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A Blockchain-Based Load Balancing in Decentralized Hybrid P2P Energy Trading Market in Smart Grid

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ABSTRACT Local energy generation and peer to peer (P2P) energy trading in the local market can reduce the energy consumption cost, emission of harmful gases (as renewable energy sources are used to generate energy at user's premises) and increase the smart grid resilience. However, local energy trading with peers can have trust and privacy issues. A centralized system can be used to manage this energy trading but it increases the overall cost of the system and also faces several issues. In this paper, to implement a hybrid P2P energy trading market, a blockchain-based system is proposed. It is fully decentralized and allows the market members to interact with each other and trade energy without involving a third party. Smart contracts play a very important role in the blockchain-based energy trading market. They contain all the necessary rules for energy trading. We have proposed three smart contracts to implement the hybrid electricity trading market. The market members interact with the main smart contract, which requests P2P and prosumer to grid smart contracts for further processing. The main objectives of this paper are to propose a model to implement an efficient hybrid energy trading market while reducing cost and peak to average ratio of electricity.

INDEX TERMS Blockchain, consumers, energy trading, load, PAR, power, prosumers, security.

I. INTRODUCTION

Electricity has become an analytical underpinning constituent that is essential for the development of new technologies [1]. It has supported and given raise to the technologies in several areas of human adequacy. It is the main driving commodity for modern technologies and in its absence, they are unusable [2], [3]. The role of electricity in the fields of innovation, transportation, communication, education, business, computation, etc., cannot be repudiated. The demand for electricity is increasing drastically with each passing day and its pattern is also dynamic. To meet this energy demand, a utility needs to install backup power plants which result in higher production cost, emission of harmful gasses, etc., as it does not have any control over the demand pattern. The smart grid (SG) has emerged as a modern form of the power grid. It has two-way communication between energy consumers and producers and enables efficient energy management. It eliminates the requirement of thermal power plants and conserves electricity. It also reduces the electricity consumption cost by making the electric grid sustainable.

The evolution of the power grid has revolutionized the electricity market, where new players have been introduced to control, generate and distribute the electricity in the market. Renewable energy sources (RESs) based distributed energy generation (DEG) has acquired popularity because of its environment-friendly method of electricity generation. Declining costs of wind turbines and solar panels allow the growth of DEG in microgrids and smart homes. Moreover, smaller and cheaper sensors, smart devices and new

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communication protocols are paving the way for hlthe peer to peer (P2P) communication between electricity generators and consumers in a market. This market reduces the electricity consumption cost. The amount of electricity generated by RESs is highly affected by environmental factors e.g. speed of the wind and amount of sunshine a solar panel and wind turbines receive in a particular period. This intermittent nature of RESs makes them unreliable, so, the connection of energy consumers with the main grid is mandatory.

With the emergence of modern technologies, the smart energy market is moving from being centralized to decentralized. In a centralized P2P energy market, scalability, robustness, security and privacy issues are the major concerns. Moreover, the energy exchange between two peers is controlled by a central entity that keeps track of all the transactions and is responsible for the implementation of the market mechanism. Both energy consumers and prosumers have to pay some cost to this central entity which results in higher energy consumption cost for consumers and less revenue for the prosumers. Besides this, the participants of the local energy market still get more benefits as compared to energy trading with SG. The P2P energy coalition empowers the small scale energy prosumers and encourages them by incentivizing the local generation. For the successful operation of P2P trading in the local market, improved and innovative mechanisms for trading are required. These mechanisms should be secure, smart and trustworthy.

The blockchain has emerged as a promising, user-friendly and efficient technology for the implementation of secure and reliable decentralized P2P energy trading market. It enables transparent communication of the local energy market's participants and allows them to make decisions about energy coalitions in a decentralized and trustless environment. Recently, it has gained the attention of several researchers and became the new hot topic in the smart grid domain. The blockchain is used to keep the energy coalition record regarding the amount of energy and its price while maintaining a healthy environment for energy consumers and prosumers. Dang *et al.* [4] have proposed an energy market mechanism where blockchain is used to balance the load of energy consumption. Load management is done on a day-ahead basis. Zanghi *et al.* [5] proposed a conceptual framework for a distributed remote metering system for the SG. This study aims to provide a smart monitoring system of electricity load using metering information for a more reliable smart power grid environment. Lin [6] have used the blockchain in the P2P energy trading market on a small scale. Auction based trading is implemented with different bidding strategies. Motivated from the existing work and integration of blockchain technology in the smart grid, in this paper, a consortium blockchain-based hybrid P2P electricity trading system is developed. This paper is extension of [7].

The rest of the paper is organized as follows. Related work is presented in SectionII. In Section III problem statement is defined and Section IV summarizes the proposed solution and contributions of our work. The Section V contains the information about the system, its market participants and smart contracts. Simulation results are illustrated in Section VI. In the end, the paper is concluded in Section VII.

II. RELATED WORK

Christidis *et al.* [8] explored the use of blockchain in the internet of things (IoT) sector. Several smart contracts and scripts of blockchain are studied and their impact on this sector is analyzed. In this study, it is observed that the blockchain technology is contributing positively in service sharing and resource allocation. It allows us to automate workflows by implementing crypto-graphical authentication. While, before the implementation of blockchain, one needs to take care of certain considerations e.g. transactional privacy and digitized assets for trading. It is concluded that the emergence of blockchain with IoT is paving new ways for new and secure decentralized environments for the new industrial models. It is a powerful technology which is paving new ways for distributed applications.

An expert system shell with blockchain is proposed in work by Acevedo *et al.* [9]. The expert system works using a neural network as its inference engine. A user accesses this system with the help of a terminal and server with an internet connection. The whole system is implemented in the form of a smart contract. When a user enters some query in the system, it costs them. The cost depends on the complexity of the query, more complex query costs more.

Ferreira *et al.* [10] proposed a system which enables to build an open energy market for a community of users. For energy flow accounting, an IoT based system is used. Blockchain is used to eliminate the requirement of a central control entity by keeping track of distributed energy transactions. These two approaches are used to create an energy trading market where the market participants have pre-defined goals. The proposed market approach increases the possible befits of participants which encourages more participants to take part in it. Electrical vehicles are also included in this model in addition to the in house energy-generating participants. Besides, gamification is used to control the users' behavior in the energy market and achieving its goals.

Silvestre *et al.* [11] proposed a blockchain-based model to handle the technical issues in a microgrid. In addition to the economic aspects of the market, the proposed model is used to make the technical decisions for the distributed operations of the market. The main focus of this study is to keep the record of transmission line losses of energy transactions between different entities. It is stated that the inclusion of such information has a great effect on the information gathering in real-time and the possible role of prosumer and distributors of energy in the market. In a microgrid, the physical power flow varies from the virtual power flow and it creates mismatch and results in poor power loss allocation. In this paper, authors have included the generator as well as real-time attribution of power losses of each transaction along with the reactive power generation. This model provides a more accurate view of these losses.

Kang *et al.* [12] proposed a blockchain based P2P electricity trading model for plug-in hybrid electric vehicles (PHEV). Instead of the traditional way of importing electricity from a distant source, this model works on demand response and attracts the consumers to participate in it by providing them incentives. Each participant takes part in this system and balances the electricity demand with supply to get the maximum incentives. To address the challenges of security and privacy, consortium blockchain is used. The electricity pricing structure is very important in such P2P trading. In this paper, a double auction-based system is implemented to set the price for a specific amount of electricity. The simulation results depict the effectiveness of the proposed P2P market model.

Gao *et al.* [13] proposed a model that enables users to monitor their energy usage and their respective cost. It is stated that in a smart grid the meter reading is obtained online, so, there is a high chance of data tempering from an unauthorized user. Moreover, users are not aware of their energy consumption patterns and energy consumed by different appliances. A blockchain based solution is proposed in this paper to tackles these issues. The smart contract is developed to execute the procedure successfully and in an efficient manner. Besides, the privacy and security issues are tackled by using sovereign blockchain which ensures transparency and feasibility of the system.

A P2P electricity sharing system is proposed in [13]. It consists of two layers: a multi-agent system layer and a blockchain-based transactions management layer. Former is used to model the users' behavior and make decisions about trading as well as take part in the coalition process for efficient and cost-effective trading. The second layer is used to keep track of all the transactions between consumers and prosumers securely. The proposed system is validated using simulations. For this purpose, the Java agent development environment has been used.

A P2P energy trading system for microgrids is proposed in [14]. It is stated that renewable energy generation sources are of intermittent nature and coalition between multiple microgrids can solve this problem. A blockchain-based coalition formation method is proposed which is distributed in nature and robust as compared to the legacy centralized methods. Multiple coalition algorithms are executed in parallel which reduces the computational time and allows the microgrids to trade energy more frequently. The distributed nature of the system makes it scalable and algorithms converge quickly. As energy is traded locally, so, transmission losses are also reduced and usage of blockchain makes the network secure. Simulations are carried out to depict the effectiveness of the proposed system. It is evident from the results that the proposed model successfully achieves the desired objectives.

In paper [15], blockchain is implemented in the chemical industry for machine to machine energy exchange. In the given scenario, two electricity producers trade electricity with one consumer. Blockchain is used to record the transactions between these producers and consumers. Both energy producers send their available energy and price information to the market and energy consumer compares both offers to accept the most suitable offer. Flowsheet model is used to provide realistic data to the market participants and proof-of-work is used for the implementation of a given scenario on the blockchain. It is concluded that the machine to machine communication along with blockchain technology has great potential and enhances the efficiency and reliability of the system.

Wu and Tran *et al.* [16] provided a review of the application of energy internet and blockchain. In this paper, the possible applications of the mentioned technologies are also provided. Additionally, the compatibility of both technology, as well as the possible challenges, are also discussed. It is concluded that the use of blockchain with energy internet solves its many problems e.g. issue of proper control and management of distributed forms of energy. The objective of this paper is to provide the researchers with the current status of these technologies and promote their practical implementation.

An electric vehicle charging scheme is proposed in [17]. These schemes play a very important role in the reduction of operational costs and improve the stability of the grid. The objective of this paper is to decrease the possible power fluctuations caused by the huge penetration of electric vehicles. A decentralized electric vehicle charging scheme based on blockchain is developed. The problem formulation section of this paper includes the possible power fluctuations, electric vehicle charging rate, battery capacity and behavior. The charging and discharging schedules are obtained by using the ice-burg algorithm. Simulations results depict the effectiveness of the proposed model.

Zhang *et al.* [18] proposed an incentives based system for electric vehicle charging. The huge penetration of RESs has increased the intermittency of the power grid and electric vehicles can play a very important role to maintain its sustainability as their load is shiftable. A blockchain based real time system has been proposed which uses the concept of priority and SMERCOIN. The electrical vehicle users who follow the charging schedules of the system are provided incentives in the form of SMERCOINS. They can later exchange them with real currency or buy priority to buy more energy. On the other hand, the users who do not follow the rules face penalties. To evaluate the performance of this system, it is implemented in a real-world scenario for 15 months. Results depict that this system works great and it also increases the use of solar energy.

In paper [19], it is stated that the integration of RESs has created several challenges in maintaining the sustainability and reliability of the smart grid. One of the major challenges is to keep energy demand and supply balanced. Esther *et al.* proposed a P2P based local energy trading system. It is stated that energy prosumers should be able to exchange the surplus energy with their energy deficit neighbors. In this way, they will increase their profit while keeping the energy within their local market. In this paper, a microgrid energy market mechanism is proposed which is based on blockchain technology. Brooklyn microgrid project is used to evaluate the effectiveness of the proposed system. The results depict the satisfactory performance.

The IoT is expanding rapidly and it is playing a very important role in smart homes also. With the use of this technology, several devices are connected and exchanging data daily. The connectivity of devices on this platform also has some security and privacy risks which need to be addressed efficiently. Qu *et al.* [20] have proposed a solution for this issue by integrating blockchain technology with IoT. As the smart devices in the IoT environment are lightweight and have less storage and computational capacity, this issue has been solved by these researchers by using hypergraphs. The proposed model reduces both, storage and security, issues. Storage nodes are organized using hyperedge and the resultant network is part of network storage. Moreover, the security issues and uses cases related to the model are also discussed in detailed. The efficiency of the proposed model is proved with the help of simulations. The simulation results depict the effectiveness of the proposed system.

In IoT, another big concern nowadays is access control. Several traditional access control mechanisms are available but they are not sufficient to maintain the security and privacy of the information over IoT. Another challenge is the centralized authorization system where a central server has full authority. This server could face a performance bottleneck or single point of failure issues. To address these issues, Xu *et al.* [21] proposed a blockchain based solution. In this system, everything is decentralized and there is no central controlling authority. Smart contracts are used for the registration process and this mechanism is made more secure by introducing identity-based capability token. The nodes are of two types: one type of node has high computational powers while the other one is computationally less powerful i.e. Raspberry PI nodes, and both machines use proof of concept protocol. Simulations are carried out to evaluate the performance of the proposed model. Results depict that the proposed system has significant potential while there is still room for improvement for security issues.

From literature review, it is observed that blockchain technology has evolved as a promising solution for the issues being faced by centralized local energy trading. With the help of this technology, an efficient blockchain-based P2P energy trading market can be developed for local users to efficiently trade energy with each other and main grid. This P2P trading will have positive impact on sustainability of main grid by reducing the power generation overhead from it in on-peak hours. Market participants will also get benefits in the form of low electricity prices. In this regard, we propose a P2P energy trading mechanism, which is elaborated in Section V.

III. PROBLEM STATEMENT

With the rapid increase in energy demand and distributed energy generation, new demand-side management methods are developed. In these methods, monetary penalties and incentives are defined that encourage users to take part in the proposed demand response programs. To manage energy demand and generation, a blockchain-based demand response program is proposed [22], [23]. The electricity users' follow this signal to get incentives and avoid penalties. However, their load is balanced through load curtailment which is not efficient for their comfort. To overcome this limitation, P2P energy trading is a promising solution. In a blockchain-based P2P energy market, electricity prosumers use RESs to generate energy locally. After the fulfillment of their energy demand, surplus energy is traded with energy deficit users in the market. Energy trading prices in the local P2P market are low as compared to the energy purchasing prices from the main grid [24]–[26]. However, in an open book energy trading market [24], [26], the energy trading prices between peers vary and some buyers pay more energy prices than others. This results in imbalanced energy prices in the market. In [25], a P2P energy trading mechanism is proposed, where energy trading prices for all market participants are fixed. However, this fixed price mechanism is not beneficial for prosumers as energy prices are considered 70% less than the electricity pricing tariff of the main grid. In addition, RESs have intermittent nature so, all market participants are also dependent on the main grid. The effect of local P2P trading on the main grid should also be observed to maintain its sustainability.

IV. PROPOSED SOLUTION AND CONTRIBUTIONS

In this paper, our objectives are to reduce electricity consumption cost at consumers' level, minimize PAR at grid level (to make it stable) and implement hybrid energy trading markets using the blockchain. We propose a hybrid P2P energy trading market mechanism where both P2P and prosumer to grid (P2G) energy transactions are implemented. In comparison to [23], [25], [26], it is a decentralized market, based on double closed book auction. Here, surplus energy can be sold and deficit energy can be purchased from neighbor prosumers or utility grid unlike [23]. The P2P energy trading's effects on the main grid are also studied and rules are defined to maintain the stability of the main grid which is the limitation of [22]. The energy trading price for the P2P scenario is determined the same for all transactions in a specific time interval which sets this work apart from [23]–[26]. Moreover, in P2P trading, suitable prosumers are selected based on their distance from consumers to reduce the possible transmission losses. Smart contracts are developed accordingly to implement this market scenario.

The main contributions of this paper are as follows:

- Monopoly of the main grid is eliminated by the decentralization of the electricity trading market using a blockchain-based hybrid P2P energy trading model and a new bidding mechanism is proposed.
- Self-enforcing smart contracts are designed for efficient energy transactions between peers and the main grid. The proposed smart contracts control P2P and P2G

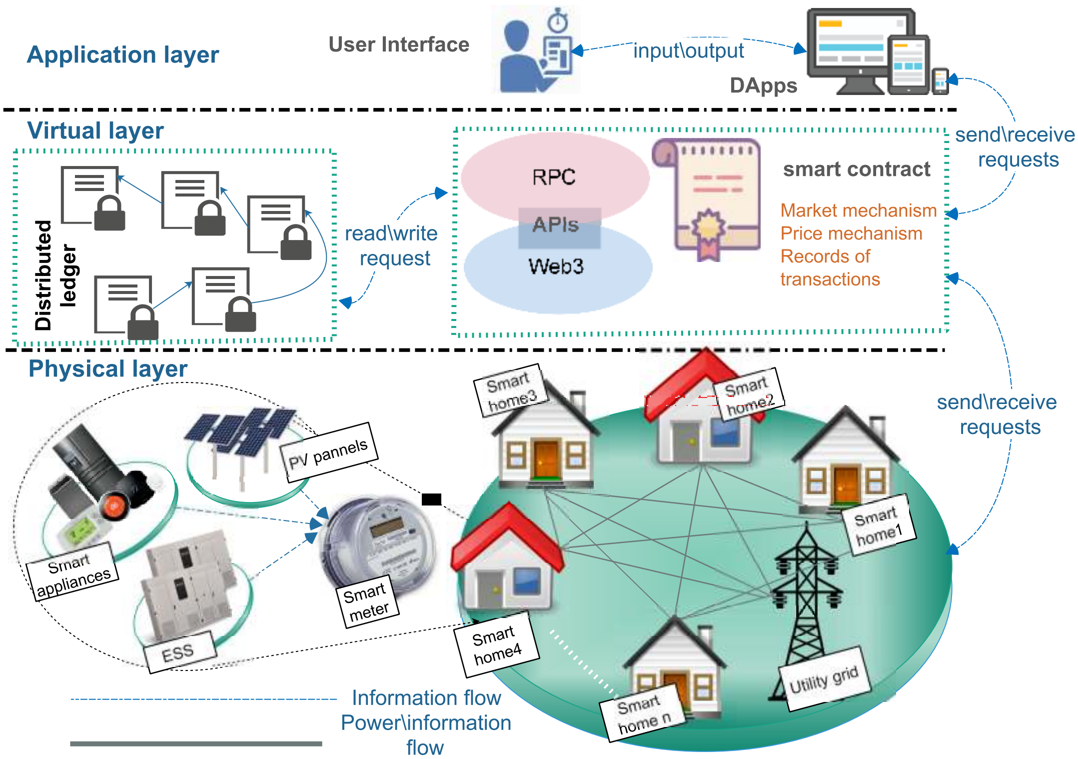

FIGURE 1. Three layered architecture of blockchain.

energy transactions and reduce its demand from the main grid during on-peak hours.

- Peak to average ratio (PAR) and the cost of electricity are reduced which benefits both utility grid and energy consumers, respectively.
- The energy exchange between peers is done based on the physical distance between them which reduces the possible line losses up to some extent.

V. SYSTEM MODEL

In our work, a three-layered architecture of the blockchain-based energy trading market is proposed. Figure 1 shows these layers along with their respective components. On the physical layer, the physical structure of the energy trading market is depicted. Multiple smart homes are connected with the utility grid and they also have a direct connection with each other for information as well as energy transfer. The electricity is transferred between smart homes using the same power lines that are used to transfer energy from the grid to smart homes. Smart homes are equipped with energy storage systems (ESSs), PV panels, smart appliances and a smart meter. ESS sends its current status information, PV panels send their current energy generation data and smart appliances send information related to their energy consumption to the smart meter. Smart meter processes this data to acquire knowledge about the current energy state of the smart home. A smart home can have one of the following three states: surplus energy, deficit energy or equilibrium state. Its owner can act as both an energy prosumer as well as an energy consumer, depending on smart home's current energy state. The state information of a smart home is sent from smart meter to the virtual layer to participate in trading.

On the virtual layer, the blockchain is implemented. All users in the market are nodes of the blockchain and have a copy of the distributed ledger. An energy prosumer places the bid to sell energy in the energy trading market through a smart contract. The smart contract contains all the rules and market mechanisms of energy trading between two parties. If all the rules are fulfilled then a transaction is made, otherwise, the transaction is reversed and an error message is sent to the respective party. On the confirmation of a transaction, a new block is created and added to the chain of previous blocks. The header of the current block contains the hash of the previous block, in this way the whole chain of blocks is maintained. This layer contains all the necessary APIs which are required to communicate with a smart contract. The third layer of this architecture is the application layer. It consists of user interface and decentralized applications (DApps) through which the user interacts with the smart contract and enters its information and keeps track of important data. A network participant interacts with the system using application layer. It uses DApps to enters data related to its energy consumption (either he needs energy or he wants to sell it) and requests for a transaction. This information is sent to the smart contracts that are present on the second layer. User's request is processed at this layer and if all the conditions of energy trading are fulfilled (discussed in sub-section V-F) then the transaction is approved. The actual energy transmission then takes place at the physical layer.

A. MARKET PARTICIPANTS

For the implementation of a hybrid P2P energy trading market, energy consumption data of two types of market participants is considered. To demonstrate their energy consumption pattern, two types of appliances are considered: shiftable and non-shiftable (detail can be found in [26]). The identities of market participants are not revealed. Each participant on the network has a public and private key pair. Public keys of participants are shared with other participants on the network and mathematically a user cannot guess the private key of another user, using his public key. A hash function is used to generate unique addresses for participants from their public keys. These unique addresses are used to identify them while trading on the network. In this way, their real identities are kept secret. So, malicious nodes cannot access the sensitive data of legit participants of the network and privacy is ensured. The market participants are categorized based on their energy consumption patterns and their ability to produce energy locally using RESs. The following subsections contain information regarding these participants.

1) ELECTRICITY PROSUMERS

These market participants can produce electricity locally using PV panels or wind turbines. They are called electricity prosumers as they can both sell and buy energy to and from the main utility. The electricity prosumers also have storage devices to store the electricity when they are producing more energy than their demand on a specific time interval. In the case of surplus energy, they sell the additional energy to either neighbor electricity consumers or the main grid. For the load pattern of energy consumption, a house with multiple family members is considered.

2) ELECTRICITY CONSUMERS

These market participents do not produce energy locally nor they have storage devices. They are further divided into two groups to simulate their energy consumption pattern: one group is of single consumers and the other is students. The energy consumption pattern of both groups vary from each other.

a: SINGLES

These consumers generate energy demand in the morning and after five in the evening. As they go to the office or their workplace in the day time, so, their energy consumption during these intervals becomes zero.

b: STUDENTS

Students have different energy demand patterns than singles as they leave for their institute late and have irregular patterns of sleep and going out. Mostly, their energy consumption in the initial hours of the morning is flat or very basic and their energy demand increases at midnight.

B. LOAD CONSUMPTION

The load consumption of electricity consumers depends on the number of appliances they are using on a specific time interval, their length of operational time and power rating. Each electrical appliance has a different power rating and length of operational time. The following equations are used to compute the power consumption of electricity consumers on an interval basis and their total energy consumption in a day.

$$Load_c(t) = \sum_{a=1}^{n} Pow_c(a) \times St(a)(t) \quad (1)$$

$$Load_{pro}(t) = (\sum_{a=1}^{n} Pow_{pro}(a) \times St(a)(t)) - Gen_{res}(t) \quad (2)$$

$$St(a)(t) = \begin{cases} 1 & \text{if appliance is on} \\ 0 & \text{otherwise} \end{cases} \quad (2a)$$

$$TLoad(t) = Load_c(t) + Load_{pro}(t) \quad (3)$$

$$TLoad = \sum_{t=1}^{24} (Load_c(t) + Load_{pro}(t)) \quad (4)$$

Equation 1 shows the energy consumption of electricity consumers. Here, $Load_c(t)$ represents the load consumed by all operating appliances at a time interval t which is equal to the power rating of consumers' appliances $Pow_c(a)$ multiplied by their status $St(a)(t)$. Equation 2 represents the energy consumption of electricity prosumers at a specific time interval t. In this equation the load consumption at a time interval is calculated after subtracting local energy generation $Gen_{res}(t)$ form it. In both equations the value of $St(a)(t)$ depends on the on/off status of appliances. In Equation 3, load of both consumers $Load_c(t)$ and prosumers $Load_{pro}(t)$ is added to get the total load at time interval t. Equation 4 is used to compute the total load consumed in a day.

C. COST OF ELECTRICITY

For electricity cost, electricity price is categorized into two types: price issued by utility grid and price set in local market. To calculate the final cost, we need to compute it according to both prices. The cost of electricity purchased from grid is computed according to the price issued by grid and cost of electricity purchased from local market is determined according to the market price.

$$Cost_c(t) = GPower_c(t) \times P_G + PPower_c(t) \times P_M \quad (5)$$

$$Cost_{Pro}(t) = GPower_{Pro}(t) \times P_G + PPower_{Pro}(t) \times P_M \quad (6)$$

$$GPower_{c/Pro}(t) = \begin{cases} 0 & \text{if } PPower_{c/Pro}(t) = Load_{c/Pro}(t) \\ > 1 & \text{otherwise} \end{cases} \quad (6a)$$

$$PPower_{c/Pro}(t) = \begin{cases} 0 & \text{if } GPower_{c/Pro}(t) = Load_{c/Pro}(t) \\ > 1 & \text{otherwise} \end{cases} \tag{6b}$$

$$Profit_{Pro}(t) = (GSell(t)+PSell(t)) \times P_M \tag{7}$$

$$DProfit_{pro} = \sum_{t=1}^{24} Profit_{pro}(t) \tag{8}$$

$$DCost_c = \sum_{t=1}^{24} Cost_c(t) \tag{9}$$

$$DCost_{Pro} = \sum_{t=1}^{24} Cost_{Pro}(t) \tag{10}$$

$$MCost_c = \sum_{d=1}^{31}(DCost_c(d) \tag{11}$$

$$MCost_{Pro} = \sum_{d=1}^{31}(DCost_{Pro}(d) - DProfit_{Pro}(d)) \tag{12}$$

In Equation 5, $GPower_{Pro}(t)$ is the amount of power purchased from the grid and it is being multiplied by P_G which is the price of electricity issued by the utility. $PPower_c(t)$ is the amount of power purchased from peers in the local energy market and it is multiplied by cost set in local market P_M. Both costs are added to get the total cost $Cost_c(t)$ of electricity consumption on a specific time interval t for consumers. Equation 6 shows the electricity cost computation for prosumers, both equations have the same parameters. In both equations, $GPower_{c/Pro}(t)$ would be equal to zero if all demand is fulfilled by the local energy market. Similarly, if the demand is only fulfilled by the main grid then $PPower_{c/Pro}(t)$ will be zero. For electricity prosumers, as they sell surplus energy to other peers and utility, so, they also get some profit from it and Equation 7 computes their profit. Where, $GSell(t)$ represents the amount of energy sold to main grid and $PSell(t)$ is the amount of energy sold in local market, both are added up and final amount is multiplied by electricity trading price in local market P_M to get the final profit $Profit_{Pro}(t)$ at time interval t. Equation 8 shows the profit of prosumers for one day. The Equations 9 and 10 are used to compute the per-day cost of both electricity consumers and prosumers, respectively. The next Equation 11 is used to compute the monthly cost of electricity for the consumer. In Equation 12, $DProfit_{Pro}(d)$ is the daily profit of selling surplus energy and it is being subtracted from $DCost_{Pro}(d)$ which is the daily energy consumption cost of energy purchased from peers and utility grid to give the final monthly cost $MCost_{Pro}$ for prosumers.

D. PAR OF ELECTRICITY MARKET

PAR is an important factor in energy trading. It affects the efficiency and reliability of the main grid. Following eqnarray 13 is used to compute the PAR of a hybrid P2P energy trading market.

$$PAR = \frac{\sum_{t=1}^{24} TLoad(t)}{max(TLoad)} \tag{13}$$

E. PRICING MECHANISM FOR LOCAL TRADING

The price of electricity trading is set between the upper and lower limit of electricity prices issued by the utility grid. The reason is that no prosumer wants to sell the electricity at a lower price than this limit and no prosumer will be willing to purchase electricity from its peers more expensive than the main grid. Instead, it will prefer to purchase it from the main grid. So, the electricity trading price is always set between this limit. At market bidding time, all the prosumers place their bid containing the amount of available surplus energy and its cost.

$$Prices = \{Price_{p1}, Price_{p2}, Price_{p3}, \ldots, Price_{pn}\} \tag{14}$$

$$P_M = min(Prices) \tag{15}$$

Equation 14 represents the price of electricity bids placed by prosumers to sell their local electricity. $Price_{p1}$ is the price offered by the first prosumer and there are n numbers of prosumers, so, the last bid is represented as $Price_{pn}$. After bids placement, the final price of electricity is selected. Equation 15 shows that the minimum price offered from a set of prosumers is selected as the electricity trading price in the market.

F. BLOCKCHAIN SMART CONTRACTS

Blockchain was introduced as an enabling technology of bit-coins (electronic currency) by Nakamoto [27]. It was then later used in the field of smart grid in 2014 [28] and ever since it has grabbed the attention of several researchers. It is a widely accepted technology but still lacks a standard definition. It is a technical solution for a reliable decentralized database that is transparently open and secured [29].

Each block in the blockchain has two parts called header and body. The former stores the hash value (address) of the previous block and later contains the data. This data contains the information and records of transactions. Each block can store multiple transactions. The hashed value of the current block is generated by using the hash value of the previous block, information of the current block and a random number. The integrity of the blockchain is ensured by connecting all the blocks in a sequential manner. In a smart grid application scenario, each block of data records the information related to the transactions. A transaction can store data related to the sender and receiver of energy, amount of energy, price, time of the transaction, the current balance of both participants and their status. After a block is created, it is broadcasted over the network in real-time. After confirmation, the new block is added to the chain. The consensus algorithms are used to mine the key of this block which enables each node on the network to add it to its chain. The miner node which guesses the key first is awarded with reward. In this way, the blocks on the blockchain become non-repudiation and hard to temper as if some intruder tries to temper the information of a block then it has to alter all the preceding blocks of 51% of the network nodes. So, it becomes computationally very expensive and not beneficial.

A smart contract in an essential component of blockchain which contains all the necessary rules for a successful transaction. It can also be considered as a finite state machine where predefined rules and instructions are executed whenever a specific event occurs. It checks the predefined conditions before committing a transaction. In a smart grid energy market, the smart contract controls the energy transactions between two parties by following predefined rules. The rules in a smart contract cannot be altered once it is deployed on the network. It ensures a transparent energy trading market for all participants. Moreover, market participants trust these contracts for their energy and payments which eliminates the requirement of central parties to control these trading activities. In this paper, we have developed three smart contracts for efficient P2P and P2G energy trading in a smart energy market. Details of these contracts are given in the following subsections.

1) MAIN SMART CONTRACT

A main smart contract is developed to control all the operations of energy trading in the local energy market. Market participants interact directly with this smart contract. It first checks the validity of the user and allows the registered users to participate in the local trading. Algorithm 1 shows the basic steps of the main contract. When a market participant sends an energy surplus or deficit request, it checks the status of both P2P and P2G smart contracts. It checks the validity of the user if it is registered in the market or not. If a participant is registered then it proceeds to the next step, else it first registers the market participant and adds the necessary information in the system. When an electricity prosumer sends the power surplus request, main contracts calls the *seller* function of the P2P smart contract and in case of the buyer, it calls *buyer* function.

As the energy market is a closed auctioned market, so, it checks the time and on reaching the marking clearance it calls the *clearMarket* function of the P2P smart contract. In this way, all the bids from electricity sellers are matched with buyers and results are sent back to the main contract. Now, it checks whether some buyers are still left with deficit power or sellers with surplus energy. In both cases, the additional power is bought and sold to the main grid by calling *buyEnergy* and *sellEnergy* functions of the P2G smart contract, respectively. Lines 25 to 35 contain three functions. The first function is trading_result() which stores the results and allows the electricity consumers and prosumers to exchange energy. The second function returns users' information when called and the last function returns the monthly billing report when called by the P2G smart contract of a legal participant.

2) P2P SMART CONTRACT

Algorithm 2 depicts the P2P smart contract. It is responsible for the whole trading mechanism of the local energy market. Market participants cannot invoke it directly. They access it through the main smart contract. A P2P smart contract receives the necessary inputs from the main contract and information related to energy consumers and prosumers. The *seller* function of this smart contract stores the sellers' related data that is used afterward. It also checks the proposed selling price of electricity by seller and compares it with already proposed lowest electricity selling price. In the case of the lowest price, it is set as the current electricity trading price for the market unless another seller proposes a lower price. In the case of the higher energy selling price, the new price is discarded and the old price is kept as electricity trading price of local market.

When the bidding time ends, the main contract calls the *clearMarket* function (Lines 11-37). This function checks the tag of each buyer and seller and trades energy according to the minimum distance between electricity consumers and prosumers to reduce the power losses and make trading more efficient. The market is divided into three areas and each participant is assigned a tag according to its area.

Algorithm 1 Main Smart Contract

```
1:  Input request, requester
2:  Check status of P2P and P2G contracts
3:  Check market time
4:  if requester == registered
5:      Store input values
6:  else
7:      Register requester
8:      Store input values
9:  end if
10: if requester == seller
11:     P2P.seller()
12: else if requester == buyer
13:     P2P.buyer()
14: end if
15: Check market time
16: if time == finished
17:     P2P.clearMarket()
18:     if deficit energy
19:         P2G.buyEnergy()
20:     else if surplus energy
21:         P2G.sellEnergy()
22:     end if
23:     trading_result()
24: end if
25: function trading_result(){
26:     Start energy transaction
27:     Store results
28: }
29: function billing(){
30:     Return user's information
31: }
32: function monthelyBilling(){
33:     Calculate the bill
34:     Return billing formation of one month
35: }
```

Algorithm 2 P2P Smart Contract

```
1: Input request, requester, sllers, buyers
2: function seller() {
3:    if sellerPrice<MPrice
4:       MPrice = sellerPrice
5:    end if
6:    Store seller in sellers
7: }
8: function buyer() {
9:    Store buyer in buyers
10: }
11: function clearMarket() {
12:    for i = 1:buyers.length
13:       for j = 1:sellers.length
14:          if (buyers[i].tag == sellers[j].tag)
15:             matchBid(j,i)
16:          end if
17:       end for
18:    end for
19:    if sellers.length>0 && buyers.length>0
20:       for i = 1:buyers.length
21:          for j = 1:sellers.length
22:             if (buyers[i].tag+1 == sellers[j].tag+1)
23:                matchBid(j,i)
24:             end if
25:          end for
26:       end for
27:    end if
28:    if sellers.length>0 && buyers.length>0
29:       for i = 1:buyers.length
30:          for j = 1:sellers.length
31:             if (buyers[i].tag+2 == sellers[j].tag+2)
32:                matchBid(j,i)
33:             end if
34:          end for
35:       end for
36:    end if
37: }
38: function matchBid(){
39:    if sellers.length == 0 || buyers.length == 0
40:       break
41:    end if
42:    if (sellers[j].amount - buyers[i].amount) >= 0
43:       remainder = sellers[j].amount - buyers[i].amount
44:       calcAmount = sellers[j].amount - remainder
45:       buyEnergy(calcAmount, buyers[j],sellers[i])
46:       seller[j].amount = remainder
47:       if remainder==0
48:          removeSeller(j)
49:       end if
50:       removeBuyer(i)
51:    else
52:       remainder = buyers[i].amount - sellers[j].amount
53:       calcAmount = buyers[i].amount - remainder
```

Algorithm 2 *(Continued.)* P2P Smart Contract

```
54:       buyEnergy(calcAmount, buyers[j],sellers[i])
55:       buyers[j].amount = remainder
56:       if remainder==0
57:          removeBuyer(i)
58:       end if
59:       removeSeller(j)
60:    end if
61: }
62: function buyEnergy() {
63:    Store transaction information
64:    Main.trading_result(buyer,seller,MPrice)
65: }
66: function removeBuyer() {
67:    Remove buyer from buyers
68: }
69: function removeSeller() {
70:    Remove seller from sellers
71: }
72: function getBuyerCount() {
73:    Return number of buyers
74: }
75: function getSellerCount() {
76:    Return number of sellers
77: }
78: function getBuyerInfo() {
79:    Return information of all buyers
80: }
81: function getSellerInfo() {
82:    Return information of all sellers
83: }
```

Trading between the participants of the same area is preferred. When trading between the same area is not possible then trading between adjacent areas is preferred. In this way, the whole market is cleared and results are sent back to the main smart contract. When tags of two participants match then *matchBid* function is called to process requests. If the seller has more surplus energy than its matched buyer then the buyer is assigned energy and it is removed from buyers array and the status of the seller is updated by remaining surplus energy. In contrast, if a seller has less energy than the buyer's need then the seller is eliminated from sellers after giving its energy and the power deficit status of the buyer is updated with its current deficit power value. The *buyEnergy* function is called and the value of the current amount of energy exchange along with buyer and seller information is passed.

The *buyEnergy* function stores this information and passes the buyer's and seller's information to the main smart contract with the market price of electricity. The next two functions (lines 66-71) are used to remove the buyers and sellers from the market as their role in the market ends. The *getBuyerCount* and *getSellerCount* functions are used to

Algorithm 3 P2G Smart Contract

```
Intialize all necessary parameters
function buyenergy() {
    CPrice = price at current hour
    Check peak hour
    if peak hour == true
        CPrice = CPrice + (CPrice*0.8)
    else if off-peak hour == true
        CPrice = CPrice*0.05
    end if
}
function sellEnergy() {
    CPrice =MPrice
    Store information
}
function billing() {
    main.consumerInfo(address of consumer)
    Store information
}
function monthlyBill() {
    main.monthlyBill(address of consumer)
}
```

check the number of participants in the market and the main smart contract uses these functions to check the status of the market. The last two functions (lines 78-83) are used to get the information of all buyers and all sellers at once.

3) P2G SMART CONTRACT

In this work, the main focus is to implement an efficient and reliable local energy market where RESs are used to generate energy locally and surplus energy of prosumers is traded with neighbors. However, the RESs are of intermittent nature and their performance depends on the weather conditions. So, the connection with the main grid cannot be disconnected. In-spit of having RESs, the prosumers also need connection with the main grid. Algorithm 3 shows the smart contract designed for P2G energy trading. Market participants buy energy from the main grid when they are power deficit and prosumers sell back the surplus energy after fulfilling their energy demand and selling it to the power deficit neighbors. Market participants request the main contract for energy. After market clearance, if consumers still need energy then the main smart contract sends a request to *buyenergy* function of the P2G smart contract. Here, the price of electricity for the current hour is determined and conditions are checked. In the case of off-peak hours, the electricity is sold with a five percent discount than the original prices. The price of electricity is increased by 20 percent in case of on-peak hours.

On clearing the market if the prosumers have surplus energy then it is sold back to the main grid using the main smart contract. *sellEnergy* function is called and amount of power and market price, at which energy is being sold back to the main grid, is passed and information is stored. The *billing* function is used to get the billing information of the consumers and prosumers. The last function of the algorithm is used to get the monthly information from the main contract at the end of each contract.

G. INTERACTION BETWEEN MARKET PARTICIPANTS AND SMART CONTRACTS

In this section, the transactions and interactions between market participants and smart contracts are explained. Figure 2 is the graphical illustration of these interactions.

1) A customer sends the request to the main smart contract. This request can be sent through a smart meter or a separate communication device. If a customer has surplus energy, it sends sell request and in the case of energy deficit, it sends buy request to the main smart contract, respectively. In this request, the customer also sends its identity, amount of power to sell or buy and the price at which it wants to sell electricity.
2) When a main smart contract receives the buy/sell request, it processes it and checks the validity of the customer. It makes sure that the requester is a valid market participant and it is in the state of buying and selling energy.
3) After verifying the validity of the request, the main smart contract checks the status of the P2P smart contract. In this step, it checks whether market time has expired or it still has some time left. Moreover, the number of available consumers and prosumers is also checked. P2P contract responds to these requests by sending the acknowledge signal or required data back to the main smart contract.
4) In the active energy trading market, the main smart contract forwards the request of energy buy/sell to the P2P smart contract. This request contains the information related to the buyer/seller and the amount of power they need to buy/sell.
5) At market clearance time, P2P smart contract processes all the energy buy/sell requests and suitable matches of peers are made to exchange energy efficiently. These pairs are made based on the distance between two peers. It is preferred to make all the pairs in such a way that all peers have a minimum distance between them. This approach reduces the possible power losses. After successful pairing, the smart contract sends its information back to the main smart contract.
6) The amount of available energy to sell cannot always be equal to the demanded energy in the local market. Sometimes demand increases as compared to the locally generated energy and HLat other times it becomes lower. In both cases, energy can be sold or bought from the main grid. So, P2P smart contract informs the main smart contract about the current status.
7) Main smart contract sends the electricity buy/sell request to the P2G smart contract. It also sends the price of electricity at which it wants to sell energy. P2G smart contract receives the request and acknowledges it.

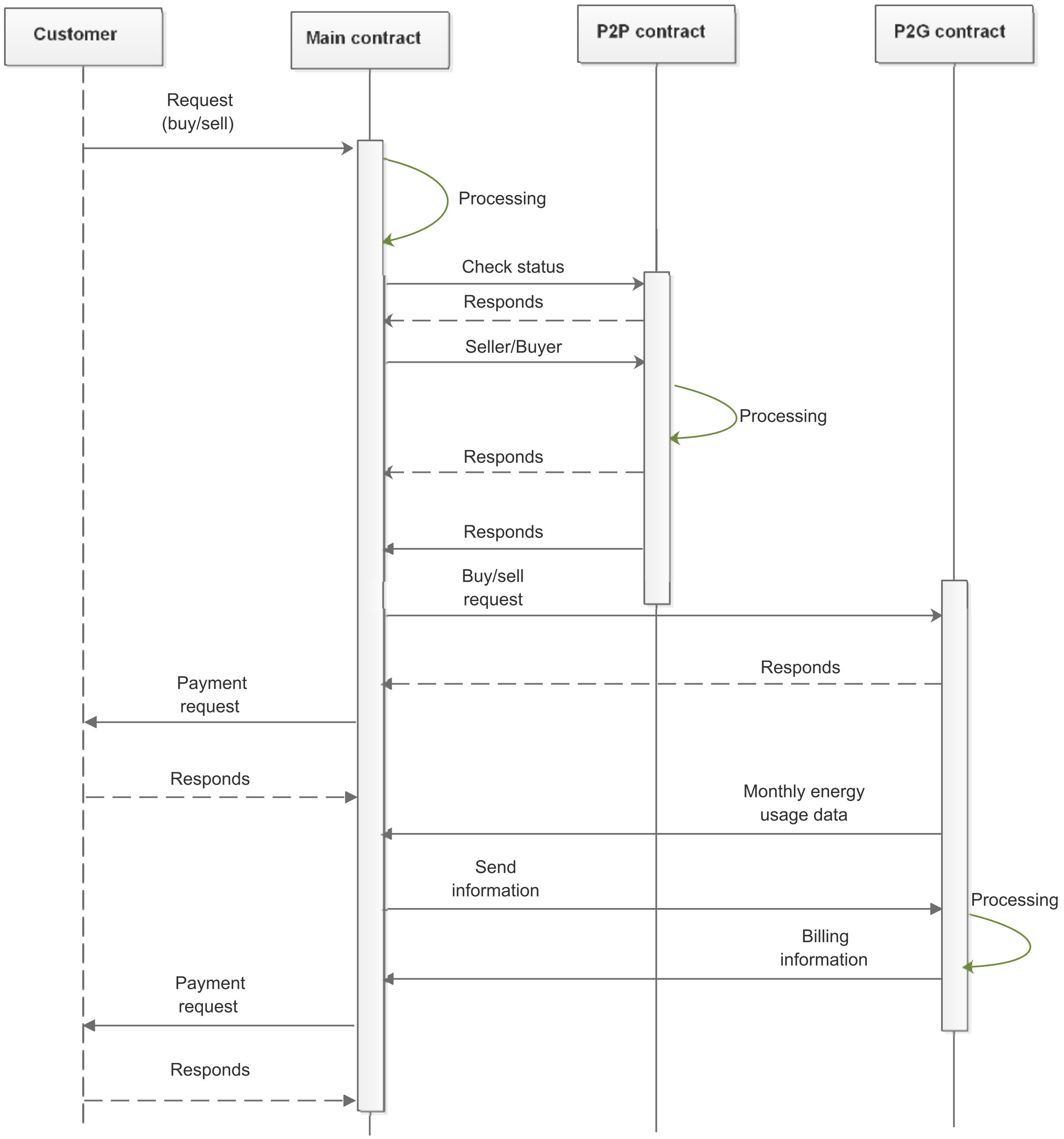

FIGURE 2. **Interactions between smart contracts.**

In the case of selling energy, it sends back its current price of selling energy. It also sends a signal which indicates its agreement on buying or selling the required amount of electricity.

8) The main smart contract sends the payment request to the customers. This payment request includes the bill of electricity bought from the local market which is cleared daily. It can also be cleared at the end of each month as there is no restriction on it.
9) Customers respond to the main smart contract's request and pays their bills. These bill transactions are made in the form of e-money. The main smart contract maintains the e-wallet for each market participant. The prosumers may instead of paying bills, get money for the energy they have sold to peers and the main grid.
10) P2G smart contract sends a request to the main smart contract to get the detailed energy transaction information of each customer. In its response, the main smart contract sends it the history of the whole month.
11) Upon receiving the information of the whole month, P2G smart contract computes the monthly bill of each customer and sends the request for payments.

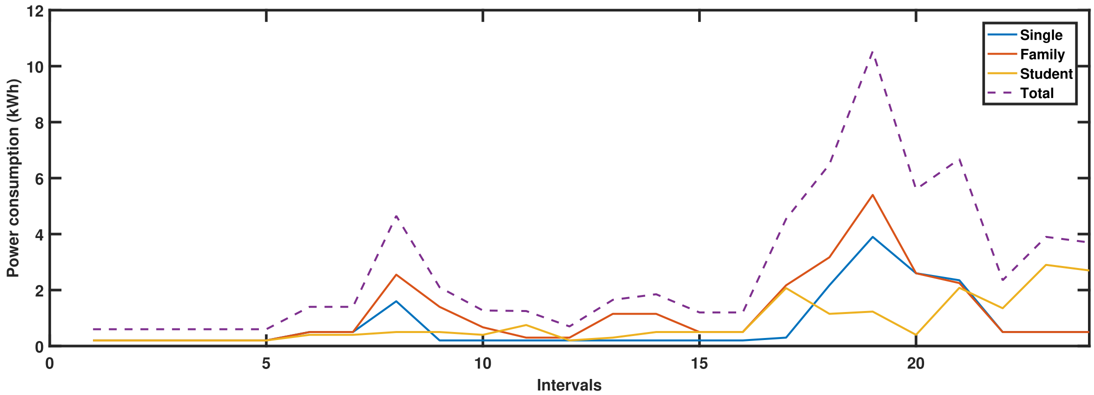

FIGURE 3. Load consumption pattern of users.

12) This monthly bill payment request, received by the main smart contract from P2G smart contract, is forwarded to each related customer. A request is made to pay the monthly electricity bill. The customers in response, pay the bill and continue participating in the local energy trading market as well as with utility grid through smart contracts.

VI. SIMULATION RESULTS

In this section, a local energy trading system is simulated. For development of smart contracts, solidity language is used, which is a special language for smart contracts. Ethereum is used as a platform with Ganache. Following are the constraints of this system which must be followed during electricity trading:

- Only registered consumers can participate in trading.
- One consumer can place only one bid on a specific time interval.
- A prosumer can either buy or sell energy at a time.
- Price of electricity in the local market must reside between the lowest price set by utility grid and highest price.
- Energy trading price in the local market will always be lower than the price offered by the utility.

This system is also connected with the main grid and gets power from it when needed. As described in the previous section, three types of energy consumers are considered. The student and single energy consumers do not produce their energy and third consumers' type is family and they act as energy prosumers in the market. Both students and single consumers either buy energy from the local market or the main grid. Energy prosumers have PV panels and ESSs for local energy generation and storage, respectively. The energy transactions are made using a blockchain-based hybrid P2P energy trading mechanism suggested in this paper. The outcome of simulation will prove the economic benefit of this hybrid energy trading mechanism over the traditional P2G energy trading mechanism. Moreover, the positive effect of this system on the utility grid will also be depicted by increasing the stability of the main grid by clipping the peaks and reducing the PAR. Before simulation results, characteristics of smart homes, PV panels and ESS should be clarified.

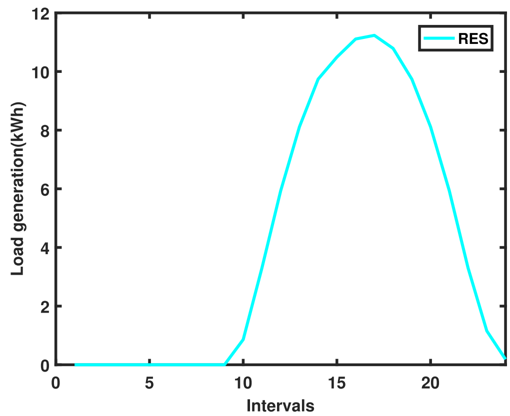

FIGURE 4. Power generation pattern of PV panels.

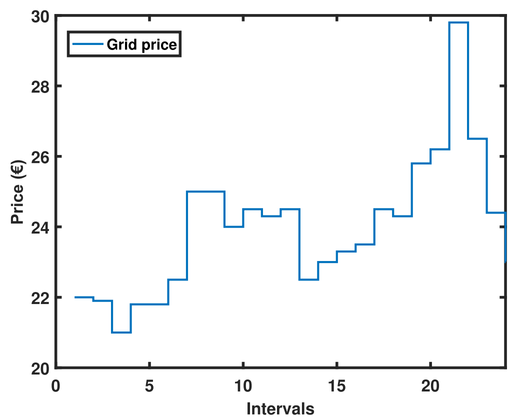

FIGURE 5. Electricity price signal.

The PV panels considered in this system have 54 cells of 1480 × 1000 mm height and width. Each cell can collect 250 Wh of maximum energy. 48 PV panels are assembled to make a solar panel for a smart home that can collect a maximum of 12 kWh of energy on a full bright sunny day. The installation price of this solar panel is

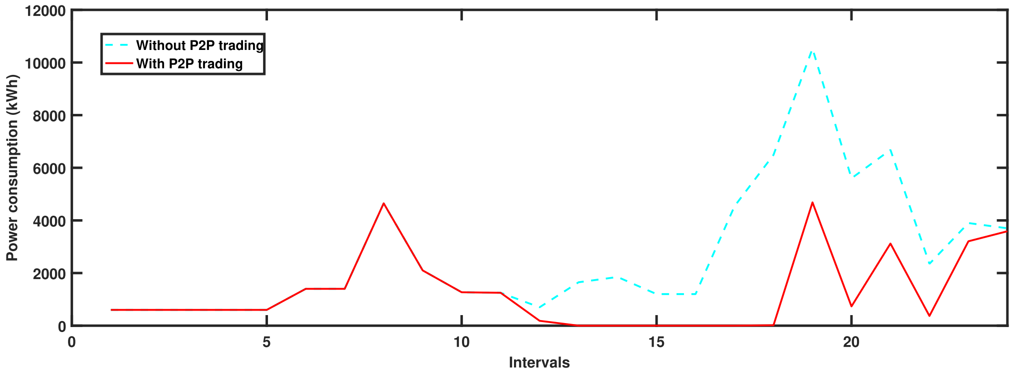

FIGURE 6. Load consumption pattern from the main grid after coalition.

estimated at around 9,370.16 € (each panel is of worth 195.21 €). An ESS costs 2928.93 € and can save energy up to 6.4 kWh. Two ESSs are installed in a smart home for energy storage up to 12.8 kWh and their installation cost is 5857.86 €.

To validate the proposed blockchain-based P2P and P2G electricity trading market mechanism, a total of 1000 users are considered, 600 of which are electricity prosumers and rest are only consumers. Figure 3 illustrates the power consumption pattern of all three power-consuming groups separately on individual basis [26]. The blue line represents the load profile of a single electricity consumer with a peak of 3.9 kW. The orange line represents the energy consumption pattern of the family with a maximum peak of 5.4 kW, this peak is formed on the 19th hour. The energy consumption pattern of a student is represented by the yellow line. It forms a peak at 23rd hour and power consumption on this hour is equal to 2.9 kW. The dotted line represents the total energy demand of these three consumers. The peak load is 10.53 kW in the 19th hour. This load consumption data is used to generate the electricity load of 1000 users. The load is randomly generated following these load patterns of electricity consumers and total load pattern.

Figure 4 represents the energy generation curve of PV panels [30]. This data is for one PV panel installed in a smart home. It can be observed from the figure that the maximum energy collection is close to 12 kW. A total of 24 intervals are considered. Each interval is of 1 hour. The maximum energy collection period is from the 13th hour to the 17th hour. During this interval, the energy collection varies between 9-11.7 kW. The electricity price signal is illustrated in Figure 5. It is a real-time pricing signal and it can be observed that initially the electricity price is low and as the energy consumption increases the price of electricity also increases. According to Figure 3, the peak hour is in the 19th hour. Similarly, in Figure 5, the electricity price increases in the following next two hours. Electricity supplied by main grid during these intervals is expensive for the consumers and compels them to decrease the usage of power during these intervals.

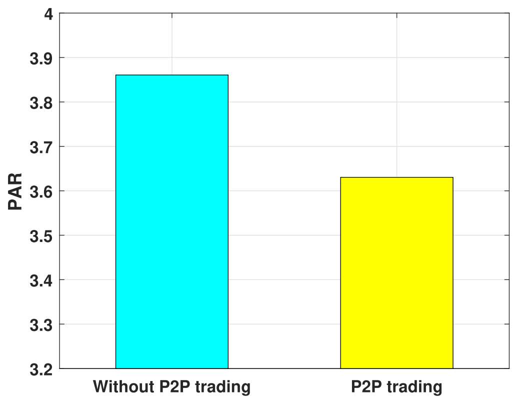

FIGURE 7. Comparison of PAR for both scenarios.

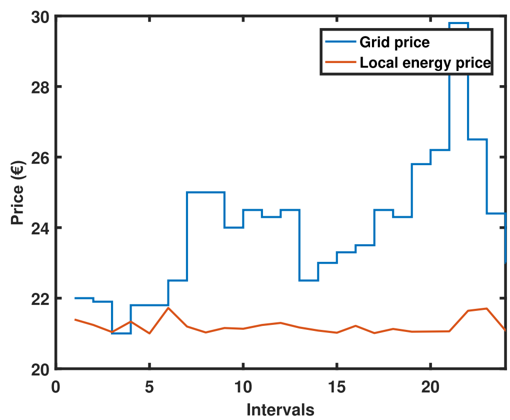

FIGURE 8. Comparison of electricity pricing signal for both scenarios.

In our proposed blockchain-based P2P and P2G electricity trading mechanism, P2P energy trading plays a vital role during these peak hours. As discussed in the previous section, the electricity prosumers produce electricity locally, so, they use this energy first and if required they buy energy from the main grid. Moreover, in the case of surplus energy, where these prosumers are generating more energy than their requirement, they will sell this energy to their peers

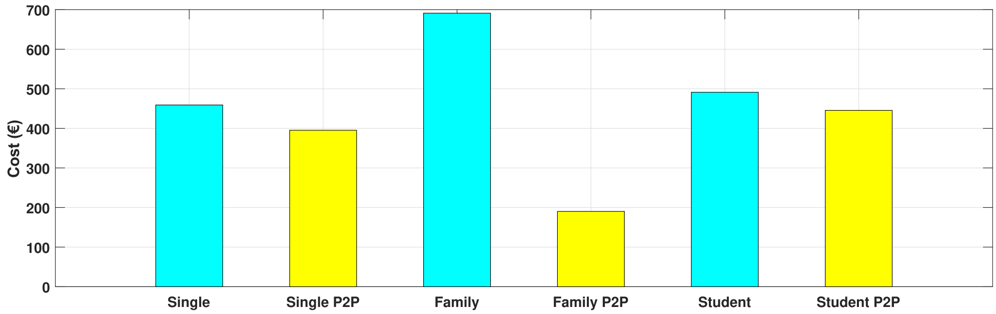

FIGURE 9. Comparison of cost for both scenarios.

on comparatively less cost than the main grid. If they still have surplus energy then this energy will be sold back to the main grid. Figure 6, depicts the effect of hybrid P2P energy trading on the overall energy demand curve from the main grid. The values of load consumption patterns are computed using Equations 1 to 4. The red line represents the energy demand from the main grid by consumers when P2P trading is integrated. The dotted line shows the electricity demand of consumers in the conventional scenario. Initially, it is night time and no renewable energy is being produced. So, the energy consumption patterns of both hybrid P2P and P2G are similar. After the 11th interval, the pattern of both curves starts changing. In the case of a hybrid P2P scenario, no power is being purchased from the main grid and power demand of the local market is being fulfilled by local energy trading between neighbors. As the energy generation from PV panels increases, the surplus energy can also be sold back to the grid and ESSs can be charged as well. After the 16th hour, as the energy demand increases rapidly, the additional energy demand is fulfilled by purchasing energy from the main grid. In the next intervals, the electricity demand is fulfilled by both P2P and P2G trading. After 22nd interval the energy consumption pattern of both curves becomes similar.

Figure 6, depicts that the peak of electricity demand from the main grid has also reduced. Peak reduction contributes to the more stable main grid and prevents the possibilities of blackouts. The electricity demand peak in the conventional scenario is equal to 10.53 MW and after peak reduction, it becomes 4.6 MW. Moreover, PAR has also decreased as illustrated in Figure 7, it is computed using Equation 13. It is depicted in this figure that without P2P trading the PAR was up to 3.8607 which has been reduced down to 3.6304. Owing to these results, it is clear that the proposed electricity trading model is beneficial for the main grid as it clips the peak and reduces the PAR. On the other hand, it is also beneficial for the consumers.

In the traditional energy optimization methods, the cost of energy consumption is reduced by either shutting down the electrical appliances or shifting the load from on-peak hours to off-peak hours. In both cases, the users' comfort is compromised. Low electricity bills are obtained on the cost of the inconvenience of appliances' operation. Contrary to this, in our proposed model the cost of electricity for consumers is reduced without compromising their comfort. As we have already discussed in the previous section about the pricing mechanism in a hybrid P2P trading system, the price of electricity bought from prosumers instead of the main grid would always be less. All the electricity prosumers with surplus energy place the bid of their energy selling price in the smart contract. The bidders choose the electricity selling price between the lowest and highest price limits set by main grid. In the end, the market clearance price for electricity is chosen which is the lowest among all the placed bids. The smart contract sets this price as the final electricity trading price and each prosumer sells its surplus power to consumers on this rate.

The low electricity purchasing price motivates the buyers to buy electricity from local prosumers instead of the main grid. Figure 8 illustrates the comparison of the energy consumption prices of both the main grid and local prosumers. The blue line represents the real-time pricing signal from the main grid and the red line represents the local energy trading price. The local energy trading price is much lower as multiple prosumers announce their price within the price limit set by the main grid and every time smart contract picks the lowest price. In Figure 9, the comparison of electricity consumption cost in both scenarios is presented. Equation 12 is used to compute the energy consumption cost for all users. In case of singles and students, the profit is zero as they do not have local generation. Whereas, prosumers have profit because of their local energy generation. In case of single consumers, the cost in conventional grid scenario is equal to 459.1710 € and in case of hybrid P2P it has reduced down to 394.8177 €. For students, the initial cost was 491.2680 € and it is reduced to 444.1003 €. Lastly, the prosumers (family) group was paying 700 € and now their cost has been reduced down to 190.2050 €. The highest cost reduction is of prosumers as they are not only producing electricity locally but also selling it in the market and making profit.

From the simulation results, it is evident that the cost-saving of prosumers is up-to 510 € per month. The total installation cost of RESs and ESSs is approximately 15,277 €. So, prosumers can get back their invested money in two and a half years and they can earn profit from next years.

VII. CONCLUSION

In this paper, it is demonstrated that the integration of blockchain technology in the hybrid P2P electricity market has a positive influence. A truly distributed and P2P system is developed and a trustless environment is created between market members while eliminating a central controlling entity. The consortium blockchain is used to design a hybrid P2P energy trading market where electricity consumers and prosumers trade electricity with one another and the main grid. Three smart contracts are designed to implement this local energy market. The main smart contract is responsible for the registration of the members and storage of necessary data related to all transactions. The P2P smart contract is responsible to manage the local trading of the market and the P2G smart contract manages the prosumers to grid electricity transactions. To reduce the transmission losses, energy trading between nearest neighbors is preferred. The simulations are carried out to check the performance of the proposed system. The results depict that our objectives, cost and PAR reduction, are successfully achieved.

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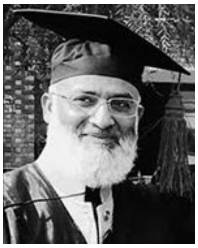

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