DESIGN AND IMPLEMENTATION OF PEER-TO-PEER ENERGY TRADING SYSTEM USING INTERNET OF THINGS AND BLOCKCHAIN

By

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Dedication

This work is respectfully dedicated

to

My Father

For earning an honest living for us

My Mother

A strong and gentle soul

My First teacher

Who taught me

to

Trust in Allah

Believe in hard work, honesty and

Never give up

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Acronyms

IoT	Internet of Things
DG	Distributed Generation
P2P	Peer-to-Peer
HMI	Human–Machine Interface
SBC	Single-Board Computer
Pi4B	Raspberry Pi 4 Model B
HTTP	Hypertext Transfer Protocol
CPU	Central Processing Unit
CLI	Command-Line Interface
SSID	Service Set Identifier
PV	Photovoltaic
FID	Field Instrumentation Device
IP	Internet Protocol
MQTT	Message Queuing Telemetry Transport
ESS	Energy Storage System
UI	User Interface
SBC	Single Board Computer
SoC	System on a Chip
GUI	Graphical User Interface
HOMER	Hybrid Optimization of Multiple Energy Resources

ABSTRACT

With advancements in renewable energy technologies, consumers are becoming prosumers, and renewable energy resources are being used in distributed networks. In an isolated distributed system, peer-to-peer (P2P) energy trading is one of the most promising energy management solutions. In this research, we propose a P2P energy trading method for micro-grids using open resources and technology. A DC-micro-grid has been designed for a remote site in Pakistan. This site is in the northern part of Azad Jammu and Kashmir, Pakistan, within the lower area of the Himalayan Mountain range. Several of the modern amenities, including road access, are lacking in this area. For this remote site, an open-source and low-cost P2P energy trading system is designed and implemented. A photovoltaic (PV) system is also designed using HOMER Pro. The microgrid design is composed of PV panels and battery banks, designed after considering the load profile of each house. The proposed P2P energy trading platforms mainly comprise an Internet-of-Things (IoT) server to transfer the energy amongst the peers without human intervention. An Ethereum based private blockchain is suggested for money transfer in the form of cryptocurrency. The IoT server enables the peers to control and monitor self-produced energy, while Ethereum based private blockchain facilitates the financial transactions associated with the energy transfer. The proposed open-source P2P energy trading platform facilitates energy trading amongst the peers and provides real time data acquisition, monitoring, and control of self-generated energy at a remote location. This research involves the use of four different techniques in order to establish a P2P energy trading architecture, as well as a microgrid design with low-cost, low-power components and open-source technology for a remote community. The first technique to set up the P2P energy trading platform involves the following key components, Arduino UNO, ACS 712 hall-effect current sensor and a relay. The current sensor data is sent in real-time to Arduino for onward communication to the IoT server. A user-friendly interface is developed on

the server to perform various energy trading tasks. Peers have the choice to access the server remotely to perform energy trading tasks. Energy trading events can be shared amongst peers through e-mail notifications. For financial transactions, we utilized Ganache graphical user interface (GUI), a private Ethereum blockchain that eliminates the need for financial institutions. The proposed P2P energy trading model has been successfully tested for energy trading between two peers. The details of the proposed hardware and software setup explain how low-cost P2P energy trading can be achieved.

In the second technique, the trading activities are done on a web interface that uses a private Ethereum blockchain. A smart contract is deployed on the Ethereum blockchain and the trading activities performed on the web interface are recorded on a tamper-proof blockchain network. An IoT platform is used to monitor and control self-generated energy. Energy data is collected and processed by means of ESP32-S2 microcontrollers using field instrumentation devices that are connected to the voltage source and load. An open source decentralized P2P energy trading system, designed on the blockchain and IoT architecture is proposed. The hardware setup includes a relay, a current sensor, a voltage sensor, a Wi-Fi router and ESP32-S2 microcontroller. For data transfer the Message Queuing Telemetry Transport (MQTT) protocol is used over a local network. ESP32-S2 is set up as MQTT client and Node-Red IoT server is used as MQTT broker. Hypertext Transfer Protocol (http) request method is implemented to connect the Node-Red server with the web interface developed using React.JS library.

The third method involves a Raspberry Pi 4 Model B (Pi4B), which is used to host the main server of the trading system, including the user interface and the Ethereum blockchain server. The Ethereum blockchain is used to deploy smart contracts and the IoT servers run on ESP32 microcontrollers. Sensors and actuators connected to the ESP32 are field instrumentation devices that facilitate acquiring, monitoring, and transferring energy data in real-time. A blockchain-enabled user interface is developed using the React.JS open-source library, to perform trading activities. As a communication channel, the proposed system uses a Wi-Fi network. For system security, the designed system has restricted authorization. For information security and data integrity, other security measures are also considered, such as login credentials, private keys, firewalls, and secret recovery phrases. To facilitate communication between the server and the client, a Hypertext Transfer Protocol is implemented.

As part of the fourth technique, we have implemented a Raspberry Pi 4 Model B (Pi4B) as the main server on which the user interface (UI) and local Ethereum blockchain are hosted. Additionally, the blockchain implements the smart contract. Open-source Angular framework is used to develop the UI that facilitates trading activities. This method of P2P energy trading also explores the development of an Internet of Things (IoT) server using the latest ESP32-S3 microcontroller. Data is acquired by field instrumentation devices (FIDs) and transmitted to an IoT server via the microcontroller. An immutable record of all transactions is maintained by the blockchain network. By configuring the system locally, hosted on a private network with restricted access, security is ensured. Additional security measures are also considered for information security and data integrity, including a secret recovery phrase, firewalls, login credentials, and a private key. A Hypertext Transfer Protocol is implemented amongst the servers and clients. Within the scope of this thesis, we present four different methods of P2P energy trading designed for remote communities that involve renewable energy sources. All design details, simulations results, experimental test results are included in the thesis.

Chapter 1
Introduction and Literature Review

1.1 Introduction

As electric vehicles (EVs) become more popular, smart appliances become more prevalent, and living standards rise, the demand for electrical energy may rise by 20% over the next decade [1]. All the countries around the world are focusing on renewable energy sources such as solar power and wind power to meet the electric demand and reduce greenhouse gas emissions [2]. With the escalation of Distributed Energy Resources (DER) such as Photovoltaic (PV), Battery Energy Storage Systems (BESS), Electric Vehicle (EV), Wind Energy Conversion Systems (WECS) and advances in information and communication systems technology, a new market for electricity has emerged [3]. As low-cost renewable energy technologies have gained popularity and electric energy demand has grown, there has been an increase in prosumers in the electric market [4]. Renewable energy has sparked a significant transformation in the energy sector worldwide as a result of the energy transition. There has been an evolution from a consumer to a prosumer of energy. The proliferation of distributed energy sources has contributed to the growth of the prosumer in the energy sector [5].

Traditionally, Electric power is generated in distant regions by large power plants with megawatt capacity, which are delivered to end-users via utility networks over a long distance. Electrical energy is transferred from producers to consumers, while cash flow is transferred in the opposite direction. A conventional energy transmission and trading system is unidirectional in terms of both the flow of energy and cash. Recent years have seen the energy industry shift towards the decentralized model, driven by technological advances in information technology and distributed energy technologies [6].

The growing adoption of distributed energy resources in the residential sector will require several new marketing approaches. As opposed to the conventional electricity market, participants now prefer distributed generation and the sale of electrical power. Renewable energy sources allow consumers to regulate their power consumption and production. It is now imperative to have a state-of-the-art platform for energy trading to support this emerging concept of prosumers.

The ability to set the optimal trading time, as well as complete trading autonomy, financial security, and pricing liberty is all provided by this trading platform. Peer-to-peer (P2P) trading has become the only alternative for consumers to participate actively in the energy market in recent years. In the P2P energy trading, energy is traded directly between consumers and prosumers.

Peers can trade surplus energy through the use of peer-to-peer energy trading, which can be beneficial for both buyers and sellers [7]. Prosumers can trade energy like goods and services in peer-to-peer energy trading, which is a key component of energy trading over P2P. Furthermore, P2P trading can aid grid peak demand too, reducing the need for reserves, and preventing network outages. The GridWise Architecture Council, terms P2P as transactive energy (TE), a system that effectively controls supply and demand. Over $4 billion is expected to be generated by the P2P industry by 2026 [8].

P2P energy trading is the trade of energy between prosumers and consumers with no contribution from a third party. In P2P the prosumers and consumers are referred to as peers. The P2P model requires that peers trade among themselves rather than relying on a third-party intermediary. Generally, it is the national level that determines energy market prices. On the contrary, P2P energy trading allows participants to determine energy prices on their own. A shared economy model is the foundation for P2P energy trading in a distributed network [9]. P2P energy trading has become a leading solution for energy management as it allows peers to contribute to the electricity market, either by reducing their demand or by selling excess energy [10]. Prosumers can buy and sell energy in general or within a community at large. Microgrids are an ideal environment for P2P energy trading [11]. Information and communication technology, blockchain technology and intelligent devices have revolutionized the P2P market. As a result of blockchain technology, the prosumer can conduct financial transactions independently. However, smart devices, coupled with Internet-of-Things (IoT), provide a low-cost method of energy trading. An entirely new market structure has been created for electricity due to blockchain technology and the internet of things. It is now feasible for peers to perform transactions independently instead of relying on centralized authority.

By combining blockchain technology with the Internet of Things, P2P energy trading platforms can become more efficient. Rather than buying energy from utilities, consumers can now purchase it on local energy markets. A blockchain-based platform for energy trading can provide prosumers with greater efficiency and control. It can also provide real-time transparency of energy consumption and funds utilization through the immutable blockchain ledger.

Internet of Things (IoT) refers to the concept of connecting things to the Internet. In other words, it minimizes human intervention and automates things. This will ultimately result in better service and information. IoT has revolutionized many traditional aspects of life in today's high-tech era. It has been instrumental in the transformation of cities, homes, pollution control, energy conservation, smart transportation, and industries. We are constantly surrounded by the Internet of

Things, which improves our quality of life in a variety of ways [12]. A wide range of technologies are combined in IoT, including sensors, computing, embedded devices, and communications. Following the internet and Information and Communication Technologies (ICT), the Internet of Things represents the fourth major revolution. IoT is predicted to have an even greater impact on society's well-being and the economy than the internet, and information and communication technologies [13]. A key characteristic of the IoT is that electronic, sensor, and software devices can be connected to each other and to an operator, allowing real-time data to be captured and shared [14,15]. Essentially, it enables physical devices to become smarter by transforming traditional forms into smart ones [14]. It is apparent that the IoT can play an essential role in the transformation of the energy sector in the direction of decentralization, which will in turn benefit prosumers and renewable energy producers economically.

A blockchain is composed of blocks assembled into a chain. In these blocks, data from each participant in the network is stored [14]. A set of transactions is executed in a block format. Once the transactions have been generated, they are grouped into blocks and linked to one another in chains - along with their timestamps [4]. As a result of these blocks, a distributed ledger known as a blockchain is continuously updated with records of data [16]. This chain mechanism provides an additional layer of security, as even the smallest modifications invalidate subsequent blocks. Additionally, if only the hash of the last block is verified, the validity of the entire chain can be established. In the early stages of blockchain technology, economic transactions were tracked without the need for trusted intermediaries (such as banks). Although blockchain has its roots in economic transactions, like Bitcoin, it has been proven to be a useful technology in other fields when distributed approaches are preferred to centralized approaches. In the case of energy purchases or sales, blocks can be arranged in tables with information such as seller ID, buyer ID, amount of transferred energy, duration, time stamp, and power profile [17].

Renewable energy sources have undoubtedly had a significant influence on the conventional electricity market. Nevertheless, it has not yet completely captured the traditional electricity market. In this study, an energy trading platform based on blockchain and IoT is proposed. Featuring a decentralized structure, the proposed system provides participants with access to the most recent solutions for energy trading, such as financial transactions, energy transfers, and energy metering. It focuses on enabling local energy trading and utilizing cryptocurrencies as a financial incentive through a private blockchain. Within the scope of this study, design and implementation of fully decentralized P2P architectures are proposed that allows peers to connect and trade energy without intervention from third parties. Using a locally configured user interface (UI), the proposed IoT and blockchain-based P2P energy trading platform connects participants into trades. Through the platform, prosumers can use distributed generation in a cost-effective manner, as the energy pricing is set by participating peers solely, which can be lower than in local markets. This is advantageous for both producers and consumers. Energy exports will determine the seller's payment, and energy consumption will determine the consumer's charge. As a part of this study, energy exports and energy consumption are monitored and controlled with the IoT platform, and financial transactions are ensured with blockchain technology.

1.2 Literature Review

As part of this research, a comprehensive literature review was conducted, and some of the most relevant findings are presented here. Considering its many applications, electricity plays a vital role in our daily life. Additionally, the energy crisis is the biggest challenge for humans, and it will remain so for the foreseeable future. The lack of electricity affects nine hundred forty million people worldwide [18]. People in developing countries live without electricity at a high rate. There are 58.65% of Pakistani rural households without electricity, which is a great concern [19]. Electricity availability is an issue that affects the daily lives of people living in hi-tech societies, leading to the installation of isolated microgrids for off-grid communities to take advantage of distributed energy resources. In [20], a hybrid microgrid combining photovoltaic (PV), battery energy storage, and diesel generators (DiGs) is described. The purpose of this model is to determine the optimal size and location of a BESS system, as well as the optimal size of a PV system. This case study examines a remote off-grid community in northern Canada. This study takes into consideration operation and configuration constraints when determining the optimal system size. In district Tharparker, Sindh, Pakistan, 95% of the houses are not electrically powered. A comprehensive analysis of the sizing, cost analysis, and installation of off-grid PV systems has been undertaken by the authors of [21]. As compared to the national grid, the authors claim that off-grid solar PV offers a lower cost of energy generation. The researchers compared the cost of electrifying the area under research with the cost of electrifying the area with grid power and concluded that solar PV is the best option, and it costs 63% less than grid power.

For Dakhla, Morocco, a hybrid microgrid design is presented in [22]. The optimal composition of a hybrid microgrid would include PV, wind, diesel, and batteries. The authors propose an equilibrium optimizer for minimizing costs, improving stability, and serving loads in diverse environments. The main goal of the research is also achieved through sensitivity analysis. As a result of their efforts, the authors were able to reduce the net present cost of the microgrid designed for Dakhla, Morocco. Likewise, another study [23] found that remote islands could benefit from stand-alone hybrid solar-wind-battery systems. This system has been analyzed from a techno-economic perspective by the authors. They used HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software to analyze the system and estimate the levelized cost of energy. This study claims to present a cost-effective renewable energy solution for remote islands. Aiming to understand factors that influence social acceptability of solar photovoltaic systems in northwest Pakistan, the authors of [24] identify factors that influence social acceptance. A binary logistic model was used to evaluate the determinants of social acceptability of PV systems. The study area has 46 percent of households using solar PV systems. It was emphasized by the authors that Pakistan has abundant solar energy that can be converted into electricity by the use of solar photovoltaic systems. A specific recommendation of the study is that the government adopt policies aimed at encouraging the use of solar energy in Pakistan via incentives. As stated in [25], off-grid PV systems are important for electrifying remote areas. Identifying and assessing solar energy potential in remote regions of Sindh, Pakistan. For the selected rural areas, the tilt angle was determined to increase solar energy generation capacity. Compared with conventional energy sources, solar PV off-grid systems are inexpensive and have a lower cost. As a result of this study, researchers believe Pakistan's government will be able to utilize off-grid solar PV energy generation systems.

As outlined in [26], a blockchain-based IoT system is proposed. By utilizing the Internet of Things, power flows are accounted for, while a blockchain platform eliminates the requirement for a central authority. In the proposed system, a local energy market was established to handle distributed energy transactions and central authority was eliminated. An energy tag system (a smart contract embedded in a blockchain) is proposed in [27]. Data is collected via IoT applications regarding the energy requirements of a consumer or prosumer within a smart home. Each member of the platform receives a purchase or selling tag depending on whether the prosumer has surplus energy to sell or whether the consumer is seeking to meet its own energy needs. Energy tags are verified by the participants involved in the energy transaction with the original consumer or prosumer. Upon the validation of the transaction, the tag is assigned to the block. Following the generation of the block, a ledger is triggered between all participants involved in that particular transaction and it is then distributed to all participants on the energy-transaction platform. Based on the work proposed the concept of pure and hybrid P2P energy trading has been further categorized. The research presented in [28] suggests the development of a P2P energy trading system for Virtual Power Plants (VPPs). A P2P energy trading and bidding mechanism was developed using Ethereum blockchain technology and smart contracts.

A public blockchain platform has been used to address cost and security concerns, and smart contracts have been used to facilitate auctions. An energy bidding platform based on blockchain technology was developed, as well as an environment for testing cryptography in order to achieve economic P2P energy trading that is efficient and transparent. Several software products are interconnected through the suggested auction-based bidding model, such as Solidity, Remix, Metamask, Infuro.io, and Ropsten, to create a real-life cryptographic environment to facilitate trading of energy based on blockchain technology. In accordance with [29], the operating costs of direct current (DC) and alternating current (AC) operated electrical devices are evaluated using bill sharing and the mid-market rate method for different levels of PV penetration both for households and for communities. Using a bill-sharing method, all peers within the network share the operational costs and income based on the share of energy they generate or consume. Using the mid-market rate method, the internal price is calculated using the total generation and demand relationships.

EVs and distribution networks (DNs) trade energy using the Byzantine-based blockchain consensus framework [30]. For the duration of the peak load period, DN requires more power from EVs. During this practice of energy trading, the blockchain is used to ensure the security of the shared energy and information from potential malicious attacks. Blockchain applications are characterized by Byzantine general problem structures. In [31], the authors emphasize the use of a novel game-theoretic platform to facilitate P2P energy trading between consumers in a community. Consumers may adjust their energy needs based on the quantity and price of energy offered by sellers. There were two types of trading competitions considered by the authors: 1) the price competition between the sellers, and 2) the seller selection competition between the buyers. A noncooperative game is designed for the price competition between the sellers. An evolutionary game theory is applied to the selection of sellers by buyers. Furthermore, a Stackelberg game method based on M-leaders and N-followers is employed to shape the interaction between the buyer and seller. Two algorithms are proposed in order to maintain equilibrium between the games. According to this research, peer-to-peer energy trading has substantial technical and financial benefits for the community and appears to be an alternative to energy storage systems that are costly and inefficient.

Among local households, P2P energy trading has surfaced as an emerging technique that offers both consumers and operators potential benefits. In P2P trading, blockchain and smart contract technology have gained increasing attention due to their secure nature. However, there is still room for improvement in latency and computation costs for blockchain-based P2P energy trading. The authors of this study propose a blockchain-based energy trading system for a P2P market that specializes in community-based demand-response management. Two noncooperative games are used to develop the proposed demand-response mechanism, in which dynamic pricing is applied to suppliers. As a smart contract running on a Hyperledger blockchain, the proposed energy trading system is prototyped on a cluster network. Based on this study, the proposed demand-response games reduce net peak load tremendously, and at the same time, the off-chain processing mode keeps the same system integrity as the on-chain mode while reducing latency and overhead [32].

Another study [33], examines Vehicle-to-Vehicle (V2V) energy trading using blockchain technology. As the authors point out, V2V energy trading has emerged as an attractive alternative for relieving the load placed on the traditional grid by allowing two individuals to trade energy directly without mediators. It has recently been proposed to use blockchain technology to implement V2V energy trading. This study proposes a Block Alliance Consensus (BAC) mechanism that is capable of maintaining Hashgraph throughput and resisting Sybil attacks on a large-scale P2P energy trading network. BAC and ETB are implemented on the Hyperledger Fabric platform. The authors of [34] propose an innovative strategic framework for P2P energy trading that considers network constraints. Using the sharing form alternating direction method of multipliers (ADMM) algorithm, consumers can estimate the allowed power injection before engaging in P2P energy trading. An algorithm that includes a transaction fee in continuous double auction (CDA) matching is proposed to quantify the cost of network usage for prosumers. The distribution network limits are taken into account in an adaptive aggressiveness-based bidding strategy. The P2P energy trading framework created profits and supported distribution network operations in testing with IEEE 37-bus distribution network, according to the authors. The peer-to-peer energy trading has evolved into a high level of energy management that allows peers to control their demand for electricity or sell excess energy [35]. As an open ledger, blockchain allows peers to connect and verify transactions with each other. Alternatively, blockchain is regarded as a system for keeping records of all transactions without allowing any interference. Smart contracts are the basis for these transactions [36].

Through an overview of the current state-of-the-art P2P trading, the authors discussed the various operating algorithms of P2P energy trading along with their characteristics, features, and standards in [37]. A case study of Nepal's energy system is presented in this article along with an analysis of Nepal's micro and mini-grids, challenges, limitations, and potentials. In conclusion, the authors propose a model that addresses the specific problems associated with the Nepalese energy market. The authors of another study [38] propose two novel methods for identifying households' mutual energy trading preferences on an entirely local P2P market. First, excess power supply is matched with peer demand, and second, the distance between the participants is considered. To determine how bilateral trade preferences affect energy prices and trade volume, both strategies are evaluated. A decentralized network of entirely P2P energy trading markets is used to generate the data on a day-ahead basis. To implement the P2P trading market, a permissioned blockchain smart contract is used. The simulations are based on real domestic data from a community in the Netherlands, which includes several different decentralized energy sources. P2P networks reduce energy purchasing costs and grid interaction, according to the authors. Similarly, if trading preferences are distance-centered, the sum of P2P energy traded is higher at a lower price. Another study [39] concluded that P2P market mechanisms normally entail a significant computational burden, and real-time trading demands fast calculations. The authors emphasize the difficulty involved in developing and operating such systems in real-time. To maximize social welfare, the authors present and analyze a novel online consensus alternating direction multiplier algorithm for the P2P market utilizing real-time market information. Additionally, the authors claim that the algorithm can reduce computational complexity.

A number of case studies have been performed to demonstrate the high efficiency, superior convergence, and tracking capabilities of the authors' algorithm. A user-centric cooperative mechanism is described in [40] that allows users to participate actively in peer-to-peer energy trading. The proposal aims to make economic transactions as simple and straightforward as possible by taking into account the preferences of all parties involved in the ordering process. As part of the Higashi-Fuji demonstration experiment, a case study has been conducted in Japan in order to demonstrate the proposed mechanism. Accordingly, the study revealed that consumers could buy renewable energy economically, efficiently, and automatically, and that prosumers could sell surplus energy. As well, they recognized that the key to facilitating P2P energy trading is to design incentives that will motivate participants to participate. P2P energy trading is discussed in [41] as a promising energy trading and management solution in an isolated microgrid. Through open technology and resources, the authors propose an IoT and Ethereum blockchain-based trading platform that is claimed to be state-of-the-art. Due to the increasing use of distributed energy resources in distribution systems, low-voltage networks may be able to utilize new methods of operation according to the authors in [42].

A growing number of peer-to-peer energy trading schemes have been emerging due to recent trends in cryptocurrencies and blockchain technology, which enables neighbors to exchange electricity without the intervention of conventional intermediaries. In accordance with the authors' findings, a sensitivity analysis can be used to evaluate how such an exchange impacts network constraint. The proposed method is tested on a low-voltage network in the United Kingdom. This study concluded that it is possible to provide users with economic benefits while meeting network constraints under P2P schemes. The peer-to-peer energy trading method [43] has also been identified as an effective method by which a distribution network can provide renewable energy to multiple consumers. There is still a need to comply with distribution voltage constraints when implementing energy transactions, as this study emphasizes the importance of implementing them securely. In this study, the researchers propose a P2P decentralized protocol for trading energy that can be used to regulate voltage. A case study is used in order to verify the effectiveness and efficiency of the system in accordance with IEEE bus-33 and 69 standards.

According to Zheng et al. in [44], distributed energy resources have led to peer-to-peer trading. It appears that there is a growing consensus among experts that peer-to-peer is the future of the energy market. As a means of reducing capital expenditures and increasing storage devices' efficiency, this study examines the concept of shared energy storage, based on the sharing economy principle. This study presents a P2P energy trading model for residential homes that have a shared energy storage system. The economic benefits of energy trading through peer-to-peer networks have been demonstrated through numerical simulations, while the introduction of shared energy storage may further reduce the cost of energy. According to researchers in [45], energy trading has increased in recent years because of the availability of distributed sources of energy and the ability of electricity producers to export surplus fuels for a profit. Through the energy trading system, energy from multiple sources is successfully combined, providing better facilities for energy consumers and consistent resource usage. The authors discuss how blockchain can enhance transparency and performance through decentralization, scaling, and device reliability. In addition, the importance of a blockchain-based smart grid is demonstrated. Additionally, the research examines the use of blockchain technology to ensure the decentralization, security, and scalability of future autonomous electric grids.

A decentralized energy trading market could be developed as a result of the convergence of blockchain, distributed renewable energy, and IoT. As a result, prosumers and consumers will be able to engage in peer-to-peer energy trading. As described in [46], the authors propose a blockchain-based system for peer-to-peer energy trading in a smart grid. It consists of a single-phase grid-connected inverter-based smart grid that delivers 220V and 50Hz power. The trading of energy is facilitated through the use of IoT and blockchain technologies. A sinusoidal pulse width modulation (SPWM) inverter is designed, and the grid connection is established by means of phase control. Inverter implementation is carried out in MATLAB, while blockchain and IoT are developed in Python. Approximately 43% of the population of Sub-Saharan African countries does not have access to electricity, and the number is even lower in rural areas, at 28%. In view of the distances involved and the high investment costs, it is not feasible to connect small remote villages to the national utility grid. Rural electrification can be achieved through the use of off-grid photovoltaic and energy storage systems. In [47], the authors present a concept for a local energy market that includes a blockchain-based peer-to-peer (P2P) market for solar-powered off-grid systems. According to [48], the authors propose the concept of a double-chain blockchain and the corresponding peer-to-peer transaction model based on a reorganization of the power chain and transaction chain. To maximize the prosumer's economic interests, peer-to-peer independent decision-making is achieved through the transaction chain (public chain). A security check is performed, and the transaction scheme is adjusted through the power chain (alliance chain) as well as through the constraints of the power network. The IEEE 14-node distribution network is simulated using the Ethereum blockchain development platform. According to the simulation results, the proposed double-chain blockchain is more efficient in terms of processing transactions than the single-chain blockchain. According to the authors, prosumers can conduct peer-to-peer transactions safely and autonomously by using the proposed method.

1.3 Research Objectives

On the basis of the literature reviewed, two distinct streams of literature were identified. Researchers in the first stream focus on off-grid PV systems and on their social adaptability. In contrast, the other stream examines P2P energy trading utilizing blockchain technology and contends that peer-to-peer trading is the most promising energy management and trading solution. The author believes that this is the first study to present the complete design and technical details of a low-cost, open-source, P2P energy trading platforms and P2P energy trading implementation to an un-electrified remote community in Pakistan. The motivations for proposing the IoT and blockchain-based P2P energy trading system for this remote community include (a) low cost, (b) low energy consumption, (c) high possibility of implementation in unserved remote communities, and (d) potential use in remote areas with no access to the internet. According to the literature reviewed, the proposed P2P energy trading methods have never been considered before, and thus can also be considered novel in terms of their use and application.

This research aims to design and implementation of a P2P energy trading platform using IoT and blockchain with the following main objectives:

1. To select a remote site with no services and design a PV based DC microgrid.
2. To design and implement an innovative P2P energy trading platform using open-source resources with real-time settlements, technical and economic efficiency.

3. Design and implement a novel P2P energy trading platform by installing a decentralized web interface, Ethereum blockchain, and locally installed IoT server hosted on a local network. Since an open source, P2P energy trading network has never been seen before.

4. Development and application of an open-source and low-cost, local server hosted on a private network for peer-to-peer energy trading, using a ganache command-line interface (CLI) private Ethereum blockchain and a raspberry Pi to host the server.

5. To design and implement an optimal energy trading system for remote communities to achieve energy trading and monitoring independence without internet.

1.4 Significance of the Research

The increasing demand for renewable energy sources to meet the energy requirement and the technological advancements have raised the number of prosumers in the electricity market. To add to this, the emerging technologies like blockchain and the IoT have given a new trend to the electricity market. Blockchain technology has given financial liberty to the users and eliminated the need for third-party solutions for financial transactions. While the IoT excluded human interventions. This paradigm shift requires state-of-the-art energy trading solutions that can facilitate prosumers in monitoring generated energy, transfer of energy, energy metering, and freedom of financial transactions.

This thesis identifies a straightforward and unique approach to designing and implementing an IoT and blockchain-based open-source platform for peer-to-peer trading of energy. As a result of the development of four platforms, the prosumers will be able to monitor and trade energy without the involvement of any central authority with fast and efficient financial settlements.

1.5 Thesis Organization

As part of the preparation of this thesis, a manuscript format has been adopted. Accordingly, the remainder of the thesis is arranged as follows:

A DC-microgrid is designed and analyzed in Chapter 2. The site selected is an un-electrified remote community in Pakistan. An overview of the proposed microgrid configuration and details about connections are included in this study. In addition, this study provides information on peer-to-peer energy trading to allow prosumers to get financial incentives. Throughout this chapter, the work is focused on achieving objective 1 outlined in section 1.3 of this thesis.

In chapter 3, a P2P energy trading method for microgrids based on open resources and technology is proposed. The setup includes an Internet of Things server for transferring energy between peers without the need for human intervention, and an Ethereum-based private blockchain for the transfer of money. This chapter contributes to Objective 2, as stated in Section 1.3

A novel P2P energy trading platform is described in Chapter 4 of this thesis. This is accomplished by installing a decentralized web interface, Ethereum blockchain, and a locally installed IoT server. It provides remote monitoring, control, and real-time data acquisition for self-generated energy in addition to financial independence over blockchain.

Chapter 5 contributes to the development and application of an open-source, low-cost, local server that implements P2P energy trading using a Ganache command-line interface, a private Ethereum blockchain, and a Raspberry Pi.

Chapter 6 discusses the use of blockchain technology to trade energy across peer-to-peer networks. The main server is a Raspberry Pi 4 Model B (Pi4B), on which the user interface (UI) and private Ethereum blockchain are configured. In order to develop the user interface that provides assistance in conducting trading activities, an open-source Angular framework is used. A microcontroller ESP32-S3 is also used to develop an Internet of Things (IoT) server.

This thesis concludes with a discussion of its conclusions and recommendations for future research in Chapter 7.

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Chapter 2

Design and Analysis of an Isolated DC-Microgrid for a Remote Community in Pakistan

Co-authorship statement

This chapter presents the design and analysis of an isolated DC-microgrid and contributes to objective 1 of this thesis as stated in section 1.3. The main objective of this chapter is to design a photovoltaic (PV) system for ten houses in the community. Through the use of HOMER Pro, it has been possible to achieve the optimal design for the DC-microgrid. It consists of PV panels and a battery bank designed after considering the load profile of each home. This chapter presents the solar energy potential, load profile, optimal configuration of the proposed system. This study also provides details about the proposed microgrid configuration and its connections. A basic technical overview of Peer-to-Peer energy trading is also provided, which enables prosumers to gain financial returns.

I, Mirza Jabbar Aziz Baig, am the principal author. I contributed to the conceptualization, methodology, software investigation, and writing of the original draft. The research in this chapter was supervised by Dr. Tariq Iqbal, Dr. Mohsin Jamil and Dr. Jahangir Khan. The supervisors contributed to the conceptualization, methodology and provided resources. They also supervised the entire chapter, reviewed and corrected the research manuscript. The work in this Chapter has been published in 2021 IEEE 12th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), New York, NY, USA, 2021, pp. 0712-0716, doi: 10.1109/UEMCON53757.2021.9666665.

Abstract— This chapter presents the design and analysis of an isolated dc-microgrid. The site is an un-electrified remote community of Pakistan, and the people are living their life without electricity in this modern era. The main objective of the paper is to design a photovoltaic (PV) system for ten houses in the community. The optimal design of the dc-microgrid has been achieved using HOMER Pro. The proposed system is composed of PV panels, battery bank, designed after considering the load profile of each house. The solar energy potential, load profile, an optimal configuration of the proposed system has been presented in this chapter. As a part of this study, a description of the proposed microgrid configuration and details about connections are also provided. The basic technical information on Peer-to-Peer energy trading is also provided beyond the scope of this study that enables the prosumers to get financial returns.

Key words- Isolated microgrid, PV system, Renewable energy, Peer-to-peer (P2P).

2.1 Introduction

Electricity is an essential part of man's daily life, given its various applications. In addition, the energy crisis is also and will remain the biggest challenge for human beings. Nine hundred forty million people in the world do not have access to electricity [1]. The percentage of people living without electricity is high in developing countries. Unfortunately, 58.65% of the rural population of Pakistan is living without electricity [2]. In countries like Pakistan the energy crisis is because of increasing population, limited financial resources of government, required installation of long transmission lines for the people living in remote areas. People's daily lives are affected by the lack of access to electricity in this hi-tech world, that encourages the need to get advantage from distributed energy resources and install isolated microgrids for off-grid communities. Particularly the communities with plentiful renewable energy resources. Of most importance, such studies are particularly required, which present methods for getting returns on the investments. For this study, literature reviews have been conducted in great detail, and some are shown here as a reference. A hybrid microgrid developed using photovoltaic (PV), battery energy storage system (BESS), and diesel generators (DiGs), is presented in [3]. This model determines the optimal size and location of BESS systems, as well as the optimal size of PV system. This case study focuses on a remote off-grid community in Northern Canada. To achieve the optimal size of the system, the annual system cost is minimized, considering operation and configuration constraints. The authors in [4] focused on complete sizing, cost analysis, and installation of off-grid PV for some houses in district Tharparker, Sindh, Pakistan, which is 95% un-electrified. The authors claim in their results that the cost of energy generation by the off-grid solar PV system is less as compared to the energy supplied by the national grid. They also compared the cost of electrification of the area under research by the off-grid solar PV system and if the area is electrified by means of grid supply and concluded that the solar PV system is most suitable for the site, and it costs 63% less than the utility grid. In [5], a hybrid microgrid design is presented for Dakhla, Morocco. The optimal hybrid microgrid is composed of PV, wind, diesel, and battery. An equilibrium optimizer is proposed to design the system for cost minimization, improving stability, and to serve load under distinct environments. Sensitivity analysis are also conducted to attain the main goal of the research. The authors successfully reduced the net present cost for the microgrid designed for Dakhla, Morocco. Another study [6] also presents the feasibility of a stand-alone hybrid solar–wind–battery system for a remote island. The authors have performed a techno-economic analysis for the system. They used HOMER (Hybrid Optimization of Multiple Energy Resources) Pro software to analyze the system and to find the levelized cost of energy for the proposed system. In this study, the author also claimed that they have presented a cost-effective renewable energy solution for the remote island.

Although research such as these discussed above provides a solid basis and justification for planning and designing microgrids, however, we find nothing from the literature reviewed about the Peer-to-Peer (P2P) energy trading scheme associated with microgrids. Also, the energy system proposed in this chapter has never been considered in this geographical area. Thus, this work is novel with respect to geographical zone and P2P energy trading scheme associated with the isolated dc-microgrid. This study has made the following significant contributions.

This study proposes an isolated dc-microgrid design for an un-electrified remote community in Pakistan.

i. An optimal lowest net present cost dc-microgrid is designed and presented for selected site.
ii. The proposed Peer-to-Peer energy trading scheme for the isolated microgrid helps the community members monitor and trade energy without relying on any central authority and get returns on their investment besides fulfilling daily electricity needs.

iii. This study will help design and install isolated microgrids with Peer-to-Peer energy trading features for remote communities in the world with rich solar resources.

Figure 2.1. Proposed site

Figure 2.2. Aerial view of the proposed site

2.2 Site Description

The site selected for this study is in the Neelum valley, the Northern part of Azad Jammu and Kashmir, Pakistan encompassing the lower area of the Himalayas. The optimal design of an isolated microgrid with P2P energy trading features has been attained for a small community comprising thirteen houses. In virtue of the location 34°49'06.6"N 74°13'06.5"E it receives daily average irradiance of 4.63 kWh/m^2/day.

The proposed site view is presented in figure 2.1, and figure 2.2 shows the aerial view extracted from google earth of the proposed remote community. In figure 2.1 and figure 2.2, we can see that there are no power lines and no road access to this community. Additionally, the houses on the site are so close to each other that it is easy to set up a Wi-Fi-based private communication link to facilitate P2P energy trading for the proposed isolated microgrid. A P2P energy exchange platform has been presented that is associated with an isolated microgrid for the deemed site. The system will enable its users to monitor, control and trade self-generated energy with no central entity.

Figure 2.3 represents the monthly average solar global horizontal irradiance data of the site. Based on the average monthly solar global horizontal irradiance data for the proposed site, it can be determined that the proposed site could accommodate an isolated dc-microgrid.

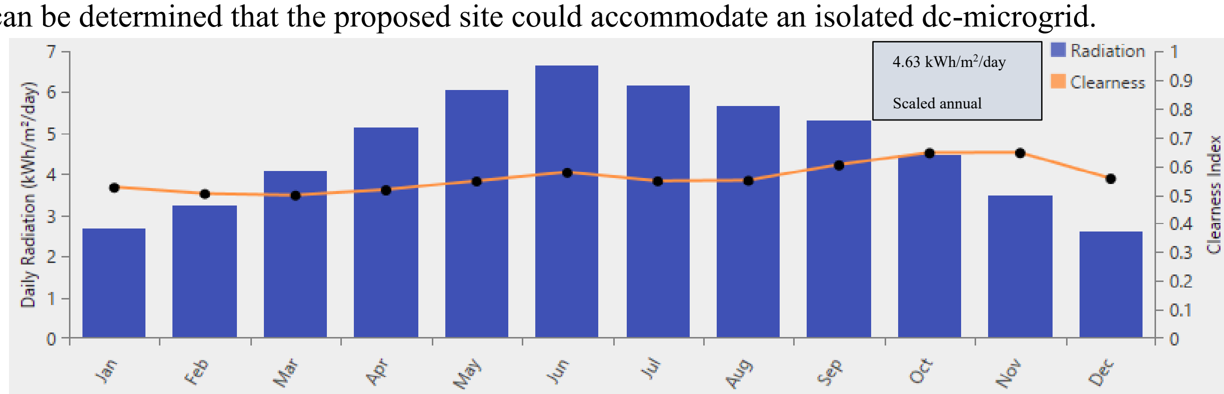
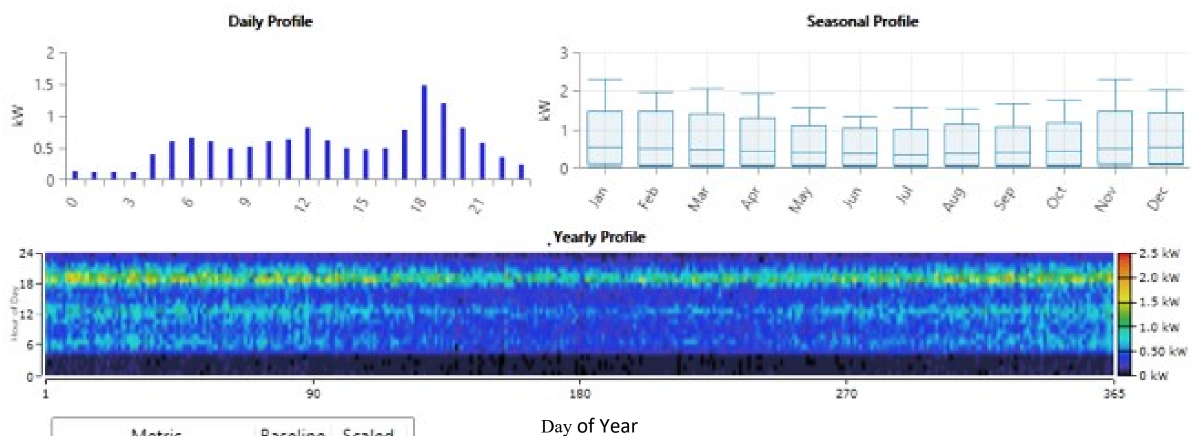


Figure 2. 3. Monthly Average Solar Global Horizontal Irradiance (GHI) data

2.3 System Design

In this study, initially, we chose ten houses from the community for the proposed system design, considering the system limitations. The optimal system design of the proposed isolated microgrid has been achieved using HOMER Pro software. HOMER Pro-optimization and sensitivity analysis features help in system sizing and analysis and provide the most cost-effective solution. A total of 2708 solutions were simulated, and the optimal design is presented in the following sections as a result of the analysis, sizing, and design for the remote site.

The load profile, as shown in figure 2.4, is a critical aspect of designing an isolated microgrid. The sizing and modeling of the system cannot be precise without a proper load profile. The efficiency and reliability of the systems also depend on the accuracy of the load profile. Within the scope of this study, we considered all important factors in developing load profiles for each house within the community. The heat and cooking needs of the household are met either by kerosene or firewood. Weather-dependent cooling is also not required. The typical load of the household is extremely small. It is very rare for the household in that area to have a larger load.



Metric	Baseline	Scaled
Average (kWh/day)	11.25	1.6
Average(kW)	.47	.07
Peak (kW)	2.32	.33
Load factor	.2	.2

Load Type: AC DC

Figure. 2.4. Daily, monthly, and yearly load profile of one house in the community

Taking into account the nearest electrified household electricity bill in the vicinity, we estimated the average load of a typical household as 1.6 kWh/day. The results presented in this chapter are based on this load. For the purpose of estimating the load of other houses, and to achieve optimal design of isolated microgrid within the community, we have made some small adjustments to the average load and achieved the load profile of ten houses in the remote community under this study. The maximum load in the community is 2.00 kWh/day for the house at serial no. 10, Table 1, and the house with the smallest load presented at serial no. 1 with a load of 1.28 kWh/day. Figure .2. 4 also shows the daily, monthly, and yearly load profile of the system with a dc-base load of 1.6 kWh/day.

Table 2.1. Homer System and Optimization

Sr. No.	**Load Profile of connected Houses (kWh/day)**	**No. of PV panels (0.34 kW each)**	**Initial capital Rs.**	**No. of Batteries (12 V 85 Ah each)**	**System Autonomy (Hrs.)**
1	1.28	3	133,419	4	60
2	1.36	3	143,110	4	56.5
3	1.44	2	188,221	8	107
4	1.52	2	191,350	8	101
5	1.60	2	195,147	8	96.1
6	1.68	2	198,721	8	91.5
7	1.76	2	202,538	8	87.3
8	1.84	2	207,315	8	83.5
9	1.92	3	210,460	8	80.1

10	2.00	3	215,425	8	76.9

We have presented the details of number of solar panels with capacity, no. of batteries with their ratings, the initial capital cost of the system, and the system autonomy in hours for the proposed isolated dc-microgrid. The proposed system configuration and the details of the components are presented in the next section of this chapter.

A breakdown of the electrical loads for each installation can be found in Table 2.1.

2.4 System Configuration and Components

The system configuration by HOMER Pro is shown in figure 2.5. It shows a PV module, load and a battery connected to a DC bus. The bus voltage selected for the proposed system is 48V.

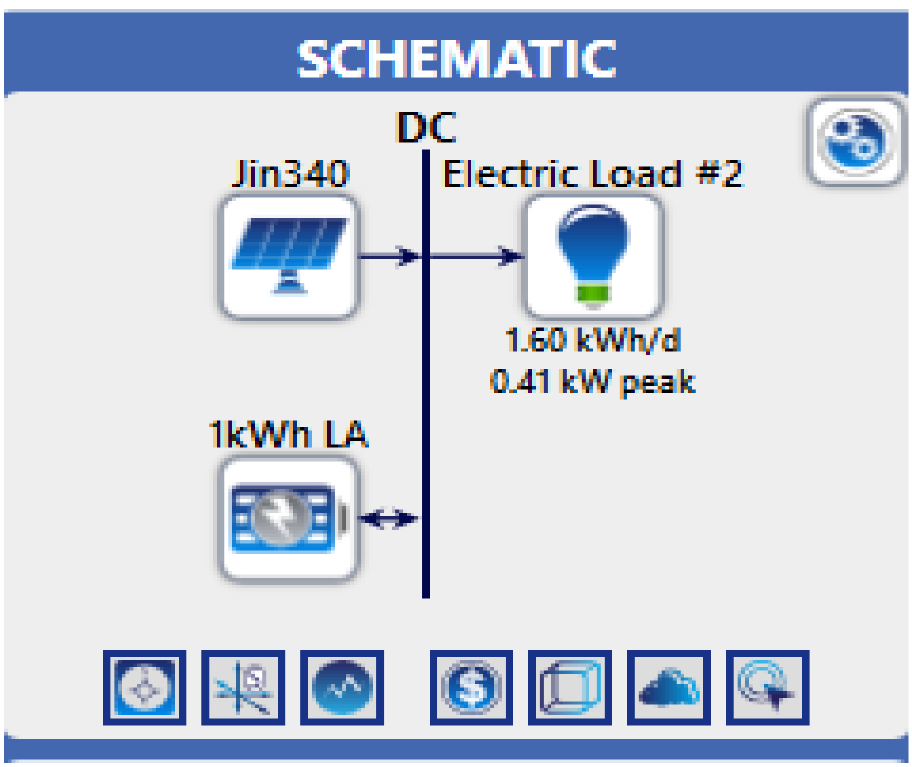


Figure 2.5. Optimal configuration of the proposed system

This system has a 25-year life expectancy. With the initial capital cost of Rs. 133,419 for an average load of 1.28 kWh/day. Different combinations of PV panels and battery banks were simulated using HOMER Pro, and the best combination was selected based on various factors like net present cost (NPC), cost of energy (COE), and initial capital cost in local currency. The depth of discharge of the battery bank in the proposed system is 80%. All the houses connected in an isolated microgrid have a battery bank, and the house with the basic load has an autonomy of 2.5 days/60 hours.

Within the scope of this study, ten houses are connected with the microgrid and the details of load profile of each house, no. of PV panels required with the capacity of 0.34kW each, no. of batteries (12V 85 Ah) required with the battery specification and the system autonomy are presented in Table 2.1. The monthly electric production of the basic system at sr. No. 1 in Table 2.1 is shown in figure 2.6, which shows the 100% renewable energy fraction of the proposed system. It follows that the system is self-sufficient to serve the community's energy needs. Effective energy storage is also demonstrated by the system whereby the batteries could provide

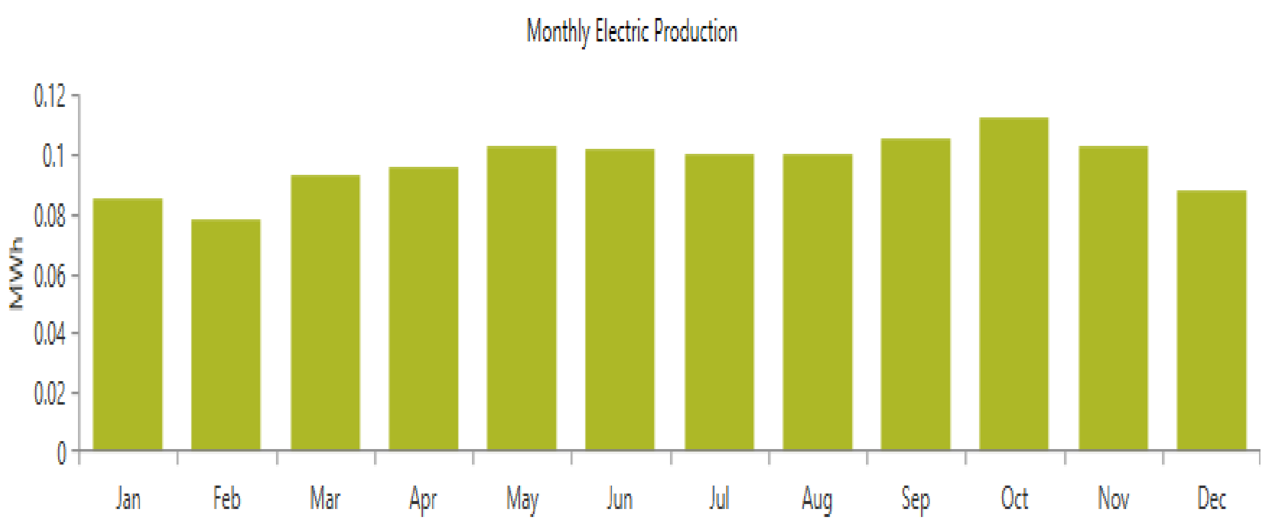


Figure 2.6. Monthly electric production for one house in the community

power to the community for a longer period. The system components selected for the proposed site are easily available in the local market. Reference [7, 8] provides the price and details of the solar panels and the batteries used as a part of HOMER Pro optimization.

Configuration of isolated dc-microgrid for the proposed site with P2P energy trading scheme is presented in the next section of this chapter.

2.5 Microgrid Configuration and P2P energy Trading Scheme

The microgrid configuration for the site is proposed as part of this study. In figure 2.7, we present the microgrid configuration with connections details. Each house as a part of dc-microgrid

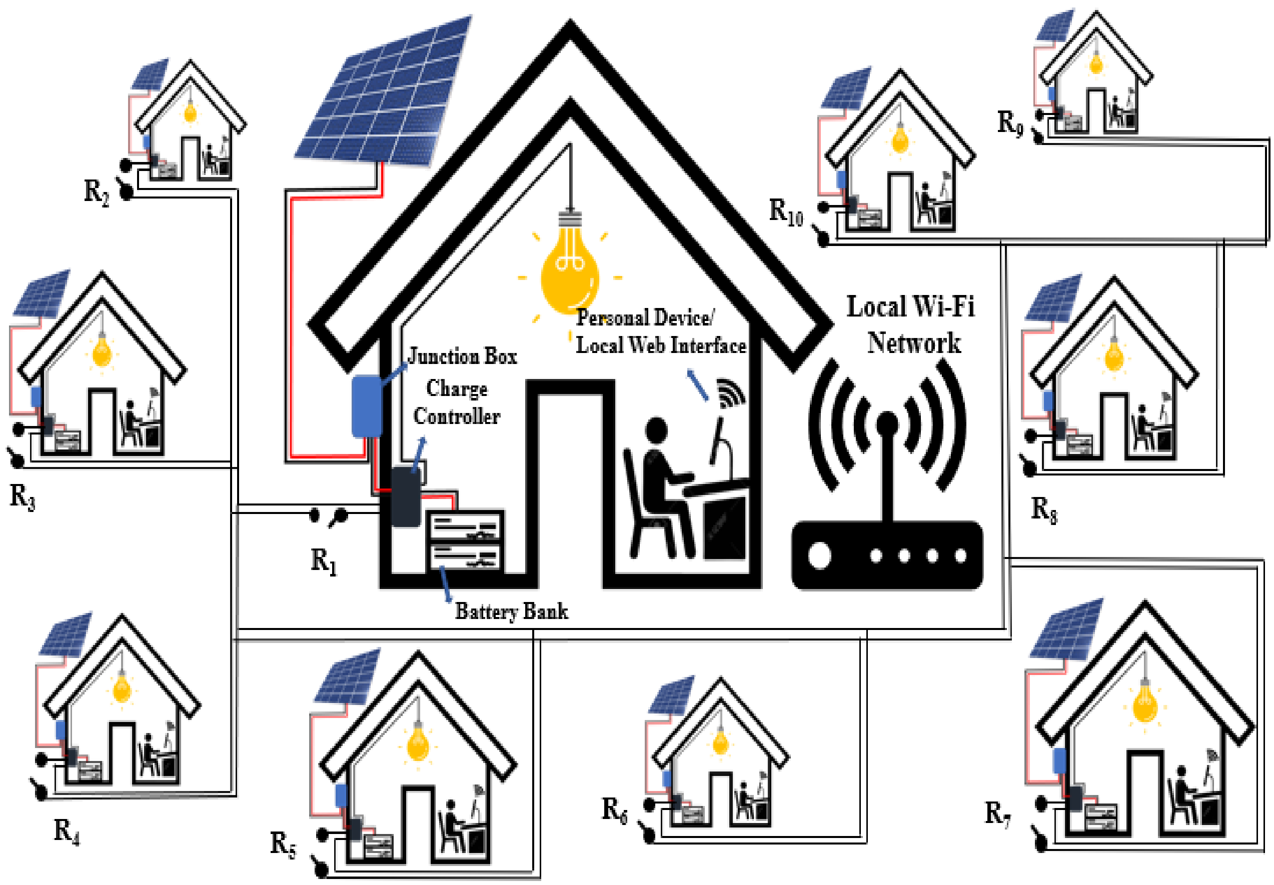


Figure 2.7. Configuration of the proposed microgrid with P2P energy trading scheme

has a battery bank and a PV system installed. All the houses are connected with each other. The authors also emphasize P2P energy trading within the microgrid. A P2P trading platform associated with the microgrid not only gives energy management and control solutions but also provides the prosumers to have returns on their investments. In [9], the authors provide a basic concept of P2P energy trading. The authors also suggested P2P energy trading platform is the state-of-the-art solution for energy management and trading without the involvement of a third party. Although P2P energy trading doesn't come under the scope of this study, however, we propose P2P energy trading for prosumers to gain returns on investments. This can be achieved using internet of thing (IoT) platforms that enables one to monitor and control distributed generation. Blockchain technology can be used to keep the record of the energy transactions and to get financial in terms of cryptocurrency. In figure 2.7, a local Wi-Fi network is shown that can be used to set up a private communication link between the personal devices in each house to facilitate P2P energy trading. The symbols R_1 to R_{10} in figure 2.7 represent the relays at each premises. The energy buyer/energy seller can use their personal devices to trade energy within the microgrid with tamper-proof records. If house1 wants to trade energy with house 5 the relay R_1 and R_5 will turn on for the duration of energy trading by means of a locally installed web interface. The energy monitoring and control can be achieved using field instrumentation devices and IoT platforms, and details are presented in [10].

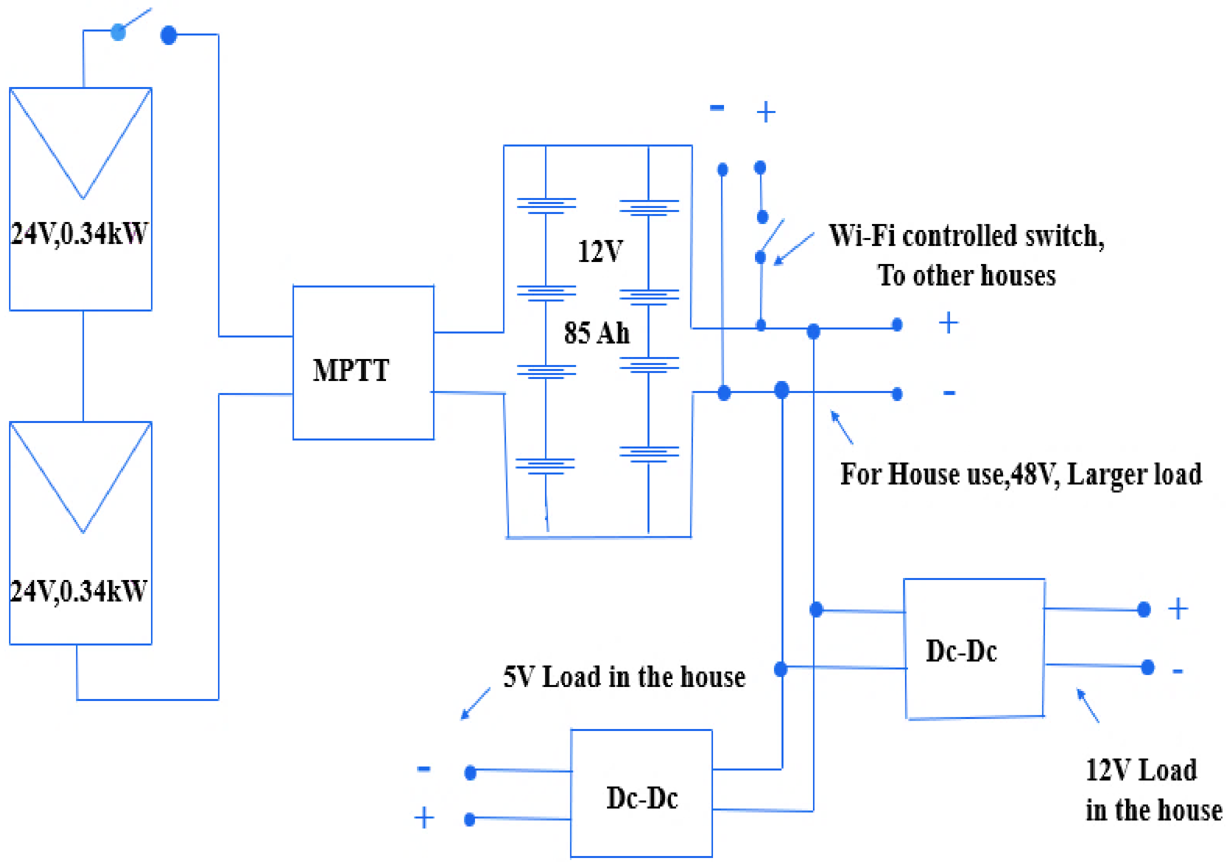


Figure 2.8. System connection within a house

Figure 2.8 shows the connection details of the PV system within a house. It shows that 72 cells solar panels of 24V and 0.34kW have been used based on HOMER Pro optimization. A maximum power point tracker (MPTT) is also part of the PV system to track the maximum Power Point. A battery bank comprising eight batteries 12V 85Ah each is used as a backup supply that provides system autonomy. The bus voltage of the system is 48 volts, and dc-to-dc converters are used for smaller loads within the house. A connection to facilitate P2P energy trading is also shown in figure 2.8 that enables the community members to trade energy within the community.

2.6 Conclusion

The primary objective of this study is the design and analysis of a dc-microgrid for a remote community in Pakistan. HOMER Pro is used for system optimization, and optimal system design has been achieved. In this case study, the heating and cooking load is not considered, and the system is designed only based on basic domestic needs such as lighting, small refrigerators, electronics, etc. The proposed system fully satisfies the needs of each house. Essential technical information on P2P energy trading and connections details are also provided. Based on the results, isolated dc-microgrids are the best solution for un-electrified remote settlements with good solar resources.

2.7 Future Work

For future work, the authors aim to provide full technical details and implementation methodology of Peer-to-Peer energy trading using the internet of things and blockchain technology for the site under consideration.

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Chapter 3

Peer-to-Peer Energy Trading in a Microgrid Using Internet of Things and Blockchain

Co-authorship statement

An open resource and technology-based P2P energy trading method is presented in Chapter 3. A blockchain based on Ethereum is proposed for money transfer in the form of cryptocurrency, and an Internet of Things server is proposed to transfer energy to peers without human intervention. In addition to software implementation, this chapter also discusses hardware setup. A user-friendly interface has been developed on the server to perform various energy trading tasks. Energy trading events can be shared among peers through e-mail notifications. Ganache's graphical user interface (GUI) uses a private Ethereum blockchain to facilitate financial transactions. Chapter 3 provides details of the proposed hardware and software setup and explains how low-cost P2P energy trading can be achieved. This chapter contributes to Objective 2, as indicated in Section 1.3.

I (Mirza Jabbar Aziz Baig) am the principal author, and I was involved in conceptualization, methodology, software and hardware implementation, and the writing of the initial draft and editing of this chapter. This chapter was supervised by Dr. Tariq Iqbal, Dr. Jahangir Khan, and Dr. Mohsin Jamil, who reviewed and corrected the manuscript. The first draft of this chapter was peer reviewed, accepted, and presented at the 11th IEEE Annual Information

Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada, 2020, pages 0402-0406, doi: 10.1109/IEMCON51383.2020.9284869. While the full technical details of Chapter 3 are published in the ELECTRONICS JOURNAL, Electronics, vol. *25, no. 2*, 2021, doi: https://doi.org/10.53314/ELS2125039B.

Abstract——With advancements in renewable energy technologies, consumers are becoming prosumers, and renewable energy resources are being used in distributed networks. In an isolated distributed system, peer-to-peer (P2P) energy trading is one of the most promising energy management solutions. In this chapter, we propose a P2P energy trading method for microgrids using open resources and technology. The proposed setup comprises an Internet of Things (IoT) server to transfer energy amongst the peers without human intervention, and an Ethereum based private blockchain is suggested for money transfer in the form of cryptocurrency. The IoT server enables the peers to control and monitor self-produced energy. Arduino UNO, ACS 712 hall-effect current sensor, and a relay are the main components used in the hardware setup. The current sensor data is sent in real-time to Arduino for onward communication to the IoT server. A user-friendly interface has been developed on the server to perform various energy trading tasks. Peers have the choice to access the server remotely to perform energy trading tasks. The energy trading events can be shared amongst peers through e-mail notifications. For financial transactions, we utilized Ganache graphical user interface (GUI) a private Ethereum blockchain eliminating the need for financial institutions. The proposed peer-to-peer energy trading model has been successfully tested for energy trading between two peers. This chapter provides details of the proposed hardware and software setup and explains how low-cost P2P energy trading can be achieved.

Keywords—Blockchain, Energy Trading, Ethereum, Internet of Things (IoT), Micro-grid, Peer-to-peer (P2P), Smart Contract.

3.1 Introduction

Increasing demand of electric vehicles (EV), use of smart appliances and higher living standards may increase the demand for electrical energy by 20% in the next decade [1]. In recent years, increased utilization of renewable energy sources (RES) has been seen worldwide. By 2022, renewable energy will be around 30% of world's energy production [2]. To meet the electricity demand and reduce greenhouse gas emissions, countries around the globe are focusing on renewable energy sources such as solar and wind [4]. The rise in prosumers (buyers and sellers) has been witnessed because of less expensive renewable energy technologies. Interest has been high to sell or share self-produced energy within communities [3].

In conventional power systems, power is produced by larger power plants with megawatts capacity situated in distant regions and sent to end-use customers over a significant distance by the utility network. The electrical energy goes from the producers to the consumers, and the cash flow goes the other way. The flow of both energy and cash is unidirectional in the conventional system of energy transmission and trading. In recent years, the energy industry is switching towards the decentralized model as information technology, and the distributed energy technologies have been further developed [5]. At present, energy is produced at larger scales by conventional energy production methods such as hydropower, natural gas, coal etc., causing huge environmental deterioration and high transmission losses.

In the case of renewable energy sources, the consumers can control their power consumption and production. The energy trading between the prosumers and consumers without the involvement of any third party is called peer-to-peer P2P energy trading. The prosumers and consumers here are referred to as peers. It also means that the peers are trading amongst themselves, and they do not rely on any mediator. Energy market prices are usually set on the national level. While in P2P energy trading, the participants have the liberty to set the prices themselves. The basis for P2P energy trading in a distributed network is founded on a shared economy model [6]. The IoT platform facilitates the energy trading process. The advantage of using the IoT platform is that it minimizes human intervention. In traditional energy trading networks, the energy transactions are unidirectional from a source of energy generation over a long distance, causing transmission loss with a contrary cash flow. On the other hand, P2P energy trading is not unidirectional in terms of both cash and energy transactions [7].

Peer-to-peer (P2P) energy trading became an advanced level of energy management solution for smart grid, which permits peers to participate in electricity market either by reducing their demand or by selling excess energy [8]. P2P energy trading platform enables prosumers to buy or sell energy generally or within a community. P2P energy trading is thought to be an appropriate trading model in microgrids [9].

Blockchain is an open ledger where different peers can connect with each other and are able to perform and verify transactions. Otherwise, considered as an accounting record system, blockchain keeps the details of all the transactions without allowing any interference. These transactions are based on smart contracts [10]. Blockchains are distributed data arrangements used to store digital transactions with no central authority. They can allow numerous users at a time to make changes to the ledger without requiring any central authority. Every participant has access to the records' chain in the blockchain network. All the new transactions are linked with the previous transaction with cryptograph making it more adaptable and secure. Every network participant can confirm the validity of the transactions in blockchain which authenticate the transparent, tamper proof and trustable transactions [11].

In this chapter, we propose an IoT-based energy trading platform associated with blockchain-based financial transactions. The primary concept is to enable energy trading locally and to get financial incentive in the form of cryptocurrency. The proposed platform is a decentralized platform that allows the peers to connect and trade energy with no involvement of any third party. The proposed IoT and blockchain-based P2P energy trading platform connects the participants using a web-based user interface. The platform can facilitate prosumers in a cost-effective utilization of distributed generation. It is beneficial to both the energy producer and the consumer as the pricing mechanism is based on negotiations between the peers, which may be lower than the local energy markets. In this particular work, energy trading is considered between two peers only. The seller will be paid depending on the energy export, and the consumer will be charged according to the negotiated price and energy consumed. The IoT platform is used to monitor and control energy export and energy consumption, and the blockchain technology is used for secure and transparent financial transactions.

The significant contribution of this chapter is that it covers both the financial side and the technical side of a Peer-to-Peer energy trading platform. As the current published research only address the complex financial solutions of the P2P energy trading systems and ignoring the practical transfer and monitoring of renewable energy. This chapter is unique because it provides full implementation details of a P2P energy trading setup. We have provided a complete server setup including electrical side and software implementation. The technical side helps the peers in the physical transfer of electric power, energy metering, and available energy monitoring. At the same time, the financial side is helpful for financial transactions on a secured blockchain network.

It also enables the platform participants to decide the price of energy themselves which may be lower than the local energy markets. To the best of our knowledge such information is not found in any publication. The proposed research work is successfully tested, and the results are presented in the following sections of the chapter.

3.2 Related Work

In [5] an IoT and blockchain-based system is proposed. IoT is used to account for power flows, while a blockchain platform eliminates the need for a central authority. The proposed system developed a local energy market to deal with distributed energy transactions and eliminated central authority. In [12], the authors proposed an energy tag (smart contract embedded in the blockchain) system. The IoT applications are used to collect data regarding the energy needs of a consumer or prosumer within a smart home. Based on whether the prosumer has surplus energy to sell, or a consumer wants to fulfill its own energy needs, a purchase or selling tag is established and sent to all members of the platform. The participants who are interested in the energy transaction confirm the energy tag with the original prosumer or consumer. After the transaction becomes valid, the tag is assigned to a block. A ledger is then triggered between the participants involved in that particular transaction once the block is generated and then sent out to all the participants of the energy-transaction platform. The work proposed in [12] furthers categorize pure P2P and hybrid P2P energy trading.

The research work presented in [13] suggests a P2P energy trading system for a Virtual Power Plant (VPP). The authors focused on the financial side using the Ethereum blockchain and smart contract and developed a P2P energy trading and bidding mechanism. The platform addressed cost and security concerns using a public blockchain, and the concept of smart contracts is used for auctions. A blockchain-based bidding platform was developed, and a cryptography testing environment was set up to achieve economic P2P energy trading with efficiency and transparency. The suggested auction-based bidding model interlinks various software, e.g., Solidity, Remix, Metamask, Infuro.io, and Ropsten, to enable a real-life cryptographic environment in blockchain-based energy trading.

In reference [14], the operational costs of alternating current (AC) and direct current (DC) operated electrical devices are evaluated using bill sharing and the mid-market rate method for various levels of PV penetration considering both households and communities. All the peers in the network share the operational cost and income as per the share of energy they generate or consume using a bill-sharing method. Total generation and demand relationships are used in the mid-market rate method to calculate the internal price at the average of export and import price. In another research work (see [15]), the authors recognized seven different microgrid power market standards and evaluated the Brooklyn Microgrid based on those standards. The authors established and shaped a local electricity market with a focus on a private Ethereum blockchain that enables participants to trade self-produced energy on a distributed trading system with no contribution of any central authority.

The authors in [16] employed wireless networks to develop a blockchain based secure power trading structure designed for the smart grid. In the proposed system, power data collected by the wireless network is recorded using blockchain, and trading decisions are made using the smart contract. To improve power trading and renewable energy utilization, the authors introduced local energy trading blockchain and renewable energy trading blockchain named dual-chain structure. They also modeled a renewable energy incentive method. The authors proposed the energy trading system using blockchain by employing a wireless network with improved security.

Here, issues such as data transmission and single point of failure are addressed in the electricity market. The suggested system performs reliable distributed energy trading without any central party between consumers and prosumers.

In [17], the Byzantine-based blockchain consensus framework is utilized for energy trading amongst EVs and distribution networks (DN). DN begins the energy trading by requiring more power from the EVs for the duration of the peak load period. In this energy trading practice, the blockchain is used to secure the shared energy and information from vulnerable attacks. Byzantine general problem structure is used to feature the application of blockchain. The research work in [18] emphasizes P2P energy trading between the prosumers in a community using a novel game-theoretic platform. The energy needs of the consumer can be adjusted based on the quantity of energy offered by the sellers and the price. The authors considered two different trading competitions: 1) price competition among the sellers; and 2) seller selection competition among the buyers. The price competition between the sellers is designed as a noncooperative game. For the buyers to select the sellers, an evolutionary game theory is applied. Additionally, an M-leader and N-follower Stackelberg game method is employed to shape the interaction between the buyers and sellers. To maintain the equilibrium between the games, two algorithms are suggested. The research shows how P2P energy trading delivers substantial technical and financial benefits to the community, and it appears to be an alternative to cost-intensive energy storage systems.

The latest research work is presented as a part of the literature review in this chapter section. All the papers use public blockchain except [15], which uses private blockchain to adopt only bill sharing techniques. None of the papers above is presenting a complete solution for energy trading. The related work shows that the authors benefitted the P2P community by providing accounts of power flow, categorizing P2P and hybrid P2P energy trading, cost analysis, and efficiency of power trading between DN and EVs. Contrarily the proposed Peer-to-Peer energy trading platform gives a state-of-the-art energy trading solution to the P2P community. The peers can monitor and trade energy and get full benefits of blockchain technology in financial transactions on a private blockchain. The system can efficiently perform real-time energy and financial transactions, which is not addressed in published work. The system proposes a complete buying and selling platform including financial transactions which have not been addressed in the previous work.

Table 3.1 Summary of Related Work

Blockchain platform/ Method used	**Objective**	**Proposed approach**
Steemit platform, Public blockchain [5]	Prosumers engagement in the energy market. Considered privacy and security of participants, accounting of energy flow.	An IoT (Internet of Things) system to account the energy flows and blockchain approach to eliminate the need for a central control unit.
Smart contract and public blockchain [12]	For efficient electrical energy transaction between prosumers, categorize pure P2P and hybrid P2P energy trading	Proposed an energy tag (smart contract embedded in the blockchain) system

Smart contract and public blockchain [13]	To address cost and security concerns and to achieve efficient, transparent, and economic energy trading	Auction-based bidding mechanisms is introduced
Operational cost comparison [14]	Boost energy trading	Mid-market rate and bill sharing method for different levels of PV penetration.
Private blockchain [15]	Reduce electricity cost in the local market	A decentralized market mechanism using a private blockchain is proposed
Local Energy trading blockchain and renewable energy trading blockchain [16]	To enhance the efficiency of power trading and renewable energy utilization	An energy trading system using blockchain by improving security of wireless networks. Also introduces an incentive mechanism.
Byzantine based blockchain [17]	Enhancement of energy and information data security in trading	Byzantine general problem framework is utilized to feature the application of blockchain.

	process between EVs and DN	
Game-theoretic model [18]	Substantial financial and technical benefits for P2P community	Noncooperative game is used for sellers and for the buyers' evolutionary game theory is applied. Stackelberg game approach to maintain the attraction between the participants

3.3 Internet of Things

Internet of Things (IoT) is a generalized notion of connecting *things* to the internet. It minimizes the human intervention with things and automates them. Ultimately, we can get better service and information. In IoT, we connect humans, objects, etc., to the internet and gather various information for further processing and analysis. Moreover, the IoT comprises actual and virtual objects with their own individual features and is all around incorporated into the data organization. IoT can convey/respond to things, conditions, and information. The things also respond based on the conditions and the information detected. To understand IoT, it is important to utilize sensor, devices and technologies that can incorporate with IoT platforms [19].

IoT devices are primarily used for accumulating data and information from the physical things around to facilitate our daily life. The IoT platforms are also used to control IoT devices remotely and hence increasing the quality of life. IoT communicates with things by utilizing sensors and communication technologies [20], and in response, objects respond autonomously without the involvement of humans, thereby increasing the efficiency. In this way, IoT can play an essential role in the transformation of the energy sector towards decentralization, which, in turn will yield economic benefits to the prosumers or renewable energy producers.

Figure 3.1. Internet of things and renewable energy trading

Figure 3.1 depicts the IoT connecting different components that are considered important in a P2P energy trading network. IoT platforms can connect different peers to transfer energy in a decentralized network and can manage energy storage and renewable energy resources. They can also be utilized for charging electric vehicles from distributed energy resources. IoT platform provides the peers a decentralized network to monitor and control energy trading sessions.

After navigating through a decade-long journey, IoT technology is currently ushering in various opportunities. Numerous IoT gadgets and modules with multiple communications protocols, computation technologies, and security algorithms have been developed, while others are still in a developing phase. IoT platforms use different communication protocols such as MQTT, CoAP, DDS, XMPP, and HTTP for communication with IoT devices [21]. However, the wired communication protocol can also be used to facilitate communication between the IoT platform and the IoT devices.

3.4 Blockchain

Blockchain uses a distributed ledger technology controlled by the participating peers with no involvement of any central authority. The idea of blockchain was hailed through a white paper by Satoshi Nakamoto on October 31st,2008. He presented the concept of an online platform of bitcoin transactions between the participating peers and eliminated the need for a financial institution [20]. In a blockchain, the blocks are assembled in the form of chains, and each block stores the data for all transactions. Each block performs a vital role in linking the earlier block to the next block instantly after the next block appears in the network [20]. All the participants in a network store historical data. These are distributed in a block format, called a set of transactions. Every node has a public and a private key. The participating peers can perform digital signatures on the performed transactions using the hash function and private key. The blocks holding these transactions are organized in the form of chains and are connected without any interruption– together with the time flow after being formed. As the blocks are linked in the form of chains, the information stored in the blocks cannot be changed. All the network participants can verify the transactions by accessing the ledger they hold. The transactions without validations cannot be stored in blocks [10]. Hence, the characteristics of blockchain are data integrity, security, and decentralization.

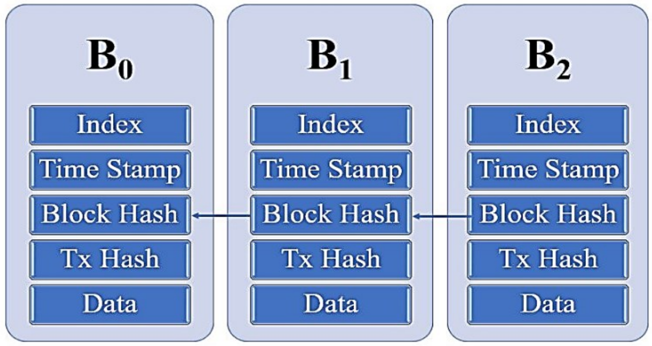

Figure 3.2. Basic blockchain

Figure 3.2 represents the basic blockchain structure. Each block contains information such as index; timestamp, which keeps the record of the exact block mining time, block hash, the unique block identity; Tx hash (Transaction hash, the unique identity of every traction performed on a blockchain), and data. Each block is also connected to the previous block making a chain of blocks. Referring to figure 3.2, block $B_{0,}$ always present in the blockchain, is called genesis block, the first block of every blockchain. The rest of the blocks in the blockchain stacks over the genesis block. In a P2P network, the participating peers manage the blockchain independently without the involvement of any central authority. As we shift the energy sector from a centralized to a decentralized network, blockchain is an essential factor, as it can address security and transparency issues in energy trading. Such a process can be either local (between the peers) or wholesale [22].

3.5 Smart Contract

Nick Szabo introduced the smart contract concept in 1994. He defined a smart contract as "*A computerized transaction protocol that executes the terms of a contract*." Consequently, the advent of blockchain unfolded the significance of smart contracts. In terms of blockchain, smart contracts are scripts recorded on the blocks forming a blockchain. Each contract has a unique address as it dwells on a chain. These contracts are generated by addressing transactions to them. Afterward, smart contracts execute automatically in a specified method on the network nodes [10]. Figure 3.3 shows the working of a smart contract, where a response is dependent on the pre-set conditions. Once the pre-decided conditions are fulfilled, the desired response will occur.

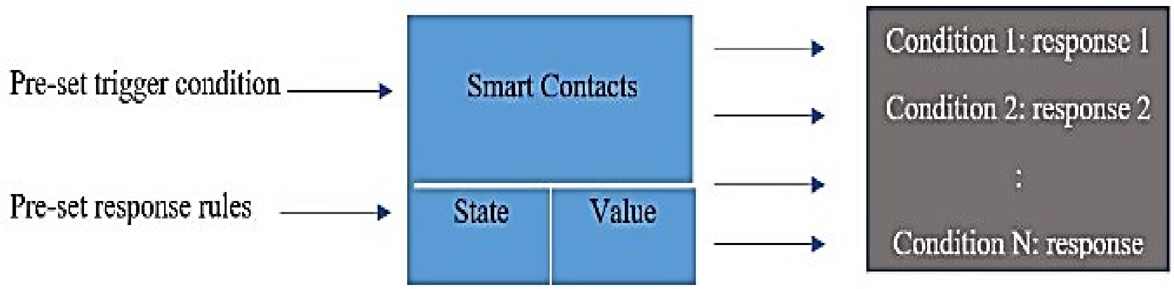

Figure 3.3. Working of smart contract [17]

As compared to traditional agreements, smart contracts do not depend on any mediator. This idea of executing smart contracts without any mediator became successful only because of blockchain‒a system that can self-execute the contracts.

There are different platforms to develop smart contracts, e.g., NXT, Bitcoin, or Ethereum [23]. On a blockchain, a smart contract shall not be changed. However, it can be monitored, authenticated, and self-enforced. Bitcoin first implemented smart contracts. In 2015, Vitalik Buterin developed Ethereum‒a blockchain-based decentralized network for payment execution inclusive of a development environment for a wide range of smart contracts on blockchain [24].

Ethereum blockchain allows smart contracts to execute independently. In this platform, at first, the contract amongst the participating peers is applied as a script and then deployed to the blockchain network. On the execution of the digital commands, the smart contract is initiated automatically on the blockchain network, and the condition already set up in the smart contract are followed. Hence all the transactions are executed independently without relying on any central authority. In cryptocurrency, the smart contracts can be deemed as wallets because they contain balance and account addresses like traditional cryptocurrency accounts [13].

3.6 System Description

In most countries, the conventional energy trading model is entirely managed by utility companies, and the energy consumers are altogether dependent on the service providers. Besides, the electric power is produced by large-scale power plants installed at distant locations from the load centers. There is also no uniform policy regarding the pricing mechanism, and the energy price is decided centrally without the direct involvement of the end-users. As described in Section 3.1, increasing demand for electric energy and the penetration of renewable energy witnessed an increasing number of prosumers. Also, modern technologies emphasize decentralized networks where people can deal with each other without the involvement of any mediator. Peer-to-Peer (P2P) energy trading is the most advanced solution towards decentralized energy trading involving independent production, consumption, and financial incentives. In a P2P network, the peers can decide the energy price by themselves and manage their energy needs without relying on any central entity.

In this work, the proposed peer-to-peer (P2P) energy trading model consists of an IoT server with a user interface associated with a private Ethereum blockchain. The user interface is developed in a user-friendly manner and is simple to use. The developed system enables the participating peers of the proposed P2P energy trading model to manage their energy needs either by selling the excess amount of energy or they may buy the energy if their energy demand is increased. The participating peers may be the energy buyers or the energy sellers.

The P2P energy trading model connects Prosumers together and facilitates the energy trading amongst them. In this P2P energy trading model peer can consume self-produced energy and sell the excess energy by using the developed user interface (UI) of the server. The UI enables the prosumers to give buy or sell calls, transfer energy, measure the energy transferred, and execute payments. There are also options to refuse the buyer in case energy is not available to sell. Also, an emergency stop button may be used to stop energy flow if an emergency occurs. The peer (buyer or seller) can show the willingness to buy or selling by using the "Buy" or "Sell" button on the UI of the server. Once peer1 initiates the buy call with the buy call button, it will send an e-mail notification to peer2 showing the inclination of peer1 to buy energy. If peer2 to have enough energy and is ready to sell energy to peer1, peer2 will transfer energy to peer1 by using the "Energy Transfer" button on UI. For financial incentives, we used here a fully private Ethereum based blockchain technology to ensure secured, transparent and tamper proof financial transactions. Blockchain enables the peers to perform efficient and speedy transactions to get incentives for the energy exported. It allows direct financial transactions between peers and eliminates the need for any central financial institution.

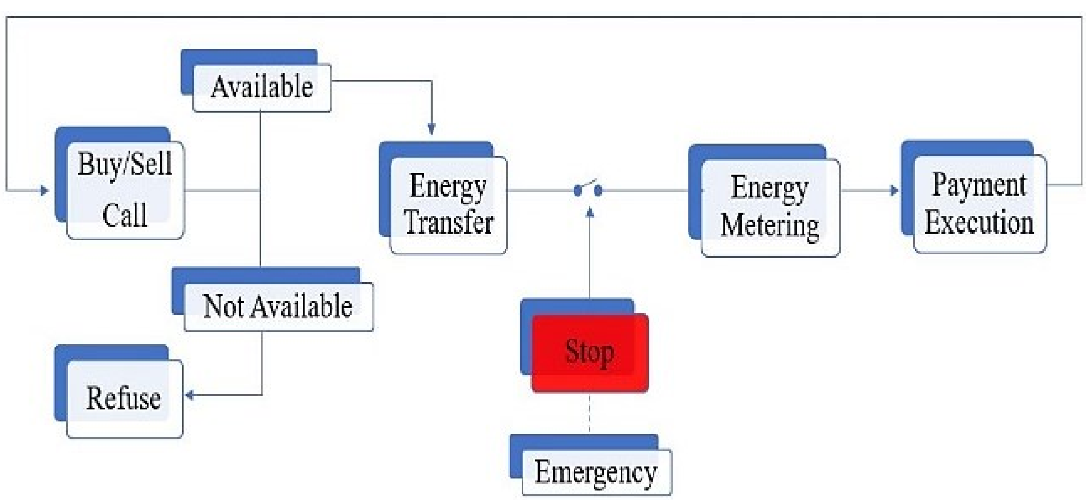

Figure 3.4. Block diagram of P2P energy trading

Figure 3.4 shows the block diagram of a P2P energy trading model. The P2P energy trading process starts from buy or sell calls. After a peer receives a buy call, he/she will be able to sell energy. If a sell call is received, the peer may accept the energy selling offer. The next step is to transfer the energy between the peers if enough energy is available. If the available energy is not sufficient for selling purposes, this peer has the choice to refuse the other peer. When ready, the peers may utilize the UI to initiate the transfer of energy. The developed system is fully decentralized and reduces human interventions to a minimum. Once the peers transfer energy, the system automatically disconnects the power supply according to the predetermined time intervals. The server of the P2P energy trading model is developed using Node-Red visual programing language, which can measure the energy consumed and send e-mail notifications of energy consumption to the peers. The block diagram also shows a payment execution block that shows that the system is also enabled to perform the financial transactions in response to the consumed energy. The developed model is also associated with the fully private Ethereum blockchain to perform financial transactions. After the energy transaction is completed between the peers, the buying peer (energy importer) will receive an e-mail notification to pay for the energy consumed, and the financial transactions are then performed using the Ethereum blockchain. The P2P energy trading model, in addition to empowering the participating peers to refuse if sufficient energy is not available, has also an option to stop energy transfer in case of an emergency. The block diagram shows how the P2P energy trading model facilitates the P2P energy trading in a decentralized manner and eliminates the need for any central authority.

The P2P energy trading model presented in this chapter is fully autonomous and works in a decentralized manner. The system can transfer energy between the peers without human interventions, and the associated Ethereum blockchain enables the peers to get the incentive for energy trading. There is no central authority to decide the price of energy. In this P2P energy trading model, the electric energy price is pre-decided amongst the peers allowing energy prices lower than the local energy market. The system can manage energy needs and measure energy

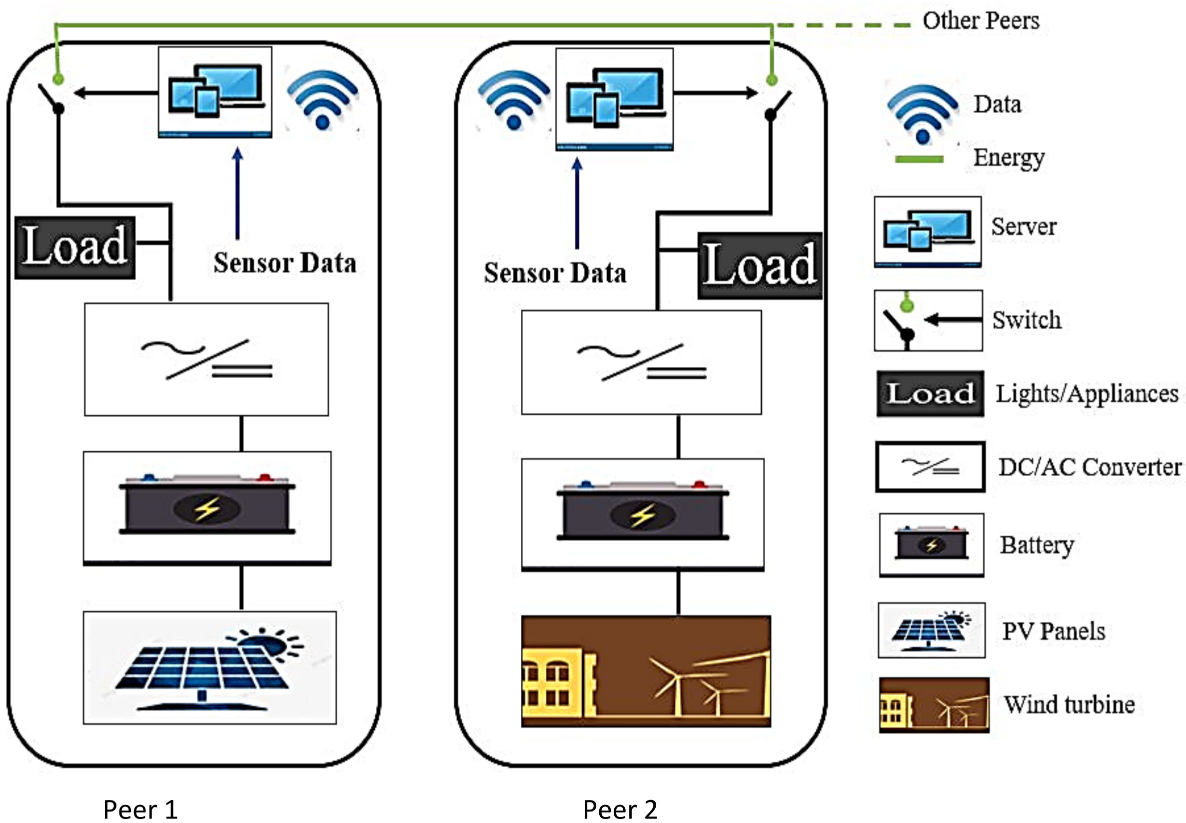

Figure 3.5. Schematic diagram of the proposed System

consumption in real-time, and the buyer must also pay for the energy consumed using the Ethereum blockchain under sufficient security and transparency. The P2P energy trading model developed here is adequate to accommodate 10 participants. However, as an initial test, we have applied it for only two peers, the details of which are presented in the next sections.

Figure 3.5 presents the schematic diagram of the P2P energy trading model. In the figure two peers named "peer1" and "peer2" are shown. Both the peers are equipped with the distributed energy resources. Peer1 is equipped with solar energy resource as photovoltaic panels appears in the figure while peer2 is utilizing wind energy to fulfill its energy needs. The P2P energy trading models enables the participants to share energy after fulfilling their own energy requirements and get the financial benefits in the form of crypto currency. The details of each component are presented below:

- Server: A server has been developed for the P2P energy trading model to facilitate energy trading between peers. Peers are programmed in a Node-Red IoT platform and Ethereum blockchain.
- Data: All the information regarding the energy trading and financial transaction is transmitted between the participating peers of the system using a private network.
- Energy: For the physical transfer of energy services, wires are used in this P2P energy trading model.
- Switch: Switch is used for the physical transfer of energy between peers.
- Load: Load can be lights, motor, appliances, etc. However, for testing this system, two light bulbs of 100 watts each have been used.
- DC/AC Converter: DC to AC converter can be used as most of the renewable energy resources gives DC output, and commonly used household loads are in AC.
- Batteries: Batteries can be used to store energy and supply surplus energy between peers.
- Photovoltaic panels represent a renewable energy source.

- Wind turbine: Represents a renewable energy source.

The proposed peer-to-peer energy trading model has major contribution to facilitate P2P community, it satisfies all the requirements of a fully decentralized P2P energy trading network which has not been addressed yet. IoT platform enables the peers to trade energy with high efficiency. Blockchain technology allows peers to perform and verify financial transactions without relying on any third party.

3.7 Experimental Setup

The proposed P2P energy trading model has two main components:

(1) hardware setup

(2) software-based setup.

3.7.1 Hardware Setup

The hardware setup of the proposed system is presented below in figure 3.6. The structure comprises an Arduino UNO microcontroller, ACS 712 Hall-effect current sensor, relay board, jumper wires, LED, a resistor, and wires to supply energy to the connected load. Arduino UNO is selected based on its compact size and is programmed using Arduino IDE to receive data from the current sensor and onward transmission of data to the IoT server. In this setup 30A module of ACS 712, Hall-effect current sensor is used to measure the current ranging from 0A to 30A. The switching capacity of the SRD-05VDC-SL-C relay board used in this hardware setup is 10A. Figure 3.7 shows the load connected to the system for testing. The load is composed of two light bulbs: 100 watts each. A wired communication protocol is used for the communication of data between the hardware setup and the IoT server.

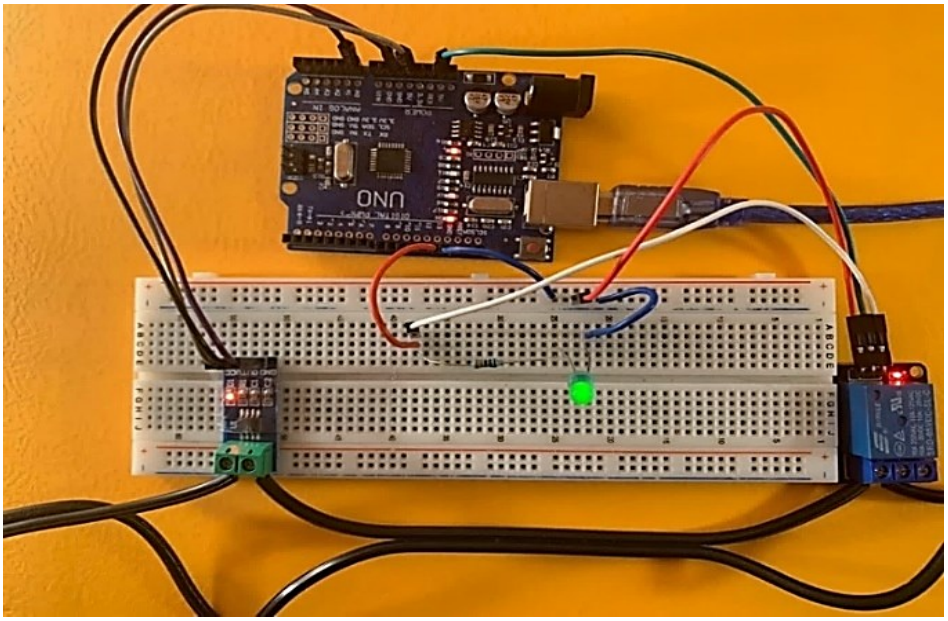

Figure 3. 6. Hardware setup of P2P energy trading model

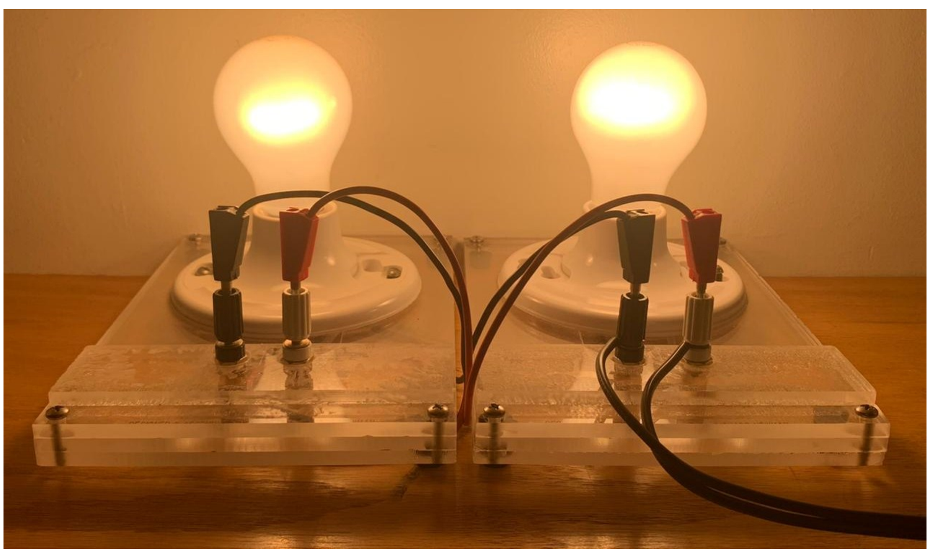

Figure 3. 7. Load connected to P2P energy trading model

After connecting the load to the system, the current sensor senses the current flow and transmits the sensed values to the IoT platform. The IoT platform starts measuring the consumed energy by taking the voltage value as standard AC 120V using payable energy node and based on the information transferred by the Arduino microcontroller (The system is tested in St. John's

Newfoundland, Canada with standard values of AC as there is no voltage fluctuation here). Arduino UNO analog pins are used to transfer the data sensed by the current sensor to the server, and digital pins support the energy transfer process. The relay here is used to perform automatic switching operations. The relay operates based on the signal received by the IoT platform. Once the relay gets the signal from the IoT platform automatically starts or stops the energy transfer process. As soon as the energy transfer is complete, an e-mail notification is generated and sent to the energy consumer, and the system is disconnected. Here, an LED is used to indicate the trading session. Once the trading session starts, it turns on. After the trading session is over, it automatically turns off. Table 3.2 summarizes the hardware used in the proposed P2P energy trading model and the purpose of the hardware being used.

Table 3.2 Hardware Description

Hardware used	**Purpose**
Current sensor	Used to sense current drawn by the load.
Arduino board	Arduino microcontroller digital pins are used to perform energy transfer function/indication. Analog pins are used to transmit sensed current value.
LED	LED is used to specify trading session.
Power Supply	Standard 120 V 60 HZ AC power supply is used for testing purposes
Relay	To start or stop energy transfer process automatically
Electric wires	To supply energy to the load
Jumper wires	To connect circuit components
Light bulbs	Two light bulbs 100 watts each are used to serve as load

3.7.2 Software Setup

The software setup comprises a Node-Red IoT platform, Ganache graphical user interface (GUI), Ethereum blockchain, and MetaMask. Node-Red visual programming language is used to develop the flow-based server and create the UI for the proposed P2P energy trading model. Node-Red flow is used to assign tasks to the nodes and to connect the nodes with each other, while the user interface helps the peers to perform the required tasks for efficient energy trading. The peers may access the server remotely and are able to complete required transactions even not being on-site. After completing energy transactions, payment execution can be done on the private Ethereum blockchain using ganache GUI and MetaMask. In this platform, occasionally, the participating peers will have to pre-decide the price of energy themselves without being dependent on any intermediary. Table 3.3 describes the software used to build the server. The hardware setup communicates with the software setup through USB serial ports.

Table 3.3. Software Setup Description of the Proposed P2P Energy Trading Model

Program	**Purpose**
Node-Red	Used to develop the flow to connect different nodes using Node-Red visual programming language.
Node-Red User Interface	Helps peers to perform different tasks, such as ‘Buy’, ‘Sell’, ‘Refuse’, ‘Transfer’, or ‘Stop’.

Ethereum Blockchain	Ganache GUI is used to develop local Ethereum blockchain for test run.
MetaMask	MetaMask is used to perform transactions.

3.7.2.1 Node-Red flow

Figure 3.8 represents the flow, programmed using Node-Red visual programming language for the proposed P2P energy trading model. It represents buttons to facilitate 'Buy' and 'Sell' calls and respond to the respective calls. Peers are connected to each other through e-mail communication. Arduino nodes represent the connection with Arduino board. After the connection is established between the Arduino nodes and the Arduino board the current sensor transfers the data to the server, which facilitates the power measurement through 'Power Meter' and energy measurement using the 'Payable Energy' node as shown in figure 3.8. Node-Red node named 'Payable Energy' is placed to notify the energy consumption of a 'start event', to calculate the energy consumed in KWh, and to show the event time in seconds.

It also declares a 'stop event' after energy transfer is over. Once the stop event is declared by the specific node, it sends an e-mail notification to the peer (energy exporter) notifying the

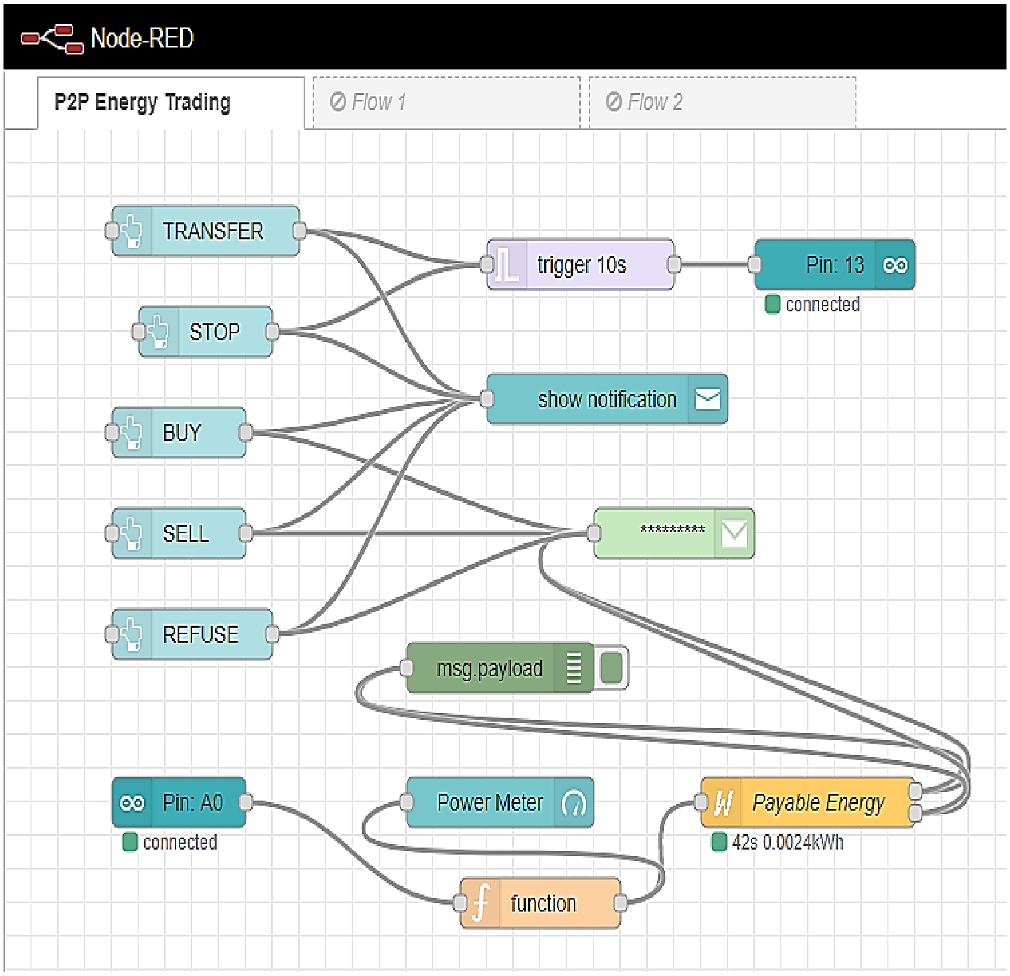

Figure 3. 8. Node-Red flow for the proposed P2P energy trading model

consumed energy and the time for which energy was consumed. For sending e-mail notifications between the peers, the Node-Red e-mail notification node is used, shown in figure 3.8. A trigger node is also shown in figure 3.8, which is used to facilitate the energy transfer for a particular interval of time. After the pre-set time span is over, the trigger node generates a signal that halts the energy transfer process by actuating the relay. A debug node is also used to display all the data on the server itself.

3.7.2.2. Node-Red User Interface (UI)

Figure 3.9 shows the Node-Red dashboard user interface (UI) composed of different buttons and a power meter. A peer can give different calls by tapping on this UI and able to monitor the supplied power on the power meter. It also shows the notification in response to a 'Buy' call generated by peer1. When peer1 makes a 'Buy' call showing the willingness to buy energy, a notification will pop up on the screen. At the same time, peer2 will receive an e-mail notification, as shown in figure 3.10.

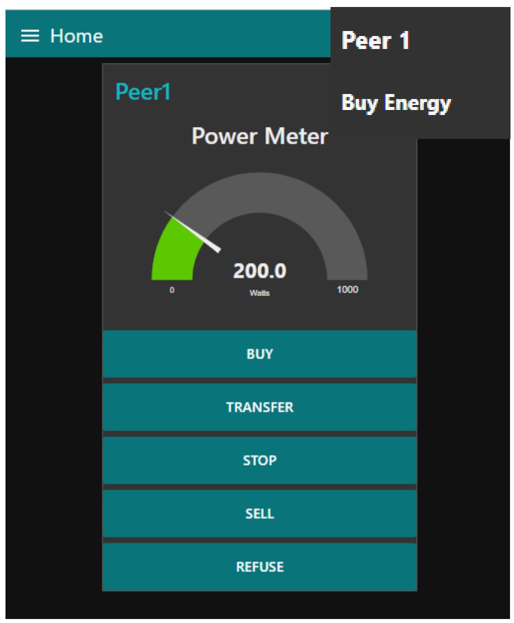

Figure 3.9. Node-Red User Interface

Figure 3.10. Email notification of energy

```
11/23/2020, 11:56:43 AM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "start" }
11/23/2020, 12:00:27 PM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "stop", time: 224, energy: 0.0125 }
11/23/2020, 12:00:27 PM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "start" }
11/23/2020, 12:10:22 PM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "stop", time: 595, energy: 0.0331 }
11/23/2020, 12:10:22 PM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "start" }
11/23/2020, 1:10:25 PM   node: a214c30a.f2b92
msg.payload : Object
 ▸ { name: "Payable Energy", event: "stop", time: 3603, energy: 0.2005 }
```


Figure 3.11. Events shown in debug window

If the excess energy is available or peer2 is willing to sell energy, peer2 will transfer energy using the 'Transfer' button, and energy transactions would start between the peers. Peer1 will get an e-mail notification indicating that the energy transfer has started. After the energy is transferred, the system will automatically disconnect the power supply based on the pre-set time between the peers. Peer1 will again receive an e-mail notification of payable energy showing time (in seconds) and energy consumption (in KWh). The UI of the sever gives the peers some other options such as 'sell', 'refuse', and 'stop'. Peers willing to sell energy can also send the sell call. If the energy is not enough to be sold, the UI allows them just to tap the 'Refuse' button, and the other peer will receive an e-mail notification that energy is not available. In figure 3.9, a 'stop' button is also shown, which allows the participants of the proposed P2P energy trading model to stop the transfer of energy instantly during any unwanted incident.

The system has been tested for various time intervals after connecting the load. All the trading sessions have been shown on the server and communicated to the peer (energy user) at the time energy transfer started and once the trading session was over.

Figure 3.11 shows the start of the energy trading sessions, which also declares that the trading session is over by indicating the ‘event: stop’ notification with time stamps.

The server developed on the Node-Red IoT platform enables peers to trade energy freely according to their choice and without relying upon any utility company. All the trading sessions appear in the Node-Red debug window. At the same time, the energy consumer is notified about the energy trading session through e-mail notifications, as shown in figure 3.12. All the

Figure 3. 12. P2P energy trading e-mail notification

information regarding energy trading would appear in the debug window on the server, and at the same time, all the trading events would be communicated through e-mail notifications. Figure 3.12

shows the e-mail notification from Node-Red regarding the trading session, which is the same as the information that appeared on the server itself. After the peer gets the information about the energy consumed, he/she will then pay for the energy consumed using the Ethereum blockchain. Details are presented in the next section.

3.7.2.3 Payment Execution

For payment execution, we use Ganache GUI, which provides the local network of Ethereum blockchain with 10 accounts. Each account is associated with public and private keys and a balance of 100 Ethers, which can be used to run tests. Ether is a cryptocurrency, and Ganache GUI allows financial transactions in Ethers.

After successful transactions, Ganache GUI creates real-time blocks. It also helps the participants to explore the blockchain, transactions and to deploy smart contracts. Peers can connect using RPC Server.

Figure 3.13 shows the created accounts for the testing purposes, the balance of 100 Ethers in each account except the accounts on INDEX 0 and INDEX 1 as we had performed transactions between these two accounts. The TX COUNT (Transaction count) represents that two transactions have been performed using the accounts at INDEX 0 and 1. For the rest of the accounts, the TX count is 0. The private key is hidden for all accounts. It is important to hide and secure the private key as it gives the peers the rights to funds with the associated address.

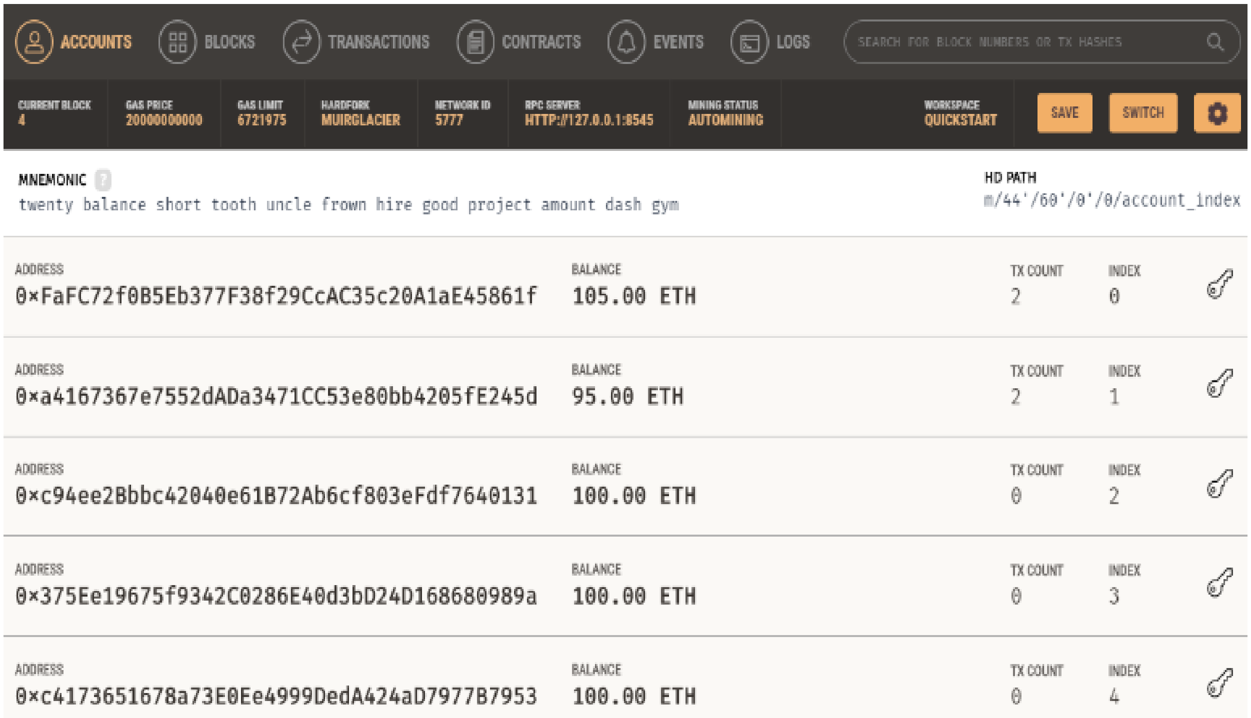

Figure 3. 13. Accounts with associated balance on server

The TX COUNT in figure 3.13 shows that 04 transactions have been performed using the address 0xFaFC72f0B5Eb377F38f29CcAC35c20A1aE45861f and 0xa4167367e7552dADa3471CC53e80bb4205fE245d, hence four blocks have been mined on the blockchain server the status of which is shown in figure 3. 14. It also shows the transaction details and the amount of GAS used.

In cryptocurrency, the network charges a fee from the peers, which is called GAS. It only exists inside the Ethereum blockchain just to check the amount of work done. However, the transaction fee is charged based on the GAS price in the form of Ethers. If we explore the transaction in a block, it gives us important details of the addresses amongst which the transaction is performed, as well as Tx Hash (Transaction Hash), block hash and the time stamp. The transaction Hash is a unique string of characters associated with each transaction. The details saved in block 4 regarding the transaction performed on the private Ethereum blockchain are shown in figure 3.15.

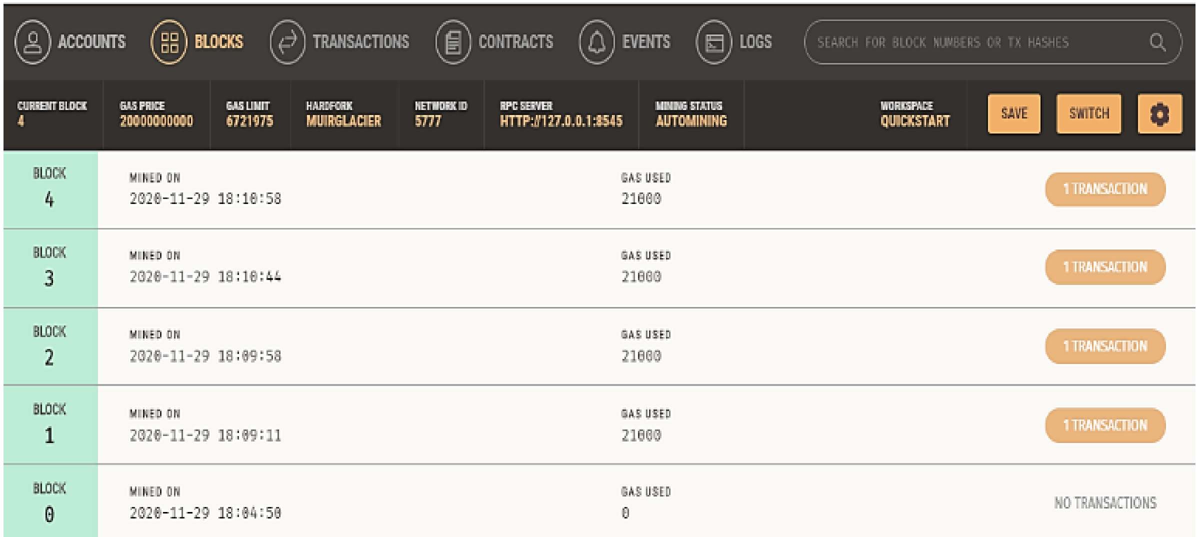

Figure 3.14. Blockchain status on the server

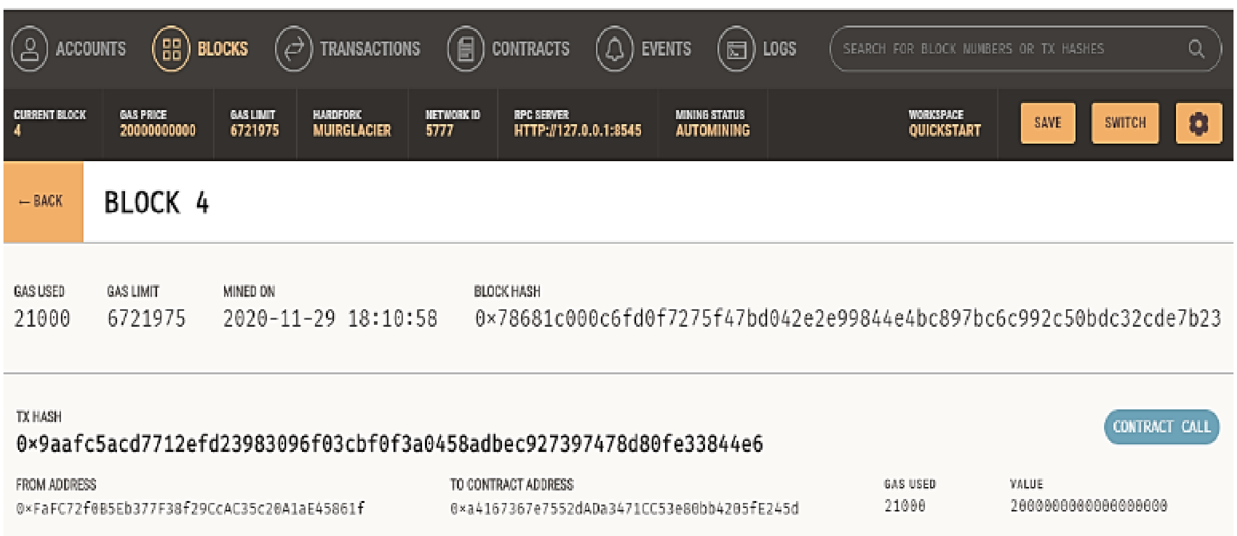

Figure 3.15. Block details

Figure 3.16 shows the MetaMask plugin extension that is used to access the distributed applications of Ethereum as an add-on extension in Google Chrome. Ganache GUI can be accessed using MetaMask to perform transactions.

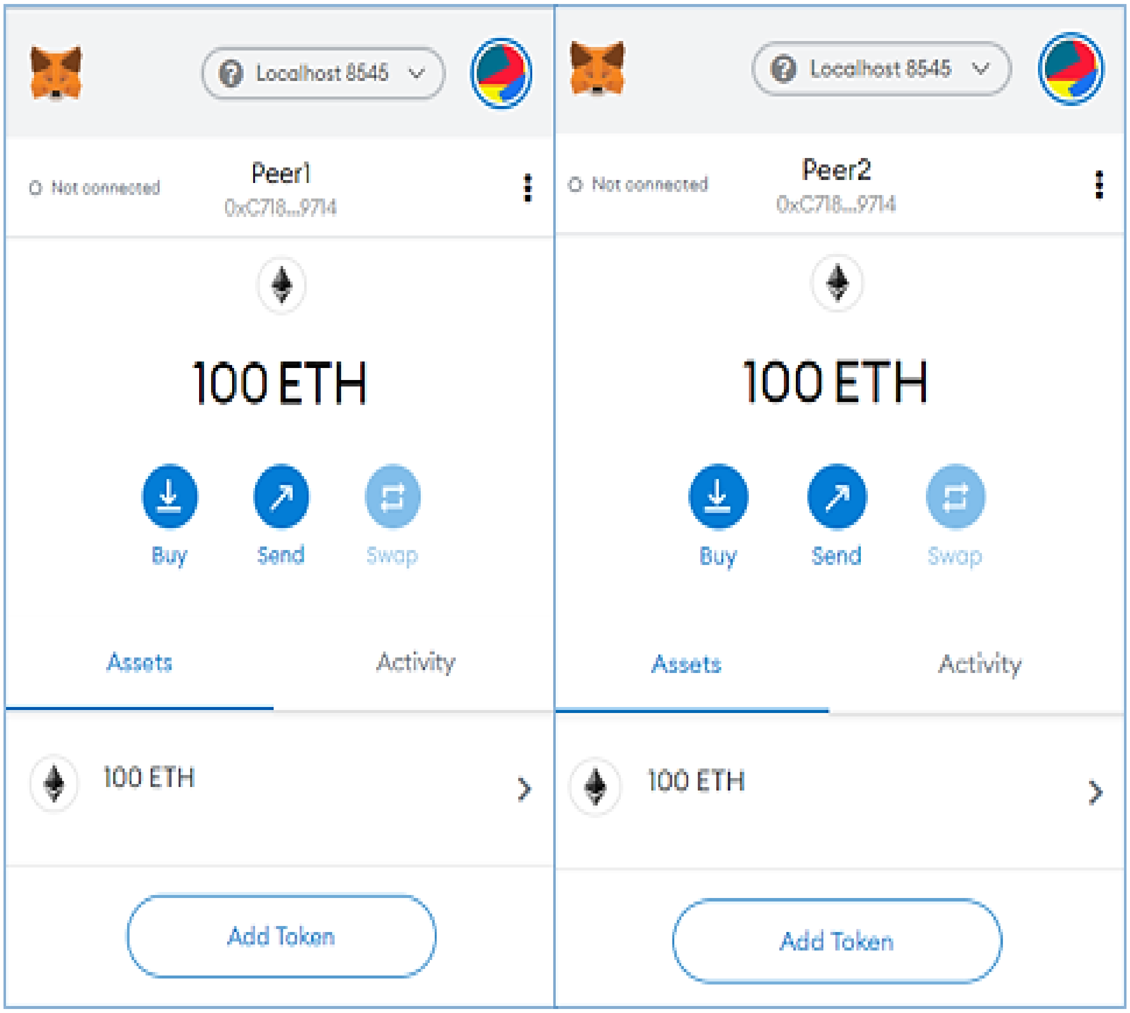

Figure 3.16. MetaMask plugin

The balance of the accounts can be imported to MetaMask using the private keys of the accounts. To perform the transactions between peer1 and peer2, we have imported the balance using the private keys of the accounts into MetaMask. Once the private key is imported in the MetaMask, the balance associated with the private key appears, as shown in figure 3.16. The balance associated with account 0xFaFC72f0B5Eb377F38f29CcAC35c20A1aE45861f for peer1 and account 0xa4167367e7552dADa3471CC53e80bb4205fE245d INDEXED at serial 1 for peer2 has been imported using the private keys, showing 100 Ethers for each account. Once the accounts are imported, the transactions can be performed by the peers, and the blocks are mined with timestamps following each transaction.

In this way, the participating peers of the P2P energy trading model are able to perform secured financial transaction on a private Ethereum blockchain using a unique private key that gives participant access to his ganache account and uses funds in a secured manner. While for the technical side, every participant has access to its own Node-red IoT server to monitor and transfer energy. The participants use e-mail notifications for communication, secured by built-in features of e-mail security like password and two-factor authentication.

3.8 Conclusion

The proposed P2P energy trading model has a unique and simple architecture. As compared to the existing P2P energy trading platforms, the proposed system is user-friendly, open-source, and may introduce increased efficiency and profitability. The existing P2P energy trading platforms mainly focus on software-based financial transactions to facilitate P2P trading. However, the proposed system in this work not only covers the financial side using the blockchain technology but also proposes hardware set up connecting with Node-Red for transfer of energy in real-time to get financial benefits as blockchain server provides a secure and transparent system for financial transactions. We have demonstrated how an open-source platform can be utilized to achieve all the tasks in a P2P network. An interactive user interface has been developed to transfer energy. Ethereum blockchain is used for payments of the consumed energy. The proposed platform provides a complete open-source solution for energy transfer, metering, and fund transfer for P2P energy trading. Although the proposed P2P energy trading model has been tested in real-time for two peers only, this system is able to accommodate 10 peers at a time and can be extended at an inter-community level. This fully decentralized platform gives the opportunity to the peers to decide the price of energy they are producing. They can also control and manage their energy requirements. As such, this system yields financial benefits to the participants of P2P network. The peers can access the server remotely and start trading any time just by tapping on the UI. The proposed system is fully automated and eliminates the need of human intervention. In addition, peers can enjoy the distinct features of blockchain without relying on conventional financial institutions.

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Chapter 4

Design and Implementation of an Open-Source IoT and Blockchain-based Peer-to-Peer Energy Trading Platform using ESP32-S2, Node-Red and, MQTT protocol

Co-authorship statement

Chapter 4 describes a P2P energy trading system that provides real-time data acquisition, monitoring, and control of self-generated energy at a remote location. Trading activities are conducted through a web interface using a private Ethereum blockchain and smart contracts. To implement this system, a combination of software and hardware is used. The monitoring and control of self-generated energy is achieved through the use of an internet of things platform. For financial transactions, the Private Ethereum blockchain is used. This chapter presents system design, implementation, testing, and results. This chapter is based on objective 3, as outlined in section 1.3.

I, Mirza Jabbar Aziz Baig significantly contributed to the Methodology, Software and hardware implementation, Data curation and Writing – original draft of this manuscript as a principal author. This research work is also supervised by Dr. Mohammad Tariq Iqbal, Dr. Jahangir Khan and Dr. Mohsin Jamil who supervised this research work in addition to conceptualization, resources, correction and editing the original draft of the manuscript. This chapter is a version of “M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, “Design and implementation of an open-Source IoT and blockchain based peer-to-peer energy trading platform using ESP32-S2, Node-Red and, MQTT protocol,” *Energy Reports*, *vol. 7*, pp. 5733–5746, 2021, doi: https://doi.org/10.1016/j.egyr.2021.08.190.”

Abstract: An open-source P2P energy trading platform facilitates energy trading amongst the peers. The proposed system provides real time data acquisition, monitoring and control of self-generated energy at a remote location. The trading activities are done on a web interface that uses a private Ethereum blockchain. A smart contract is deployed on the Ethereum blockchain and the trading activities performed on the web interface are recorded on a tamper-proof blockchain network. An internet of things platform is used to monitor and control the self-generated energy. Energy data is collected and processed by means of ESP32-S2 microcontrollers using field instrumentation devices which are connected to the voltage source and load. An open-source decentralized Peer-to-Peer (P2P) energy trading system, designed on the blockchain and internet of things (IoT) architecture is proposed. The hardware setup includes a relay, a current sensor, a voltage sensor, a Wi-Fi router and ESP32-S2 microcontroller. For data transfer the Message Queuing Telemetry Transport (MQTT) protocol is used over a local network. ESP32-S2 is set up as MQTT client and Node-Red IoT server is used as MQTT broker. Hypertext Transfer Protocol (http) request method is implemented to connect the Node-Red server with the web interface developed using React.JS library. The system design, implementation, testing, and results are presented in this chapter.

Key words: Peer-to-Peer (P2P), Ethereum blockchain, Message Queuing Telemetry Transport (MQTT), Hypertext Transfer Protocol (http), Internet of things (IoT).

4.1 Introduction

The proliferation of Distributed Energy Resources (DER) such as Photovoltaics (PV) systems, Battery Energy Storage Systems (BESS), Electric Vehicles (EV), Wind Energy Conversion System (WECS) along with advancements in information and communication systems technologies, has introduced a new electricity market [1]. A significant demand for electric energy and the availability of low-cost renewable energy technologies has raised the number of prosumers in the electricity market. As a result, a considerable interest of selling or sharing electrical energy has been witnessed in the electricity market [2]. Blockchain and internet of things has given a new shape to electricity market. Rather than rely on centralized authority, peers can now perform transactions on their own. Blockchain technology and the Internet of Things can boost the efficiency of peer-to-peer energy trading platforms. Now, consumers can buy energy on local energy markets, instead of having to buy it from utilities. Blockchain and internet of things-based energy trading platforms can be more efficient and controllable for prosumers. The immutable blockchain ledger can also provide a transparent energy and funds usage data in real-time.

As the residential sector is increasingly adopting distributed energy resources, several new market approaches will be necessary. Market participants now prefer distributed generation and to sell electrical power, contrarily to the conventional electricity market. This emerging concept of prosumers now requires a state-of-the-art platform for energy trading. A platform that can provide full trading autonomy, the financial security and pricing liberty and to choose the best suitable time for trading sessions. The direct exchange of energy amongst consumers and prosumers is known as P2P energy trading. Over the past few years, peer-to-peer (P2P) trading has become an only option for consumers to participate actively in energy market. Peers can trade excess energy production with peers through peer-to-peer energy trading, which is beneficial for both parties[3].

Consequently, their investment can yield a return. An important part of peer-to-peer energy trading is that it helps prosumers to trade their energy similar to goods and services. In addition, energy trading on a peer-to-peer basis can also help reduce peak demand on the grid, lowering the need for reserves, and reducing network outages [4]. As described by the GridWise Architecture Council, P2P is also defined as transactive energy (TE), a system for dynamically managing supply and demand across the electric grid. The P2P platform industry is expected to generate revenues of over $ 4 billion by 2026 [5].

A blockchain-based P2P energy trading system is presented in [5]. The system includes bilateral contracts, the Vickrey-Clarke-Groves (VCG) mechanism, an electronic commerce platform, and the ability to trade with the main grid. This multi-layered mechanism accommodates changes in electricity generation and consumption preferences. Furthermore, the VCG mechanism minimizes market power by ensuring that bids are truthful and transparent. To compensate for the disadvantage of VCG, namely, the unbalanced budget, different remedies are also proposed. In their description of the trading framework, the authors described it as multi-settlement and quasi-ideal. To evaluate the execution of proposed P2P frameworks and the solutions for the VCG's inability to maintain balanced budgets, the authors conducted several case studies. An energy trading market concept that is fully P2P is presented in [6], the study incorporates two methods of identifying market preferences. In the first strategy, excess supply and demand are matched, whereas in the subsequent method, the distance between participants is considered. Moreover, the two strategies are evaluated and compared in terms of the effect they have on the price and amount of traded locally energy. The study explains how P2P energy trading market can be developed onto the blockchain in a decentralized manner. The authors emphasized on P2P energy trading model for private houses, integrating electric heating model and optimization model.

Electricity can be purchased and sold locally by plug-in hybrid electric vehicles (PHEVs) in smart grids by using a peer-to-peer (P2P) approach. The authors provide incentives to PHEVs so that local electricity demand balances with local fleets of PHEVs instead of traditional methods that distribute electricity long distances and through complex electricity networks. As part of the study, the authors examine a promising consortium blockchain technology to enhance transaction security without requiring any mediator. The proposed system illustrates the detailed operations of localized P2P electricity trading with the consortium blockchain method (PETCON). To maximize social welfare, an iterative double auction mechanism is used to determine the price of electricity and the amount of electricity traded among PHEVs. Using PETCON, authors increase security and privacy of transactions. The application of the double auction mechanism to a real map of Texas shows that social welfare can be maximized while protecting PHEV privacy [7]. In another research article, an energy trade system that employs P2P energy trading while simultaneously considering demand response is presented. The energy market is conceptualized as a non-cooperative Stackelberg game amongst prosumers and auctioneers. Prosumers, as buyers, maximize social welfare by solving optimization problems. The auctioneer also boosts the average social welfare of sellers. The authors proposed a unique Stackelberg Equilibrium (SE) that is the ideal solution to the optimization problem. Blockchain technology is used by the authors to implement the proposed algorithm, which provides enhanced security and privacy protection, and demonstrates the feasibility of the P2P energy trading approach. This blockchain-based energy trading approach is also measured for throughput, latency, and running time [8].

A latest research presents simulations results of P2P energy trading based on real-world data by introducing a market mechanism and a decentralized market clearing method with the blockchain integration. Markets and blockchain are two key components of the proposed platform.

The market layer is based on a short-term pool-supported auction and is cleared through a unique decentralized Ant-Colony Optimization procedure. Using this market procedure, players' privacy is preserved, and they can trade products between different time periods. Blockchain technologies facilitate real-time settlements through automated processes, security, and the implementation of smart contracts. In this study, the authors simulated energy trading, clearing markets, smart contract operation, and blockchain-based settlement conducted through a platform based on real-world data [9]. Ref. [10] examine the possibilities for self-governing peer-to-peer energy trading from within microgrids utilizing blockchain technologies and auction mechanisms. A continuous double auction framework and a uniform-priced double-sided auction framework are designed that both employ Ethereum's smart contract functionality. A/B tests were performed on a real-time data to validate the proposed design. To compare the two frameworks, the authors presented a number of cost analyses. The authors emphasized a P2P trading platform that incorporates blockchain technologies and agent-based systems could revamp the current centralized energy grid.

During peak hours, a central power system can decrease energy demand of its customers by using a peer-to-peer (P2P) energy trading approach. As a result, a cooperative Stackelberg game is devised, in which the central power system acts as the leader that determines a price during the peak demand period to compensate for prosumers not consuming energy from it. By contrast, prosumers act as followers and form coalitions with neighbors to take part in peer-to-peer energy trading to meet their energy needs in reaction to the leader's decision. Stackelberg's proposed game is examined for its properties. Because of the stability of prosumers' coalitions, the game uses a unique and stable Stackelberg equilibrium. At equilibrium, the leader formulates its strategy using a closed-form expression, while the prosumers select their coalition structure. Peer-to-peer (P2P) energy trading is suggested in this chapter to lower the total electricity demand of a central power system during peak hours. In this study, the authors propose an algorithm that facilitates the equilibrium solution between the centralized and the prosumer power systems. The proposed scheme has been proven beneficial in numerous case studies [11]. With the help of Ethereum's blockchain and smart contracts, the authors enabled peer-to-peer (P2P) energy trading amongst consumers and producers. Smart contracts reside on a blockchain shared by the participants, thus guaranteeing exact execution of trades, and keeping immutable records of transactions. The system eliminates the high costs and overheads of conventional server-based P2P energy trading. The study implements, Microgrid dynamic pricing to balance total supply and total demand, preventing double sales, automatic and autonomous operation [12].

A wealth of literature review has been carried out as a part of this research and some is presented here in this chapter. Our research has not found any publications referring to the usage of a locally installed Node-Red IoT server for monitoring and controlling energy in a Peer-to-Peer energy energy trading system design. Moreover, the use of ESP32-S2 micro-controller in our design, ensures that a local participants of P2P energy trading network can visualize the state of the process by visualizing data information on the Node-Red dashboard. A private Ethereum's blockchain is also integrated with a web interface developed using React.JS library for performing trading activities on a locally installed server. This not only helps in performing trading activities but also to maintain the tamper-proof records of energy trading sessions. Both the servers are fully automated and interconnected with each other by means of http request method. The proposed platform is locally installed on a machine and can be accessed remotely.

This article presents a novel peer-to-peer trading platform, with the following key contributions:

- This chapter presents an innovative Peer-to-Peer energy trading platform design using open-source resources with real time settlements, technical and economic efficiency.

- Design and installation of server on a local machine and communication channel makes it useful for remote locations with no internet access.
- Implementation of a Peer-to-Peer energy trading platform by installing a decentralized web interface, Ethereum blockchain, locally installed Node-Red IoT server hosted on a local network is the main feature. The fact that an open source, peer-to-peer energy trading network has never been seen before is novel to the best of our understanding.
- After a thorough review of the available research, we present a straightforward and unique approach to the design and implementation of an IoT and blockchain-based open source P2P energy trading platform. Any future participant planning to carry out such an exercise will find this chapter a useful guide.

The remaining parts of the paper are arranged as follows. Section 4.2 of the paper presents an overview of the technologies used in this chapter including blockchain, internet of things and MQTT protocol. Section 4.3 describes a brief overview of the proposed open-source IoT and blockchain-based Peer-to-Peer (P2P) energy trading platform. Section 4.4 represents the details of the components used for the design and implementation of the proposed P2P energy trading platform. This includes ESP32-S2 microcontroller, relay, current sensor, voltage sensor, Energy storage system (ESS)/ battery and load. In section 4.5 we discussed the web interface and IoT server and http request method to connect the servers. Node-Red flow, based on Node-Red visual programing language are also discussed in this section. Section 4.6 depicts the implementation methodology used in this chapter. It describes how the required data is collected and energy trading sessions are performed. As a part of section 4.7 and 4.8 system design, implementation and experimental setup are discussed. Section 4.9 includes the testing and results of the proposed P2P energy trading platform. In section 4.10 discussion about the key features of the system is presented. In section 4.11, we conclude the paper and section 4.12 depicts the future work direction.

4.2 A Brief Overview of Technologies

Throughout section 4.2, the major technologies incorporated into the design and implementation of our proposed open-source peer-to-peer energy trading platform are briefly introduced. Ethereum blockchain and internet of things (IoT) are two of the technologies upon which P2P energy trading platforms are based, as well as Message Queuing Telemetry Transport (MQTT), a lightweight protocol for IoT data transfer.

4.2.1 Blockchain Technology

A blockchain is made up of blocks put together in the form of a chain. Data from each of the participants in the network is stored in these blocks. This is done in a block format, called a set of transactions. Following their formation, these transactions are grouped into blocks and connected to one another in chains - along with the time stamp [2]. These blocks are records of data that are continuously added into a distributed ledger called a blockchain [20]. An additional layer of security is provided by this chain mechanism, even the smallest modifications invalidate subsequent blocks. Furthermore, if only the hash of the last block is verified, the validity of entire chain can be ascertained. Initial applications of blockchain were used to track economic transactions without requiring trusted intermediaries (such as banks). Even if its origins are in economic transactions, like Bitcoin, the blockchain has proven to be an applicable technology to other fields, when distributed approaches are the choice to centralized ones. For energy purchases or sales, blocks can be organized into tables with details such as seller ID, buyer ID, amount of transferred energy, duration, timestamp, and power profile [21]. As part of this study, we have used a local Ethereum blockchain, which is provided by Ganache graphical user interface (GUI).

Ganache GUI is a personal Ethereum blockchain which can be used for distributed application development. It ensures that dApps can be developed, deployed, and tested in a deterministic and secure environment [22]. Users can deploy smart contract and run tests using Ganache. Ganache also provides 10 accounts with 100 fake Ethers in each account. These Ethers and accounts can be used to perform test runs. To manage the wallet and to perform transaction MetaMask is used which is a google chrome extension. Peers willing to use P2P energy trading platform can be connected to each other on a blockchain server using remote procedure call (RPC) protocol. Figure 4.1 shows the overview of Ganache GUI, a local Ethereum blockchain used as a part of this research. The digital address of each account can be seen in figure 4.1 with 100 ETHS in each account. Each account is also associated with a unique private key that ensures the security of wallet.

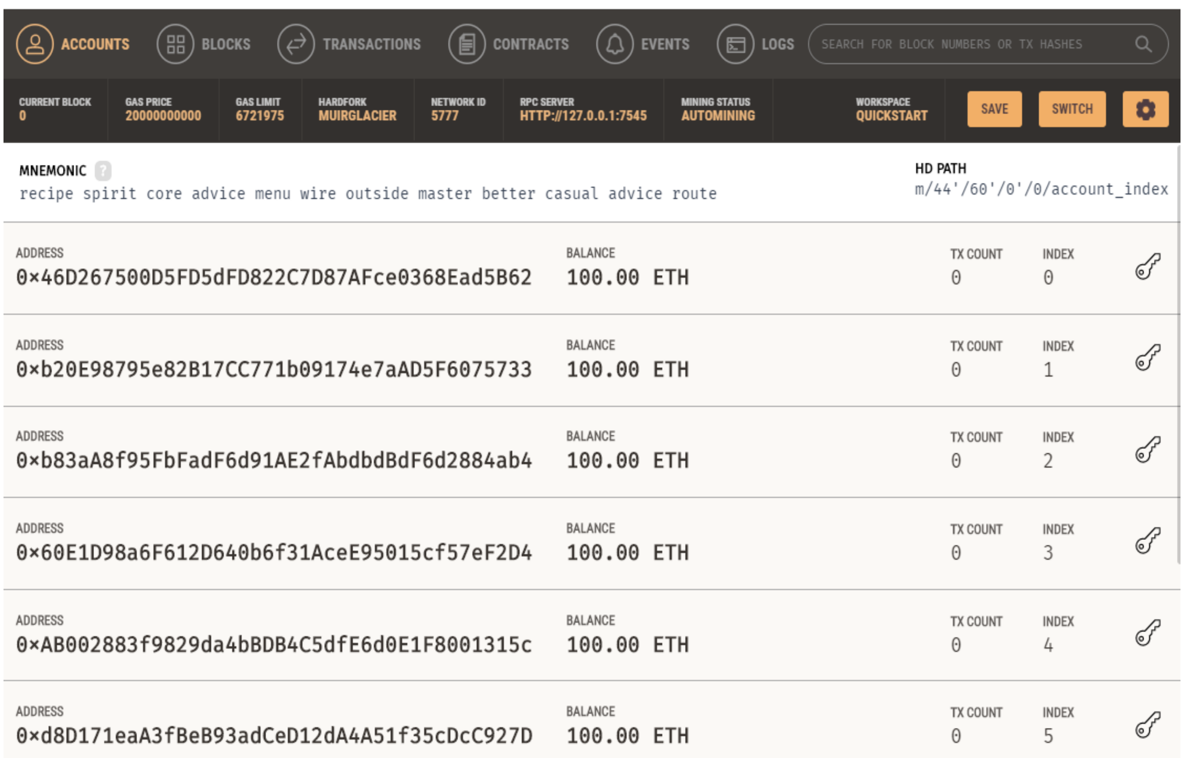


Figure 4.1. Blockchain Server

4.2.2 Internet of Things (IoT)

In this high-tech age, the Internet of Things (IoT) has changed many traditional ways of living. IoT has allowed cities, homes, pollution control, energy conservation, smart transportation, and industries to undergo amazing transformations. We can sense the Internet of Things everywhere we go, constantly increasing our quality of life. Overall, IoT encompasses a wide variety of smart systems, structures, devices, and sensors [23]. Internet of Things (IoT) combines sensor, computing, embedded, and communication technologies. The Internet of Things aims to offer smooth services to anyone, anywhere, at any time. IoT is bringing the fourth major revolution following the internet and Information and Communication Technologies (ICT). Researchers and developers predict IoT will improve society's well-being and industries more than the internet and ICT [24]. Basically, the internet of things (IoT) lets electronic, sensor, and software devices to interconnect with each other, as well as an operator, to facilitate the collection and sharing of real

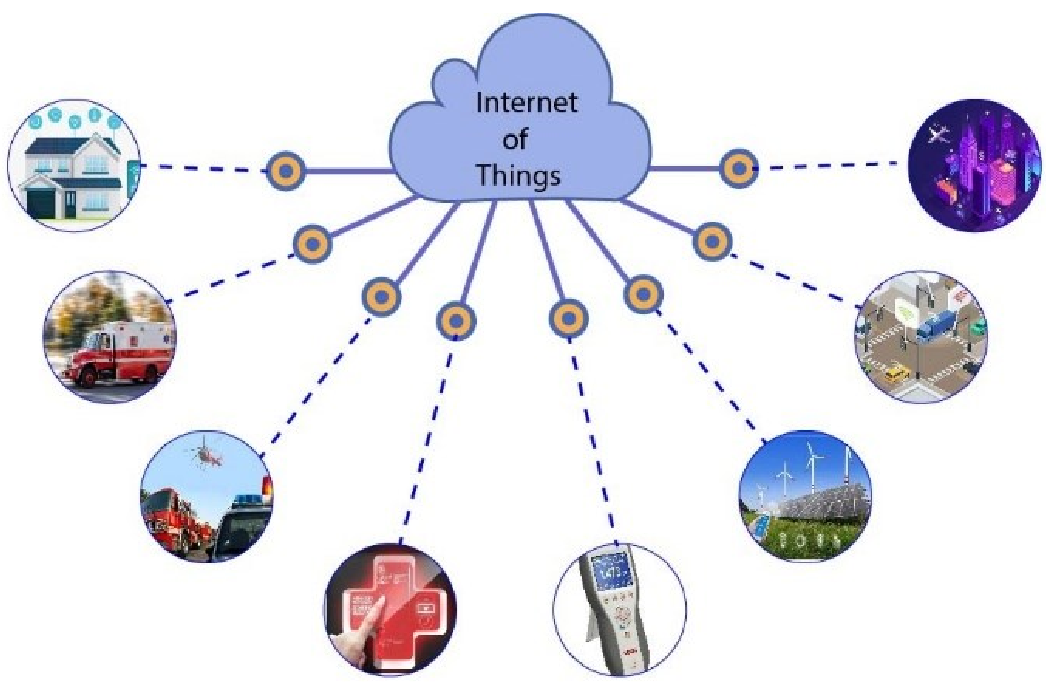


Figure 4. 2. Internet of things platform

time data [13,19]. It allows physical devices to be made smarter through the transformation of traditional forms into smart ones [13].

Smart energy management systems, smart emergency response systems, smart healthcare systems, smart transportation and industrial automation, smart homes and smart cities, etc. have been developed in recent years, utilizing the IoT model [13,19]. Also shown in figure 4.2, various smart platforms are connected with an IoT platform.

Node-Red has been selected for use as a preferred IoT platform. Locally installed Node-Red server on a private machine ensures platform's security and privacy. Node-RED allows users to replace common coding tasks with visual drag-and-drop to connect web services and gadgets. Various components are linked together to create a flow using Node-Red editor.

4.2.3 Message Queuing Telemetry Transport (MQTT) Protocol

A lightweight data communication for machine-to-machine interaction can be achieved using Message Queuing Telemetry Transport (MQTT) protocol [13]. MQTT's 2-byte fixed header makes it ideal for internet of things applications, since it can handle applications having low bandwidths, low computing power, little memory, and low batteries, which are common in IoT applications [14,15]. Andy Stanford-Clark of IBM and Arlen Nipper of Arcom (now Eurotech) initially developed MQTT protocol and now the Organization for the Advancement of Structured Information Standards (OASIS) recognize MQTT as an open standard [16]. For the purpose of implementing MQTT, TCP/IP connection is required, with wired or wireless local area networks [17,18]. As part of the MQTT protocol, message delivery is graded according to Quality of Service (QoS) levels 0 through 2. As a result, the MQTT protocol is ideal for IoT applications with limited resources as a reliable data transfer protocol [13,14,15,18]. MQTT is therefore considered preferable to other protocols like REST, CoAP, API and HTTP, etc. MQTT also uses TCP/IP to communicate, only CoAP uses UDP [13,18,19]. There is an extensive discussion of the properties, benefits, and drawbacks of various IoT protocols, like MQTT, HTTP and CoAP in [13,19]. For the proposed open-source IoT and blockchain-based Peer-to-Peer Energy trading platform we have used MQTT, IPv4, TCP and IEEE 802.11 IoT protocol. MQTT protocol is used to transfer data

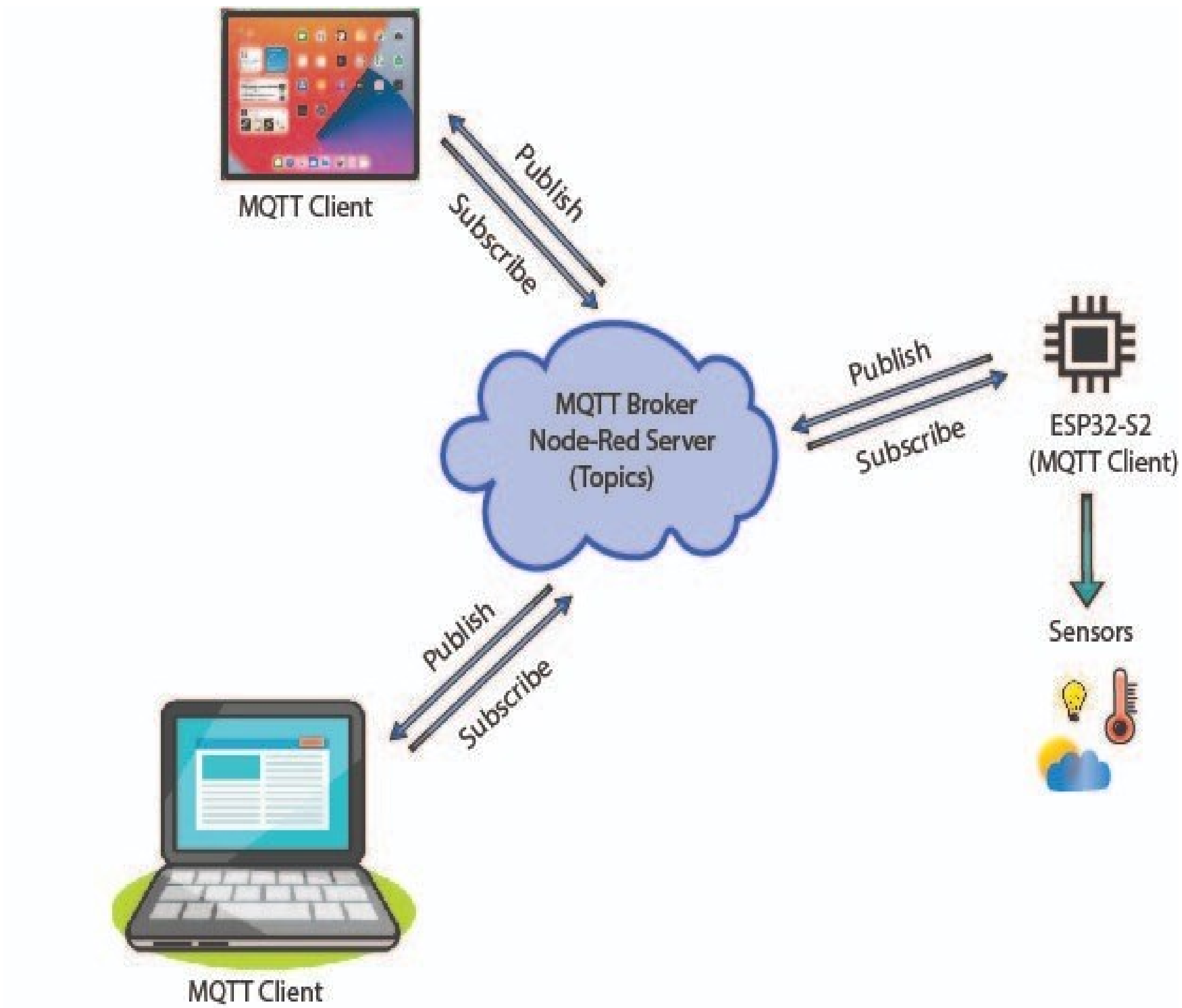


Figure 4.3. Overview of MQTT Protocol

from ESP32-S2 (MQTT client) to Node-Red IoT server . Whereas, personal smart devices (MQTT clients) can be used to subscribe topics to visualize data on Node-Red IoT server. An overview of the MQTT protocol is shown in figure 4.3.

4.3. The System Description

Throughout this section, the authors describe the architecture of the proposed open-source P2P energy trading platform. The system configuration in figure 4.4. shows a web interface hosted on a local machine to perform energy trading tasks. The web interface is connecting to the Node-Red server used to monitor and control energy. Http request method is implemented to connect the

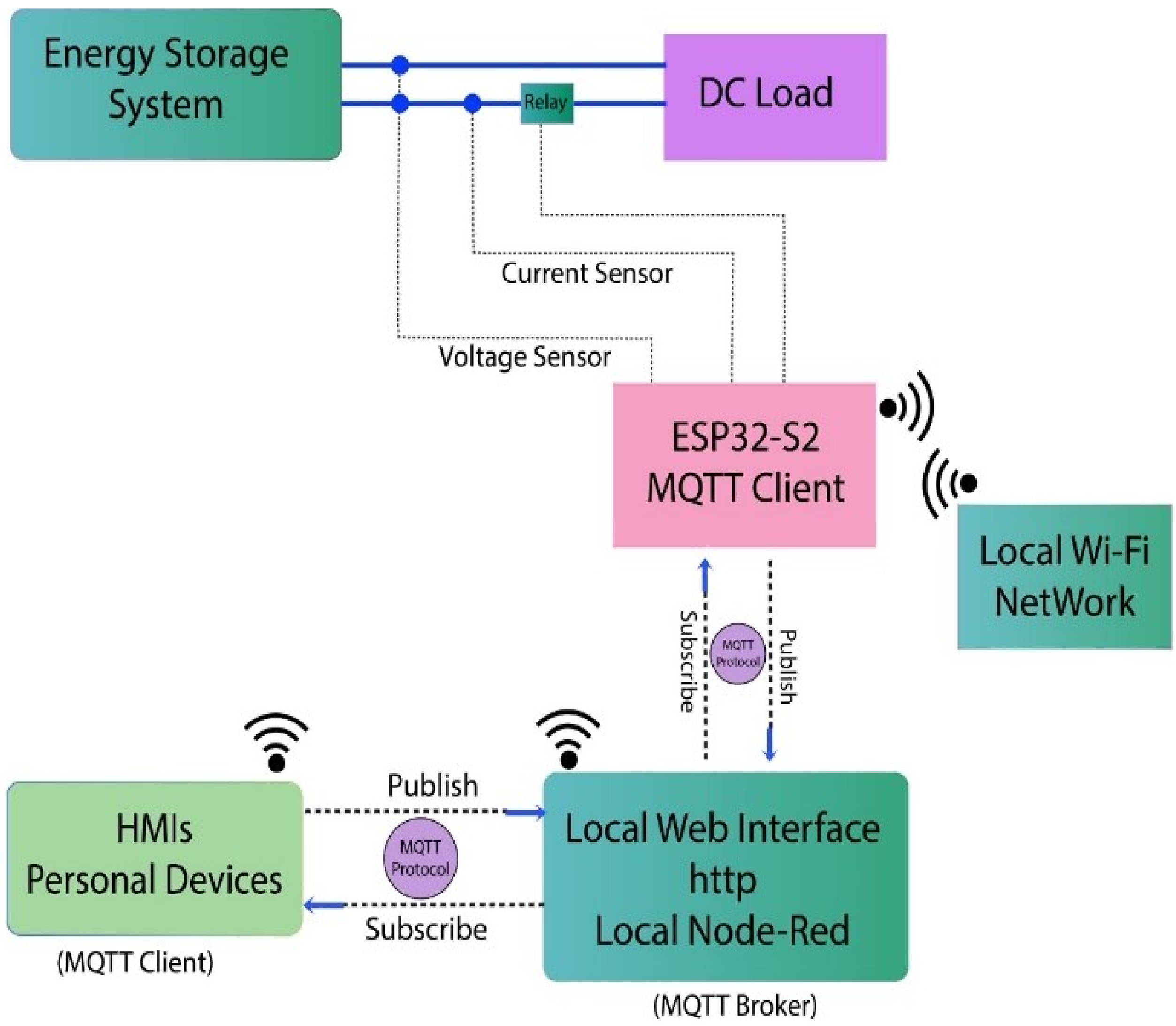


Figure 4.4. P2P energy trading platform architecture

two servers, so that an energy trading process can take place. To develop the communication link between the various components of the proposed system a Wi-Fi router is used. For system security, user authentication is set up on the router. Only authorized user can access the network.

Energy storage system (ESS) represents a battery which is connected to a DC load. ESP32-S2 (MQTT client) publishes the sensor data (voltage and current) to Node-Red IoT server (MQTT Broker) after processing. This configuration also demonstrates a relay device that facilitates energy trading sessions. On receiving an energy demand, it starts energy transfer process and after the demand is successfully fulfilled it halts the process. This is done by means of an algorithm without any human intervention. The participating peers can access the system using personal devices on the same network.

4.4 Components of Proposed Peer to Peer energy Trading Platform.

4. 4.1 Sensors

4.4.1.1 ACS 712 Hall Effect Current Sensor

ACS 712 Hall effect current sensor is used to measure load current using Hall Effect principle. It provides voltage isolation of 2.1kVRMS and a low resistance conductor that is integrated into the sensor. Hall ICs convert the magnetic field generated by copper conductors into proportional output voltages by converting the current flowing through the copper conductors. As a result, an output voltage is produced which is proportional to the measured AC or DC current [26]. This module is available to sense the current of 05A, 20A and 30A with the output sensitivity range of 66mV/A to 185mV/A at a supply voltage of 5VDC. It uses the ACS712ELCTR chip as its central component [26]. To measure analog signals, the ESP32-S2 uses a maximum range 3.3VDC supply, so by connecting the Vcc pin ACS-712 Hall effect current sensor with the 3.3V pin of this sensor and selecting appropriate value of sensitivity accuracy of measured values is ensured. As a part of this study, we have used 20A DC module.

4. 4.1.2 Voltage Sensor

ESP32 is a 13-bit device, and its ADC pins are capable to read 3.3V. To convert the bus voltage of the proposed open-source P2P energy trading platform to the readable signal range of ESP32-S2 ADC pins, a simple voltage divider circuit is used in this project. Equation (1) shows the voltage divider equation.

$$V_{out} = V_{in} \times \frac{R_2}{(R_1+R_2)} \quad (1)$$

Where V_{out}= ESP32-S2 ADC voltage (3.3) and V_{in}= Source voltage or Battery voltage (12V), Whereas R_1 and R_2 are calculated using V_{out} and V_{in}as a reference.

With voltage divider circuit, the bus voltage of 12V is converted to 3.3V, which ensures the proposed design is capable to sense the bus voltage of the proposed platform.

4.4.1.3 ESP32-S2 Micro-Controller

ESP32-S2 a single core Wi-Fi microcontroller is designed by ESPRESSIF and featured with high performance, low power consumption, and a vast array of I/O (inputs and outputs). An integrated product featuring extremely low power consumption and 2.4 GHz Wi-Fi on a system-on-chip solution makes it ideal for IoT applications. The Wi-Fi solution is offered by this chip fully complies with the IEEE 802.11b/g/n protocol. There is a 32-bit Xtensa® LX7 processor on this chip that operates at 240 MHz. This device has a rich set of peripheral interfaces including I2S, I2C, UART, SPI interface, LED PWM, LCD, camera interface, ADC, touch sensor, DAC and temperature sensor, in addition to 43 GPIOs (General Purpose Inputs and Outputs). In addition, it supports full-speed USB On-The-Go (OTG), which allows USB communications [27].

4. 4.1.4. Wi-Fi Router (Communication Channel)

For data communication on the TCP/IP Wireless Network between ESP32-S2 (MQTT Client) and Node-Red server (MQTT Broker) and web interface we have used D-Link Router (DI-524 Airplus G). To establish a local Wi-Fi connection network, the router is used, since the ESP32-S2 microcontroller used in this project is compatible with TCP/IP and IEEE 802.11b/g/n Wi-Fi standards [18,27]. In this way ESP32-S2 publishes sensor data to Node-Red IoT server over MQTT protocol. Wi-Fi network connections is restricted to authorized persons using service set identifier (SSID) and password.

For the successful testing and to obtain required results, we have also used a 12V, 7.2Ah/20HR battery as source voltage and 12V, 50W DC light bulb as load. We have also developed an interactive user interface to perform energy transactions using React.JS and a Node-Red server is set up to monitor and control the self-generated energy. More details about the server are presented in the following section of the paper. Table 4.1 presents the name of the components used to design an open-source P2P energy trading platform.

4.5 Web Interface and Node-Red IoT server

We have used React.JS (an open-source tool used to create user interfaces for web applications) library to create front-end/web interface for the proposed open-source P2P energy trading platform which is also locally installed on the system and accessible from http://localhost:3000/ and is integrated with MetaMask and Ganache GUI. The smart contract has been deployed on the local Ethereum blockchain. Reloading is made faster with the virtual document object model (DOM) since the virtual DOM allows rendering to be sped up. The React.JS framework is also used by many real-time applications, including Facebook and Netflix

[28]. The source code used for web interface, connectivity with Ganache GUI and smart contract are extensions of [30] to develop an appropriate P2P energy trading platform. The detailed installation guide on the basic concept can be found at [31]. Participating peers of the proposed open-source P2P energy trading platform can access the user interface at http://localhost:3000/ to perform energy trading tasks. Figure 4.5 shows an interactive and user-friendly interface developed for the P2P energy trading with a MetaMask plugin. The user interface is linked with local Ethereum blockchain on which smart contract is deployed. All the transaction performed are saved on an immutable blockchain network. As shown in figure 4.5 participating peers can bid their energy requirement and in response the peers with access energy can also post a selling notification with price and quantity of energy. This allows the buyer to buy energy on a most suitable price, which may be less than the bidding price of the buyer.

Table 4.1. Components used in P2P energy trading platform

Module Used	**Purpose of module in the design**
React.JS Library	To develop web interface of the system
Node-Red Server	To monitor and control self-generated energy
Ganache GUI	To deploy local Ethereum blockchain
ESP32-S2 Microcontroller	Read sensors value and publish sensors data over MQTT
ACS-712 Hall effect Current Sensor	To measure load current
Voltage Sensor	To measure the voltage
Relay	To start or stop energy transfer
12V, 7.2Ah/20HR battery	Source voltage

12V, 50W DC light bulb	To serve as load
Electric Wires	To connect the components of proposed design
Jumper Wires	To connect the components of proposed design
Breadboard	Build the circuit

The user interface developed for P2P energy trading platform is integrated with Ganache GUI a private Ethereum blockchain which can be accessed through MetaMask. Peers can access their respective wallets using MestaMask plugin. Once the peers perform any type of transaction

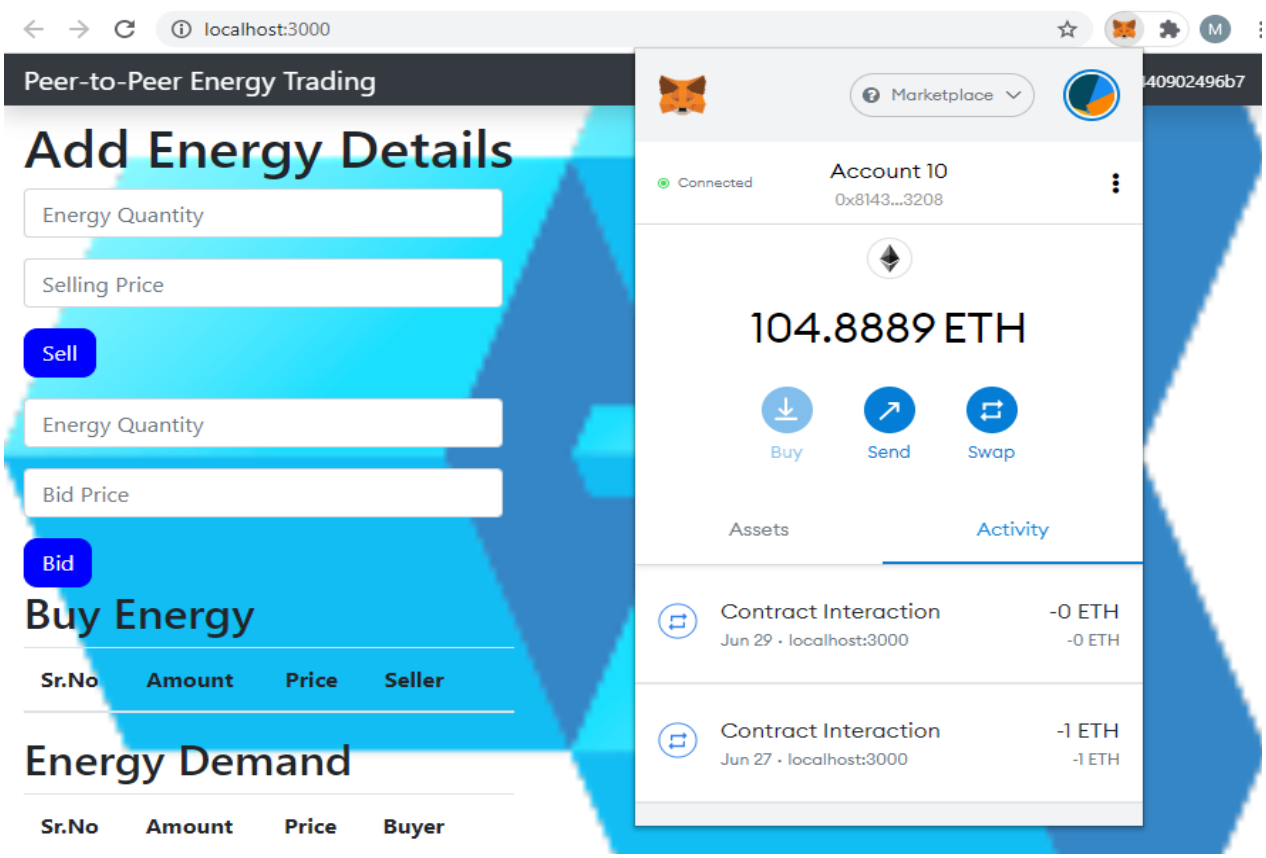


Figure 4.5. Web interface of proposed P2P platform with MetaMask add on

on the user interface MetaMask plugin will pop up automatically on the screen and peers will reconfirm the amount charged for their particular transaction, that might be the energy purchasing

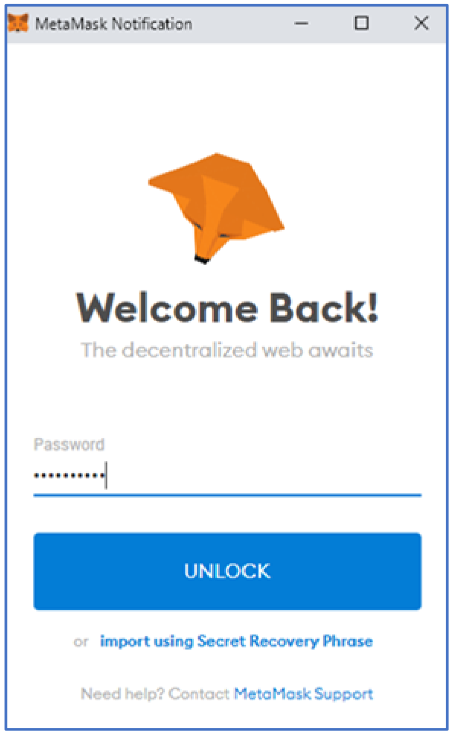


Figure 4.6. MetaMask plugin

price or gas used. Gas is a fee Ethereum charges to successfully perform the transactions on a blockchain network. Ethereum blockchain network charges a fraction of Ether in terms of fee. The price of gas is expressed in gwei, a unit of ETH, and each gwei equals 0.000000001 ETH (10^{-9} ETH). Rather than saying that your gas costs 0.000000001 ether, you might say it costs 1 gwei [29]. The MetaMask notification is shown in figure 4.6 is linked with http://localhost:3000/ and allows to access accounts on a local Ethereum blockchain. For the security of the system the peers on the P2P energy trading platform use their own password to access the platform as shown in the figure 4.6, in addition each account is associated with a unique private key, which allows the user to access their Ethereum wallets.

The proposed system incorporates the features of a fully decentralized network, the participating peers have full liberty to decide the energy quantity and price without the involvement of any central authority. Peers can also delete the posted bid/ offer if for some reason the transaction is not complete.

Node-RED an open-source solution was developed by IBM Emerging Technology. This web application is based upon Node.js (a server-side java scripting platform). Node-RED runs locally on http://localhost:1880. It also offers options to quickly build a live data dashboard using Node-RED user interface module. The user interface is accessible from http://localhost:1880/ui using a local browser [25]. Node-Red flow can be made by using simple drag and drop options and flow can also be saved, import and export as a JSON file.

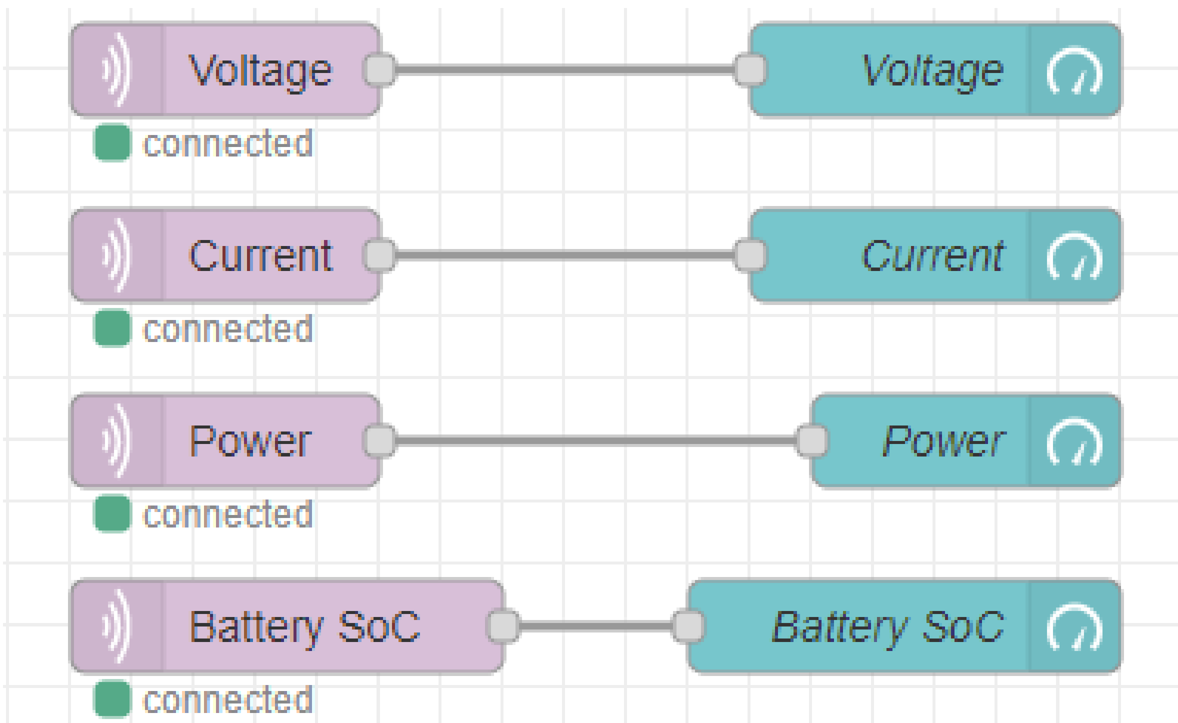


Figure 4. 7. Node-Red flow for data acquisition

Figure 4.7 shows a Node-Red flow programmed using Node-Red visual programming language. The voltage, current, power and battery state of charge (SoC) data are transferred via MQTT protocol from the hardware components of the system and can be visualized on Node-Red user interface. Node-Red server is also installed on a local machine.

For the fully automation of the P2P energy trading platform, we have implemented Hypertext Transfer Protocol (HTTP) request method. There are different http request methods like, DELETE, POST, PUT, GET, HEAD, OPTIONS, PATCH. We have used http POST method to catch the request from http://localhost:3000/. Once the participant peer of P2P energy trading platform sends a buy request to purchase energy, the amount of energy will be posted to Node-Red server and if the required amount of energy is greater than zero, it will be transferred automatically using a computer algorithm. The algorithm is implemented in the function node on Node-Red flow that will compare the energy demand with the amount of energy being transferred. Once the required amount of energy is transferred it will send a turn off message to the relay. In this way we have attained a fully automated P2P energy trading model on a local blockchain using open-source technology.

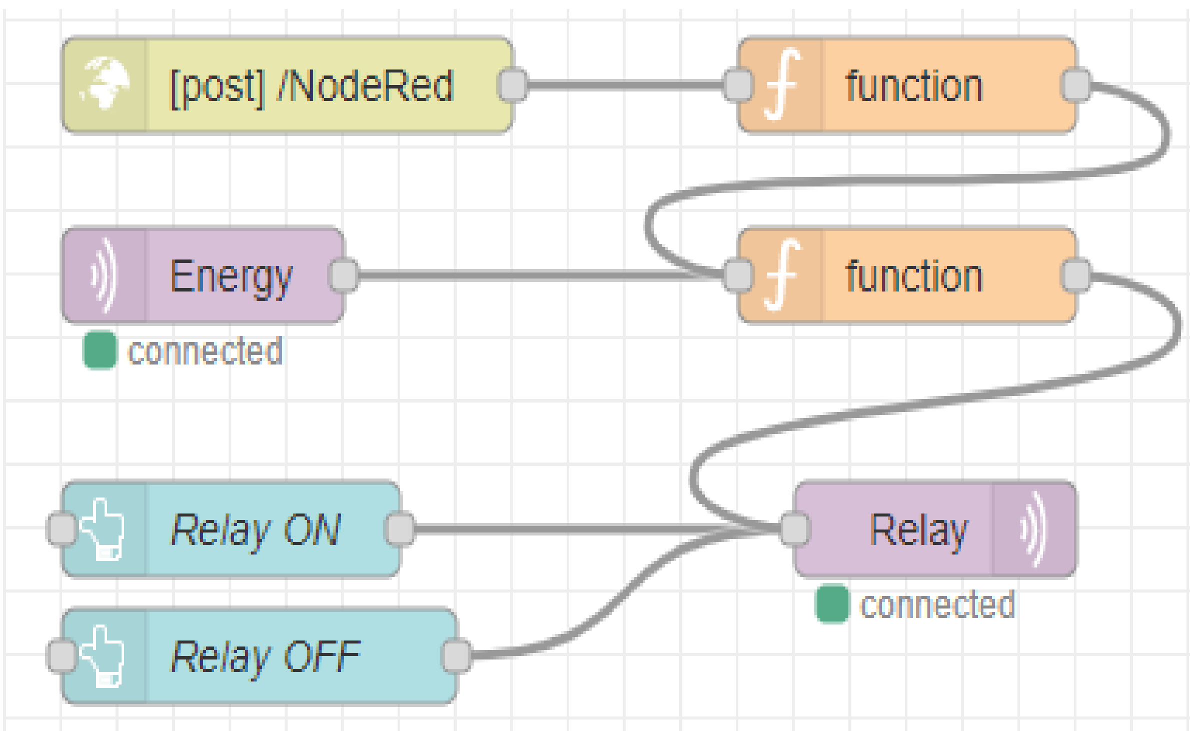


Figure 4.8. Node-Red flow to facilitate energy trading

Figure 4.8 shows a Node-Red flow that facilitates energy trading with a http request node to get the value of required energy from the web interface of the proposed P2P energy trading platform. Once the Node-Red https request node gets the energy demand from the web interface and then the attached function node converts the JSON string into the raw value to compare with the MQTT energy node using the other function node shown in the figure 4.8 attached directly with MQTT energy node. When the energy demand and energy transferred amounts are equal, compared by implementing the algorithm in the function node it will actuate the relay to stop energy transfer process.

4.6 Implementation Methodology

As a part of implementing the proposed open-source P2P energy trading platform current, voltage, and battery state of charge (SoC) data are measured and processed. Electrical wires are used to connect the current and voltage sensors to the system. The ESP32-S2 allows the measurement and collection of data using the Arduino IDE programs. ESP32-S2 micro-controller has been programmed using Arduino IDE programs.

Algorithm 4.1: Data acquisition

Initialization;

1. Voltage and current data are measured using analog sensors;
2. ESP32-S2 defined pins reads sensors values and calculates values of Battery (SoC), Power and

   Energy;
3. ESP32-S2 connects to local Wi-Fi network using SSID and Password;

4. ESP32-S2 identifies Node-Red server/ MQTT broker using server IP Address;

5. ESP32-S2 publishes sensors data to MQTT broker using TCP/IP Wi-Fi connection;

6. ESP32-S2 publishes Power and Energy data to MQTT broker using TCP/IP Wi-Fi connection;

7. Node-Red server receives data on Node-Red flow;

8. Node-Red server displays data on Node-Red dashboard;

while

9. ESP32-S2 is not connected;

10. Establish ESP32-S2 connection by passing, SSID, and password;

if

11. ESP32-S2 connection successfully established;

12. Display “Connected” on Arduino IDE Serial Monitor;

else

13. Display “Connection failed…. retry in 5 seconds” on Arduino IDE Serial Monitor;

end

The PubSubClient MQTT library is used to configure ESP32-S2 micro-controller as an MQTT client and the measured and collected data are transferred to locally installed Node-Red server (MQTT Broker) via MQTT protocol over TCP/IP Wi-Fi communication link. Node-Red server receives data and displays it on the Node-Red dashboard. Algorithm 4.1 shows the pseudocode that encapsulates the data flow process. In Algorithm 4.1 pseudocode (line 1 to line 8) explains ESP32-S2 pins read the sensors values and calculate the values of battery state of charge (SoC), power, and energy. It also shows the connection process of ESP32-S2 with Wi-Fi and the MQTT broker. The process regarding the publishing of data to the MQTT broker is also shown in this part of the pseudocode. Line 9 to 13 presents the establishment of an ESP32-S2 connection with Wi-Fi and displays the connection status on the Arduino serial monitor with a data sampling time of 100 milli seconds. In this way data and information are processed and made available to facilitate energy trading process. In Algorithm 4.2 pseudocode for energy trading process is explained. Once the peer shows the desire to buy energy and starts the process using the web interface of the proposed P2P energy trading platform. The information about amount of energy required is collected at Node-Red server and energy trading process will start. The algorithm then compares the amount of energy being transferred and required energy. Once the energy demand is fulfilled the relay will automatically disconnect the system and energy transfer process will stop.

Algorithm 4.2: Energy Transfer

```
1.    Collects energy demand data from the web interface;

2.    Collects energy transfer data from the Node-Red;

3.    Compares energy demand data with energy being transferred;
if
4.    Energy demand is greater than zero, turn on the relay and start energy transfer;
else

5.    Relay will remain close and no energy transfer;

 end
```

4.7 Hardware Design and Implementation

In this section of chapter 4 the authors have described the hardware design and implementation of the proposed P2P energy trading platform. We have used a voltage sensor to measure the real time storage battery voltage. This is done by means of voltage divider rule explained in section 4.1.2 of this chapter. The current sensor shown in figure 4.9 is used to measure current drawn by the load and the relay shown will start/stop the trading sessions automatically. ESP32-S2 micro-controller depicted in figure 4.9. above is used to collect and process data and to control relay operation

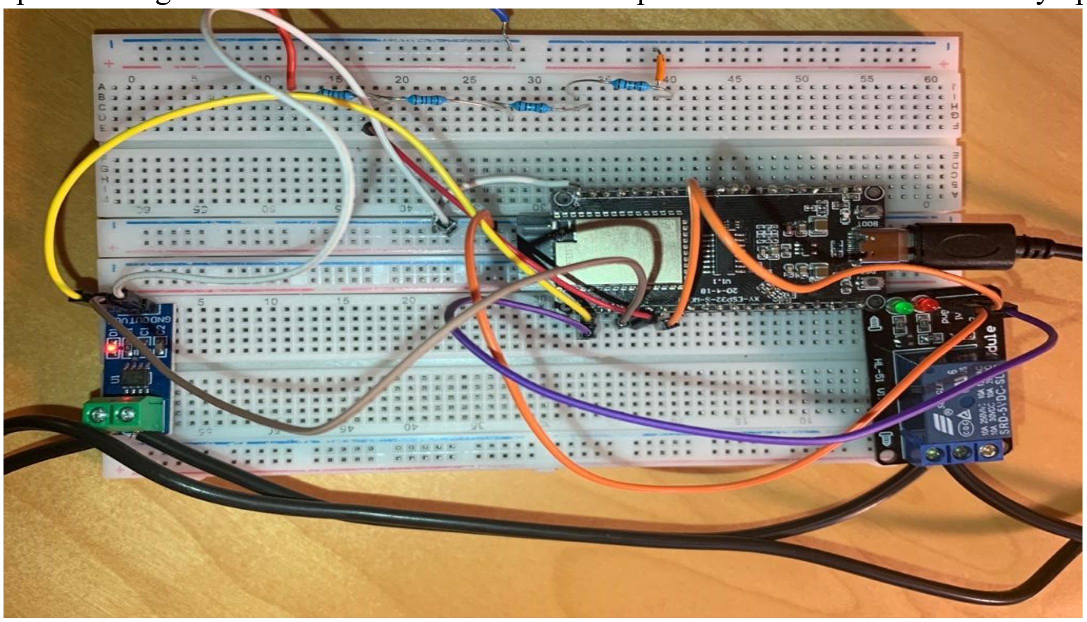


Figure 4.9 Hardware design for the proposed P2P energy trading platform

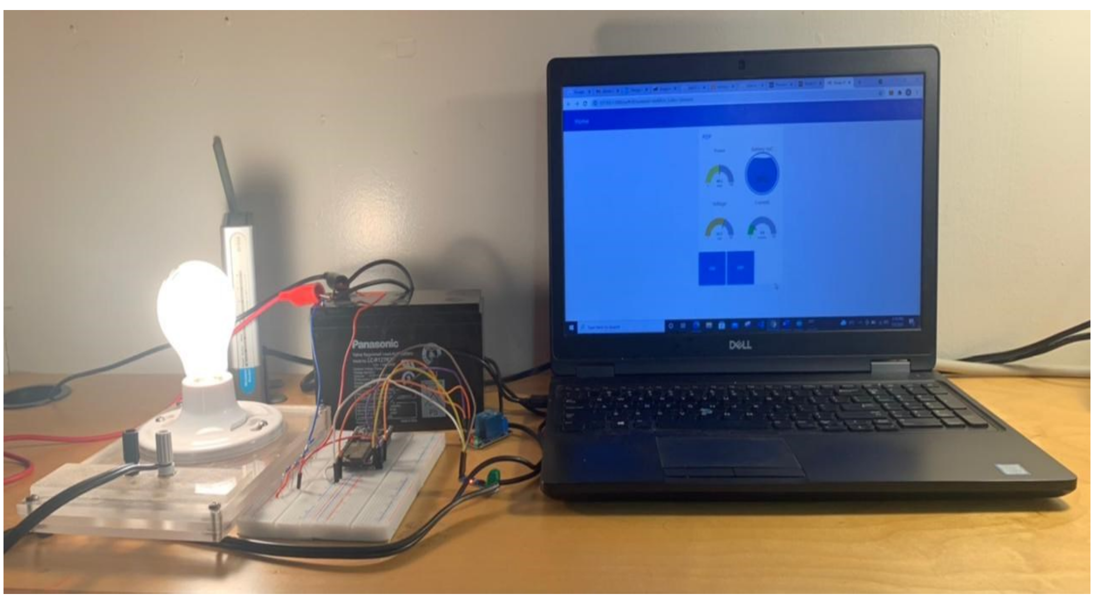


Figure 4.10. Experimental setup for the proposed P2P energy trading platform

4.8 Experimental Setup for the Proposed Peer-to-Peer Energy Trading Platform

As described in section 4.7 the design of proposed open-source P2P energy trading platform is set up for operation. The complete experimental setup of the system is shown in figure 4.10. This set up also uses a battery and load to practically demonstrate the energy transfer operation. The battery acting as source voltage of the system, is connected with the inputs of voltage sensors, while relay and the current sensor are set up between the battery and the load in series connection. The data can be collected by ESP32-S2 microcontroller using the sensors output pins and onwards transferred to the locally installed Node-Red IoT server. Node-Red IoT server receives energy demand from the web interface developed to initiate trading sessions and start energy transfer process automatically. The Node-Red is also connected with web interface to perform energy trading tasks (explained in section 4.5 of this chapter).

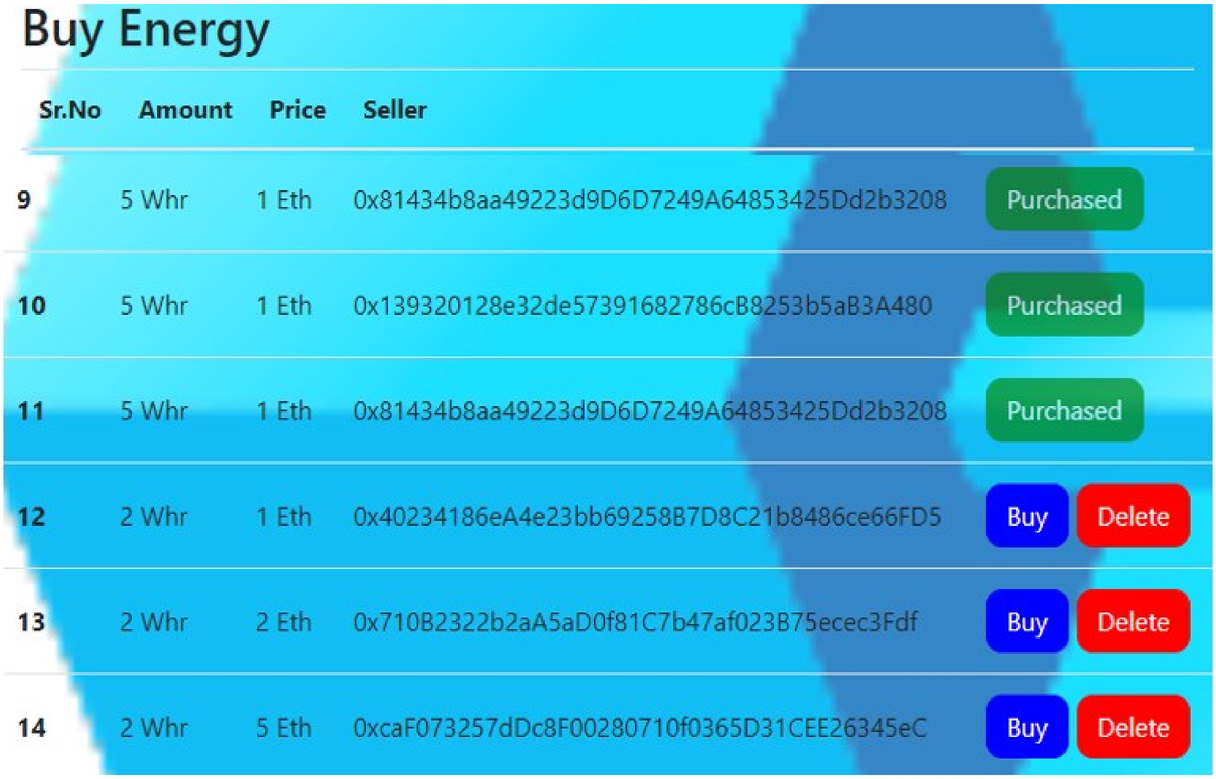
4.9 Testing and Results

The proposed open-source P2P energy trading platform has been tested to obtain the required results. Figure 4.17 shows a flow chart of the proposed system. The flow chart gives a brief overview of complete energy trading process.

The designed P2P energy trading setup is for 10 peers, there is no transaction delay, and the designed server can easily handle all requests. The participants may face delay in transactions on a public blockchain network like bitcoin due to a large ledger. However, in the proposed system, the ledger is small and maintained on a private server. It can process transactions immediately.

4.9.1 Results

The web interface incorporated with private Ethereum blockchain is developed using React.JS library and is connected to Node-Red server, and to the hardware side of the proposed open-source P2P energy trading platform. Once a peer bids energy demand, in response the other peers on the platform can post the available energy at their premises and the price they are willing to sell the energy on the web interface details explained in section 4.5 figure 4.5 of this chapter. This gives the buyer an opportunity to choose amongst the various available options even with a greater amount of energy as required at a lesser price. All the energy demands posted by the peers will appear in the energy demand section as shown in figure 4.11. The other peers on the P2P energy trading platform can visualize the bids on HMIs (dashboards). In response they can post the available energy on the web interface at the price of their own choice. The amount of energy available to sell will show up in the buy energy section of the web interface. If a participating peer of the energy trading platform changes his mind after posting any trading action, there is also an option to delete. In figure 4.11 serial no. 4, a peer is willing to buy 1 Whr of energy at a price of 1 ETH. In response of his bid, he has an option to buy say 2 Whr of energy for 1 ETH, as shown in figure 4.12 serial no.12. Similarly, another participating peer (serial no 5 figure 4.11) of the proposed P2P energy trading platform willing to buy 2 Whr of energy at a price of 3 ETH. Whereas, he has the option to buy the required amount of energy at lesser price as shown in figure 4.12 serial no. 13. This platform gives an option to both buyers and seller to sell energy at their desired price according to the market response.



Buy Energy

Sr.No	Amount	Price	Seller	
9	5 Whr	1 Eth	0x81434b8aa49223d9D6D7249A64853425Dd2b3208	Purchased
10	5 Whr	1 Eth	0x139320128e32de57391682786cB8253b5aB3A480	Purchased
11	5 Whr	1 Eth	0x81434b8aa49223d9D6D7249A64853425Dd2b3208	Purchased
12	2 Whr	1 Eth	0x40234186eA4e23bb69258B7D8C21b8486ce66FD5	Buy Delete
13	2 Whr	2 Eth	0x710B2322b2aA5aD0f81C7b47af023B75ecec3Fdf	Buy Delete
14	2 Whr	5 Eth	0xcaF073257dDc8F00280710f0365D31CEE26345eC	Buy Delete

Figure 4. 11. Energy demand posted by the buyer

Energy Demand

Sr.No	Amount	Price	Buyer	
1	1 whr	1 Eth	0x81434b8aa49223d9D6D7249A64853425Dd2b3208	Purchased
2	3 Whr	2 Eth	0x139320128e32de57391682786cB8253b5aB3A480	Purchased
3	11 whr	6 Eth	0x81434b8aa49223d9D6D7249A64853425Dd2b3208	Purchased
4	1 whr	1 Eth	0x139320128e32de57391682786cB8253b5aB3A480	Sell Delete
5	2 Whr	3 Eth	0x81434b8aa49223d9D6D7249A64853425Dd2b3208	Sell Delete
6	2 Whr	4 Eth	0x27b62Dd1eD0394018B22c2D38b13E01C83e8b862	Sell Delete

Figure 4. 12. Available Energy posted by sellers

All the trading actions performed by the peers on the web interface will appear on the local Ethereum blockchain. We have performed 66 transactions using the web interface and all the transactions are recorded on the blockchain server. The blocks are mined with the timestamps and

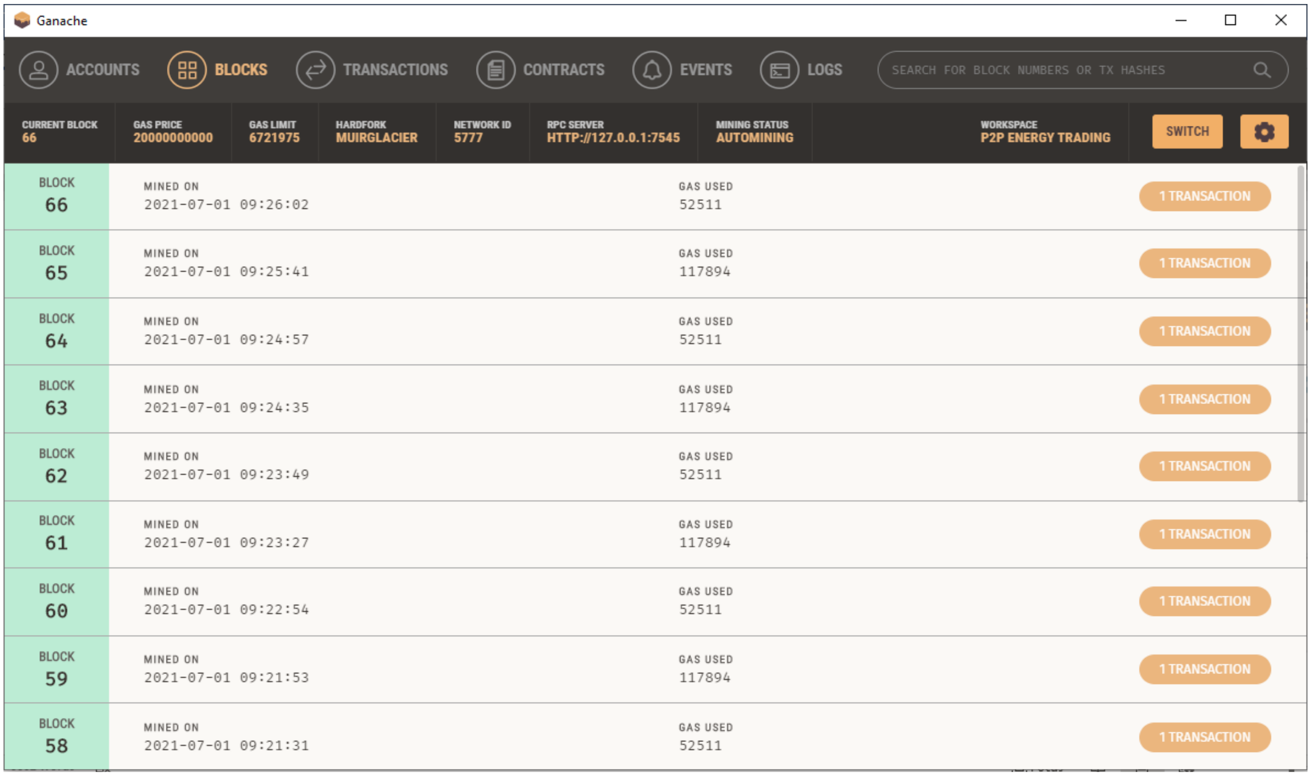


Figure 4. 13. Blockchain status on server

can be explored to get the details of the transaction performed. Figure 4.13 depicts, 66 blocks are formed in response of different trading tasks performed using web interface.

Figure 4. 14 shows details of block 63. 0xB4C003Ed923FC3F971Deb44d8d54e5ECEF50D189 is the address where the smart contract is deployed. The energy demand posted by the seller (0x27b62Dd1eD0394018B22c2D38b13E01C83e8b862) using the web interface and this will

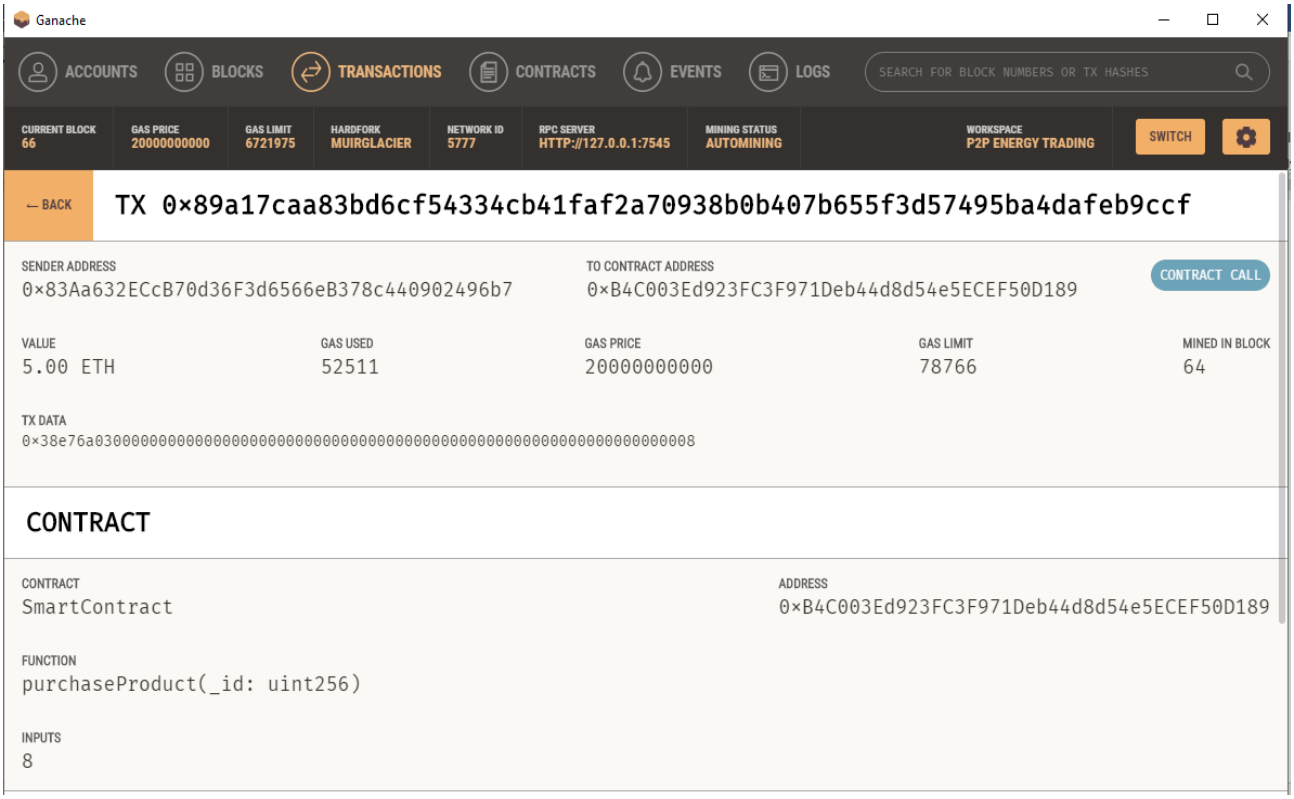


Figure 4.14 Details of block 64 on the blockchain server

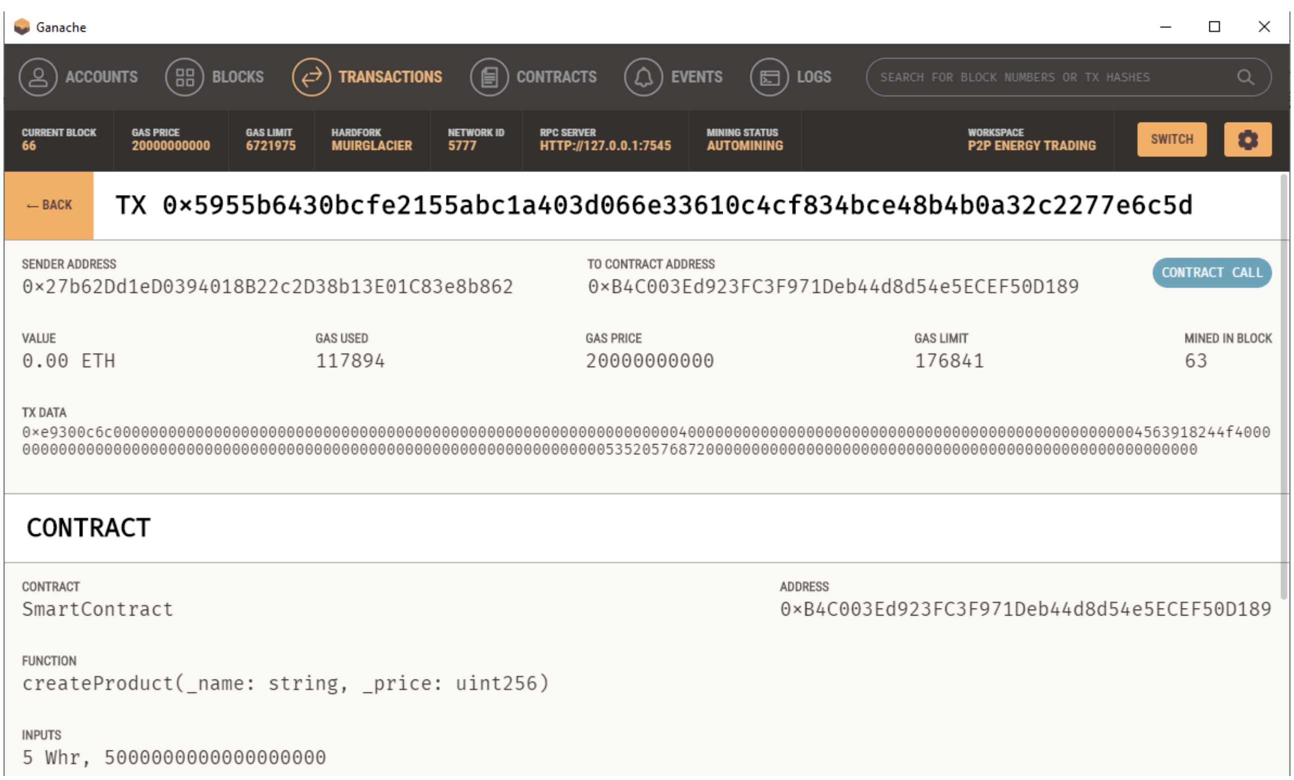


Figure 4. 15 Details of block 63 on the blockchain server

appear on the blockchain. A small amout of gas is used a fee to deploy the transaction on the seen blockchain server. A unique id is assigned to this transaction called transaction hash and can be in block 63 as TX 0x5955b6430bcfe2155abc1a403d066e33610c4cf834bce48b4b0a32c2277e6c5d. Function in each block shows a product is created to sell in the energy market in response of the action performed at web interface.

In figure 4.15 the inside details of block 64 are shown. When we explore block 64 of the blockchain, where a buyer purchases the required amount of energy with a buyer ID 0x83Aa632ECcB70d36F3d6566eB378c440902496b7 the function now shows purchase product and an amount of 5 ETH has been charged with a some gas as a fee. The block 64 mined in response of energy purchased. It also has a unique transaction hash assigned to it. Once the trading sessions is complete it is recorded on the blockchain and can also be visualized on the web interface of the proposed P2P energy trading platform as shown in figure 4.16.

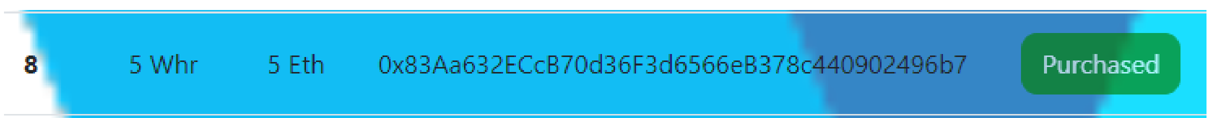


Figure 4.16. Successful transaction status on web interface

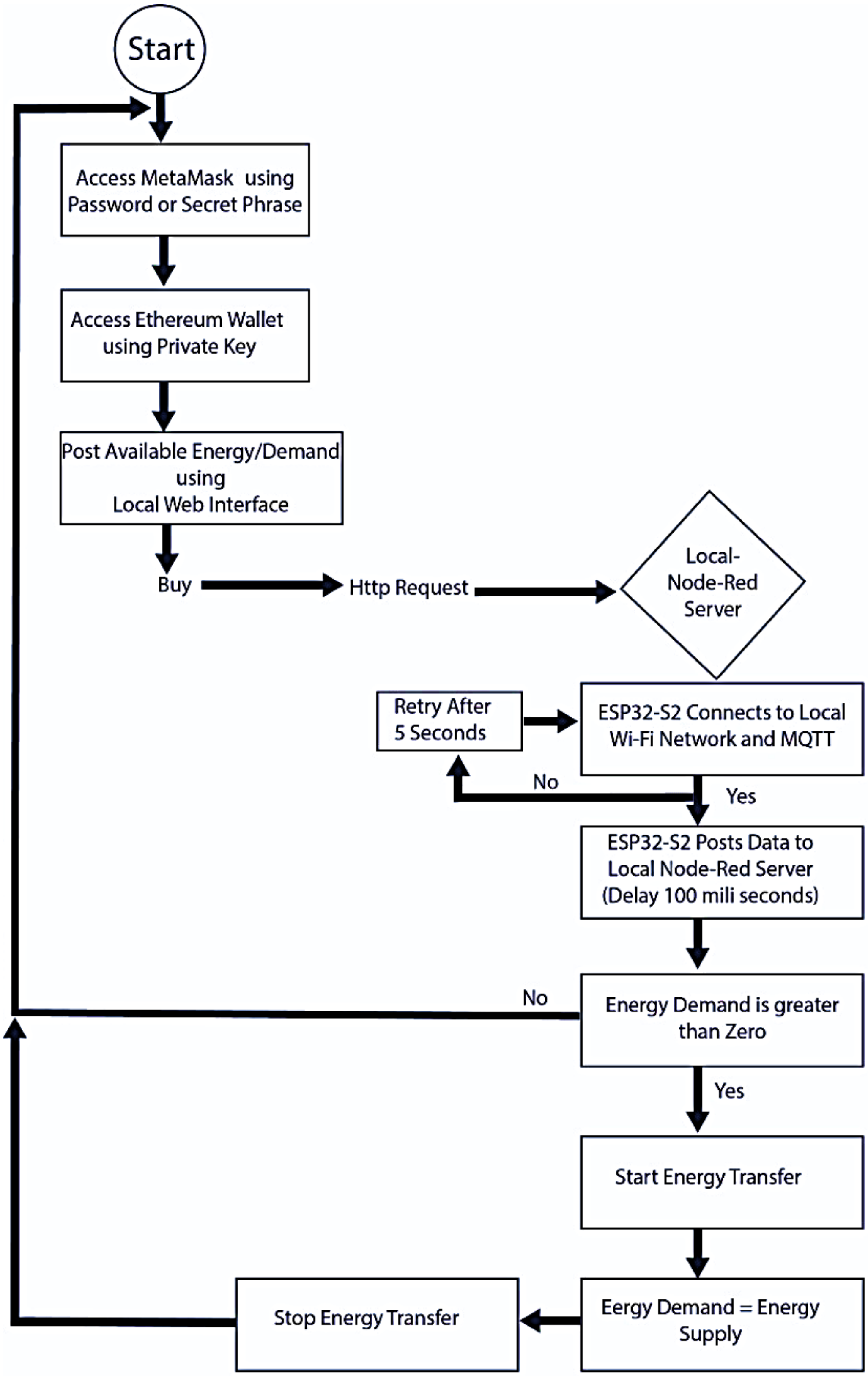


Figure 4.17. Flow chart of proposed P2P energy trading platform

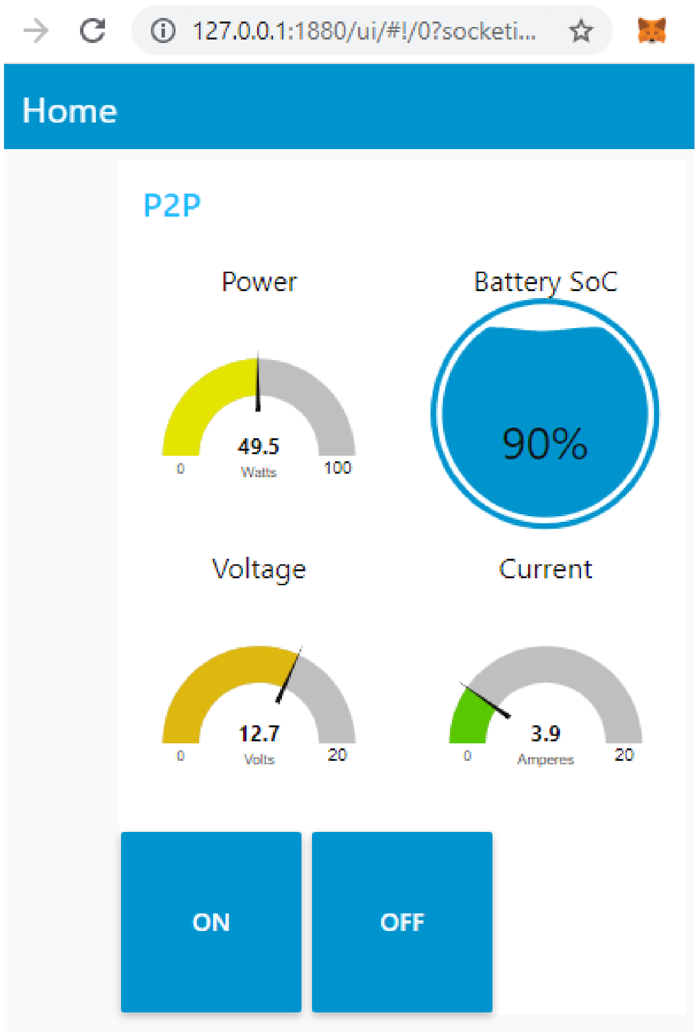


Figure 4.18. Node-Red dashboard

After collecting the sensor data ESP32-S2 microcontroller transmits data to Node-Red IoT server which is responsible for monitoring and control of energy. The data collected and processed by ESP32-S2 microcontroller can be visualized on Node-Red dashboard as shown in figure 4.18. The On and Off buttons shown here are developed here to initiate or stop energy trading sessions using Node-Red dashboard only.

The proposed P2P energy trading platform can be used for a small community of 10 houses within the range of local communication link set up through the Wi-Fi router, which can be increased and decreased depending on the community's need. The Wi-Fi router used for the current project has a range of 328 Feet indoor and 1312 Feet outdoor.

4.10 Discussion

This section describes a few of the key characteristics of the proposed open-source IoT and blockchain-based Peer-to-Peer energy trading platform realized after successful testing of the system:

- **Blockchain and IoT based P2P energy trading platform:** The proposed open-source P2P energy trading platform is based on IoT platform and a private Ethereum blockchain. The proposed platform introduces vital components that a blockchain-based P2P energy trading system should include for proper energy monitoring, energy metering and money transaction in a decentralized manner. This includes blockchain-based web interface, Node-Red IoT server, ESP32-S2 microcontroller, Field instrumentation devices and MQTT protocol communication channel.
- **Energy Trading:** A web interface is developed for Human machine interactions. Real time settlements can be done using the web interface. This web interface can be accessed remotely to perform energy trading tasks.
- **Ethereum Blockchain:** A private Ethereum blockchain has been used to deploy smart contract and maintain digital ledger of transactions. All the trading activities performed using the web interface are recorded on an immutable blockchain network with timestamps with all the security features of blockchain.

- **Fast Transactions:** The proposed P2P energy trading platform can perform transaction on a blockchain network immediately. There is no delay in the transactions and system can handle all requests easily.
- **Data Acquisition:** The proposed system is capable of data acquisition using field instrumentations devices commonly available in the market.
- **Monitoring and Control:** Locally installed Node-Red IoT server is used to monitor and control self-generated power. Peers can monitor the available energy and are able to transfer energy in response to a buy call.
- **Security:** The proposed P2P energy trading platform is restricted to authorized users only. To access the Ethereum wallet MetaMask require login credentials plus Ethereum wallet itself has a unique private key for each user which ensures authorized access to the funds and platform. To add to this local Wi-Fi network also require user authentication credentials.
- **Central Server:** After implementing proposed P2P energy trading platform, there is no need for central servers to support the energy trading.
- **The Ease of Use of The System:** The proposed P2P energy trading system is developed in user friendly manner. The participant of the platform does not require any training to use the system.

4.11 Conclusion

In the current era where energy consumers are now becoming prosumers and a large amount of energy is generated by renewable energy resources particularly by using solar photovoltaic (PV) panels. The participants of energy market are exploring different ways to sell self-generated energy and looking for such platforms which can help them to get returns on their investment in renewable energy resources. Peer-to-Peer energy trading platforms are such platforms which makes renewable energy more accessible to everyone and participants can make better use of self-generated energy. Such platforms can help to grow renewable energy resources and can reduce extra burden on the power system. Also, the participants of P2P energy trading platform can get profit on their investment.

In this chapter, the authors presented an advanced open-source P2P energy trading platform using internet of things and blockchain. We have demonstrated both the software and hardware implementations of our proposed P2P energy trading platform. The software implementation is done by installing web interface hosted on a local machine using React. JS library with Ganache GUI a private Ethereum blockchain. The web interface facilitates all the trading activities which are recorded on a blockchain network. For data monitoring and energy control we have used Node-Red server that is also hosted on a local machine. In hardware implementation we have used ESP32-S2 microcontroller with field instrumentation devices. From the testing and results we proved that the proposed P2P energy trading platform works perfectly. The system operates in a decentralized manner and all the transactions are documented on digital ledger. The system performs all the trading sessions properly and monitors energy data accurately. Although, the system has been tested on a small storage 12V battery and 50W load, customization of the system is also possible to facilitate energy trading to fulfill the energy needs of a household.

4.12 Future work

As a future work the authors aim to implement this project to the remote location with poor/no electricity network and no internet access. Particularly smaller communities with abundant renewable energy sources. This project aims to facilitate such parts of the world where people are living without electricity or have electricity for shorter period during the whole day. We plan to add auto sale and purchase features along with full electrical connection details for a remote site in Pakistan. The increased range of communication link setup for this decentralized network is also the part of future work extension. Details will be published in future papers.

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Chapter 5

A Low-Cost, Open-Source Peer-to-Peer Energy Trading System for a Remote Community using the Internet-of-Things, Blockchain, and Hypertext Transfer Protocol

Co-authorship statement

In chapter 5, a low-cost, open-source peer-to-peer (P2P) energy trading system for a remote community is presented. This community has never had access to electricity or other modern amenities due to its geographical location. In this study, the author seeks to design and implement a P2P energy trading system for this remote community in order to facilitate the use of distributed energy resources by its residents. A summary of the overall system design, implementation, testing, and results is presented in this chapter. This chapter satisfies the objectives 4 and 5 of section 1.3.

I, Mirza Jabbar Aziz Baig is the principal author of this chapter and was involved in developing the methodology, implementing the software and hardware, evaluating data, and writing the original draft. Dr. Mohammad Tariq Iqbal, Dr. Jahangir Khan, and Dr. Mohsin Jamil reviewed and edited the original manuscript as well as conceptualized and contributed resources. This chapter appears in the following research publication "M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, "A Low-Cost, Open-Source Peer-to-Peer Energy Trading System for a Remote Community Using the Internet-of-Things, Blockchain, and Hypertext Transfer Protocol," *Energies*, vol. 15, no. 13, p. 4862, Jul. 2022,: ."

Abstract**:** A low-cost, open-source peer-to-peer (P2P) energy trading system for a remote community is presented in this chapter. As a result of its geographic location, this community has never been able to access electricity and other modern amenities. This study aims to design and implement a P2P energy trading system for this remote community. That allows residents to take advantage of distributed energy resources. A Raspberry Pi 4 Model B (Pi4B) hosts the main server of the trading system that includes the user interface and a local Ethereum blockchain server. The Ethereum blockchain is used to deploy smart contracts. The Internet-of- Things (IoT) servers run on an ESP32 microcontrollers. Sensors and actuators connected to the ESP32 are field instrumentation devices that facilitate acquiring, monitoring, and transferring energy data in real time. To perform trading activities, React.JS open-source library was used to develop the blockchain-enabled user interface. An immutable blockchain network keeps track of all transactions. The proposed system runs on a local Wi-Fi network with restricted authorization for system security. Other security measures like login credentials, private key, firewall and secret recovery phrase are also considered for information security and data integrity. Hypertext Transfer Protocol is implemented for communication between the servers and the client. This explains overall system design, implementation, testing, and results.

Keywords: Peer-to-Peer (P2P), Distributed Generation (DG), Internet-of-Things (IoT), Blockchain, Hypertext Transfer protocol, Open-Source.

5.1 Introduction

Electricity serves as a necessity in a variety of aspects of life and is, therefore, one of the basic amenities of modern civilization. It is impossible to imagine improving the quality of life without electricity. With the rapid advances in technology, social well-being cannot be envisioned without electricity. The modern hi-tech life relies heavily on electricity. Undoubtedly, people today can enjoy all the necessities of life, such as watching TV, turning on their laptops, using the internet, having heating or air conditioning, etc. Yet, it is not elusive that there are people worldwide who lack access to electricity. The world bank estimates that 13 percent of the world's population did not have access to electricity by 2019 [1]. Growing percentages are witnessed in developing and underdeveloped countries.

Regarding Pakistan, 75.4 percent of the country's population has access to electricity [2] and for rural areas it stands at 60.8 percent. This percentage remained 59 percent from the year 2000 to the end of the year 2019 [3]. The huge population of Pakistan living without electricity underscores the need for alternative energy solutions. Considering Pakistan's immense photovoltaic (PV) generation capacity, electrification of remote areas can be best achieved with off-grid photovoltaic systems. In the context of remote communities this is particularly true, where power is not available through the national grid. In this research, we have designed a low-cost, open-source Peer-to-Peer (P2P) energy trading system for a remote community in Pakistan. The people at the selected community do not have access to electricity, thereby isolating them from the modern world.

Raspberry Pi 4B is employed as the main server of the proposed system, making it a low-cost system. Several low-cost servers have already been developed on Raspberry Pi devices. Raspberry Pi has proven useful for development of servers and technologies as a low-cost device

[41-43]. The authors in [41] developed a low-cost SCADA system based on Rasberry Pi. The claim of Raspberry Pi as a low-cost single board computer is suported by authors in [42], where the authors developed low-cost point-of-care technologies for cervical cancer prevention using Raspberry Pi.

5.2 Literature Review

A comprehensive literature review has been conducted during the course of this research, and some of the useful literature reviewed are set forth. In [4], considering the energy crisis in Pakistan, the authors designed an off-grid PV system for district Tharparkar, Pakistan, which is 95 percent un-electrified. An evaluation of the system size and the associated costs is conducted. Based on the load, the authors determined the ratings of each component in the PV system. In addition, the authors did a cost analysis and concluded that PV systems are significantly less expensive than national grids for electrifying this area. According to the authors, the annual energy cost per unit is 63 percent less than if it was supplied by the grid. This study [5] aims to identify factors that influence the social acceptability of solar photovoltaic systems in northwest Pakistan. The research evaluated the determinants of social acceptability of PV systems with binary logistic models. Solar PV systems are being used by 46 percent of the households in the study area. The authors emphasize that Pakistan has plenty of solar energy available for converting into electricity using solar photovoltaic systems. Specifically, the study recommends that the government adopt policies aimed at promoting solar energy in Pakistan through incentives. The authors in [6] emphasize the importance of off-grid PV systems in the electrification of remote areas. Identifying the potential and viability of solar energy in remote regions of Sindh, Pakistan. A suitable tilt angle was determined for the selected rural regions, resulting in an increased generation capacity of solar energy. Solar PV off-grid system is inexpensive and has a lower cost than conventional energy sources, according to this research. Researchers claimed that this study would aid the government of Pakistan in taking advantage of off-grid solar PV energy generation systems.

Energy consumers, rather than large energy producers, are integrating distributed energy resources into the current power market, gradually evolving from unidirectional, centralized to bidirectional decentralized markets, as well as consumers are becoming prosumers. Energy trading and the management of distributed generation (DG) can be enhanced by P2P, an evolving architecture in the field of local energy markets. The authors discussed in depth the various operating algorithms of P2P energy trading along with their characteristics, features, standards, and scope through an overview of current state-of-the-art P2P trading. Additionally, this article uses Nepal's energy system as a case study and explores Nepal's micro/mini-grids and the challenges, limitations, and prospects they present. The authors concluded with a model that addresses the specific problems associated with the Nepalese energy market [7]. In another study researchers propose two novel approaches for identifying households' mutual trading choices in an entirely local P2P energy market. The first approach aims to match excess power supply with demand from peers, and the second one compares the distance between the participants. Both strategies are evaluated to determine how energy prices and trade volume are affected by bilateral trade preferences. The data is generated in a day-ahead setting using a decentralized network of entirely P2P energy trading markets. A permissioned blockchain smart contract is then used to implement the P2P trading market on the digital platform. For simulations real domestic data from a community in the Netherlands is used, including distinct decentralized energy resources. The authors agreed that in the proposed system, energy purchasing cost and grid interaction is reduced in the P2P network. Likewise, when trading preferences are distance centered, the sum of P2P energy traded is higher at a low cost. The comparison with electric heating and without electric heating in the household is also presented [8]. This study [9] recommends UBETA (a permissioned blockchain-based energy trading and payment settlement architecture) which incorporates three diverse kinds of energy markets. As part of the UBETA system, an enterprise Ethereum blockchain known as Hyperledger Besu is used, along with the Istanbul Byzantine Fault Tolerance (IBFT) consensus algorithm. The performance of the system was compared with the existing systems based on the actual energy trading statistics from the Western Australian energy market. They concluded that the suggested integrated energy trading platform holds lower latency and involves fewer blockchain transactions.

Another study found that P2P market mechanisms normally imply a heavy computation burden and real-time trading requires fast calculations, the authors emphasize that developing and operating such systems in real-time can be technically challenging. It is therefore the primary contribution of the authors to present and analyze an online optimization framework utilizing real-time market information for the P2P market using a novel online consensus alternating direction multiplier algorithm to maximize social welfare. In addition, the authors claim that the algorithm can reduce the computational complexity to meet real-time needs. Several case studies were performed to demonstrate that the authors' algorithm has high compute efficiency, superior convergence, and tracking capability [10]. According to a recent article, an open-source P2P energy trading platform was developed configured using the internet-of-things (IoT) and the blockchain. Technical details are provided on acquiring real-time data monitoring and controlling energy. A web interface is used to facilitate trading through smart contracts on a private Ethereum blockchain, while monitoring and controlling energy consumption is done via an IoT platform. To achieve a complete system design, the authors used Message Queuing Telemetry Transport and Hypertext Transfer Protocol along with microcontrollers and field instrumentation devices [11].

In another research the authors describe a user-centric cooperative mechanism that enables users to participate actively in P2P energy trading. To conduct economic transactions in a cost-effective manner, the proposal attempts to reflect the preferences of all actors in the ordering process, making transactions as simple and straightforward as possible. A case study has been conducted in Japan to demonstrate the proposed mechanism through the Higashi-Fuji demonstration experiment. Thus, the study confirmed that consumers were able to buy renewable energy economically, automatically, and efficiently, and that prosumers were able to sell surplus electricity. They also recognize that the key to P2P energy trading is designing incentives to encourage participants to participate in the process [12]. Another pilot stage research provides technical explanation of a peer-to-peer (P2P) energy trading platform that is created on IoT and blockchain technology. According to the results, P2P energy trading offers economic benefits to participants in addition to satisfying the needs of prosumers. The study proposes an energy trading platform that provides all the key features like energy transfer, metering and digital money transfer [13]. A P2P energy trading outline appears in [14], consisting of six steps: order generation, order picking, default query, trade verification, trade execution and payment. By providing default users with either a waiting period or penalties during the default query stage, this study examines credit management influence on default behavior. The authors used the Hyperledger Fabric platform, Docker and Go to simulate the model. By proposing this model, the authors claim that blockchain users can reduce costs and realize credit management in P2P energy trading, thus enhancing the efficiency and stability of trades. In [15] the researchers give emphasis to P2P energy trading as a promising energy trading and management solution in an isolated microgrid. They propose a state-of-the-art IoT and Ethereum blockchain centered trading platform using open resources and technology.

Two distinct streams of literature were identified based on the literature reviewed as a part of this study. In the first stream the researchers emphasize the off-grid PV system and on social adaptability of PV systems [4-7]. While the other stream examines peer-to-peer energy trading using blockchain technology and claims that P2P trading is the most promising energy management and trading solution [8-15]. The authors believe that this study is the first to present complete design and technical details of a low-cost, P2P energy trading platform for an un-electrified remote community in Pakistan. In [16], we cover details regarding the analysis, and design of an isolated dc-microgrid for this community. The motivations for proposing raspberry-pi and blockchain based P2P energy trading system for this remote community includes, a) low cost, b) low energy consumption, c) high possibility of implementation in unserved remote communities, and 4) Potential use in remote areas, with no access to the internet.

This chapter explores the design of a P2P energy trading system for a remote community in Pakistan. A decentralized, open-source, P2P energy trading system architecture based on IoT and blockchain is presented. To realize the required functions of a P2P energy trading system, low-cost, low-power, reliable and readily available components are used. The proposed P2P energy trading system is tested extensively using batteries designed specifically for the storage of photovoltaic energy to demonstrate the system's effectiveness. As of today, according to the literature reviewed, the proposed P2P energy trading system for this location has never been considered prior to this, and hence can be considered novel with respect to the geographical region. This chapter makes the following significant contributions:

- As a pioneer in peer-to-peer energy trading with a low-cost server in a remote area of Pakistan, this study particularly stands out in terms of its site and application.

- Development of an open-source and low-cost, local server hosted on a private network for peer-to-peer energy trading, using ganache command-line interface (CLI) private Ethereum blockchain. Our best understanding of this work is that it entails a novel approach since the authors used either web-based servers or extremely expensive machines.
- The optimal P2P energy trading system configuration for each house in the community to achieve energy trading and monitoring independence.
- This study provides a path forward for developing low-cost, blockchain centered peer-to-peer energy trading systems, particularly for remote locations without access to the internet.

The rest of the chapter can be summarized in the following manner. Section 5.2 overviews the site description. It contains details about the area, including its remoteness. In section 5.3, information regarding the hardware and network structure of the proposed P2P energy trading system is presented. It also covers micro-grid configuration with a P2P energy trading scheme for the proposed site. Detailed descriptions of technology and each of the components of the proposed IoT and Blockchain based P2P energy trading system are presented in Section 5.4. The prototype design and experimental setup for the proposed system are covered in section 5.5 and section 5.6 respectively. In section 5.7, we discuss the implementation methodology. A description of the tests performed, and their results are presented in Section 5.8. As part of Section 5.9, we discuss the key characteristics of the system, analyzing power consumption and cost. Section 5.10 concludes the article, and Section 5.11 presents future research directions.

5.3 Site Description

Figure 5.1**.** An aerial view of the selected location

Figure 5.2. Actual view of the proposed site

This section of chapter 5 aims to provide the reader with an overview of the site we have selected for this particular study. The site (34°49'06.6"N 74°13'06.5"E) is in the district Neelum valley of Azad Jammu and Kashmir (AJK), Pakistan. This region is the northernmost part of AJK, Pakistan, encompassing the lower part of the Himalayan Mountain range. Several factors contribute to the region's remoteness, including its distance from urban area, difficult terrain, and the shortage of facilities, together with modern health-care services. Roads and other infrastructure in the area are inadequate. Figure 5.1 illustrates the aerial view from google earth of the location selected for this research and the actual site is depicted in figure 5.2. It is evident from figure 5.1 and figure 5.2 that there are no power lines or roads leading to this community. The residents are using a kind of local chairlift (called grari in vernacular language) to access their homes, figure 5.2 depicts this situation. They are living without televisions, computers, electric appliances, modern health care, internet, all forms of digital communication and technology. To live without electricity, is to live without one of life’s fundamental necessities. Considering the topographical challenges an in-depth feasibility study was conducted on the possibility of an isolated DC-microgrid that is designed to use batteries and solar energy for supplying power to this site. To determine the best-case design for the system, HOMER (Hybrid Optimization of Multiple Energy Resources) is used. More details can be found in [16]. We have designed a low-cost, open-source peer-to-peer energy trading system for this community and presented details of server, components, and local communication channel to host the server. The whole system comprises of a Raspberry Pi 4B, ESP32 and Field Instrumentation Devices (FIDs) hosted on a private network. By implementing the proposed system, residents will be able to monitor and trade energy independently. A fully autonomous and low-cost system, which can be accessed remotely, has been developed.

5.4 Hardware and network structure for the proposed P2P energy trading with microgrid configuration:

This section overviews the arhitecture of the proposed IoT and Blockchain based P2P energy trading system. An illustration of the system architecture is shown in figure 5.3. The proposed low-cost, open-source, IoT and blockchain based system comprise of local secured Wi-Fi network. The local network is assured to extend to all houses connected to the isolated-microgrid. The Raspberry Pi 4B, ESP32 microcontroller, voltage sensor, current sensor, and relays make up the rest of the system architecture. The system server is set up on Pi4B, which is utilized for executing blockchain-based energy trading tasks. The server dashboard is available for human machine interface (HMIs) for remote access and P2P energy trading actions. ESP32 microcontroller is used to monitor energy transfer data with the help of voltage and current sensors. The relays are used to perform the switching operations. As soon as the energy demand is received, the relays turn on and the energy transfer process starts, and it stops as soon as the energy demand is satisfied. The process of doing so is automated using an algorithm, which does not require any effort from the human. The pseudocode for the algorithm is presented in the later section of this chapter. For the security of the system the local Wi-Fi network is configured for user authentication. Also in figure 5.3 are PV panels to represent PV energy generation, a battery bank to represent a battery storage system, and the DC-load of the participating peers. Hypertext Transfer Protocol (HTTP) is used for communication between the server and client.

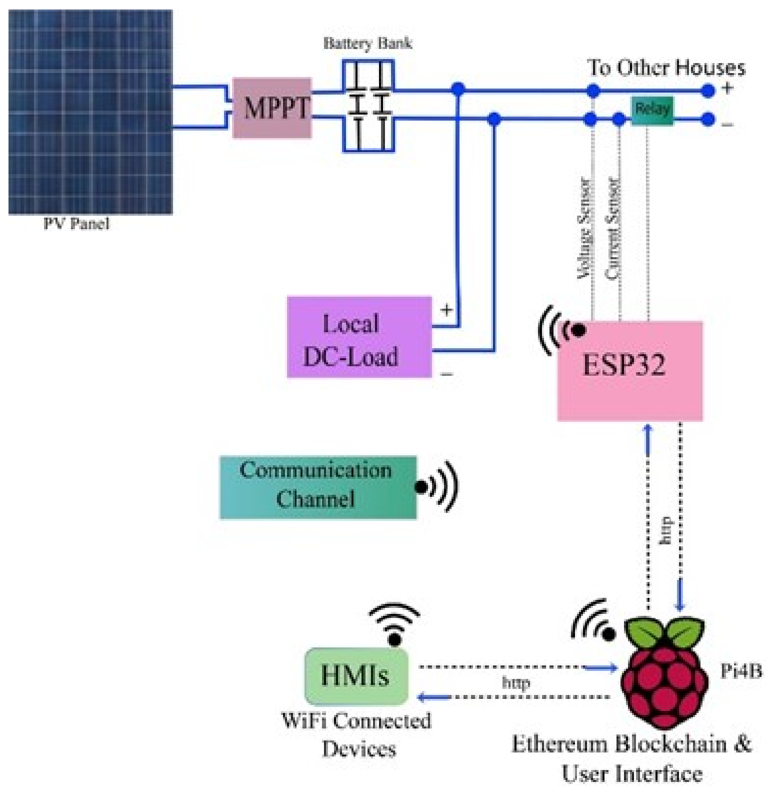


Figure 5.3. Proposed P2P Energy Trading System Architecture

The proposed P2P energy trading system is designed for remote community in Pakistan. Figure 5.4 represents the microgrid configuration of the IoT and blockchain based P2P energy trading system. Ten houses of the proposed community are connected with the microgrid. Each household is equipped with its on PV generation system and battery bank and an IoT server. There is one main server in the community that hosts private Ethereum blockchain and React.JS based user interface. The main server is a remote server configured on raspberry Pi for trading activities within the community. Each house also has an IoT server that is created for the purpose of monitoring and executing energy transfer activity. It also starts or stop trading activities upon the request received from the main server over HTTP. Once any request for the trading session is received at the main server it will figure out the Internet Protocol (IP) addresses of both the buyer and sellers with the help of a computer algorithm and will send that request to ESP32 over HTTP.

The ESP32 microcontroller will then turn on the house relay (R_1, R_2, R_3,.,R_{10}) associated to the houses and the energy trading process will start. It will stop automatically once the requested amount of energy is transferred to the buyer.

5.5 System Components and technology used

The details of each of the low-cost hardware components and open-source software used in the realization of the suggested IoT and blockchain based P2P energy trading system we present here. Among these components are the Hall effect current and a voltage sensor that serve as field instrumentation devices to monitor energy consumption, a relay for switching operations and ESP32, a versatile microcontroller configured as an IoT server at the premises to control energy consumption and enable trading. A Raspberry Pi 4B single-board computer on which the local

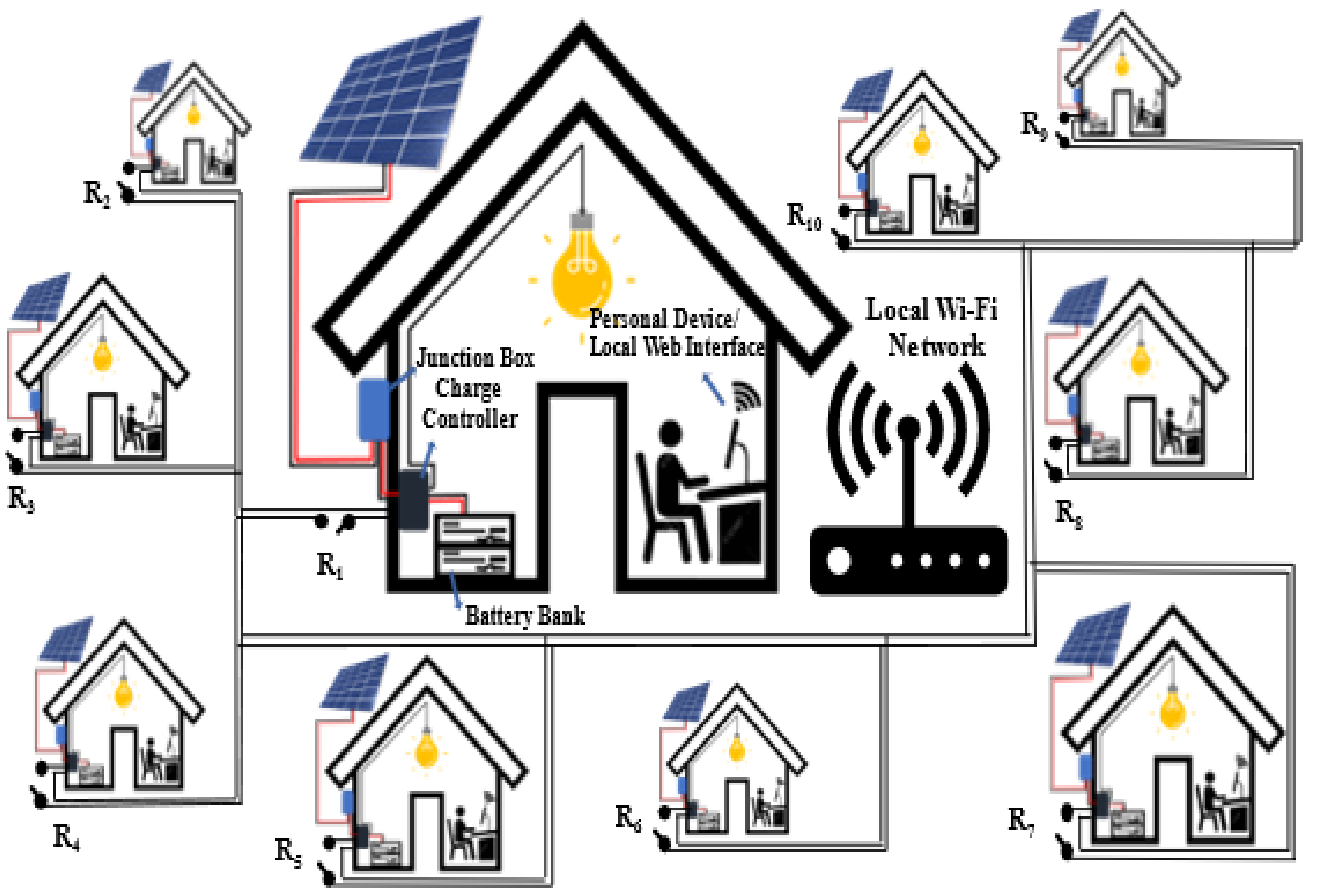


Figure 5.4. Micro-grid Configuration of proposed Energy Trading System [15]

web interface is installed and the blockchain server is hosted, which is built for human machine interactions, dashboards, and lastly, a Wi-Fi Router for setting up a private communication network.

A few limitations, such as the range of local-network, distance of peers from main servers and the number of peers, are present in the proposed system. The outdoor range of the system is 400 m/1,312 feet and the system can accommodate ten peers. This system is stable, resilient, and can easily be replicated as it is based on open-source hardware and software tools.

5.5.1 Rasberry Pi 4B

A Raspberry Pi (Raspberry Pi 1 Model B, generation 1) machine was released in February 2012, making it the first Raspberry Pi device. The low price of US $35 made the device an instant success. One of the most common terms used to describe it is Single Board Computer (SBC). The basis of this definition is that it runs a full operating system and supports adequate computer peripherals. As a low-cost SBC Raspberry Pi Foundation made is available to everyone [17]. The authors proclaim that raspberry pi is a low-cost, low power SBC that comes with all the functionalities of conventional computers. Besides being able to access and control the raspberry pi remotely as a headless computing unit, it can also be programmed in a variety of computer languages to run autonomously [18]. According to [19], Raspberry Pi 4 is a low-cost micro-computer that can support a wide range of coding functions and has high processing power.

The Raspberry Pi 4 Model B (Pi4B) used in this project is 85 x 56mm and is the first of a new generation SBC with a Quad-core 64-bit ARM-Cortex A72 running at 1.5GHz and 4 Gigabyte LPDDR4 RAM. This chip is robust and appropriate for the proposed IoT and blockchain-based

P2P energy trading system due to its low-cost compliance with IEEE 802.11b/g/n standard protocol and the following features [20].

- A 1.5GHz Quad-core 64-bit ARM-Cortex A72
- 4 Gigabyte LPDDR4 RAM
- VideoCore VI 3D Graphics
- Supports dual HDMI display output up to 4Kp60
- 802.11 b/g/n/ac Wireless LAN
- 1x SD Card
- 2x USB2 ports and 2x USB3 ports
- 28x user GPIO supporting various interface
- Mature Linux software stack
- Pi4B ambient operating temperature range 0 ºC to 50 ºC.

This study uses Pi4B as the main server that can be accessed through HMIs by browsing http://localhost:3000. This main server hosts a user interface and Ethereum private blockchain. The participating peers of P2P energy trading system can access the server to perform trading activities. All the trading actions performed by the participants will be recorded on the blockchain. One noteworthy point, this IoT and blockchain based P2P energy trading system will have one main server for participants connected with the grid. The server is installed and configured on the latest release of Raspberry Pi OS 64-bit [21].

5.5.2 ESP32-WROOM-32

ESP32 is an 18 mm × 25.5 mm size module containing two low-power Xtensa® 32-bit LX6 microprocessors that integrates a powerful Wi-Fi component following IEEE 802.11 b/g/n protocol. It is well-suited for anything from low-power sensor networks to the most demanding applications. The Central Processing Unit (CPU) clock frequency can be adjusted from 80 MHz to 240 MHz. Two CPUs have been designated as "PRO_CPU" and "APP_CPU" (for "protocol" and "application" respectively), and CPU cores can be controlled independently. ESP32 incorporates a wide range of peripherals, ranging from capacitive touch sensors, Hall sensors, Universal Asynchronous Receiver/Transmitter (UART), SD card interface, high-speed serial peripheral interface (SPI), serial communication protocol (I2S) and serial bus interface standard. With a sleep current of less than 5 µAmperes, the ESP32 is suitable for battery powered applications. [22-23]. The device is a low-cost, low-power microcontroller that includes integrated Wi-Fi, dual-mode Bluetooth functionality and energy saving features, making it highly adaptable. The wide range of temperature proved it to be an advantageous feature in an industrial setting. As a standalone microcontroller, it can act as a complete system [24].

A part of this study was the development of a local server using ESP32-WROOM-32**.** The server is configured for energy monitoring and control within individual household of the proposed community. ESP32 is connected to a current sensor, a voltage sensor, and a relay. The server receives real-time energy transfer data and displays it on a dashboard. The relay serves as a switch to initiate or stop the energy trading process based on energy demand. The dashboard can be accessed by browsing to a local internet protocol address.

5.5.3 The Blockchain

A blockchain is conceptually a chain of records referred to as blocks wherein the information stored is encrypted. This ensures privacy and security. As of now, blockchain technology is one a leading disruptive technologies that is particularly paving the way for the development of new financial and industrial services [27]. In the context of establishing trust between entities involved in a business process, blockchain technology and smart contracts are becoming increasingly important. In technical terms, it can bedescribed as a distributed digital ledger. All transactions on the ledger are immutable and auditable [28]. In many cases, blockchain-based applications and tools can easily integrate with existing systems due to their diverse tools and interconnected communication and consensus requirements. The general-purpose nature of systems [29]. In the context of this study, we have configured the Ganache command line interface (CLI), an Ethereum client. Ganache-CLI offers access to local blockchains to test and run decentralized applications. A local Ethereum blockchain server can be accessed through it. The advantages of using Ganache CLI includes, no transaction cost, reset and instantiated with a fixed amount of Ether, accounts can be re-cycled, Gas price and mining speed can be modified, blockchain technology makes it possible to use it in a variety of applications across a wide range and Transactions are "mined" instantly [30]. Figure 5.5 represents a Ganache CLI RPC (Remote procedure call) server running. It gives us ten numbers of accounts each associated with 1000 Ethers and a private key associated with each account. The application of blockchain to this study is explained in Section 5.8 of this chapter.

```
ganache v7.0.2 (@ganache/cli: 0.1.3, @ganache/core: 0.1.3)
Starting RPC server

Available Accounts
==================
(0) 0xC3E5137b5dB9becF6d144DFbeE844e3C84CF4EF9 (1000 ETH)
(1) 0x458670Be9be5A4cf0e0DC17198Ca3F05540B9615 (1000 ETH)
(2) 0xA9f40361dda608d5e2843dBcDd4Bdf46338D21Bf (1000 ETH)
(3) 0x5eF0C1e74cf5F446579360fCDEE5a7fd3007f051 (1000 ETH)
(4) 0xc5CDD0f3aE5357691651Ea85051d5A1aA9f8d5aF (1000 ETH)
(5) 0xf0084375e021D2959357e1420bb2d42b7DD56fA9 (1000 ETH)
(6) 0x21808F6aFF65863d2Cc98651773Cd5C303c25D42 (1000 ETH)
(7) 0x6bAA979B171e700d05a65499F706c2020aF1c6b3 (1000 ETH)
(8) 0x8420AE1BEc31328EB5d394645390eC26E487388e (1000 ETH)
(9) 0x451B62c63C41B2aDC58569Dcebf81e2a56328349 (1000 ETH)

Private Keys
==================
(0) 0xae3e014c76bed3f023433d6ea6886950ea7bff7e3e02913e8c5a86c0c9d924ff
(1) 0xd5a86fc5fdbcc55347b6366b6a3a19f10340317f15c81f3a54cc8f1117708ab4
(2) 0xa9b7e40d2205e759aa1aa2b2ac0eeebee3f2ef57b7ab43df37fed77af182a52f
(3) 0xa1df6fcd7037c66314787d83a3b9ee75e9315e9e579dc1779ab41483bc6181a2
(4) 0xa28e808aaa1cb8676a4e2793a2379875e43c41070da1daa77444c9b189ef7817
(5) 0x06824469a0f67896cc467e90e01a6c345e6c982e92b0e5b30259d5746a41b947
(6) 0x9f131ad97a7e8d79b3163fbfeeb31076f8b640c270ca81c65a49b92a421b67be
(7) 0xcc08166aafadd91b3cb7203bd68bdd0733f2f08e17e4061362d99fa61536b2a5
(8) 0x7df647d69496391b5c056cbc90c9f5042d7b056707d3fc547e5106b4d43e0fb5
(9) 0xf684882931cad5992d5f5e49cba0c8d7ec8e0b5773d8ba7284879da0c858afa6
```

Figure 5.5. Ganache blockchain server

5.5.4. User Interface

The user interface to execute P2P energy trading activities is described in figure 5.6. For the purposes of this study, this user interface has been configured on Pi4B and can be accessed by browsing to http://localhost:3000/. MetaMask as a chromium extension and Ganache CLI are integrated with the user interface. Local Ethereum blockchain is used to deploy the smart contract.

React.JS an open-source java script library is used in configuration of the user interface. For the development of smart contract and user interface, we extended the source codes from [31]. Reference [32] provides a detailed guide to the basic concepts and procedures. MetaMask ensures the security of the Ethereum wallet with the help of a private key, user authentication, and secret phrase (as depicted in figure 5.6). More details on the user interface and MetaMask can be found in [11].

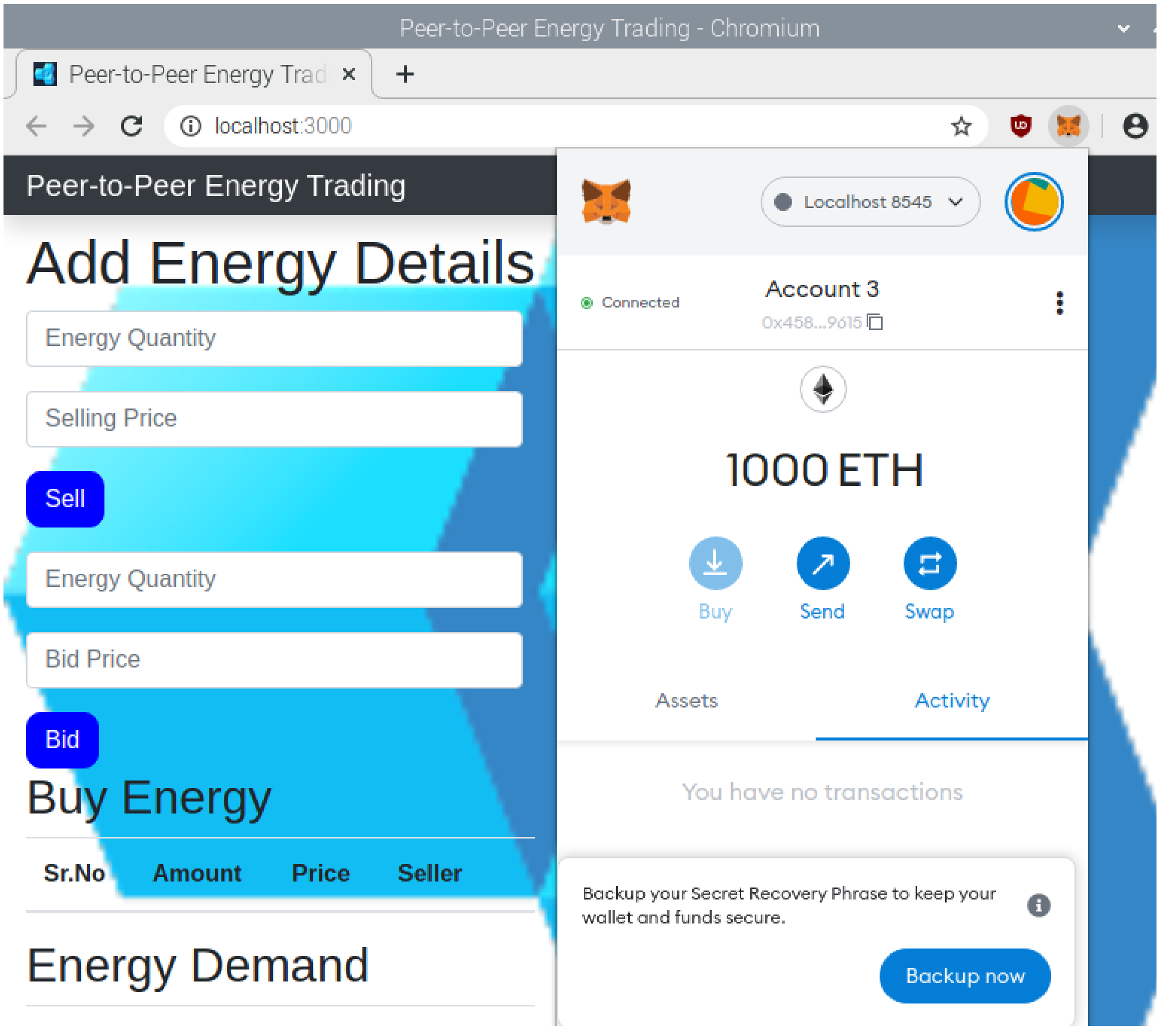


Figure 5.6. User interface for peer-to-peer energy trading

5.5.5 HTTP Request-Response Protocol

The HTTP (HyperText Transfer Protocol) is the lingua franca of the internet. An application-level protocol for client-server interaction [25]. Internet protocol HTTP is the basis of the World Wide Web. As an application layer protocol HTTP is designed for the communication of information/data between devices over the network. A typical HTTP request involves an HTTP client sending a request to a server, which then sends a response message back to the client. In response to the HTTP request, these responses convey valuable information [26].

Throughout the scope of this study, we have implemented HTTP request-response protocol to transfer energy trading data between clients and the servers. Once the main server receives a trading request from the client, it sends information to the IoT server in the individual household that then starts the trading process. After the trading request is fulfilled, the transfer stops automatically with the help of a computer algorithm.

5.5.6 Communication Channel

A D-Link DI-524 wireless router is used to create the communication channel between the IoT server and the blockchain based central server. It is IEEE network standards including IEEE 802. 11b, IEEE 802.11g, IEEE 802.3, and IEEE 802.3u compliant router. That features up to 400-meter range, 54 Mbps data transfer rates and operating frequency band of 2.4 GHz [40]. Since

Figure 5.7. The distance between houses and the Wi-Fi server

ESP32 follows IEEE 802.11 b/g/n protocol, the router is used to create a local Wi-Fi network for communication between the servers. With a range of 100m/328 feet indoors, and 400m/1,312 feet outdoors, this router can connect all the houses in the community to the local Wi-Fi network. Figure 5.7 shows the houses' location in relation to the Wi-Fi server in the proposed community. The Wi-Fi router range and the distance of each house in feet shown in figure six makes D-Link DI-524 a perfect selection for the site. The SSID and password for network access control and network security are set up, and firewall is enabled.

The other components used as a part of this study are 8.5 Watts (W) LED lights, Lead- acid 12V batteries, battery connectors, manual switches to operate house load and wires.

5.6 Prototype design and Experimental setup

This section describes the design and hardware implementation of the proposed low-cost, open-source P2P energy trading system based on above-described hardware components and their operation principles. Figure 5.8 shows Pi4B, analog current sensor, a relay, pull down resistor arrangements and ESP32 together on a Breadboard. The Pi4B acts as the main server in the proposed P2P system and hosts both a user interface and a blockchain server that can be accessed remotely. Through this server, residents of the remote community can perform trading tasks. As a household server, an ESP32 is installed in every single house connected to the micro-grid. As part of this research, the primary purpose of the ESP32 controller is to monitor and control energy using field instrumentation devices as outlined in figure 5.8.

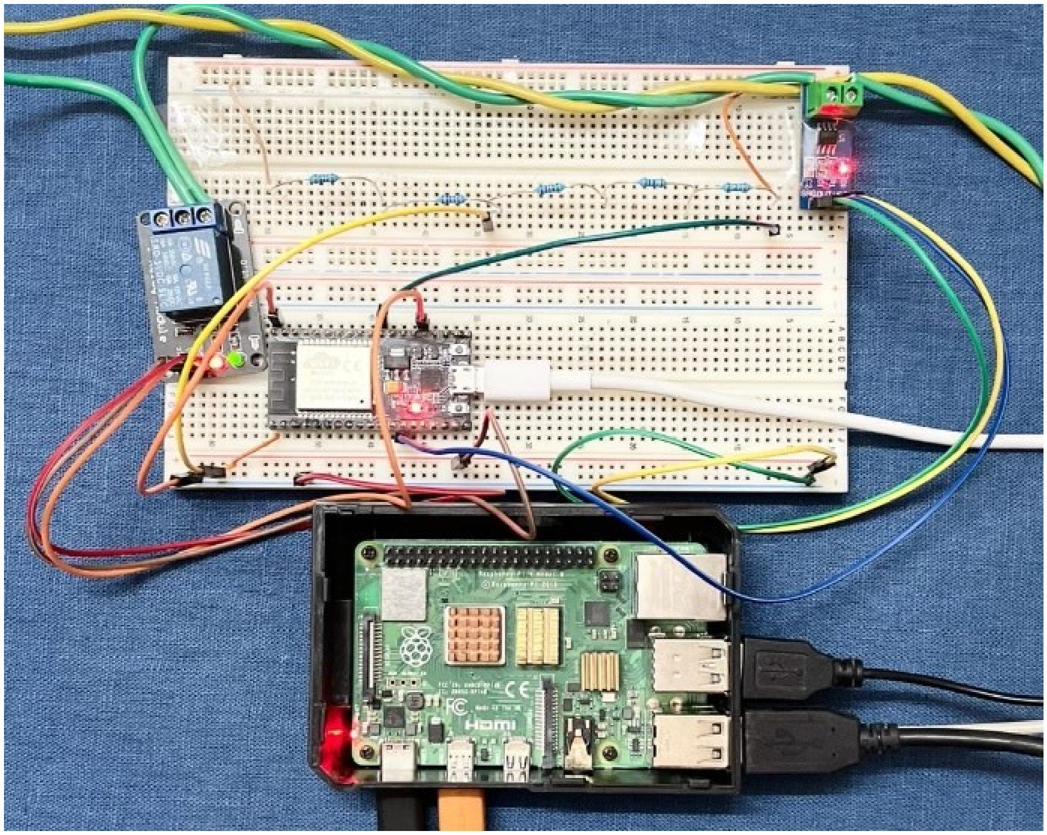


Figure 5. 8. Hardware implementation of the low-cost server

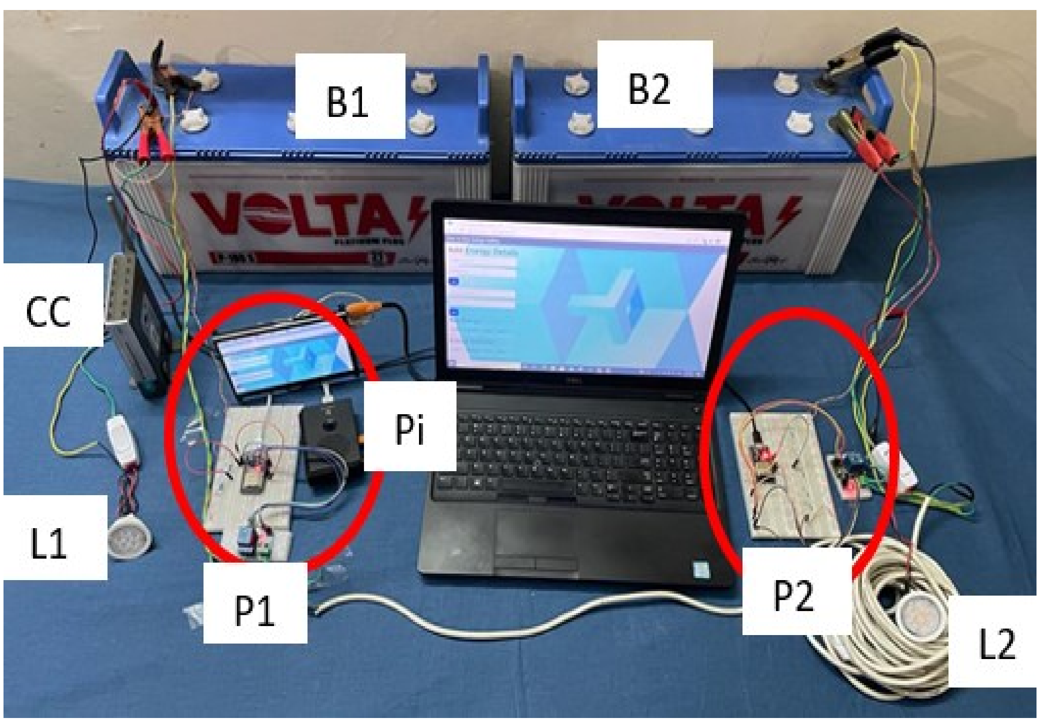


Figure 5.9. Experimental setup for the proposed P2P energy trading system

Figure 5.9 illustrates the complete experimental setup. The experimental set up include two batteries represented by B1 and B2 respectively, a Wi-Fi router designated as CC used to create a private communication channel in low-cost, IoT and blockchain-based P2P energy trading system, and a Pi to serve as the main server of the system. The system's ESP32-based servers are pictured as P1 and P2 representing peer1 and peer2 in the remote community and loads of each peer are exhibited as L1 and L2. We can see in figure 5.9 that the main P2P server is accessible using HMIs. As a scope of this study, we considered two peers and actual trading actions are performed between P1 and P2. B1 and B2 serves as the energy storage system of the peers. L1 and L2 are assigned to the peers as to represent actual household load in the hoses of the community.

The configuration of a private communication channel is done by using an IEEE 802.11 standards compliant Wi-Fi router labelled CC. The local communication channel provide access to the P2P energy trading system for the participants, enabling them to perform trading actions and transfer sensor data to IoT server.

5.7 Implementation Methodology

The proposed P2P energy trading system implements a low-cost, open-source energy trading solution on a Pi4B and ESP32. ESP32 microcontroller is programmed with the Arduino Integrated Development Environment (IDE) for receiving sensor data and sending it, later via Wi-Fi, to a web server that can be remotely accessed and monitored. Analog sensors are connected to a battery bank to collect the required data, and ESP32 receives the sensor data and transmits to the dashboard. The Blockchain server and a user interface is set up on Pi4B. Using HMI dashboards, data can be visualized, monitored, and controlled remotely. Algorithm 1 below shows the pseudocode for the implementation methodology. A connection process is represented in step 1 to

6 of algorithm 1, which connects the IoT server with the local Wi-Fi network and displays the status of the connection in Arduino IDE's serial monitor. Following receipt of energy demand, steps 7 to 16 of Algorithm 1 describe the process of trading energy. If the client posts energy demand through the main server's user interface, the IoT server will receive the energy demand over HTTP and the relay will initiate the energy trading process. The ESP32 calculates the values received from Field Instrumentation Devices and displays them on the dashboard. The server compares energy consumed with energy demand and stops the energy trading process over HTTP after the trading request is fulfilled. After disconnecting the client as described in line 17, a new process will start as illustrated in line 18 of pseudocode.

Algorithm 1: Energy trading, data acquisition and energy data display

---

Initialization;

Demand = 0;

Consumed= 0;

while

1. ESP32 is not connected to local network;

2. Establish ESP32 and local network connection by passing, SSID, and password;

if

3. ESP32 connection successfully established with local Wi-Fi;

4. Display “Connected” on Arduino IDE Serial Monitor;

else

5. Display “Connection failed…. retry in 5 seconds” on Arduino IDE Serial Monitor;

6. ESP32 connects to local Wi-Fi network;

While

7. Refresh sensor value;

If *client is available* **then**

---

8. ESP32 reads energy demand data over http;

If *demand from main server* **then**

9. Update energy demand;
10. ESP32 turns on relay;
11. Energy transfer starts;
12. ESP32 reads sensors values and calculates power and energy;
13. ESP32 displays data on local webserver;
14. Update energy consumed;

If *energy consumed >= energy demand* **then**

15. ESP32 turns off relay over http;
16. Energy transfer stops;
17. Disconnect client;
18. Step 7;

end

5.8 Results

This section outlines the results obtained after successfully testing of the proposed low-cost, open-source, IoT and blockchain based P2P energy trading system explained in the earlier sections of this chapter. Testing of the proposed low-cost, open-source P2P energy trading platform has produced the required results. Figure 5.10 illustrates a flowchart explaining the system's operation. It describes the entire energy trading process briefly.

The system is designed for ten peers to trade energy. A user interface shown in figure 5.6 allows the peers to perform trading actions. They can present energy demand to the other peers within the community using the bid option and they can also sell excess energy by clicking energy sell button on the user interface. The user interface also incorporates MetaMask as a chromium

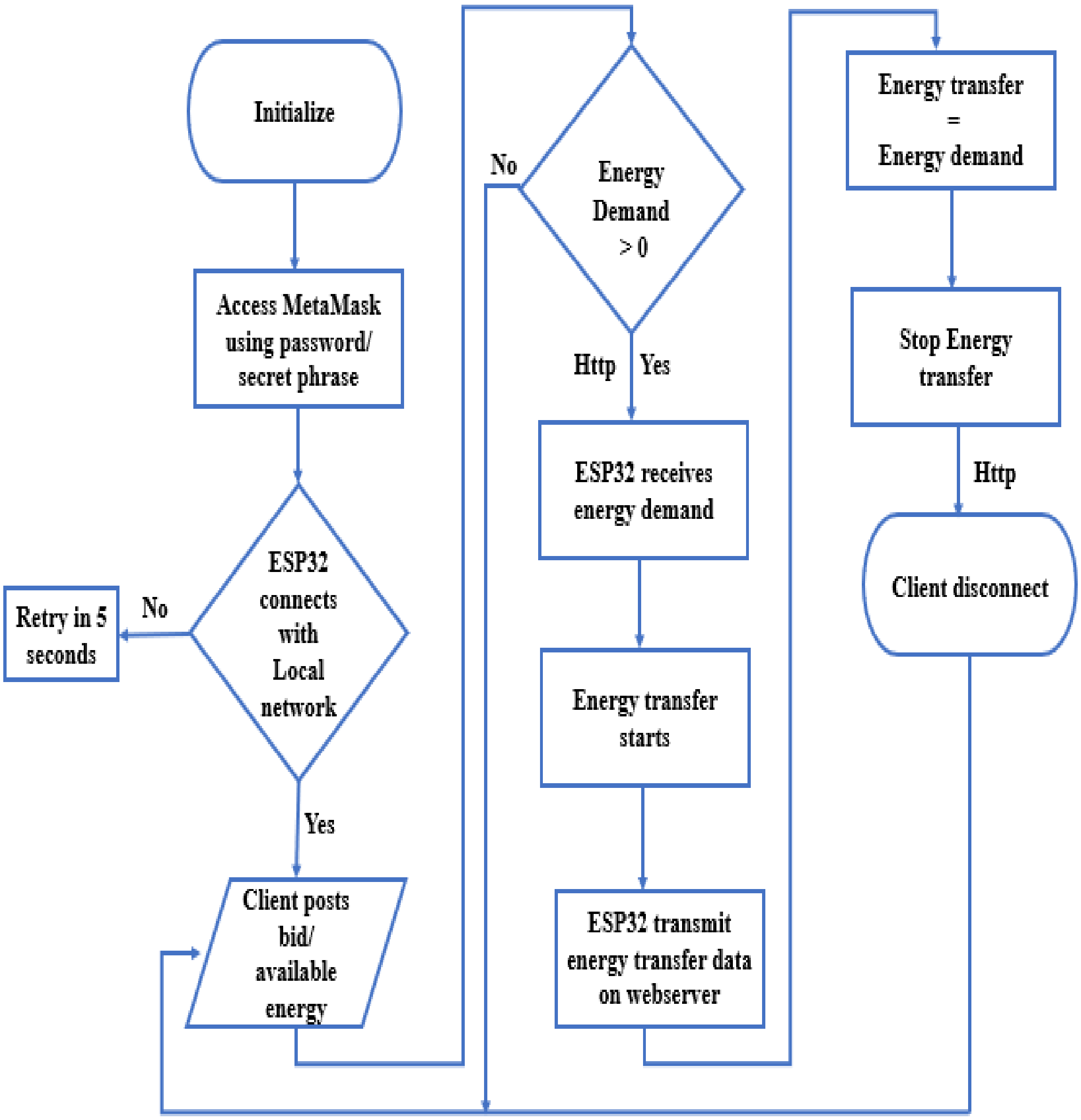


Figure 5.10. Flow chart of the proposed P2P energy trading system

extension in this study. Accounts created on the blockchain server (figure 5.5) can be imported using MetaMask for further use in trading. Once a peer inputs an energy trading request the MetaMask extension will pop up on the screen with the account details of the peer performing trading session at that time. The client will then have an option to double-check whether they confirm the transaction through their account or reject it, as shown in figure 5.11. The excess energy offered by sellers will appear on the user interface of the system and will show up under

BUY Energy with the details like amount of energy, its price, and the seller account information. Any peer on the network who accepts the offer can click on the buy button with the offer details and energy transfer will start through the relays installed with the servers of both buyers and sellers. The ESP32 server will measure the amount of energy being transferred and will disconnect the relays after the energy purchased is successfully transferred. The system also allows the buyer to

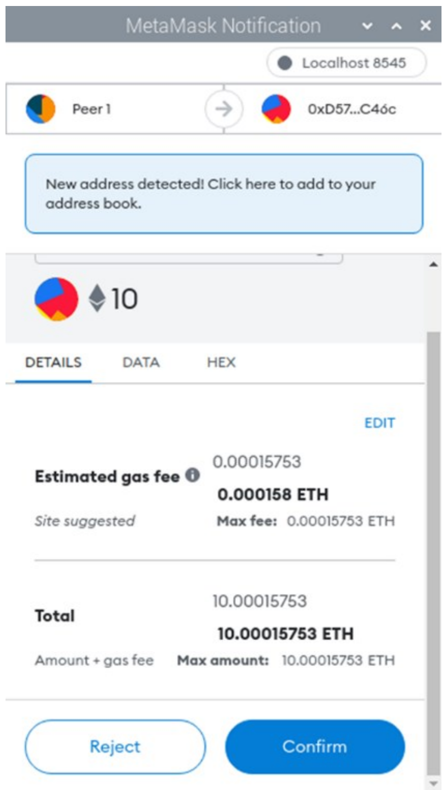


Figure 5.11. MetaMask extension

post energy demands with the price. This enables the sellers to see the price and the amount of energy required. All the peers connected with the system can see the trading activities by browsing user interface. The biding feature gives an option to other peers to sell the energy at the price of their choice after observing offered price and it provides an opportunity to buyers to fulfill their energy demand at even a lower price.

All the trading activities on the user interface are recorded on blockchain server. As a part of this study, we have implemented Ganache CLI an Ethereum client to establish a local blockchain network on main server. All the participants as a part of this network have access to the blockchain server through http://localhost:5051/. We have configured an open-source local ganache-CLI block explorer. It is a web-based block reader that lets the participants explore local blockchain network blocks.

The participants on the P2P network can explore the transaction information like block amount of energy transfer, mining details, gas limits, gas used, and size, stored within each block. In this study go language Ethereum library is used to communicate with ganache CLI client [33]. Figure 5.12 exhibits the blocks mined on the blockchain server in response to the transactions performed on user interface of the system. In total 26 blocks are generated and can be seen on the dashboard of the block explorer. Each block mined following the energy trading activities during this study is available on the dashboard of ganache-CLI blockchain explorer, which can be further explored by providing block hash to get block information option. Figure 5.14 represents the process of getting more information regarding the blocks and figure 5.13 illustrates the details of block 26 mined on the blockchain server. It shows a block hash that is a unique address of each block mined after successful transaction, the time stamp that is the representation of the time and date at which the block is mined, gas used, and an Ethereum transaction fee. Gas is paid in ether (ETH), Ethereum's native currency. The gas fee is represented in gwei, Ethereum's unit of measure for gas prices, and 1 gwei is equivalent to 10^{-9} ETH [34]. In addition, the block size, gas limit and parent hash (of the previous block) can be found there. This study's scope does not extend to information on uncle hash, which is also provided by the block explorer. Figure 5.15 shows the impact of trading on account balances and energy transaction details is presented in figure 5.16. Figure 5.17 illustrates how the buyer's energy demand appears on the user interface. In the proposed community, every household has an ESP32 controller that monitors and controls energy,

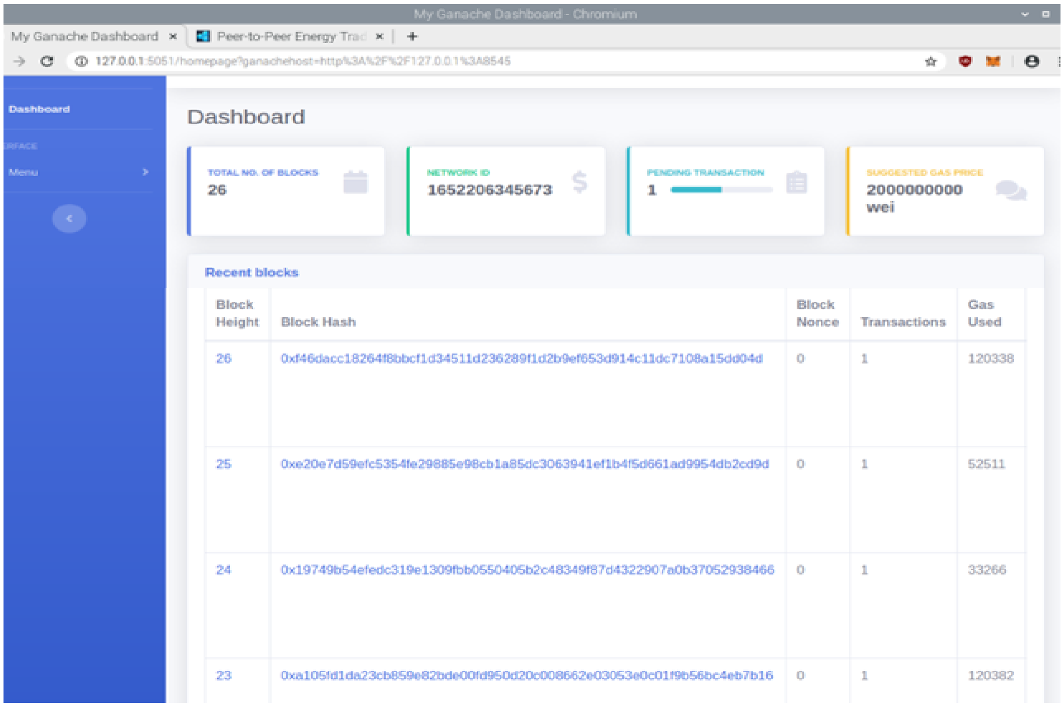
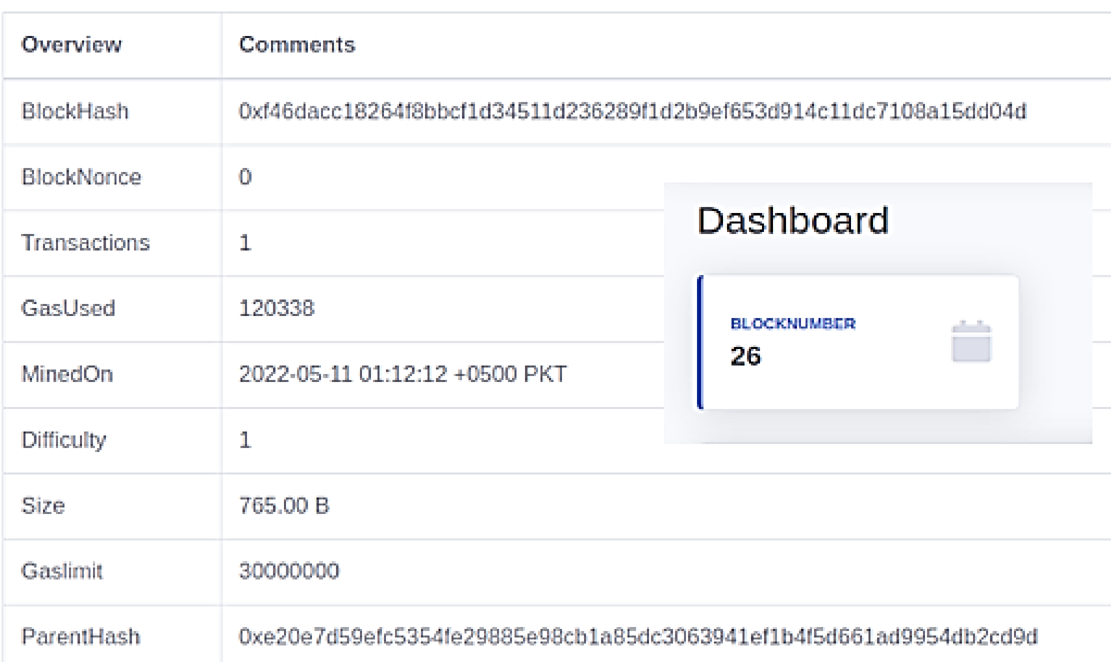


Figure 5.12. Blockchain Server



Overview	Comments
BlockHash	0xf46dacc18264f8bbcf1d34511d236289f1d2b9ef653d914c11dc7108a15dd04d
BlockNonce	0
Transactions	1
GasUsed	120338
MinedOn	2022-05-11 01:12:12 +0500 PKT
Difficulty	1
Size	765.00 B
Gaslimit	30000000
ParentHash	0xe20e7d59efc5354fe29885e98cb1a85dc3063941ef1b4f5d661ad9954db2cd9d

Figure 5.13. Block details

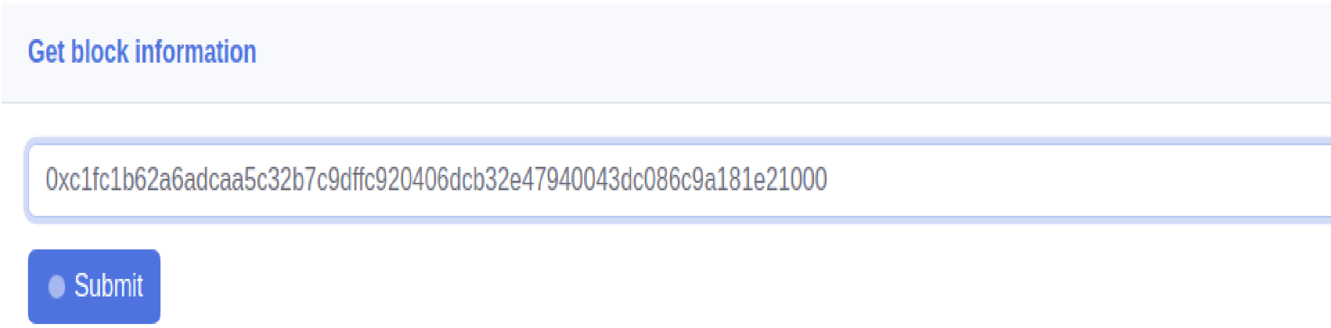


Figure 5.14. Block Details

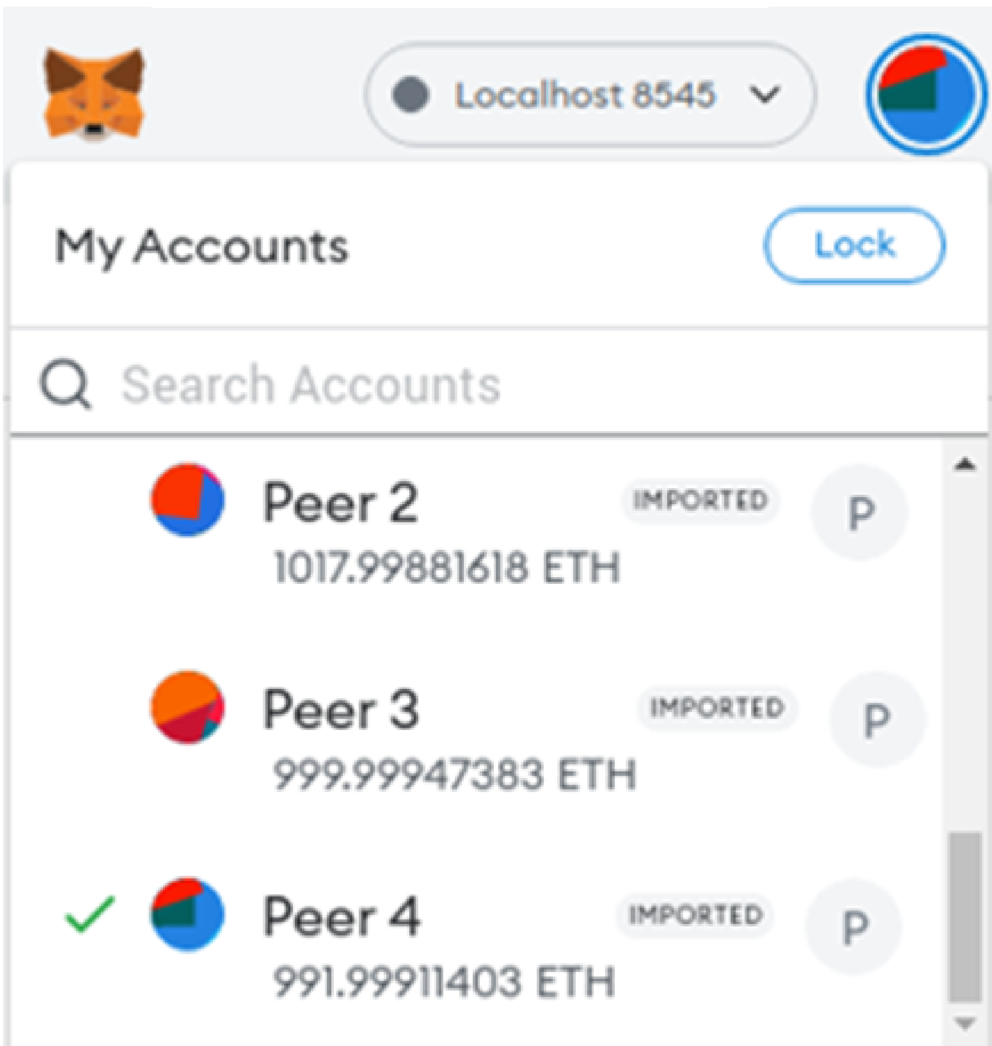


Figure 5.15. Account Status after Transaction

and functions as an energy meter. The ESP32 controller initiates the transfer process once the energy transfer request over HTTP has been received and ends once the desired amount of energy has

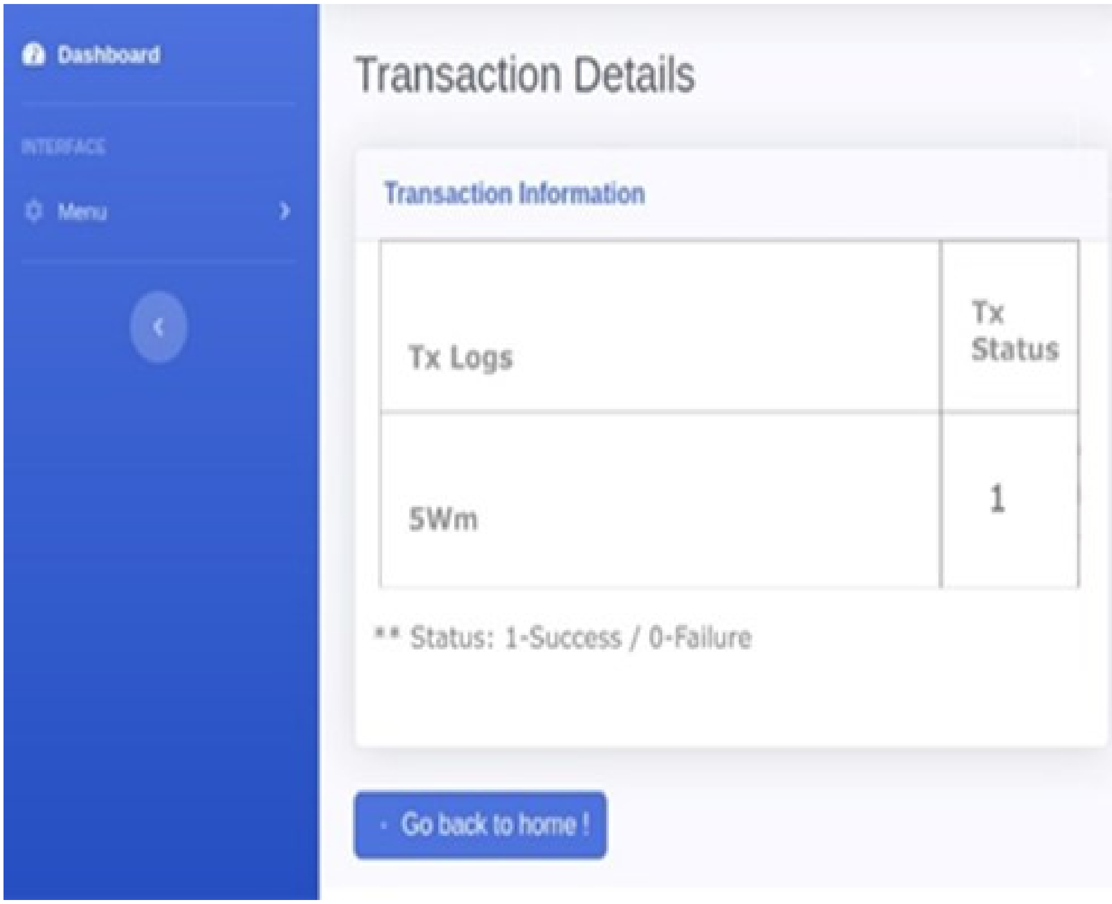


Figure 5.16. Transaction details on blockchain

Figure 5.17. Energy demand on user interface

been transferred. ESP32 controller dashboard is depicted in figure 5.18 when running on a network and the energy offers by seller are shown in figure 5.19.

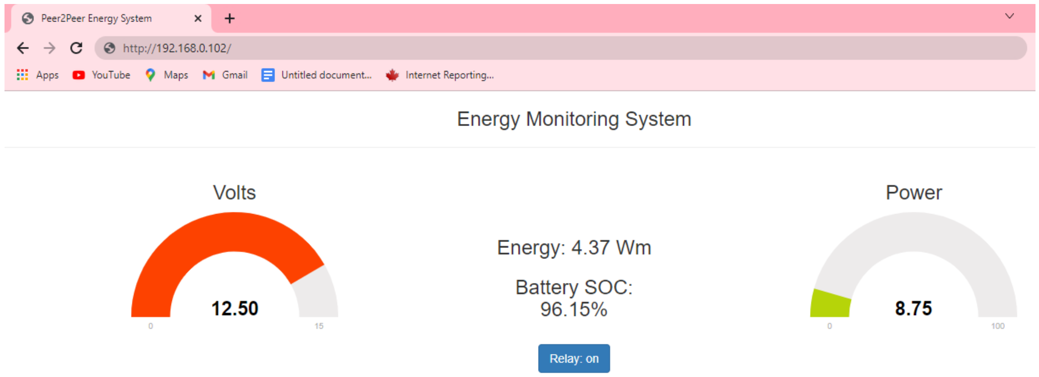


Figure 5.18. IoT server status

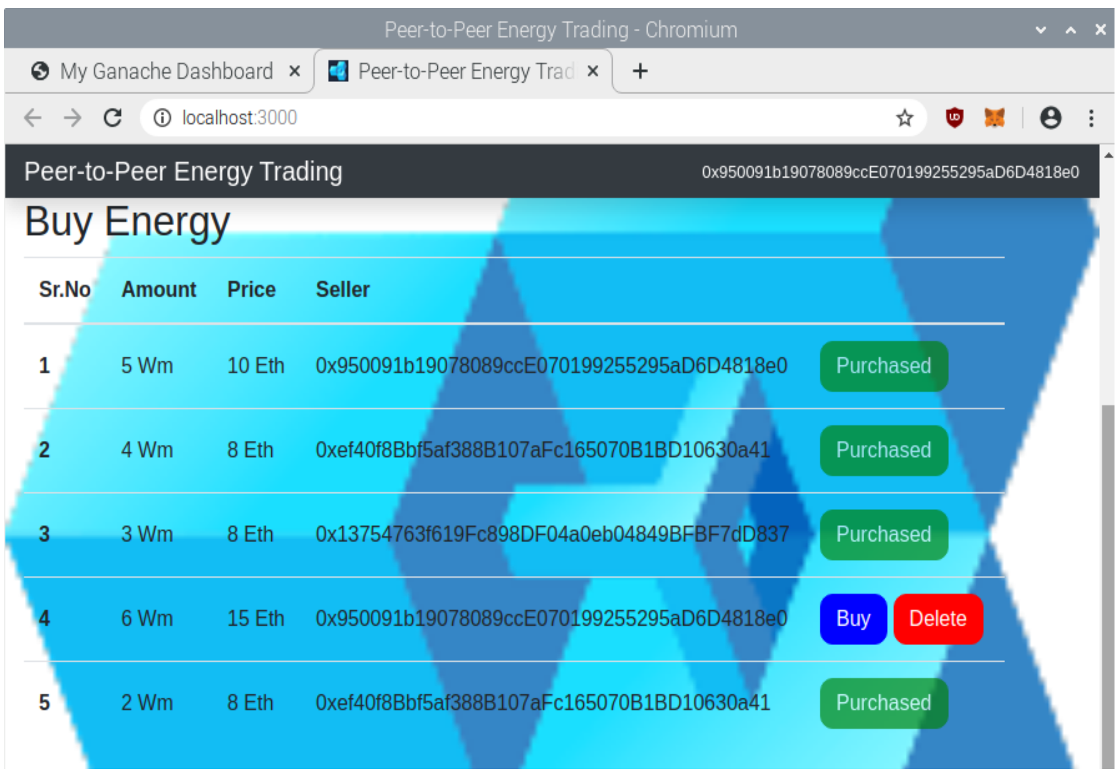


Figure 5.19. energy offered by the seller

5.9 Discussion

This section aims to highlight some of the main features and benefits of the low-cost and open-source P2P energy trading system developed for the remote community in Pakistan realized following successful testing.

- **System configurations:** The Internet-of-Things and the Ethereum Private Blockchain provided a concrete foundation for a robust distributed application for P2P energy trading in the case studied, as well as for remote locations in general. For this study, the Ganache Ethereum blockchain is used since it is fast and customizable. The number of accounts and associated balances can be customized needed. The IoT server is set up on a low-cost ESP32 that facilitates trading and monitoring in the system. This system features the essential elements for an efficient and effective blockchain based P2P network, including an IoT server, a Blockchain server, a Communication Channel, and Field Instrumentation Devices.

Table 5.1. An itemized bill of components

Sr. No	NAME OF COMPONENT	PRICE (PAK RS)
1	Raspberry Pi 4 Model B (Cost per house)	38000 (3800)
2	ESP32	899
3	Relay	140
4	Current sensor	270
5	16 GB SD Card	1400
6	D-Link DI-524 Wireless Router	2300

	(Cost per house)	(230)
7	Miscellaneous (Breadboard, Jumper wires, wires, Pi case, Resistors)	900
	Grand Total per house	**PAK RS 7639/-**

- **Low-cost and open source:** The hardware components employed in this design are readily available and are reasonably priced. The breakdown of the cost of each component as well as the total cost of the designed IoT and Blockchain based P2P energy trading system is presented below in Table 5.1. According to Table 5.1, Installation of both IoT server and the Blockchain server per house would cost Pakistani rupees 7639/-, about CAD $50, and this is indeed a low cost as compared to the hi-cost existing system presented in [11]. The system is based on free and open-source software and code, another factor contributing to its low cost. Reference [35-39], provides more details on costs.
- **Low power:** When designing an IoT-based system to operate 24x7 power consumption is a significant consideration. Thus, in designing the system, the power consumption of each component was a key concern. The main server of the proposed system is configured on Raspberry Pi that consumes 2.5 Watts. The IoT server is setup on an ESP32 that requires a maximum of 0.8 Watts. This proves the microcontroller as a low-power device. The overall power consumption of a server within a household of the community is 3.3 Watts and the Wi-Fi router consumes 4.4 Watts of power. The power consumption of each component is observed while under operating conditions, and data sheets can be referred to for details. A summary of the power consumption of each hardware component used as part of this study can be found in Table 5.2.

Table 5.2. Power requirement of the proposed system

Sr. No	HARDWARE	POWER (W)
1	Raspberry Pi 4 Model B	2.5
2	ESP32	0.8
3	Breadboard, ESP32, Sensors, Resistors	3.3
4	D-Link DI-524 Wireless Router	4.4

- **The availability and reliability of the system:** The open-source nature of all the components used in this study, and the fact they are readily available, as well as the fact that all servers, interfaces, and devices are locally installed and self-managed, allows the participants to ensure continuous reliability and availability of the system.
- **The acquisition of data, monitoring, and control**: An IoT server installed on the peer side provides real-time data acquisition, monitoring of energy transfer data and control of transmission operations based on requests from the central server via HTTP.
- **Remote monitoring and trading:** The proposed IoT and Blockchain based P2P energy trading system is human machine interaction enabled. In this manner, peers have the opportunity to perform, observe, and monitor energy trading remotely.
- **Security:** As the proposed P2P energy trading system uses Blockchain and IoT servers that are locally configured, data integrity and security are taken into account. This includes login credentials for MetaMask, a unique private key for authorized access to the Ethereum wallet, SSID and password requirements, firewall security and secret recovery phrase.
- **An easy-to-use system**: In the proposed P2P energy trading system, the interface has been designed to be intuitive and user-friendly. It does not require users to go through any special training.

- **Fast and efficient settlements:** The blockchain server implemented in this study is capable of fast settlements. It executes transactions instantly and transfers funds immediately. A smaller ledger also contributes to the efficiency of the system.
- **Electronic payment system:** A system of electronic payments is introduced to remote communities without internet access along with solutions for energy monitoring, control, and trading.
- **A comprehensive guide for future research:** This research has an important impact on providing electricity trading and management solution to this unserved community. The research described above provides a solid foundation and justification for planning and designing isolated-microgrid based P2P energy trading system for remote areas without internet access.

5.10 Conclusion

The world still has a large population who live without electricity. The World Bank estimates that 25 percent of Pakistan's population lacks access to electricity, and that figure rises to 40 percent in remote areas. Observed reasons include limited government resources, low generation capacity, and high transmission costs. Even though Pakistan has abundant renewable energy resources, lack of knowledge and know-how of such systems has been a hindrance towards its utilization. While it is important to have distributed energy generation, it is also critical to have a platform that ensures energy management and trading services among neighbours. This will raise interest in distributed generation, and ultimately result in the electrification of remote areas, since proper returns on energy can be realized.

The objective of this study is to develop a low-cost and open-source peer-to-peer (P2P) energy trading system based on the Internet-of-Things (IoT) and Blockchain for a remote community in Pakistan. The system presents the most recent technologies and is unique in the sense that we have not seen such a low-cost, open-source system implementing the latest technologies we have used as a part of this research. Another novel aspect of this system is its geographical location of the selected community. The proposed energy trading system has been designed and implemented with six critical components, including Field Instrumentation Devices, a relay, ESP32, a user interface, Ethereum private blockchain, and a Local Wi-Fi Network. To validate the design of the P2P energy trading system, an experimental setup was created. The results demonstrated that the system can be used to carry out the desired functions of a P2P energy trading system, namely Energy Transfer, Data Acquisition, Data Monitoring, Data Display, Networked Data Communication and maintaining Digital Ledger on Blockchain Network. This system is proven to be low power with its central server only consuming 2.5 W, the IoT server alone 0.8 W, the IoT server in its entirety 3.3 W, and the communication channel 4.4 W. Additionally, the system was found to be very inexpensive. Its overall cost is under CAD $50. Authentication for MetaMask, private keys for each peer to access digital assets, firewalls, login credentials, and seed phrases are also considered as data security measures.

Although the proposed P2P energy trading system in this study is considered for a remote community in Pakistan. This research can have a significant impact on promoting distributed energy generation for remote locations. It can serve as a marketplace for prosumers to sell excess electricity to their neighbors.

5.11 Future Work

The authors would like to extend the application of this study to the larger remote communities with no electricity and internet access. The authors believe that this study will encourage the adoption and investments in distributed energy generation. Expanding the range of communication channels with low power consumption can also contribute to future work extensions.

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Abbreviations

This manuscript uses the following key abbreviations:

IoT Internet of Things

DG Distributed Generation

P2P Peer-to-Peer

HMI Human Machine Interface

SBC Single Board Computer

Pi4B Raspberry Pi 4 Model B

HTTP HyperText Transfer Protocol

CPU Central Processing Unit

CLI Command Line Interface

SSID Service Set Identifier

PV Photovoltaic

FID Field Instrumentation Device

IP Internet Protocol

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Chapter 6

Blockchain-Based Peer-to-Peer Energy Trading System Using Open-Source Angular Framework and Hypertext Transfer Protocol

Co-authorship statement

A solution to energy trading across P2P networks using blockchain technology is presented in Chapter 6 by using Raspberry Pi 4 Model B (Pi4B) as the main server of the proposed system, which hosts both the user interface and the private Ethereum blockchain. Blockchain also implements smart contracts. Detailed technical information about P2P energy trading as well as security features are discussed in this chapter. This chapter also contributes to achieving objectives 4 and 5 of this research, as outlined in section 1.3.

Among the authors of this chapter, I, Mirza Jabbar Aziz Baig, am the primary author, and Dr. Mohammad Tariq Iqbal, Dr. Jahangir Khan, and Dr. Mohsin Jamil are the co-authors. As a principal author, I contributed to the methodology, software and hardware implementation, data curation and writing of original draft and the co-authors supervised the overall research work as well as conceptualization, providing resources, and reviewing and editing the chapter. This chapter is also published as M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, "Blockchain-

Based Peer-to-Peer Energy Trading System Using Open-Source Angular Framework and Hypertext Transfer Protocol,” *Electronics*, vol. 12, no. 2, p. 287, Jan. 2023, http://dx.doi.org/10.3390/electronics1202028.

Abstract: Renewable energy resources have been gaining ground in recent years and we are on the verge of a decentralized energy market with consumers becoming prosumers. Platforms that facilitate peer-to-peer (P2P) sale or purchase of energy are therefore essential. This chapter presents a way to trade energy across P2P networks using blockchain technology. The main server is a Raspberry Pi 4 Model B (Pi4B), on which the user interface (UI) as well as the private Ethereum blockchain are configured. The blockchain also implements a smart contract. For the purpose of developing the UI that provides assistance in conducting trading activities, an open-source Angular framework is used. Also explored in the study is the development of an Internet of Things (IoT) server using the latest ESP32-S3 microcontroller. The field instrumentation devices (FIDs) are connected to the microcontroller for the purpose of data acquisition and for subsequent transmission to an IoT server. The blockchain network maintains a record of all transactions in an immutable manner. Assuring security is achieved through a local configuration of the system, hosted on a private network with restricted access. For the purposes of information security and data integrity, additional security measures are also considered, such as a secret recovery phrase, firewalls, login credentials and private key. Among the servers and clients, there is an implementation of a Hypertext Transfer Protocol. The P2P energy trading approach involving renewable energy designed for remote communities is explained and illustrated in this chapter.

Keywords: blockchain; Hypertext Transfer Protocol Internet of Things; open-source; peer-to-peer; renewable energy

6.1 Introduction

As a result of the energy transition from fossil fuels to renewable energy, the energy sector globally is experiencing a significant transformation. The energy consumer has evolved into a prosumer. Distributed energy resources, such as photovoltaic (PV) systems, have been prevalent in energy markets, contributing to the growth of prosumers [1]. This creates a decentralized energy market that provides consumers with the opportunity to purchase energy locally rather than through the utility companies only. Energy can now be traded directly between individuals without the involvement of an intermediary. According to [2], consumers and prosumers trade energy directly through P2P trading. It can be greatly facilitated by the use of information and communication technologies. A revolution has been sparked by blockchain and intelligent devices on the P2P market. The blockchain enables the prosumer to conduct financial transactions independently. Conversely, smart devices coupled with the Internet-of-Things (IoT) provide low-cost means to exchange energy. There is no doubt that market for conventional electricity has been heavily influenced by renewable energy sources. Even so, it has not been able to capture the traditional electricity market in its entirety. There may be a number of factors contributing to this, including the inability to obtain a return on investment. Throughout this study the authors strive to maximize the returns to prosumers on their investment. A blockchain and IoT-centered energy trading platform is proposed by the authors. With its decentralized structure, the proposed system provides participants with the most recent energy trading solutions, including financial transactions, energy transfers, and energy metering. Participants in the proposed system will be able to conduct financial transactions using all the security features that come with a blockchain network. As for the IoT server, this enables peers to control and monitor their own energy generation. The proposed method for P2P energy trading uses two major components to host the server, a raspberry pi model 4B (Pi4B) that hosts a private blockchain server with UI and ESP32-S3 microcontroller to host the IoT server.

According to the authors' findings in [3], the increasing use of distributed energy resources in distribution systems is enabling low-voltage networks to utilize new methods of operation. P2P energy trading schemes have been proliferating recently as a result of recent trends in cryptocurrencies and blockchain, which enable neighbors to exchange electricity without any intervention from traditional intermediaries. Under this scenario, the network's technical constraints have not been adequately addressed. According to the authors, the impact of exchange on network constraints can be assessed using a sensitivity analysis. A low-voltage U.K. network is used to test the proposed method. As a result of this study, it was found that P2P schemes can still provide users with economic benefits without violating the network constraints. Another study [4] identified peer-to-peer energy trading as an effective method by which multiple consumers could benefit from renewable energy in an active distribution network. This study emphasizes the energy transactions to be implemented securely, and it is still necessary to meet the distribution voltage constraints. A decentralized P2P energy trading protocol that is capable of voltage regulation is proposed by the researchers. IEEE bus-33 and 69 standards are used to verify the effectiveness and efficiency of the system through case studies. Zheng et al. [5] describe the proliferation of distributed energy resources as leading to peer-to-peer trading. According to the authors, there is a growing consensus among the experts that the future of the energy market is P2P. This study examines the concept of shared energy storage, based on the sharing economy principle, as a way of reducing capital expenditures and increasing storage devices' efficiency. P2P energy trading model for residential homes with shared energy storage is presented in this study. It has been demonstrated through numerical simulations that energy trading through P2P is beneficial for all participants, while the introduction of shared energy storage may be capable of further reducing the energy costs. In their study [6], the authors found that P2P energy trading benefitted both consumers and operators. A key role for demand-response management will be to bridge the gap between local demand and supply in future P2P energy markets. The authors proposed a blockchain-based system for community-based P2P energy trading. Through the use of two noncooperative games, a demand-response mechanism is proposed. The proposed energy trading system uses Hyperledger blockchain to prototype dynamic pricing for suppliers in both games. On-chain and off-chain processing modes were implemented to study the system's performance. As a part of this study experiments validated that demand-response games reduce peak loads significantly, while providing lower latency and overhead compared to on-chain models. Authors have proposed deploying Verifiable Query Layer (VQL) to the cloud for data query services for blockchains in [7]. A proposal for vChain+ to support boolean range queries is presented in [8]. That supports data queries on the blockchain.

Another study [9] discusses the factors that have led to the transformation of corporate standards in the electricity sector globally due to disruptive technologies as well as the reduction in costs associated with photovoltaics. In addition to providing a customer choice aligned with the values of a community, P2P energy trading has the capability to make green energy more readily available locally. This study investigates the factors that drive and challenge implementing P2P energy trading in Thailand from the perspective of participants in the regulatory sandbox program. Political, economic, social, technological, legal and environmental factors will have a significant impact on P2P energy trading implementation, according to the authors. Among its recommendations are establishing third-party access, liberalizing the electricity market, and incorporating prosumers in existing legal structures to establish a regulatory framework towards the future of P2P energy trading. Local consumption of renewable energy is promoted by P2P energy trading. There is, however, distrust amongst users, as well as high transaction costs associated with P2P. As a solution to these issues, the authors propose a credit and blockchain-based P2P energy trading model. A six-stage P2P electricity trading process is first presented. In the next step, Docker and Go are used to simulate Hyperledger Fabric. In P2P electricity trading, the proposed model can enhance trading stability and efficiency by reducing the cost for users and managing credit [10]. According to researchers [11], there has been an increase in energy trading owing to the availability of distributed energy sources as well as the ability of electricity producers to export surplus fuels at a financial profit. Energy from multiple sources is successfully combined through the energy trading system providing energy consumers with better facilities and consistent use of resources. The authors discuss decentralization, scaling and device reliability as ways in which blockchain can enhance transparency and performance. A blockchain-based smart grid is also demonstrated in terms of its importance in future smart grid activities. Furthermore, the research briefly examines the implementation of blockchains to ensure future autonomous electric grids will be decentralized, secure and scalable. In [12], an IoT and blockchain-centered P2P energy trading platform is introduced as a pilot study. Based on open-source technology, the authors proposed a blockchain-based platform for P2P energy trading with the fundamental characteristics of a P2P energy trading platform.

The authors in [13] believe that P2P energy trading represents one of the most promising solutions for energy management in an isolated distributed system. Their proposal focuses on the development of a P2P energy trading platform based on blockchain and IoT technology. A Node-Red-based dashboard is used to perform energy monitoring and trading tasks, while email notifications are used to provide trading alerts. Through experimental results, the proposed system has been validated, and it is recommended for fast and secure P2P energy trading. An isolated DC-microgrid could benefit from a P2P energy trading solution based on blockchain and IoT, as referenced in another study [14]. In the context of [15], through the implementation of a smart contract on a private blockchain, a P2P energy trading system is proposed. As a part of this system self-generated energy is monitored and controlled using the IoT platform and to perform trading activities, and the authors developed a user interface using the React J.S library. In the suggested P2P energy trading system, a microcontroller and FIDs were used, as well as a private communication channel for data exchange using the Message Queuing Telemetry Transport protocol (MQTT). Testing and validation of the developed system are carried out using an experimental setup. Other researchers [16] have developed a low-cost P2P energy trading setup that has been implemented in a remote community using open-source technology. For P2P energy trading within the community, the authors developed a low-cost server utilizing blockchain technology and the IoT. As part of the development of the proposed system, they also used React.JS, FIDs and Microcontrollers. Hypertext Transfer Protocol (HTTP) is used in this study to communicate data over a private network, and security considerations are also considered.

Through the course of this study, the literature has been extensively reviewed, and some of it is summarized above. In light of the literature reviewed and to the best of the authors knowledge, no platform has been identified that uses Angular-6, a component-based application development platform together with ESP32-S3 microcontroller for blockchain-based P2P energy trading. A private Ethereum blockchain has also been incorporated with open-source Angular-6 as part of our design. As for blockchain server, Pi4B is used, while ESP32-S3 is utilized to host IoT server. In addition to being fully automated, each server is interconnected via HTTP. The platform is installed locally and can be accessed remotely via a Human Machine Interfaces (HMIs). An interface allows users to perform energy trading activities that is accessible at http://localhost:4200/. The proposed system offers the following key contributions.

- Angular, the framework on which many popular websites such as Paypal, IBM, Weather, Samsung, etc. are built, is configured in implementation of the proposed P2P energy trading system. In addition, Angular-based UI is deployed on Pi4B coupled with a local blockchain server as well as an IoT server running on ESP32-S3. To the best of authors' knowledge, a novel P2P energy trading system is proposed, and no such system has been reported before.
- Implementation of a P2P energy trading with locally configured servers, hosted on a private communication channel, is particularly useful for remote locations that do not have access to the internet.
- An appropriate system configuration ensures independent monitoring and control of P2P energy trading.
- Considering the fact that the proposed design is open-source, there is no subscription fee or operating cost to be incurred due to the use of open-source technology.

6.2 System Description

An overview of the proposed blockchain centered P2P energy trading system is described in this section. As illustrated in Figure 6.1, the proposed system design consists of an energy storage system (ESS) represented here with batteries, a domestic load component, a main server and an IoT server. To implement the system design, we have used ESP32-S3 microcontroller that hosts an IoT server and a Pi4B as the main server to set up the Ethereum private blockchain and user interface (UI). The proposed system is hosted on a private network represented by a Wi-Fi router in Figure 6.1 and is accessible to every participant of the P2P energy trading system using

HMIs. The rest of the system architecture is composed of FIDs such as a relay, a current sensor and a voltage sensor. In addition, the figure illustrates the connections that can be used to trade energy with other peers.

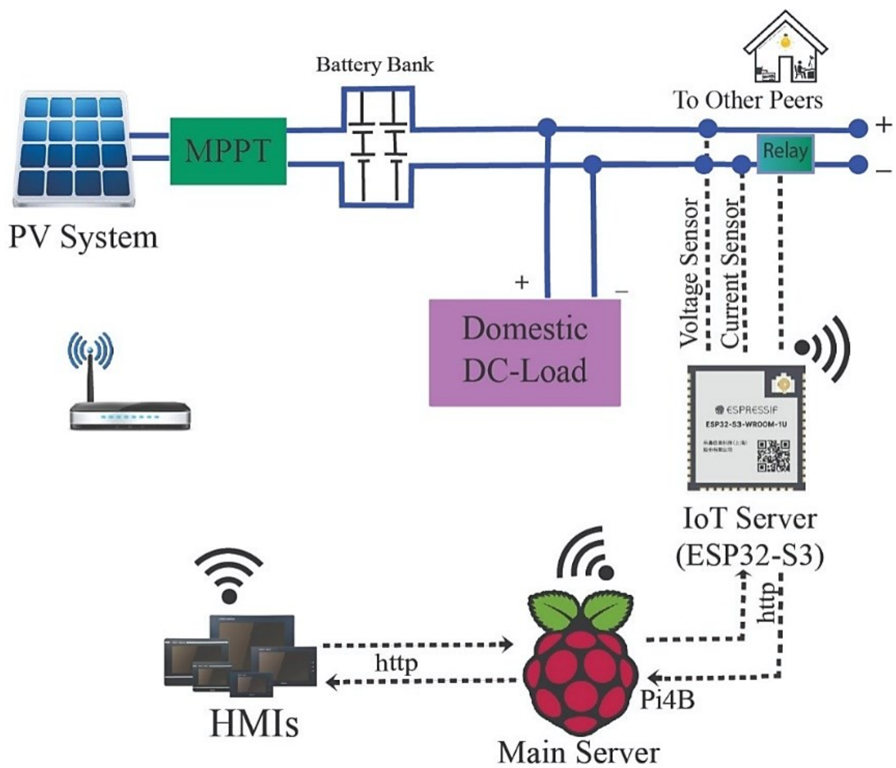


Figure 6.1. An overview of system architecture

In the event that any participant in this proposed P2P energy trading system needs to engage in energy trading, an UI allows them to access the system remotely and execute trades, such as the purchase and sale of energy. Upon receiving the trade request, the relay will be turned on and the trading session will begin. Following the transfer of the required amount of energy, the relay will shut off automatically. The trading process in this system is entirely automated and is conducted through the use of computer algorithms. Later in this chapter, we explain the pseudocode. Authentication of users has been configured to ensure network security. To facilitate client-server communication, the proposed system makes use of the HTTP request-response protocol. Open-source technology is at the core of the system.

6.3 Technology and Software

The following section provides an overview of each major technology employed in the development of our proposed P2P energy trading system developed using open-source technology. Among these technologies are a main server that is hosted on Pi4B, a single board computer (SBC) and an IoT server that serves as a data acquisition, monitoring and control system. A versatile microcontroller ESP32-S3 is used in this study as a platform for hosting an Internet of Things server. Other key components employed in this study are the FIDs. As well as this, we have also established a local communication network using a Wi-Fi router. In addition, servers' communication is carried out through HTTP protocol.

6.3.1. Raspberry Pi

In February 2012, the Raspberry Pi 1 Model B, generation 1 was released. The low price of $35 contributed to its immediate success. An inexpensive computer running Raspbian, a Linux operating system based on Debian, can be quickly assembled by adding a few peripherals. Typically, this device is often mentioned as a Single Board Computer (SBC) [17]. Raspberry Pi computers have proven enormously successful in a wide range of electronic projects. Do-it-yourself tinkerers and special purpose projects use it because of its low cost and accessibility. Its low cost has also made it possible to use it as a component in single-purpose devices, despite being a general-purpose computer [18]. Raspberry Pi Foundation, United Kingdom, developed and manufactures the Raspberry Pi (Pi). Compared with a mid-range desktop computer that typically costs between US$500 and US$600, the latest Pi 4 Model B (Pi 4B) is available for just US$35 for the base model with 2 GB of RAM [19].

A significant part of this study was conducted using Pi4B, the first of a generation of Raspberry Pi computers with significantly improved CPU, GPU, and I/O performance compared to its predecessor. Pi4B allows access to 28 BCM2711 GPIO ports via the Raspberry Pi's 40-pin header. The device features a quad-core 64-bit ARM Cortex A72 processor running at 1.5 GHz, has 4 Gigabytes of RAM and is 802.11 b/g/n standard protocol compliant. To add to this the following key characteristics, make this chip appropriate for the proposed energy trading platform [20].

- Compact size
- H.264 hardware decode (up to 1080p60)
- VideoCore VI 3D Graphics
- 1xSDCard
- 2x micro-HDMI ports supporting dual displays up to 4Kp60 resolution
- 2xUSB2ports
- 2xUSB3ports
- Linux software stack
- 0 to 50 degrees Celsius ambient temperature range.

As a main server UI is configured on Pi4B. For the purpose of energy trading UI is accessible through browser at http://localhost:4200/. In addition, the blockchain server is hosted on it. This system is configured on Raspberry Pi OS 64-bit, the latest release [21].

6.3.2. ESP32-S3

As a low-power MCU-based system on a chip (SoC), ESP32-S3 supports wireless connectivity with integrated 2.4 GHz Wi-Fi, as well as Bluetooth® Low Energy. The device consists of a 32-bit Xtensa® LX7 dual-core microprocessor and a low-power coprocessor. It is a complete Wi-Fi subsystem that conforms to IEEE 802.11b/g/n standard protocol and supports the Station, SoftAP, and SoftAP + Station modes of operation. A wide range of applications can be served by its multiple low-power modes. Among its capabilities, the ULP coprocessor is able to operate in a low-power manner. ESP-32-S3 has a powerful memory ensured by 128-bit data bus and SIMD commands, 384 KB ROM, 512 KB SRAM, 16 KB SRAM in RTC and various interfaces that allow connection to external RAM, as well as the other key features includes advanced Peripheral Interfaces, low power management and device security [22,23].

Our research involved the use of the ESP32-S3 SoC device for local data acquisition, monitoring, and control applications. For this purpose, the ESP32-S3 is connected to the FIDs for real-time data acquisition, which helps to monitor energy trading and control operations.

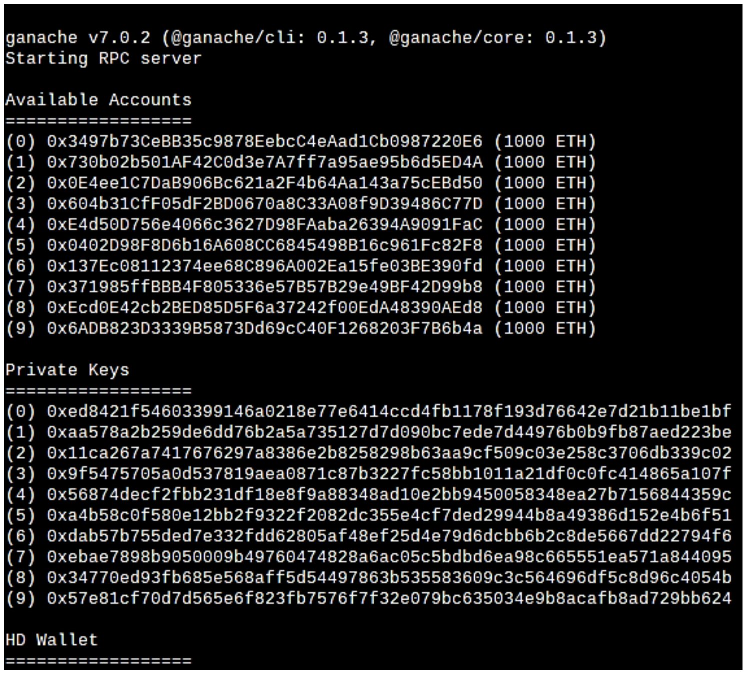
6.3.3. The Blockchain

The blockchain is a cutting-edge technology that has modernized social interactions and trade. As far as the definition is concerned, the term blockchain refers to a chain of blocks on a decentralized network that stores information with digital signatures. Bitcoin and Ethereum are examples of digital cryptocurrencies created using this technique. The primary feature of this technology has recently been focused on numerous other application domains in a variety of research and industrial studies [24]. It refers to a ledger of blocks that is timestamp able, immutable, auditable, permanent and tamper resistant. These blocks enable data to be stored and shared in a peer-to-peer manner. Data stored in the blockchain may include payment history, contracts or even personal information. The security, auditability and anonymity of blockchain technology have attracted significant attention [25].

This study is carried out using the Ganache command-line interface (CLI), a client for Ethereum. A fast and customizable blockchain emulator, Ganache CLI is the latest version of TestRPC. This allows you to access the blockchain without incurring the overhead associated with running an Ethereum node. Through it, it is possible to access and incorporate a local Ethereum blockchain server. It is advantageous to use Ganache for the following reasons [26].

- No transaction cost.
- Modifying gas price and mining speed is possible.
- Accounts can be recycled or reset.
- Accounts can be instantiated along with a predetermined number of Ethers.
- Transactions are "mined" instantly.

An illustration of the running Ganache CLI remote procedure call server (RPC) used as part of this study is shown in Figure 6.2. The account assignment gives ten accounts, with 1000 Ethers in each account, as well as a private key for every single account. This study uses v7.0.2 Ganache.



```
ganache v7.0.2 (@ganache/cli: 0.1.3, @ganache/core: 0.1.3)
Starting RPC server

Available Accounts
==================
(0) 0x3497b73CeBB35c9878EebcC4eAad1Cb0987220E6 (1000 ETH)
(1) 0x730b02b501AF42C0d3e7A7ff7a95ae95b6d5ED4A (1000 ETH)
(2) 0x0E4ee1C7DaB906Bc621a2F4b64Aa143a75cEBd50 (1000 ETH)
(3) 0x604b31CfF05dF2BD0670a8C33A08f9D39486C77D (1000 ETH)
(4) 0xE4d50D756e4066c3627D98FAaba26394A9091FaC (1000 ETH)
(5) 0x0402D98F8D6b16A608CC6845498B16c961Fc82F8 (1000 ETH)
(6) 0x137Ec08112374ee68C896A002Ea15fe03BE390fd (1000 ETH)
(7) 0x371985ffBBB4F805336e57B57B29e49BF42D99b8 (1000 ETH)
(8) 0xEcd0E42cb2BED85D5F6a37242f00EdA48390AEd8 (1000 ETH)
(9) 0x6ADB823D3339B5873Dd69cC40F1268203F7B6b4a (1000 ETH)

Private Keys
==================
(0) 0xed8421f54603399146a0218e77e6414ccd4fb1178f193d76642e7d21b11be1bf
(1) 0xaa578a2b259de6dd76b2a5a735127d7d090bc7ede7d44976b0b9fb87aed223be
(2) 0x11ca267a7417676297a8386e2b8258298b63aa9cf509c03e258c3706db339c02
(3) 0x9f5475705a0d537819aea0871c87b3227fc58bb1011a21df0c0fc414865a107f
(4) 0x56874decf2fbb231df18e8f9a88348ad10e2bb9450058348ea27b7156844359c
(5) 0xa4b58c0f580e12bb2f9322f2082dc355e4cf7ded29944b8a49386d152e4b6f51
(6) 0xdab57b755ded7e332fdd62805af48ef25d4e79d6dcbb6b2c8de5667dd22794f6
(7) 0xebae7898b9050009b49760474828a6ac05c5bdbd6ea98c665551ea571a844095
(8) 0x34770ed93fb685e568aff5d54497863b535583609c3c564696df5c8d96c4054b
(9) 0x57e81cf70d7d565e6f823fb7576f7f32e079bc635034e9b8acafb8ad729bb624

HD Wallet
==================
```

Figure 6. 2. Starting Ganache Server

6.3.4. Internet of Things (IoT)

As a concept that originated in 1999, when Kevin Ashton coined the term IoT, the Internet of Things has evolved into one of the most powerful business development tools [27]. In a recent report, the National Intelligence Council and McKinsey Global Institute claimed that everyday objects, such as furniture, paper documents, food packages, etc., will take on the role of Internet nodes by the year 2025. Through integrating technologies with the human environment, they envision the future. There is no need for humans to intervene in the IoT, as things communicate and exchange data autonomously [28]. The IoT enables sensors and devices to communicate with one another in real time, thereby facilitating real-time data monitoring and control. Furthermore, P2P energy trading was supported through the use of an IoT platform based on Node-Red [15].

In the course of this study, we have set up a local IoT server for monitoring and control purpose. ESP32-S3 chip hosts the local IoT server with a local IP address. Using IoT servers, real-time data are received and displayed on dashboards. Through browsing to a local IP address, a user may access the Internet of Things server.

6.3.5. User Interface

A description of the user interface developed as part of this research is provided in this section. As a means of facilitating peer interaction, we have developed an intuitive UI for the proposed P2P energy trading platform. The UI is configured on the main server, Pi4B, and the user can access URL (Uniform Resource Locator) by visiting http://localhost:4200/. Figure 6.3 illustrates UI for blockchain based P2P energy trading platform. For their respective energy calls, peers may use "Buy Energy" or "Sell Energy" sections of the UI. Aside from this, the peers are able to view their associated account numbers and balances on the user interface. Additionally, the UI provides application-side access to the blockchain, where the user can access the details of trading.

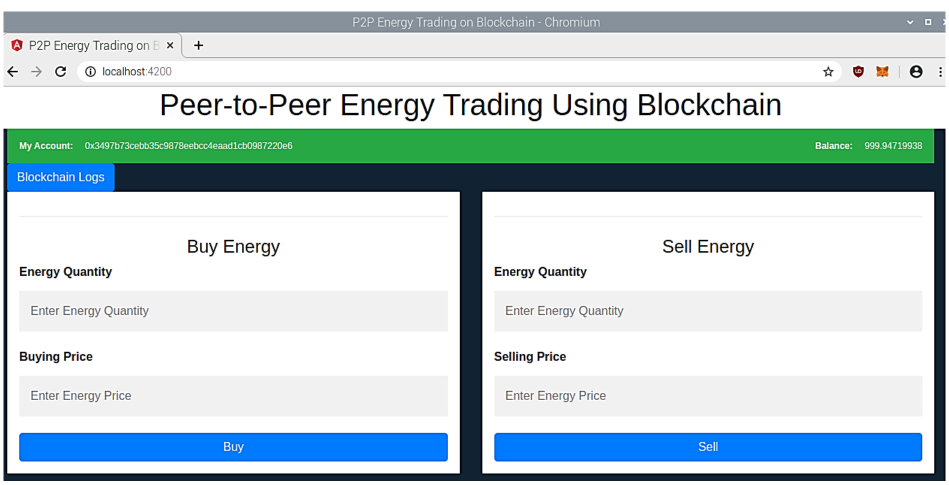


Figure 6. 3. Angular based User Interface

Angular has been used to develop the user interface in this study. The Angular framework is a suite for developers that provides a collection of well-integrated libraries with features such as management of forms and communication between the client and server. As a prototype to global deployment, Angular delivers Google's largest applications with productivity and scalability [29]. A wide range of popular and impressive websites, including business, banks, news and weather, use Angular for their front-end development. Angular framework has been successfully applied by Upwork, Deutshe Bank, IBM, Weather, PayPal, Delta and Samsung [30].

In the course of this study, we have integrated the UI with Ethereum blockchain and MetaMask. MetaMask is used to access Ethereum blockchain accounts. The MetaMask platform is a trailblazing tool that facilitates user interactions and experiences on the Web3. In addition to a browser extension, it is also available as a mobile app for Android and iOS devices, as of now. MetaMask was developed to ensure the security and ease of use of Ethereum-based websites. Specifically, it manages user accounts and connects the user to the blockchain [31]. This study involves the deployment of a smart contract on the private blockchain. We have used Angular-6 for development of UI and the basic source codes for smart contract and UI can be found at [32,33].

6.3.6. Communication and Network

Hypertext Transfer Protocol (HTTP) is the most commonly used protocol by the internet traffic. There are primarily HTTP request and response messages contained within it. In HTTP, upon receiving a request from a client, a server responds to the request. Presently, it is the most widely used application-level protocol [34]. It is the HTTP that underlies the World Wide Web. Information/data are communicated between devices over the network using HTTP as an application layer protocol. When an HTTP client transmits a request to a server, the server responds with a message. A valuable amount of information is conveyed in these responses in response to an HTTP request [35]. Our study involves the use of HTTP to transmit energy trading data amongst the clients and servers. Following the receipt of a trading call from the client, the main server transmits data information to the local IoT server, which then initiates the trade. With the assistance of a computer algorithm, the transfer is automatically terminated after the trading request has been satisfied.

In this study, The Tenda Router (N304 V2) and 2.4 GHz operating frequency band were used, to create the TCP/IP Wireless network connectivity over which the HTTP protocol is implemented for data transfer between client and server. According to IEEE 802.11n standard, this device is compliant. The ESP32-S3 microcontroller and Pi4B used in this research are also capable of supporting TCP/IP, IEEE 802.11b/g/n Wi-Fi standards, this router is configured to enable a private network and implement HTTP. In addition to the Service Set Identifier and password, firewall protection is enabled as part of network security.

The study also makes use of FIDs in order to facilitate the practical transfer of energy. With the aid of resistors and the voltage divider rule a voltage sensor is set up, which measures the voltage consumed whereas the current sensor measures the current. As a final step, a relay is used to initiate or terminate the transfer of energy. A detailed description of FIDs and their use can be found in [13]. This study involves on-chain storage of data and the use of a microSD card for system memory.

6.4. Design and Implementation of Hardware Component

Our discussion in this section is focused on the design and implementation of hardware components for the proposed P2P energy trading solution based on blockchain technology. Also included in this section will be information regarding the connections.

6.4.1 Prototype Design

A brief description of the conceptualization of a system prototype is provided here. In Figure 6.4, a voltage sensor is constructed by arranging pull down resistors on a breadboard in accordance with the voltage divider rule. In this study, ESS voltage is measured using this voltage sensor, with the inputs connected to the battery using jumper wires. A current sensor mounted on the breadboard serves to measure load current. The relay used in the hardware design of the P2P energy trading system is intended to initiate or terminate energy trading activities. In this case, an ESP32-S3 microcontroller is utilized for acquiring current and voltage data through sensors and transmitting it to the local IoT server, which is also hosted on an ESP32-S3 microcontroller. Through the IoT server, peers may monitor and control the activities associated with energy trading. Furthermore, a Pi4B is visible in Figure 6.4, which hosts the UI and a private blockchain server.

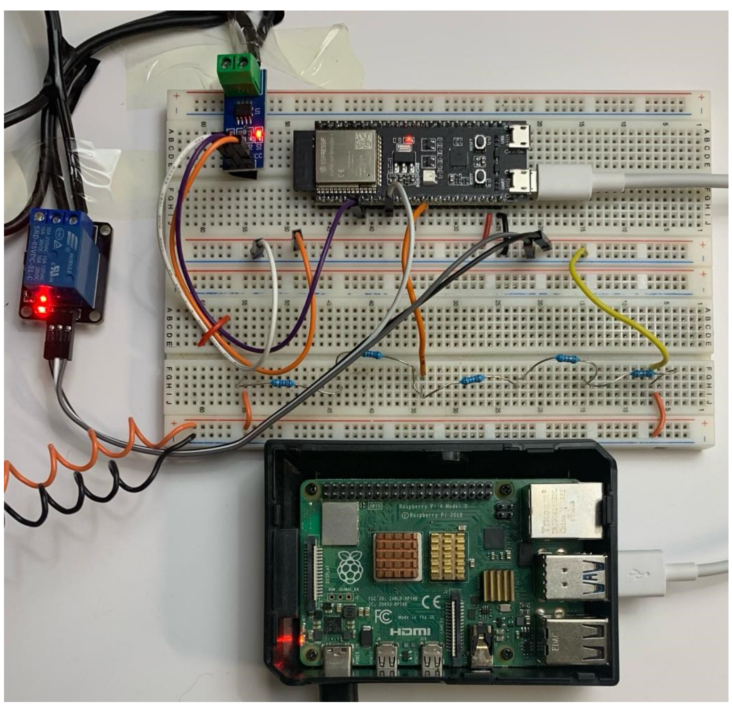


Figure 6.4. Basic Hardware Implementation

6.4.2 Experimental Setup

Preliminary to their use, the hardware components were programmed and configured in accordance with the procedures described in Section 3. According to Figure 6.5, the experimental setup consists of a battery serving as the voltage source (in a real system that will be charged using PV) and an LED light serving as the load for the purpose of demonstrating real-time energy consumption in response to a trading request. Data monitoring is performed in real time by the current and voltage sensors. The experimental set up includes a Wi-Fi router, which enables communication between the client and server using HTTP over a local network. A remote access is also demonstrated using the HMI to the local IoT and the main server. In Figure 6.5, B represents the battery a voltage source, CC represents a Wi-Fi router used as a communication channel in this study, C represents the current sensors, Espp32-S3 microcontroller is represented by M, a voltage and current sensors are represented by V and C, respectively. Raspberry Pi is presented by Pi and a laptop shows an HMI device here.

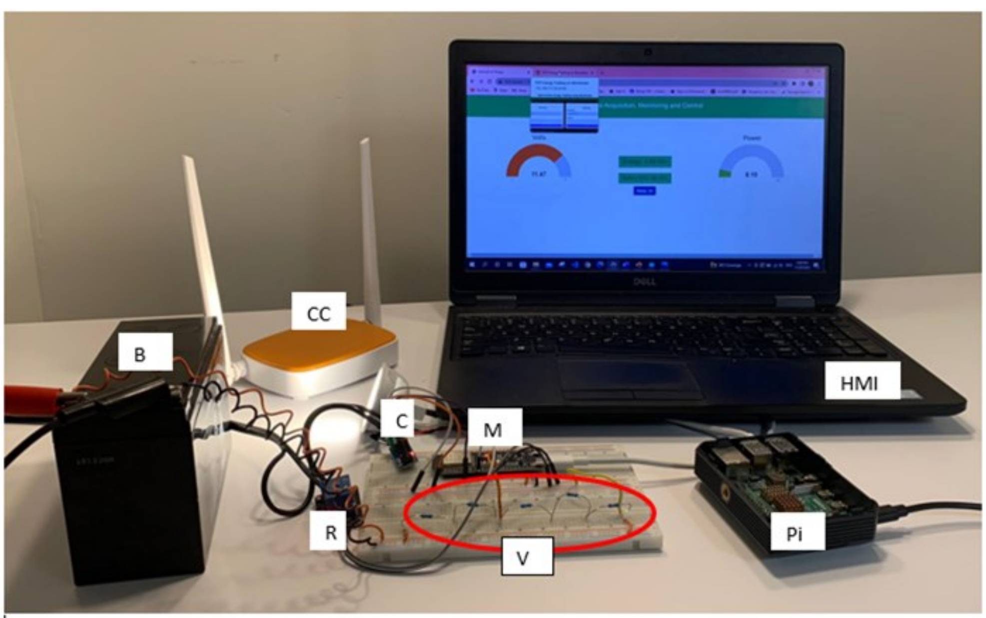


Figure 6. 5. Experimental Setup

6.5 Implementation Methodology

This section describes the data and information exchange process that occurs between the main server and local IoT server in blockchain based P2P energy trading. Our study utilizes the ESP32-S3 microcontroller for the purpose of setting up a local IoT server and obtaining data (voltage and current) through the use of voltage sensor and the current sensor. The data measurements and collection are carried out with the aid of the Arduino Integrated Development Environment (IDE) programs compiled and uploaded into the ESP32-S3 microcontroller. A private communication network enables the ESP32-S3 to further transmit these data to a local IoT server, accessible through Internet Protocol (IP) address. In Algorithm 1, a pseudocode is provided for the implementation methodology. According to Algorithm 1, steps 1 to 7 connect the microcontroller to the wireless network, then display the connection status in Arduino IDE serial monitor. A description of the process of trading energy can be found in steps 8 to 17 of Algorithm 1. During the energy trading process, the relay will start the energy transfer after receiving the trading call over HTTP from UI. In addition to data acquisition, the ESP32-S3 displays these data on local server's dashboard. Energy consumption and demand are then compared by the server, and after the trading request has been fulfilled, the energy trading process over HTTP is terminated. Upon disconnecting from the client, a new process is initiated, as illustrated in line 18 and 19.

Algorithm 1: Energy trading data acquisition, monitoring and Control.

```
Initialization;
Energy Demand = 0;
Energy Consumed = 0;
While
```

1. ESP32-S3 is not connected to private network;

2. Set up ESP32-S3 connection by passing, SSID, and password over private network;

If

3. ESP32-S3 connection established with local-Wi-Fi;

4. Display “Connected” on Arduino IDE Serial Monitor;

else

5. Display “Connection failed… retry in 5 s” on Arduino IDE Serial Monitor;

6. ESP32-S3 connects to private Wi-Fi network;

7. Display IP address on Arduino IDE Serial Monitor;

While

8. Refresh sensor value;

If *demand is available* **then**

9. ESP32-S3 reads demand data over http;

If Energy *demand from UI* **then**

10. Update energy demand;

11. Relay is turned on by ESP32-S3;

12. Energy transfer begins;

13. Power and energy are calculated by ESP32-S3 based on sensor values;

14. Data displayed on local IP;

15. Update data;

If energy consumed >= energy demand **then**

```
Switch off relay;
Energy transfer terminates;
Disconnect client;
Step 8;
end
```

6.6 Testing and Results

A blockchain-based P2P energy trading system as described earlier in this chapter, has been successfully tested and the results are presented in the following section. According to the results of the system testing, the desired outcome has been achieved.

Figure 6.6 illustrates how the system operates. In this flowchart, a brief summary of how the energy trading system works is presented, along with a closer appearance at the information. In Figure 6.3, peers can perform tasks associated with energy trading through an intuitive user interface. Through this interface, they will be able to perform energy “Buy” and “Sell” transactions. Using this platform, participants in the proposed blockchain-based P2P energy trading system can meet their energy needs and sell surplus energy as well. MetaMask is also integrated into the UI as a chromium extension for the secure management of accounts and the connecting of peers with the blockchain server. A demonstration of how accounts created specifically for this study (Figure 6.2) can be imported into the energy trading platform with the private key associated with those accounts is presented in Figure 6.7a, while Figure 6.7b depicts the user authentication process to access MetaMask. When the peer place and energy trading request on UI (Figure 6.3) Users’ account details will appear on the screen with the MetaMask extension.

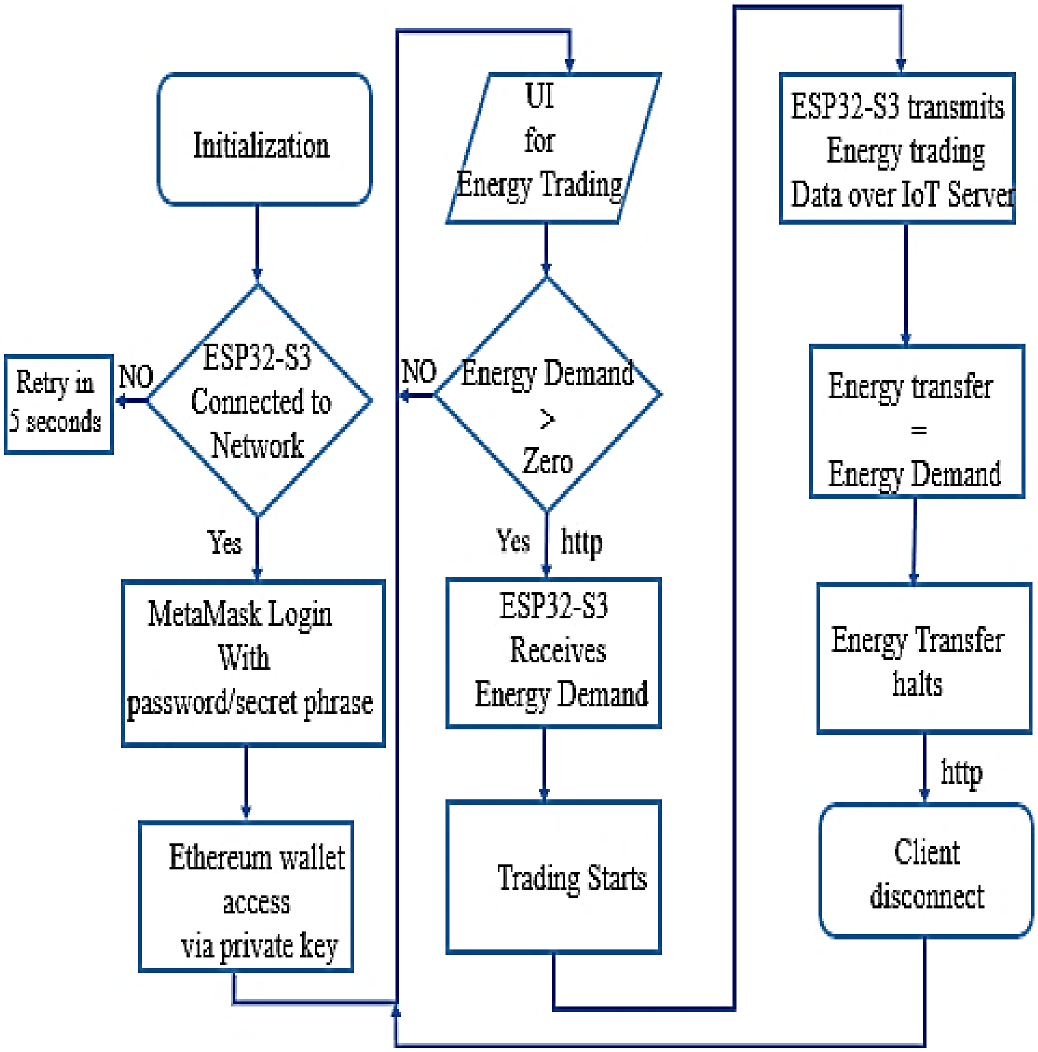


Figure 6.6 System flowchart

The same account number and balance will also be appearing in the My Account part of the UI. After this, the client can either confirm or reject the transaction by accessing their account, as demonstrated in Figure 6.8. Along with allowing users to purchase and sell energy, the proposed P2P energy trading platform will also allow users to view the trading activities of their peers, including their own. An overview of My Account status on the User Interface, where peers can view their own trading activity, is depicted in Figure 6.9. It illustrates the actions performed by the user in regard to the purchase and sale of energy. Figures 6.10 and 6.11 illustrate actions performed by other peers on the network in order to buy energy and sell energy, respectively. Through the

P2P energy trading system, users are able to see the amount of energy available for trade along with the price, as well as the owner of the particular transaction. In the event a peer performs any trading activity, the activity will appear in the respective section on the UI and all peers will be able to see it. To execute a trading call, peers can use the Buy or Sell buttons on the user interface. A local IoT server running on the ESP32-S3 microcontroller will determine the amount of energy being transferred following a trading operation. When an energy trading request is successfully completed, the relay is activated to begin or stop energy transfer.

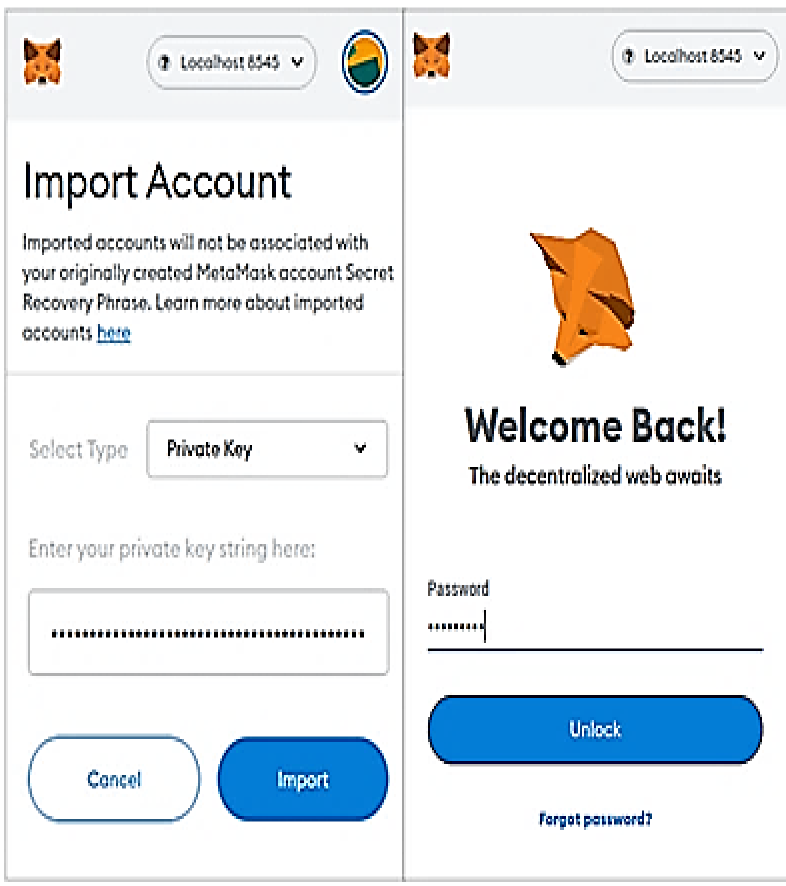


Figure 6. 7. (a) Accounts Import (b) User Authentication

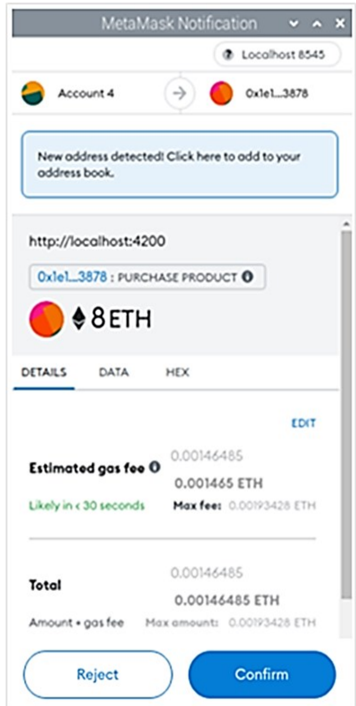


Figure 6.8. MetaMask notification for purchase

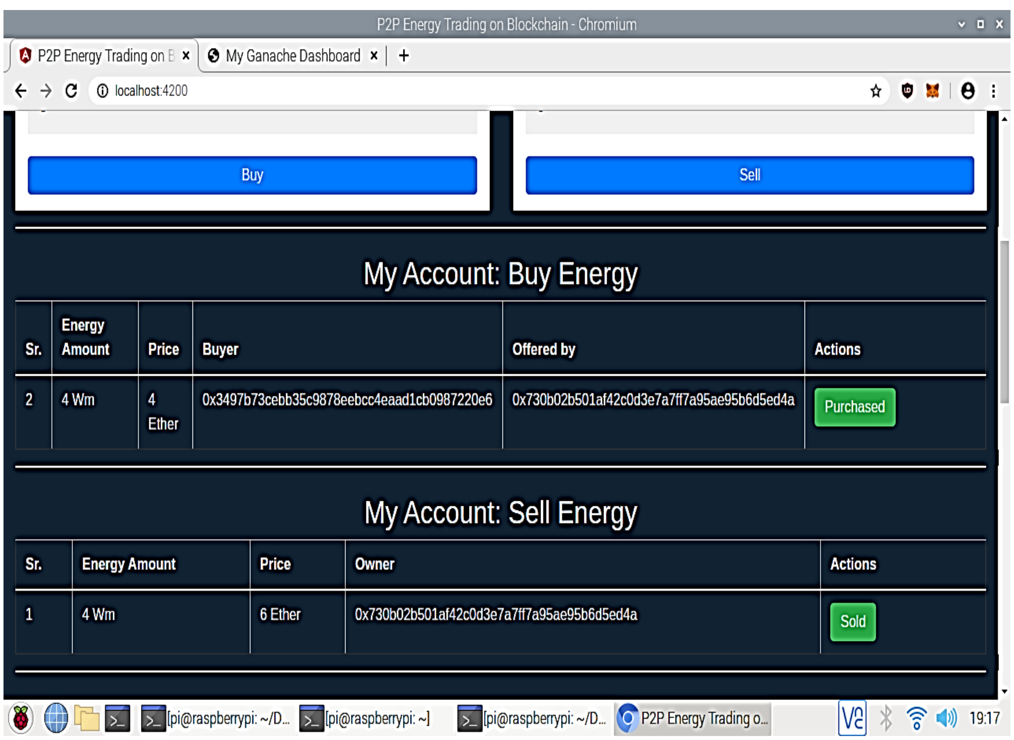


Figure 6. 9. My Account Status on UI

Buy Energy: Other Peers

Sr.	Energy Amount	Price	Owner	Actions
2	2 Wm	4 Ether	0x0e4ee1c7dab906bc621a2f4b64aa143a75cebd50	Purchased
3	3 Wm	2 Ether	0x0e4ee1c7dab906bc621a2f4b64aa143a75cebd50	Purchased
4	4 Wm	3 Ether	0x0e4ee1c7dab906bc621a2f4b64aa143a75cebd50	Buy
5	5 Wm	8 Ether	0x730b02b501af42c0d3e7a7ff7a95ae95b6d5ed4a	Buy

Figure 6. 10. Other Peers Buy Energy Status on UI

Sell Energy: Other Peers

Sr.	Energy Amount	Price	Demanded by	Actions
1	5 Wm	8 Ether	0x6adb823d3339b5873dd69cc40f1268203f7b6b4a	Sold
3	3 Wm	6 Ether	0x730b02b501af42c0d3e7a7ff7a95ae95b6d5ed4a	Request to Sell
4	10 Wm	6 Ether	0x6adb823d3339b5873dd69cc40f1268203f7b6b4a	Sold
5	8 Wm	10 Ether	0x0e4ee1c7dab906bc621a2f4b64aa143a75cebd50	Request to Sell
6	3 Wm	3 Ether	0x6adb823d3339b5873dd69cc40f1268203f7b6b4a	Requested for Sell
7	10 Wm	8 Ether	0x0e4ee1c7dab906bc621a2f4b64aa143a75cebd50	Request to Sell

Figure 6. 11. Other Peers Sell Energy Status

In order to keep track of the trading activities on the UI, a private blockchain server, an Ethereum client, is employed. The study involves the implementation of the Ganache CLI in order to establish a local blockchain network for real-time money transfers in response to energy purchases and sales. Through http://localhost:5051/ , all participants can access the blockchain server. The ganache-CLI block explorer is open source and configured locally. It enables participants to explore blocks in a local blockchain network using a localhost-based block reader. It is possible for participants to view data regarding the amount of energy transferred, mining details, block sizes, gas used, and gas limit. The ganache CLI client is communicated with using the Ethereum library written in Go language [36]. Based on the transactions entered into the UI of the system, the blocks are mined on the blockchain server as shown in Figure 6.12. This process generates 28 blocks, the block explorer can be used to view these blocks. A block is mined in response to each energy trading activity and displayed on the dashboard of block explorer. In Figure 6.13, peers are given the option to explore further by providing a block hash or block number to obtain further information regarding a particular block. On the blockchain server, block 28 is illustrated in Figure 6.14. Energy transactions within a block are illustrated in Figure 6.15. An Ethereum transaction fee is displayed as well as a block hash, which is a unique address of each block mined following a successful transaction, the time stamp, which indicates the time and date at which the block was mined, and the gas used. Ethereum's native currency, Ether (ETH), is used to pay for gas. In Ethereum, gas prices are measured in gwei, and 1 gwei is equal to 10^{-9} ETH [37]. Additionally, there is information regarding the parent hash (of a previous block), gas limit and block size. In this chapter, we propose a blockchain-based P2P energy trading system with an IoT server that is running on an ESP32-S3 microcontroller, which is used for data acquisition, monitoring and control of energy trading. An energy meter with switching capabilities and functions as a means of initiating and terminating energy trading. ESP32-S3 initiates the energy transfer request over HTTP and ends it after the specified amount of energy is transferred. The status of the IoT server is illustrated in figure 6.16.

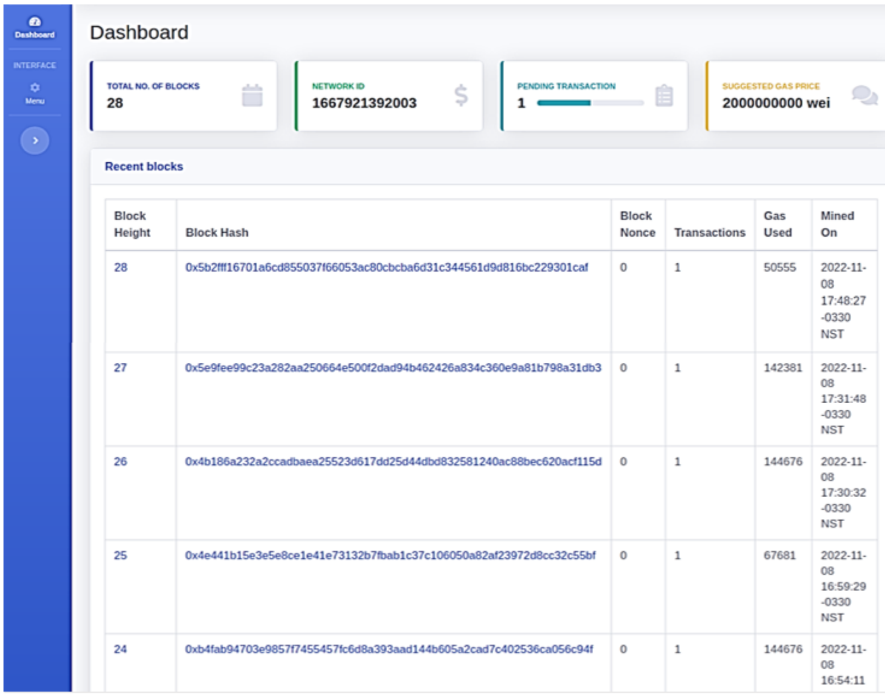


Figure 6. 12. Local Blockchain Server

Overview	Comments
BlockHash	0x5b2fff16701a6cd855037f66053ac80cbcba6d31c344561d9d816bc229301caf
BlockNonce	0
Transactions	1
GasUsed	50555
MinedOn	2022-11-08 17:48:27 -0330 NST
Difficulty	1
Size	668.00 B
Gaslimit	30000000
ParentHash	0x5e9fee99c23a282aa250664e500f2dad94b462426a834c360e9a81b798a31db3

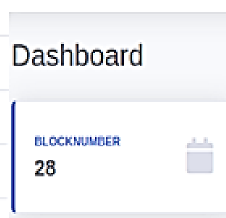


Figure 6. 13. Block details

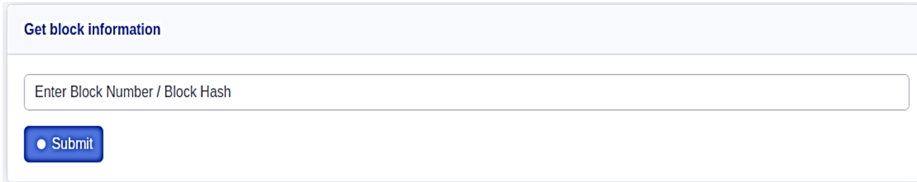


Figure 6. 14. Information about blocks

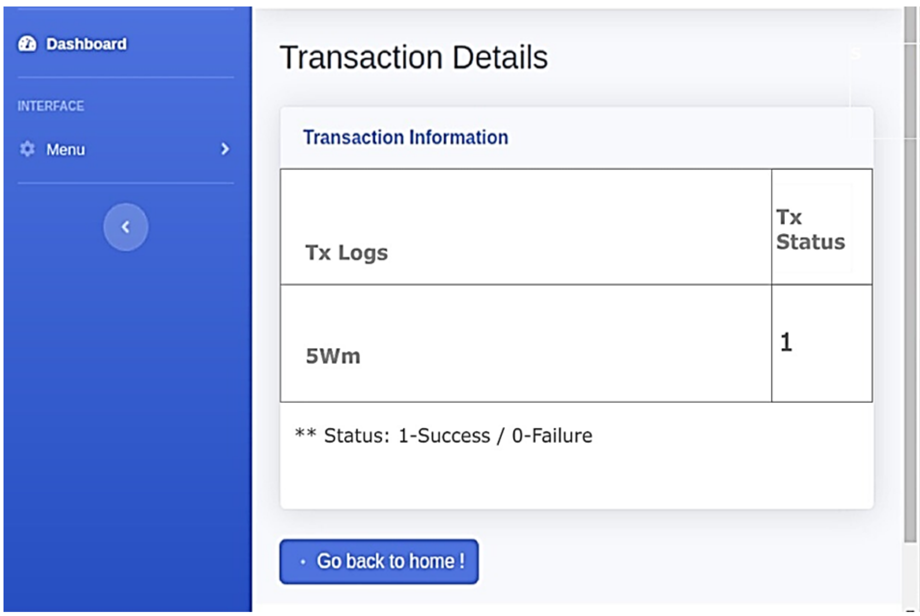


Figure 6. 15. Details of Energy transaction

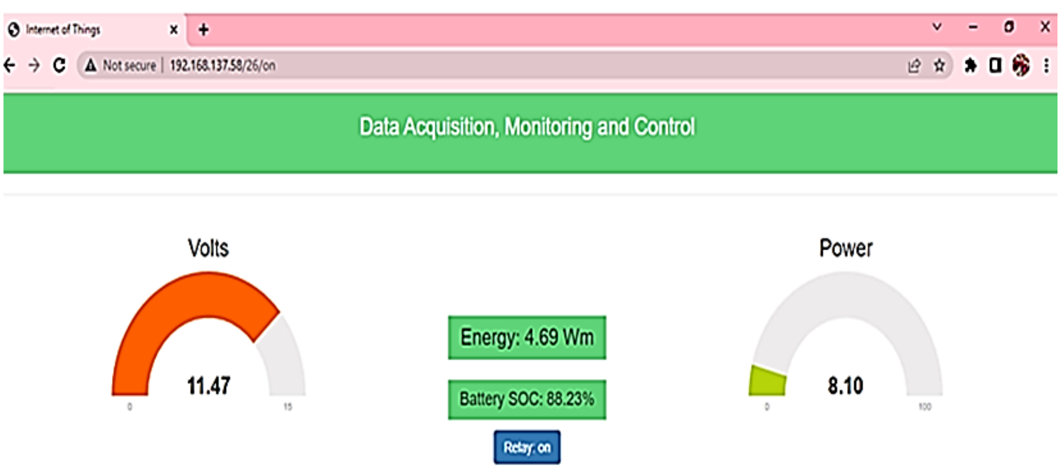


Figure 6. 16. Server status for the Internet of Things

To validate energy transactions, ten accounts have been created as part of this system. MetaMask can access a remote blockchain server by providing RPC URL and respective chain ID. The transaction processing time shown by the server on MetaMask is less than 30 s. A successful test of the system, however, revealed that the actual transaction time is 2 s.

6.7. Discussion

Following successful testing and observing the results, this section outlines some of the key characteristics of the proposed energy trading system.

Low Power: A system designed to operate 24 h a day, seven days a week is highly dependent on its power consumption. It is important to select the individual components of an IoT-based system based on their power consumption. The proposed system uses a Raspberry Pi as its main server, which consumes as low as 2.5 Watts (W). A local IoT server runs on an ESP32-S3 as a part of this research with a power consumption of 0.6 W. During the course of this study, 1.7 W of electricity were consumed by a Wi-Fi router used to establish a local communication network. Each component's power consumption is observed under operating conditions, and specific information can be found in the data sheets. The Table 6.1 below summarizes the power consumption of the hardware components used in this study.

Table 6.1. Component-specific power requirements.

Sr. No	Hardware Components	Power (Watts)
1	Raspberry Pi 4 Model B	2.5
2	ESP32-S3	0.6
3	ESP32-S3, Breadboard, Sensors, Relay, Wires	1.1
4	Tenda Router (N304 V2)	1.7

Low Cost: Through the utilization of readily available and low-priced hardware components, a low-cost system design has been achieved. Listed below in Table 2 is a breakdown of costs for each element of the blockchain-based P2P energy trading system, along with the total cost of the system. There is an overall cost of CAD $146.88 for the system. According to the current design, ten peers can be connected to the system with ten different accounts being created. Consequently, if such a system is implemented over a small remote community of ten houses, the cost per peer will be CAD $14.68.

Table 6.2. Pricing Information for Hardware Components.

Sr. No.	Name of Hardware Components	Price CAD $
1	Raspberry Pi 4 Model B	74.45
2	ESP32-S3	20.74
3	Relay	2.01
4	Current Sensors	5.25
5	16 GB SD Card	13.14
6	Wireless Router	16.29
7	Miscellaneous Resistors, Breadboard, Wires, etc.	15
	Grand Total	146.88

Open-Source Technology: The proposed system design incorporates open-source technology. There are no annual costs or subscription fees associated with the open-source software used in the design. In this way, the proposed system of peer-to-peer energy trading will have zero operating costs.

Private Network: In the designed P2P energy trading system, all transactions are conducted over a local network. Thus, the proposed system is an ideal energy trading solution for remote communities that have no access to the internet.

Energy trading on blockchain: A private Ethereum blockchain is incorporated into the proposed system design. By using this approach, peers can trade energy over a local, decentralized network without having to access the main Ethereum blockchain platform. Through a decentralized, transparent, immutable and tamper-proof structure, they are able to trade energy locally. As an added benefit, all transactions are time stamped and can be tracked easily.

Remote Access: One of the most important characteristics of the proposed system is its HMIs interaction capability. It is intended that the peer can have remote access to the UI and IoT server without being physically present at the site. Peers can then trade energy, monitor operations and control them remotely through this system.

Efficient transaction settlements: In view of the fact that the proposed system is designed and tested for ten peers at first, it has a small ledger. Moreover, a private blockchain is used in the system. Thus, the design allows for fast financial transactions within a period of less than two seconds.

Security: There is a set of security controls in place for the design systems, including SSIDs and passwords, firewalls, secret recovery phrases, MetaMask credentials and a private key used to access the Ethereum wallet. Furthermore, this locally configured system incorporates the entire blockchain security protocol.

Intuitive UI: The proposed system of peer-to-peer energy trading has been designed to have a user-friendly interface. Users do not need to undergo any special training in order to use this system.

Future research guide: Electricity trading and management solutions can be provided as a result of this research, especially in relation to remote communities. An energy trading system based on blockchain can be designed and planned based on the research described above.

System Limitations: Ganache CLI is used in this system, which is designed for use in local environments. Larger or complex systems may not benefit from this. Furthermore, it is not suitable for mining or running on public testnet.

Despite the fact that this study is intended for P2P energy trading on a community level. The work can, however, be extended to cover trade between peers and utility companies.

6.8 Conclusion

A recent shift in the energy sector from fossil fuels to renewable sources has transformed energy consumers into prosumers. Distributed resources have resulted in the decentralization of the energy market. Certainly, renewable energy sources have significantly influenced the market for conventional electricity. While this is true, it has not been able to capture the traditional electricity market on an overall basis. Inability to obtain a return on investment may be one of the factors contributing to this. As important as it is to have access to distributed generation, it is also crucial to have a platform that facilitates energy trading and generates returns on investments in the renewable energy sector. In countries with ample renewable energy resources, the use of renewables is not fully tapped due to the absence of such platforms. The use of blockchain technology, as well as smart devices, is expected to lead to a revolution in the development of these platforms such as P2P energy trading platforms. It is possible that distributed generation may gain traction by using the P2P energy trading model. It is imperative that distributed generation will gain traction by using the P2P energy trading model. Therefore, the potential for electrification of remote areas may also result from the possibility of obtaining proper returns on energy investment.

This chapter presents an advanced P2P energy trading platform based on the Ethereum private blockchain and Internet of Things, integrated with an Angular-based UI. We also demonstrated the hardware implementation of our proposed P2P energy trading solution using very few low-cost, low-power, open-source and readily available components as the essential elements of the proposed system. The hardware components include Pi4B and ESP32-S3 as crucial components of the system. Other components include FIDs and a Wi-Fi router. It was necessary to create an experimental setup in order to validate the system design. It appears from the results of the study that the system is suitable for the purpose of carrying out P2P energy trading operations. As well as performing energy transactions, the system is able to perform financial transactions. The proposed system performs data monitoring and display over the IoT server after data acquisition through FIDs. While it maintains digital ledger over the blockchain network, energy efficiency has been demonstrated by this system, as its main server consumes only 2.5 W, the local IoT server consumes 0.6 W, FIDs consume 0.5 W and the communication channel consumes 1.7 Watts. As a further benefit of the system, the cost of the system is extremely low at CAD $ 15. Lastly, security features essential for data integrity and security are incorporated into the proposed system.

6.9 Future Work

In the future, the authors intend to implement this project in remote locations lacking electricity and internet connectivity. Specifically, the project seeks to assist people living in areas without electricity around the globe. We are in the process of adding a feature for auto sale and purchase in addition to the full details of the electrical connections. The future work extensions will also include an increased range of the network. Detailed information will be provided in upcoming publications.

Abbreviations

This manuscript uses the following key abbreviations.

P2P	Peer-to-Peer
IOT	Internet-of-Things
Pi4B	Raspberry pi model 4B
MQTT	Message Queuing Telemetry Transport
FIDs	Field Instrumentation Devices
HTTP	Hypertext Transfer Protocol
HMIs	Human Machine Interfaces
ESS	Energy Storage System
UI	User Interface
SBC	Single Board Computer
SoC	System on a Chip
RPC	Remote Procedure Call
SSID	Service Set Identifier

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Chapter 7

Conclusion

7.1 Summary

Energy consumers have now evolved into prosumers, and a large amount of energy is now generated using renewable resources, particularly solar photovoltaic (PV) panels. A number of participants in the energy market are looking for platforms through which they can sell self-produced energy and obtain a return on their investment in renewable energy resources. Energy trading platforms that offer peer-to-peer trading make renewable energy more accessible and enable participants to make the most of their self-generated energy. It is important to recognize that such platforms can assist in the development of renewable energy resources as well as reduce the burden on the power system. The participants of the P2P energy trading platform can also earn profits through their investments.

Throughout the second chapter of this thesis, the design and analysis of a DC-microgrid are examined for a remote community in Pakistan. A system optimization was performed using HOMER Pro, resulting in an optimal design for the system. This case study does not take into account heating and cooking loads, and the system is designed to meet only basic domestic needs, such as lighting, small refrigerators, and electronic equipment. As proposed, the system fully meets the requirements of each household in the community. Technical information regarding P2P energy trading as well as connection details are also provided. Considering the results of the study, isolated DC-microgrids proved to be the most effective solution for un-electrified remote settlements with good solar resource availability.

The proposed P2P energy trading model outlined in the third chapter of this thesis has a unique and simple architecture. In comparison to existing P2P energy trading platforms, the proposed system is user-friendly, open-source, and may increase efficiency and profitability. A majority of the existing P2P energy trading platforms rely on software-based financial transactions to facilitate the trading process. However, the proposed system in Chapter 3 not only addresses the financial aspect by utilizing blockchain technology, but also proposes hardware setup that connects with Node-Red for energy transfer in real-time in order to achieve financial benefits since blockchain servers provide a secure and transparent method of conducting financial transactions. This research has demonstrated how a P2P network can make use of an open-source platform to accomplish all tasks. Energy transfer has been facilitated through the development of an interactive user interface. The Ethereum blockchain is used for the payment of electricity consumed. For P2P energy trading, the proposed platform provides an open-source solution that includes energy transfer, metering, and fund transfer. Despite the fact that the proposed P2P energy trading model has only been tested in real-time for two peers, this system is capable of accommodating up to ten peers at a time and can be extended across communities. Peers on this fully decentralized platform have the opportunity to determine the price for energy they produce. Additionally, they are able to manage and control their energy consumption. The P2P network participants are thus able to reap the benefits of this system financially. Using the UI, peers can access the server remotely and begin trading at any time. There will be no need for human intervention due to the fully automated nature of the proposed system. Moreover, peers may benefit from the unique features of blockchain technology without relying on conventional financial institutions.

Chapter 4 presents an advanced open-source P2P energy trading platform utilizing the internet of things and blockchain technology. Our proposed P2P energy trading platform has been demonstrated in both software and hardware implementations. Implementation of the software is carried out by installing a web interface hosted on a local machine by using React. JS library in conjunction with the Ganache GUI, a private Ethereum blockchain. A web interface facilitates the recording of all trading activities via the blockchain network. The data monitoring and energy control are conducted on a local machine using the Node-Red server. The hardware implementation consists of ESP32-S2 microcontrollers and field instrumentation devices. According to the testing and results, the proposed P2P energy trading platform works perfectly. In this system, all transactions are recorded on a decentralized ledger and are operated in a decentralized manner. As a result of the system's performance, all trading sessions are completed efficiently, and energy data is monitored accurately. In spite of the fact that the system has been tested on a small 12-volt battery and a 50-watt load, it is possible to customize the system to meet the household's energy needs. The proposed system has been tested using hardware components for real world applications. Ganache GUI allows the generation of only ten accounts with 100 ethers in wallet. However, the system is scalable with the implementation of ganache CLI that allows participants to generate customize number of accounts and the associated ethers.

Chapter 5's objective is to develop an Internet-of-Things (IoT) and blockchain-based peer-to-peer (P2P) energy trading system for a remote community in Pakistan. This system demonstrates the latest technologies and is unique in the sense that we have not seen a low-cost, open-source system that incorporates the latest technologies we have used during our research.

The geographical location of the selected community is another novel aspect of this system. There are six critical components included in the proposed energy trading system, namely Field Instrumentation Devices, a relay, ESP32, a user interface, Ethereum private blockchain, and local Wi-Fi network. A P2P energy trading experiment was conducted in order to validate the design of the system. This study demonstrated that the system could be used to perform the desired functions of a P2P energy trading system, including Energy Transfer, Data Acquisition, Data Monitoring, Data Display, Networked Data Communication, and Maintaining a Digital Ledger on a Blockchain Network. The system has been found to be power efficient, with its central server consuming 2.5W, the IoT server alone 0.8W, the IoT server as a whole 3.3W, and the communication channel 4.4W. In addition, the system has been found to be very cost-effective. The overall cost of the project is less than CAD 50. Additionally, security measures such as authentication for MetaMask, private keys for each peer to access digital assets, firewalls, login credentials, and seed phrases are considered to be data security measures. Even though this study considers a P2P energy trading system for a remote Pakistani community. It is anticipated that this research will have a significant impact on the promotion of distributed energy generation in remote areas. For prosumers, it can serve as a marketplace in which they can sell excess electricity to their neighbors. The system is designed for ten houses and the experimental setup is only for two houses depending upon the operation of accounts generated using Ganache CLI. As the operation procedures for all the accounts is same so the author used two accounts for practical demonstration of the system.

A P2P energy trading platform leveraging the Ethereum private blockchain and the Internet of Things is presented in Chapter 6, combined with an Angular-based user interface. Moreover, we demonstrated the implementation of our P2P energy trading solution on hardware using very few components that are low-cost, low-power, open-source, and readily available. Hardware components of the system include Pi4B and ESP32-S3. FIDs and a wireless router are also included. A validation of the design of the system required the creation of an experimental setup. Based on the results of the study, the system appears to be suitable for P2P energy trading. In addition to performing energy transactions, the system is also capable of performing financial transactions. After data has been acquired through FIDs, the proposed system displays and monitors the data over an IoT server. Although this system maintains a digital ledger over a blockchain network, its overall energy efficiency has been demonstrated, as the main server consumes 2.5 watts, the local IoT server consumes 0.6 watts, the FIDs consume 0.5 watts, and the communication channel consumes 1.7 watts. Additionally, the system is extremely affordable, costing only CAD $15. As a final consideration, the proposed system incorporates security features that are essential for data integrity and security.

7.2 Research contributions

The main characteristics of the proposed P2P energy trading methods are presented in this section following successful testing and observation of the results.

Design of Dc-microgrid: This study proposes a design for an isolated DC-microgrid to serve a remote unelectrified community. For the selected sites, an optimal DC-microgrid with the lowest net present cost has been designed and proposed.

P2P Trading: A complete P2P energy trading setup is presented in this study, including technical and financial components as well as software and hardware implementation.

Node-Red based design: Design and implementation of a P2P energy trading platform using a local UI, Ethereum blockchain, and a locally installed Node-Red IoT server. To the best of the author's knowledge, the concept of an open-source, peer-to-peer energy trading network is novel.

React based design: The development and implementation of an open-source, low-cost, local server hosted on a private network to facilitate peer-to-peer energy trading using the Ganache command-line interface (CLI), React. J.S. and Ethereum private blockchain. In the author's opinion, this work entails a novel approach since the previous studies used either web-based servers or highly expensive computers.

Angular based design: As part of the implementation of the proposed P2P energy trading system, Angular is configured, the framework on which many popular websites are built, such as Paypal, IBM, Weather, Samsung, etc. Additionally, an Angular-based UI is implemented on the Pi4B, closely coupled with both a local blockchain server as well as an IoT server running on the ESP32-S3. Currently, no similar P2P energy trading system has ever been described, to the best of the authors' knowledge.

System configurations: Blockchain technology and the Internet of Things serve as a foundation for a robust distributed energy trading solution for remote locations. This study uses the Ganache Ethereum blockchain, which is a fast and customizable blockchain. Depending on the needs of the customer, the number of accounts and associated balances may be customized. IoT servers are set up on microcontrollers that provide trading and monitoring capabilities. As part of this research, proposed systems include the essential elements for an efficient and effective P2P network, including an IoT server, a blockchain server, a communication channel, and field instrumentation devices.

Energy-efficient design: Power consumption is one of the most important considerations when designing a system based on the Internet of Things. For this reason, power consumption of each component was a key consideration in designing the P2P energy trading systems as part of this research. A power consumption measurement is made for each component when it is operating under normal conditions, and data sheets are also available for further information. System designs have proven to be low-power and suitable for remote applications.

Open-Source technology: The proposed system designs incorporate open-source technology. As a result of the open-source software used in the design, there are no annual costs or subscription fees. Consequently, the proposed peer-to-peer energy trading system will be free of operating costs.

Blockchain technology for energy trading: The proposed system design incorporates a private Ethereum blockchain. As a result of this approach, peers are able to trade energy over a local, decentralized network without having to access the main Ethereum blockchain platform. The structure allows them to trade energy locally in a decentralized, transparent, immutable, and tamper-proof manner. A further benefit of this system is that all transactions are time stamped and can be easily tracked.

System security: The design systems are protected by a number of security controls, such as SSIDs and passwords, firewalls, secret recovery phrases, MetaMask credentials, and a private key for accessing the Ethereum wallet. Furthermore, the entire blockchain security protocol is incorporated into this locally configured system.

Systems for electronic payments: This research introduces electronic payment systems to remote communities without access to the internet, as well as energy monitoring, control and trading solutions. Blockchain based setup executes transactions immediately and transfers funds instantly. The efficiency of the financial transactions is also enhanced by a smaller ledger.

Comprehensive research guide: In providing electricity trading and management solutions to this unserved community, this research has a great deal of impact. In the context of remote areas without internet access, the above research provides a solid foundation and justification for planning and designing an isolated microgrid-based P2P energy trading system.

7.3 Future work

IoT and blockchain-based platforms for P2P energy trading are presented as new research directions in this thesis. There are, however, a number of knowledge gaps and research areas that can be explored in order to improve the use of P2P energy trading systems. The following are some of the recommendations for future work:

- Adding auto sale and purchase functions to the proposed system could be a future research direction. Several remote locations around the globe lack electricity and internet access. Therefore, such low-power and low-cost P2P energy trading systems can be implemented to assist people living without electricity. Future work extensions could also expand the network's range.
- Increased security in the designed IoT and blockchain based P2P energy trading systems solution can be achieved through the development of reliable data encryption algorithms. Data integrity and reliability can be increased for client-server communication.
- Examine the possibility of expanding and implementing these systems in larger communities. Implement the techniques presented in this thesis in locations with internet access.

7.4 List of publications

7.4.1 Journal Articles

1. M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, "Blockchain-Based Peer-to-Peer Energy Trading System Using Open-Source Angular Framework and Hypertext Transfer Protocol," *Electronics*, vol. 12, no. 2, p. 287, Jan. 2023, http://dx.doi.org/10.3390/electronics1202028.

2. M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, “A Low-Cost, Open-Source Peer-to-Peer Energy Trading System for a Remote Community Using the Internet-of-Things, Blockchain, and Hypertext Transfer Protocol,” *Energies*, vol. 15, no. 13, p. 4862, Jul. 2022,: http://dx.doi.org/10.3390/en1513486.

3. M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, “Design and implementation of an open-Source IoT and blockchain-based peer-to-peer energy trading platform using ESP32-S2, Node-Red and, MQTT protocol,” *Energy Reports*, *vol. 7*, pp. 5733–5746, 2021, doi: https://doi.org/10.1016/j.egyr.2021.08.190.

4. M. J. A. Baig, M. T. Iqbal, M. Jamil, and J. Khan, “Peer-to-Peer Energy Trading in a Micro-grid Using Internet of Things and Blockchain,” *Electronics*, *vol. 25, no. 2*, 2021, doi: https://doi.org/10.53314/ELS2125039B.

7.4.2 Refereed Conference Publications

5. M. J. Aziz Baig, M. T. Iqbal, M. Jamil and J. Khan, "Design and Analysis of an Isolated DC-Microgrid for a Remote Community in Pakistan," 2021 IEEE 12th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON), 2021, pp. 0712-0716, doi: 10.1109/UEMCON53757.2021.9666665.

6. M. J. A. Baig, M. T. Iqbal, M. Jamil and J. Khan, "IoT and Blockchain Based Peer to Peer Energy Trading Pilot Platform," 2020 11th IEEE Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2020, pp. 0402-0406, doi: 10.1109/IEMCON51383.2020.9284869.

7.4.3 Other Category Publications

1. M. J. A. Baig, “Blockchain based Peer-to-Peer Energy Trading”, Fall 2023 Edition, IEEE Canadian Review Magazine.

2. S. A. Omidi, M. J. A. Baig, and M. T. Iqbal, “Design and Implementation of Node-Red Based Open-Source SCADA Architecture for a Hybrid Power System,” *Energies*, vol. 16, no. 5, p. 2092, Feb. 2023, doi: 10.3390/en16052092. [Online]. Available: http://dx.doi.org/10.3390/en16052092

3. S. U. Uddin, M. J. A. Baig, and M. T. Iqbal, “Design and Implementation of an Open-Source SCADA System for a Community Solar-Powered Reverse Osmosis System,” *Sensors*, vol. 22, no. 24, p. 9631, Dec. 2022, doi: 10.3390/s22249631. [Online]. Available: http://dx.doi.org/10.3390/s22249631

4. L. Ahsan, M. J. A. Baig, and M. T. Iqbal, “Low-Cost, Open-Source, Emoncms-Based SCADA System for a Large Grid-Connected PV System,” *Sensors*, vol. 22, no. 18, p. 6733, Sep. 2022, doi: 10.3390/s22186733. [Online]. Available: http://dx.doi.org/10.3390/s22186733

5. M. J.A.Baig, M.T. Iqbal “Design and analysis of a rooftop PV system for a University Building in Pakistan,” 2019, [Online]. Available: http://research.library.mun.ca/id/eprint/14659