading framework are as explained in Fig. 11 where:

i. Seller: Represents the entity that generates excess energy, such as a solar panel owner or a wind farm operator.
ii. Smart Meter: Monitors and records energy generation and consumption data. It interacts with both the seller and the buyer.
iii. Buyer: Represents the entity that wants to purchase energy, which can be a residential consumer or a commercial establishment.
iv. Energy Generation Data: The data about the amount of energy generated by the seller's energy source, measured by the smart meter.
v. Energy Consumption Data: The data about the amount of energy consumed by the buyer, measured by the smart meter.
vi. Request to Sell Energy: The procedure begins when the seller declares their intention to sell extra energy.
vii. Smart Contract Creation: A smart contract is created based on the seller's offer and buyer's acceptance. The contract contains predefined rules for energy trading.
viii. Validate and Sign Smart Contract: Both parties verify and agree to the terms of the smart contract and digitally sign it.
ix. Energy Production: The seller starts generating energy from their energy source.
x. Energy Consumption: The buyer consumes the purchased energy.
xi. Energy Payment: The buyer makes the payment for the purchased energy.
xii. Payment Verification: The smart meter or another entity verifies the payment.
xiii. Smart Contract Execution: Upon payment verification, the smart contract executes, and the energy transfer occurs.
xiv. Energy Delivery: The smart meter ensures that the correct amount of energy is delivered to the buyer.
xv. Energy Trading Completion: The energy trading process is completed successfully.

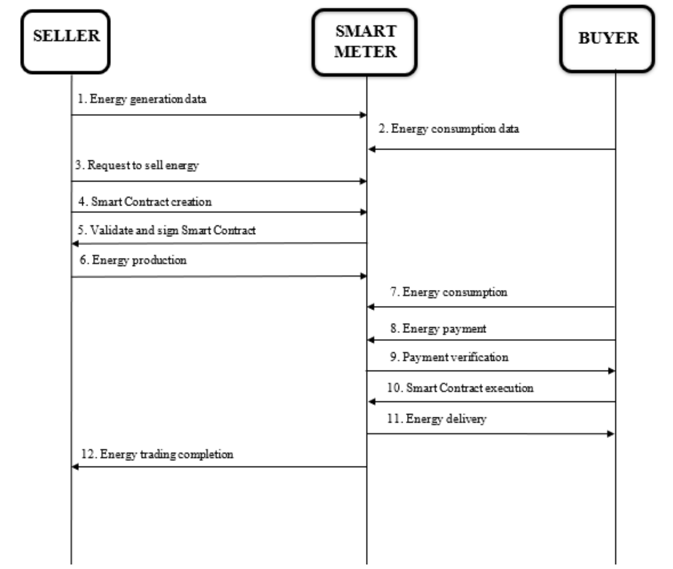


**Figure 11** Energy trading framework for the system

**Smart contract and the functionalities of the setup**

The Smart contract provides the back-end of the framework, a very high-level programming language called Solidity was used for this purpose as illustrated below. The smart contract includes functions for creating and cancelling energy offers, purchasing energy, retrieving offer details, and withdrawing the contract's balance. The contract uses a struct EnergyOffer to store information about each offer, and an array energyOffers to keep track of all active offers. The contract owner can also withdraw the contract's balance. The individual components of the smart contract model describe its functions; thus:

i. addEnergyToBalance: Energy producers (sellers) can call this function to add their excess energy to their balance within the smart contract.
ii. makeEnergyOffer: This feature allows energy sellers to establish energy offers by defining the quantity of energy they wish to sell and the unit price.
iii. purchaseEnergy: Energy buyers can call this function to accept and purchase energy offers made by sellers. They need to provide the required payment based on the agreed-upon price per unit of energy.
iv. withdrawBalance: The contract owner (e.g., a utility company) can withdraw the contract's balance, which might represent fees or profits accumulated from the energy trading process.

**Web-user interface**

JavaScript and React were used to program the front-end of the web-user interface created for this suggested paradigm. The blockchain's Smart Contract serves as the application's backend. The Solidity programming language was used to create the back-end. Checked on the "sell" and "purchase" buttons allow users to request the purchase or sale of energy, respectively. Participants who want to sell excess energy can submit a request by supplying information on the power injection's beginning time and duration, as well as the source, cost, and kW of generated power. The request initiates the smart contract's function that verifies and records the request on the blockchain. Once the validation process is successful, the request appears under "Available options." The consumer who is willing to buy a certain amount of power can access the sources displayed. A smart contract function that calculates and transfers the fees related to the required amount of power from the customer's account to the contract is activated via the "Purchase" button. Details regarding negotiated trades that are kept on the blockchain are included in the "Trade History." After verifying power delivery, the community manager clicks the "Approve" option from the second table to transfer funds to the prosumer's account.

Prosumers can utilize the deviation settlement option to adjust the product in the event of any unanticipated deviations in the generation by using the "Edit" button. Though some predefined charges will need to be provided using the "Edit" in a scenario whereby the buyer or seller intends making some alterations to already negotiated trade if not, the request will not be granted. Accessibility to the "Edit" button is only for the buyer or seller of that trade. Completed and approved trades do not have Approve and Edit buttons. The community manager is provided with the highest priority in this trading platform and as such can modify entries to ensure grid stability, reduce violation of line limits, avoid network congestion and also ensure proper operation of the distribution network. The web-user interface is shown in Figure 13.

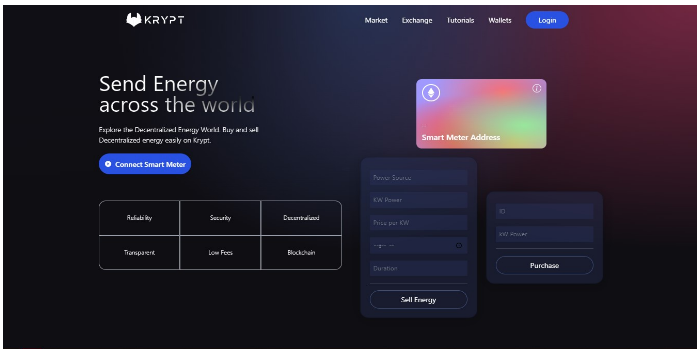


**Figure 12** Web-user interface for the trading market (front-end)

## Results and Discussion

A user web interface with its front-end designed using React-JavaScript was designed to enable participants trade energy freely without the involvement of a third party; hence the trading contributes to the achievement of desirable goal of balancing local supply and demand, minimizing the prosumer's energy costs and peak load shaving. Pricing scheme was integrated in the model to effectively eliminate overpricing and underpricing of energy. Hence, the proposed model in this research work, if implemented, will provide the benefits discussed below.

Small-scale prosumers with dispersed energy sources can successfully lower energy costs by selling any excess energy they may have to prosumers experiencing energy shortages thanks to the decentralized trading model. By means of contact amongst the participating prosumers, such a trading mechanism is facilitated. Decentralized trading is a new way to lower prosumer costs for a variety of energy trading situations, including open market urban and remote systems and community-based microgrids.

By enabling prosumers with shortages to buy the energy they require from prosumers with excess energy at a lower price than the centralized market, peer-to-peer trading lowers energy costs. The supply and demand for energy in the community must therefore be balanced for such trade to occur within a locality. A ledger with the ability to keep records of all transaction trades as well as the supply available from and demand of each of the network participants. Blockchain based platforms are thus used to achieve that. Prosumers use the blockchain platform to identify the energy consumption patterns of various sellers and buyers, control their own energy use through residential demand response programs and then trade with one another when appropriate within the local community to maintain balance between supply and demand.

For the trading mechanism to be effective, it is obvious that prosumers must actively be involved in the system to maximize its benefits. This can only be feasible if prosumers view the benefits of the peer-to-peer trading to be worthwhile. Hence, the market must be a prosumer-centric/consumer-centric market. The proposed model provides such market trading platform with focus on the network participants.

Prosumers' extensive participation in P2P trading and the benefits that follow only depend on the financing of transactions between the buyers and sellers who take part in the trading. As a result of this, there is need for novel pricing schemes suitable for the peer-to-peer trading. One of such schemes is the trade pooling scheme provided in this research work.

When unfavourable circumstances, such as a divergence from the projected generation or predicted demand, occur, the prosumer or consumer may choose to use the deviation settlement option to change the negotiated transaction. It can also be used by the community manager to change the completed trades in case of network congestion or other issues with the grid's stability. A specific fee will be subtracted when the prosumer or client uses this service in order to discourage schedule deviations and other fraudulent activities. The protection of data integrity and detection of any unlawful interference are the main purposes of blockchain technology. Blockchain will evolve into a unique countermeasure against network intrusions, such as the introduction of false data into microgrids. Throughout the network, the transaction ledger is stored and synchronized. To confirm transactions, every server node uses the Consensus Mechanism. All transactions are also verified, which guarantees transparency across the trading system and thwarts any potential fraud efforts. When the suggested trading model is put into practice, a decentralized market is developed that allows prosumers to freely trade energy with one another without monopolies. To prevent energy theft and enable secure energy and financial transactions, smart contracts and transaction data are stored on immutable blocks.

## Conclusion

This study presents a decentralized energy trading platform built on smart contracts, blockchain, and microgrid technology. Energy prosumers can exchange energy locally between themselves without the need for middlemen according to the suggested concept. By gradually dismantling the conventional power market, the market model aims to end the energy sector's electricity monopoly. Blockchain technology is used to store transactions and trade history records, guaranteeing security, data distribution, and transparency.

Blockchain technology's high degree of information security and efficient data management mechanism make it perfect for implementing the suggested market model. The improvement of an uninterrupted power supply and automated control for local energy trade were made possible by smart metering devices and smart contracts. A web-user interface is also developed using React-JavaScript for ease of trade for the network participants. Incorporated also in the energy web is a mechanism for deviation settlement, this discourages participants from bridging the smart contract declared schedules. In a bid to eliminate grid stability issues and other uncertainties, a community manager is incorporated in the model, to ensure grid stability, network decongestion and overall system maintenance. The trading platform was modularized to support various mobile devices. This model is developed for implementation within a local community of energy prosumers in an islanded mode (off-grid).

Though blockchain technology has received lots of attention in the past couple of years specifically in the finance sector, it is still in the infancy stage in the energy sector management research meaning that it is yet to be utilized fully for peer-to-peer energy trading and therefore, it will be necessary to include peer-to-peer energy trading into the existing energy infrastructure.

## Conflict of Interest Declarations

Authors thereby disclose that there is no conflict of interest in connection with the submitted material under this section.

## References


Alok, J. and Mishra, R. (2016). Changes and challenges in smart grid towards smarter grid. IEEE International Conference on Electrical Power and Energy Systems (ICEPES 2016). https://doi.org/10.1109/ICEPES.2016.7915907.

Baez-Gonzalez, P. E., Rodriguez-Diaz, J., Vasquez, C. and J. M. Guerrero (2018). Peer-to-peer energy market for community microgrids. IEEE Electrification Magazine, 6 (4), pp. 102–107. https://doi.org/10.1109/MELE.2018.2871326.

Barakhtenko, E. A. and Mayorov, G. S. (2023). Impact of distributed energy generation on energy supply to consumers in an integrated energy system. iPolytech Journal, 26(4), pp. 612–625. https://doi.org/10.21285/1814-3520-2022-4-612-625.

Bascom, E., Muriel, K., Nyambega, M., Rajan, R., Savage, M. and Young, A. (2014). Utility's strategic application of short underground transmission cable segments enhances power system. 2014 IEEE PES T&D Conference and Exposition, Chicago, IL, USA, pp. 1-5, https://doi.org/10.1109/TDC.2014.6863382.

Beghi, A., Cecchinato, L., Cosi, G., and Rampazzo, M. (2012). A PSO-based algorithm for optimal multiple chiller systems operation. Applied Thermal Engineering, XX (32), pp. 31–40, https://doi.org/10.1016/J.APPLTHERMALENG.2011.08.008.

Chanchangi. N., Adu, F., Ghosh, A., Sundaram, S. and Mallick, T. K. (2022). Nigeria's energy review: focusing on solar energy potential and penetration. Environment, Development and Sustainability: A Multidisciplinary Approach to the Theory and Practice of Sustainable Development, Springer. https://doi.org/10.1007/s10668-022-02308-4.

Eskandari, M. H., Li, M., Moradi, L., Siano, P. and Blaabjerg, F. (2020). Optimal voltage regulator for inverter interfaced distributed generation units part i: control system. IEEE Transactions on Sustainable Energy, 11(4), pp. 2813–2824. https://doi.org/10.1109/TSTE.2020.2977330.

Kakavand, H., Kost De Sevres, N., and B. Chilton (2017). The blockchain revolution: an analysis of regulation and technology related to distributed ledger technologies. SSRN Electronics Journal, no. 2849251. https://doi.org/10.2139/ssrn.2849251.

Lo, C. H. and Ansari, N. (2013). Decentralized Controls and Communications for Autonomous Distribution Networks in Smart Grid. IEEE Trans. Smart Grid, 4(1), pp. 66–77. https://doi.org/10.1109/TSG.2012.2228282.

Mohammadi-Ivatloo, B. and Abari, F. J. (2018). Operation, planning, and analysis of energy storage systems in smart energy hubs. Springer International Publishing. https://doi.org/10.1007/978-3-319-75097-2.

Nguyen, Q. K. (2016). Blockchain: a financial technology for future sustainable development. Proceedings - 3rd International Conference on Green Technology and Sustainable Development, GTSD 2016, 2016, pp. 51–54. https://doi.org/10.1109/GTSD.2016.22.

Omaji, S., Javaid, N. and Iqbal, S. (2020). Privacy aware energy management in smart communities by exploiting blockchain. PhD Synopsis Presentation. https://www.researchgate.net/publication/352152250.

Pee, S. J., Kang, E. S.., Song, J. G. and Jang, J. W. (2019). Blockchain based smart energy trading platform using smart contract. 1st International of Conference on Artificial Intelligent and Information Communication (ICAIIC 2019), pp. 322–325. https://doi.org/10.1109/ICAIIC.2019.8668978.

Perekalskiy, I., Kokin, S. and Kupcov, D. (2020). Setup of a local P2P electric energy market based on a smart contract blockchain technology. Proceedings - 2020 21st International Scientific Conference on Electric Power Engineering, EPE 2020. https://doi.org/10.1109/

EPE51172.2020.9269186.
Ramón, L. S. and Carou Álvarez, J. M. (2023). Smart meters, Ed. Oxford: Elsevier, pp. 441–447. https://doi.org/10.1016/B978-0-12-821204-2.00067-2.
Refaa, S. S. t, Ellabban, O., Bayhan, S., Abu-Rub, H., Blaabjerg, F., and Begovic, M. M. (2021). Smart grid architecture overview" in Smart Grid and Enabling Technologies, Wiley, pp. 1–43. https://doi.org/10.1002/9781119422464.ch1.
Sanitt, A. (2018). Smart Contracts. International Journal of Online Dispute Resolution, 4(2), pp. 62–62, https://doi.org/10.5553/ijodr/235250022017004002014.
Sayed, A., Magdy, A., Badr, A. and S. Eldebeiky (2019). Optimal management of distribution networks regarding reactive power generation. 21st International Middle East Power Systems Conference, MEPCON 2019, pp. 399–405. https://doi.org/10.1109/MEPCON47431.2019.9008055.
Smil, V. (2019). Distributed generation and megacities: are renewables the answer? IEEE Power and Energy Magazine, 17(2), pp. 37–41, 2019, https://doi.org/10.1109/MPE.2018.2884112.
Suthar, S. and Pindoriya, N. M. (2020). Blockchain and smart contract based decentralized energy trading platform. 2020 21st National Power System Conference (NPSC 2020). https://doi.org/ 10.1109/NPSC49263.2020.9331883.
Tatar, J. and Burniske, C. (2018). Cryptoassets: the innovative investor's guide to bitcoin and beyond - pdfdrive.com. McGraw-Hill Education.
Vahid-Ghavidel, M., Javadi, M., Gough, M.S., Santos, S. F., Shafie-khah, M. and Catalão, J. P. S. (2020). Demand response programs in multi-energy systems: a review. Energies, 13(17), https://doi.org/ 10.3390/en13174332.
Wongthongtham, P., Marrable, D., Abu-Salih, B., Liu, X. and Morrison, G. (2021). Blockchain-enabled peer-to-peer energy trading. Computers and Electrical Engineering, 94, p. 107299. https://doi.org/10.1016/j.compeleceng.107299.
Zheng, Z., Xie, S., Dai, H., Chen, W., Chen, X., Weng, J. and Imran, M. (2020). An overview on smart contracts: challenges, advances and platforms. Future Generation Computer Systems, 105, pp.475-491, https://doi.org/10.1016/j.future.2019.12.019.
Zhou, X., Guo, T. and Ma, Y. (2015). An overview on microgrid technology. 2015 IEEE International Conference on Mechatronics and Automation (ICMA), pp. 76–81. https://doi.org/ 10.1109/ICMA.2015.7237460.