A blockchain-based decentralized energy management in a P2P trading system

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***Abstract*—Local energy generation and peer to peer (P2P) energy trading in the local market can reduce energy consumption cost, emission of harmful gases (as renewable energy sources (RESs) are used to generate energy at user's premises) and increase smart grid resilience. In this paper, to implement a hybrid P2P energy trading market, a blockchain-based solution is proposed. A blockchain-based system is fully decentralized and it allows the market members to interact with each other and trade energy without involving any 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 main smart contract which requests P2P smart contract and prosumer to grid (P2G) smart contract 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 (PAR) of electricity.**

I. Introduction

The evolution of the power grid has revolutionized the energy market, where new players have been introduced to control, generate and distribute energy in the market. RESs based distributed energy generation (DEG) has acquired popularity because of its environment-friendly method of energy generation. Declining cost of wind turbines and solar panels allows the growth of DEG in microgrids and smart homes. Moreover, smaller and cheaper sensors and new communication protocols and devices are paving the way for P2P communication between energy generators and consumers in a market [1]. This local energy market reduces the energy consumption cost. The amount of energy generated by RESs is highly affected by environmental factors e.g. speed of wind and amount of sunshine a solar panel and wind turbines receive in a particular period of time. This intermittent nature of RESs makes them unreliable and 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 [2]. Moreover, the energy exchange between two peers is controlled by a central entity that keeps track of all the transactions and 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. Although the participants of the local energy market still get more benefits as compared to energy trading with the smart grid (SG). The P2P energy coalition empowers the small scale energy prosumers and encourages them by incentivizing the local generation [3]. For the successful operation of P2P trading in the local market, improved and innovative solutions for trading are required. The solutions should be secure, smart and trustworthy.

Blockchain has emerged as a promising, user-friendly and efficient technology for the implementation of secure and reliable decentralized P2P energy trading market [4]. It enables transparent communication of the local energy market's participants and allows them to make decisions about energy coalitions in a decentralized trustless environment. Recently, it has gained the attention of several researchers and became the new hot topic in the smart grid domain. Blockchain is used to keep the energy coalition record regarding the amount of energy and its price and maintains a healthy environment for energy consumers and prosumers.

Christidis et al. [5] have explored the use of blockchain and 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. Ferreira et al. [6] proposed a system which enables to build an open energy market for a community of users. Blockchain is used to eliminate the requirement of a central control entity by keeping track of distributed energy transactions. The proposed system is used to create an energy trading market where the market participants have pre-defined goals. Kang et al. [7] proposed a blockchain-based P2P electricity trading model for plug-in hybrid electric vehicles. 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.

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. The main contributions of this paper are

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as follows:

- Monopoly of the main grid is eliminated by implementing blockchain-based hybrid P2P energy trading model.
- Self-enforcing smart contracts are designed to make efficient energy transactions between peers and the main grid possible.
- PAR and cost of electricity are reduced which benefit both utility grid and energy consumers.
- The energy exchange between peers is done based on the physical distance between them which reduces the possible power losses up to some extent.

The rest of the paper is organized as follows. Section II contains related work. In Section III problem statement is defined and Section IV contains the information about the system, its market participants and smart contracts. Simulation results are illustrated in Section V. In the end, the paper is concluded in Section VI.

II. Related work

A P2P electricity sharing system is proposed in [8]. It consists of two layers: a multi-agent system layer and 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 Java agent development environment is used.

A blockchain based access control system is proposed in [9] for users to share data securely and efficiently. In a blockchain, proof of work algorithm is commonly used for consensus between nodes. This algorithm is computationally expensive and wastes a lot of power. Owing to this, Proof of work algorithm is replaced with proof of authority algorithm and in this way, the computational overhead is reduced. Another blockchain based solution is proposed in [10] for secure communication. For data sharing, clouds are used in which cloud nodes are used to track the states of edge service providers. For consensus, proof of authority algorithm is used.

A P2P energy trading system for microgrids is proposed in [11]. 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 reduce the computational time and allow the microgrids to trade energy more frequently. 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.

In paper [12], 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 consumer. 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.

Jiani et al. [13] 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 [14]. 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 their behavior. The charging and discharging schedules are obtained by using the ice-burg algorithm. Simulations results depict the effectiveness of the proposed model.

Tianyang et al. [15] proposed an incentive-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.

In paper [16], 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. 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.

III. Problem statement and proposed solution

In this paper, our objectives are to reduce electricity consumption cost at consumers' level, minimize PAR at grid level (to make it more stable) and implementation of hybrid energy trading markets using blockchain. Esther et al. [17] proposed a decentralized local energy market using a private blockchain network. This market mechanism allows prosumers and consumers of electricity to trade electricity directly. This mechanism is based on a double auction with the closed book with discrete closing time. However, the effect of local trading on the utility grid is not contemplated. Claudia et al. [18] proposed a blockchain-based decentralized demand-side management system. This system is designed to reduce the peaks on the grid side and incentives are provided to motivate the consumers to take part in this program. A demand response signal is generated by the utility and the user adjusts its demand accordingly. However, the simulation results depict the load curtailment by electricity consumers instead of load shifting which greatly affects the lifestyle of users and this method is not convenient for them. Moreover, P2P trading is not contemplated which can be the possible solution for the load curtailment issue. Authors proposed a game theoretic based demand-side management system and P2P energy trading system using blockchain in [19]. Their objectives are to reduce peaks in demand and lower the energy consumption cost. However, energy trading price amongst prosumers and consumers is not synchronized and mechanism for P2G is also not defined.

In this paper, we propose a hybrid P2P energy trading market mechanism where both P2P and P2G energy transactions are implemented. In comparison to [18], [19], it is a decentralized market based on a double closed book auction. A smart homeowner can act as both energy consumer as well as prosumer and surplus energy can be sold and deficit energy can be purchased from neighbor prosumers or utility grid, unlike [18]. The P2P energy trading 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 [17]. 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 [18], [19]. 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.

IV. System model

In our work, a three-layered architecture of a blockchain-based energy trading market is proposed. Figure 1 shows these layers along with their respective components. In 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. It can act as both energy prosumer as well as energy consumer which depends on its current energy state. The state information of smart home is sent from smart meter to the virtual layer to participate in trading.

The second layer is the virtual layer, where the blockchain is implemented. 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 the transactions, 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 (DAaps) through which the user interacts with the smart contract and enters its information and keeps track of important data.

A. Blockchain smart contracts

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. Details of these contracts are given in the following subsections.

Algorithm 1 Main smart contract

```
Input request, requester
Check status of P2P and P2G contracts
Check market time
Check requester for authorization and its status
If requester is seller call P2P.seller() else call P2P.buyer()
If requester is seller call P2P.seller() else call P2P.buyer()
Check market time and call P2P.clearMarket()
If there is surplus/deficit energy call P2G.sell()/P2G.buy()
Get trading_result
Get billing information
```

1) Main smart contract: A main smart contract is developed to control all the operations of energy trading in the local energy market as shown in Algorithm 1. 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. 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 that if it is registered in the market or not. If a participant is registered then it proceeds to the next step. When an electricity prosumer sends the power surplus request, the main contract calls the seller function of the P2P smart contract and in case of a buyer, it calls buyer function.

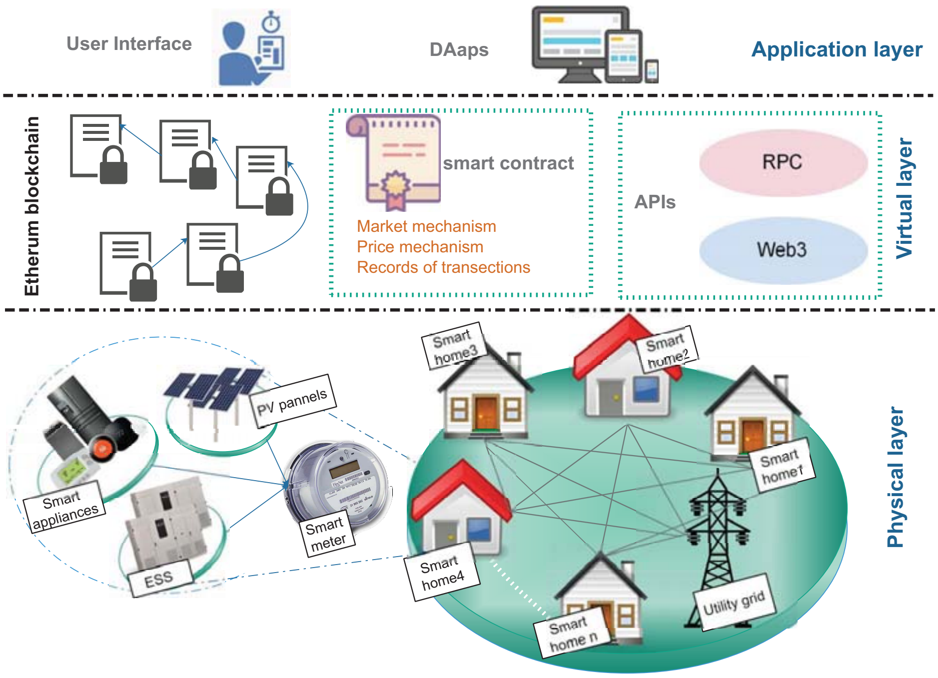

Fig. 1: Blockchain based energy trading market

As the energy market is closed auctioned market, so it checks the time and on reaching the marking clearance it calls the clear market 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.

Algorithm 2 P2P smart contract

```
Input request, requester, sllers, buyers
function seller() {
    Store seller in sellers and update price if it is lowest
}
function buyer() {
    Store buyer in buyers
}
function clearMarket() {
Trade energy and call matchBid()
}
function matchBid(){
Exchange energy between buyers and sellers
}
```

2) P2P smart contract: P2P smart contract (as shown in Algorithm 2) receives the necessary inputs from the main contract and information related to energy consumer or prosumer. 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 lower electricity prices, this price is set as the current electricity trading price for the market unless another seller proposes a lower price.

When the bidding time ends, the main contract calls a clear market function. 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. When trading between the same area is not possible (i.e., prosumers of that area don not have surplus energy) 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 match bid function is called to process requests. If a 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 transferring its energy and the power deficit status of the buyer is updated by current deficit power value.

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 prosumers also need connection with the main grid as shown in Algorithm 3. Market participants buy energy from the main grid when they are power deficit and prosumers sell the surplus energy after fulfilling their energy demand. 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

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)
}
```

buy the energy 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 as energy generation is more than its demand. The price of electricity is increased by 20 percent in case of on-peak hours as demand is very high at this time interval. These discounts and increased in electricity rates are used to motivate the consumers to take part in demand response program which plays an important role in stabilizing the main grid.

On clearing the market, if the prosumers have surplus energy then it is sold back to the main grid using the main smart contract. Sell energy 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.

V. Simulation Results

In this section, a local energy market 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. Three types of energy consumers are considered. The student and single energy consumers do not produce their energy and third type of consumers 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. The energy transactions are made using a blockchain-based hybrid P2P energy trading mechanism suggested in this paper. The load consumption and patterns of electricity consumers and prosumers are considered same as in [19].

Fig. 2: Comparison of PAR for conventional and P2P trading scenarios

The proposed model successfully reduces the PAR as shown in figure 2. 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 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 and users' are not always able to alter their energy consumption patterns to reduce their electricity bills. 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 a smart contract. 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 bidders choose the electricity selling price between the lowest and highest price limits set by main grid.

In Figure 3, the comparison of electricity consumption cost in both scenarios is presented. In the case of single consumers, the cost in the conventional grid scenario is equal to 459.1710 € and in the case of hybrid P2P it has reduced down to 394.8177 €. For the next group of consumers, 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

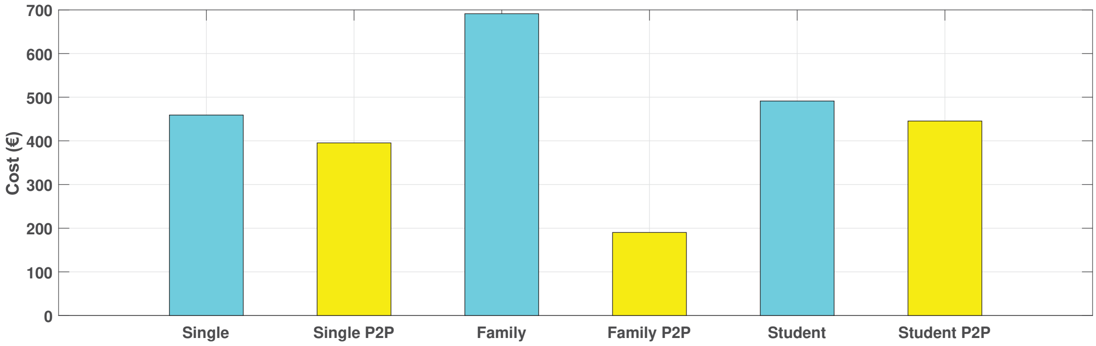

Fig. 3: Comparison of cost for conventional and P2P trading scenarios

highest cost reduction is of prosumers as they are not only producing electricity locally but also selling it in the market and making profit.

VI. Conclusion

A 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 without trusting any third party. Three smart contracts are designed to implement this local energy market. The main smart contract is responsible for the registration of the members and storing all the necessary data related to all transactions, P2P smart contract is responsible to manage the local trading of the market and the P2G smart contract manages the prosumer to grid electricity transactions. The simulations are carried out to check the performance of the proposed system. Simulation results depict that the objectives, cost and PAR reduction, are successfully achieved. In future, the proposed model will be compared with the existing closely related energy management models to check its effectiveness and significance. Moreover, the effect of energy exchange between adjacent regions will also be evaluated.

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