Blockchain based Decentralized Home Energy Management System using Double Auction

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***Abstract*—Due to increasing concern about climate change, the local energy market has been revolutionized with the increase in solar photovoltaic, electric vehicles, smart home appliances, and demand response. These technologies used in the residential sector provides new opportunities for Home Energy Management System (HEMS) to manage peak hours and gain incentives. In this paper, we develop a blockchain-based smart meter and HEMS that can collaboratively participate in energy consumption to maximize energy from renewable sources and reduce peak load. A fully decentralized blockchain-based system is used for trading energy using a double auction. Smart meters are enabled with a lightweight blockchain client that provides detailed information about energy consumption and controls the appliances from installed HEMS. Lightweight blockchain clients can be deployed on the smartphones of the owner of these smart meters. Regulations may prevent renewable electricity injection into the electricity grid. Hence, we investigate how to reduce energy consumption from the electricity grid. A test-bed is constructed and the simulations are done for two seasons: winter and summer. Different case studies and scenarios are carried out to show the proposed model's effectiveness. The results show that blockchain-based trading algorithms can impact individual users to manage energy consumption with high incentives.**

Key words - Blockchain, Home Energy Management System, double auction, energy trading, incentives, trading algorithm

I. INTRODUCTION

Due to the increasing usage of renewable energy, the local energy market has been revolutionized with the increase in the use of solar photovoltaic, electric vehicles, smart home appliances, and demand response. These technologies used in the residential sector provide new opportunities for an Energy Management System (EMS) [1] to manage peak hours and gain incentives without causing discomfort. The Energy Management System plays a significant role in maintaining the balance between demand and supply. Energy trading [2], [3] is a suitable method to balance demand and supply in EMS. Suppliers, also known as prosumers, provide surplus energy to the distribution network to satisfy the demand. Consumers and prosumers; both are rational and, therefore, try to maximize their revenues from incentive-based schemes. In a similar incentive-based trading mechanisms, energy price is a crucial component of Energy Management .

There are various incentive based approaches [4], [5] available in the literature, such as, game theory [6], auction [7] and negotiation. To model the trading mechanism, in this work, we are using double auction mechanism, which is able to maximize revenue for individual users in trading. The main contribution of this paper are as follows:

- A novel Home Energy Management System (HEMS) problem for a microgrid is presented, which is able to maximize the energy consumption from DERs and reduce peak load.
- A fully decentralized blockchain-based system is used for trading energy using double auction. Smart meters are enabled with a lightweight blockchain client that provides detailed information about energy consumption and controls the appliances from installed HEMS.
- The objective of the proposed trading algorithm is to optimize the energy demand according to real time prices. The trading algorithm is optimized using double auction mechanism.

The paper was organised as follows: We introduced pricing mechanism for decentralized HEMS using blockchain in section II with related literature. In section III, we discussed the double auction trading algorithm and blockchain architecture in section IV. The implementation, simulations and results were discussed in section V. Finally, in section VI, we presented conclusions and future work.

II. RELATED LITERATURE

A. Pricing mechanism

Pricing is a powerful mechanism to simulate prosumers and consumers to achieve high economic value. At the time of peak hours, electricity prices are high, users reschedule their load and the demand decreases. As the demand of microgrids keeps changing, electricity prices vary with time. In real-time pricing [8], the price keeps on varying with respect to energy demand and is suggested as one of the best approaches to improve the performance in the local energy market. Information regarding the change in price is timely informed to the users in the microgrid. Instead of flat-rate pricing, smart grids are now shifting towards market-driven pricing schemes where the kilowatt-hour cost changes with the day, time, weather conditions and demand. Since dynamic pricing is a concept that can be wisely used with respect to the ToU, it serves as a significant mechanism in demand-side

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management techniques. Another pricing scheme is the Time of Usage (ToU) tariff [9], which is based on energy demand for an extended time, like an hour, daytime and nighttime. Information regarding ToU is provided in advance to the users in the microgrid and stays constant for a more extended time.

B. Decentralized HEMS

Figure 1 illustrates the applications of customer based HEMS in smart appliances, demand flexibility, energy storage, and electric vehicles. Furthermore, HEMS also helps in managing peak demand, shifting the load to non-peak hours, and save energy. HEMS can be controlled using two main approaches: centralized and decentralized. The decentralized approach [10] objective is to achieve high social welfare while providing the best possible revenue to the users and Distributed Energy Resources (DERs). In the centralized approach, main grid or third party act as a controller to provide the relevant information, such as, energy demand, energy generation, forecasting information to the user in the microgrids in order to decide the price and energy according to the predefined preferences of the user [11]. In a microgrid having HEMS, which is the focus of this work, a high level of trust and transparency is required among the users and DERs, which makes decentralized approach the most suitable approach. Simply by expanding the DERs into centralized approach will not be effective for the distribution network. Some of the challenges of the centralized system are: (a) Lack of information from devices to optimize (b) Limited or delayed real time information (c) High transaction cost for settlement mechanism (d) No flexibility. Therefore, an improved, innovative, and decentralized solution is required. As a distributed ledger technology, blockchain provides such a solution. [12] proposes a decentralized energy management system problem for a distribution system with networked microgrids. The problem is solved using a stochastic decentralised bi-level algorithm that takes into consideration the intermittent outputs of DERs, the uncertain load consumption, and the coordinated operation points of all interdependent systems. [13] have explored a decentralised coordinated energy management approach for networked microgrids and future distribution system that is solved using the alternating direction method of multipliers (ADMM).

C. Blockchain

In recent years, Blockchain, the technology that nurtures the success of Bitcoin and many other cryptocurrencies, has emerged as research topic in the energy sector [14]. Blockchain is a database that stores information in blocks that are linked together. A new block is created for new data, and once the transactions are recorded in the block, it is linked in a chain with the previous block. This current block with transaction details chained into the blockchain is irreversible and is accessible to all the users in the network, making it a decentralized network. Blockchain eliminates the aggregator of the centralized network from the trading platform by keeping track of energy and price. All the transactions recorded are

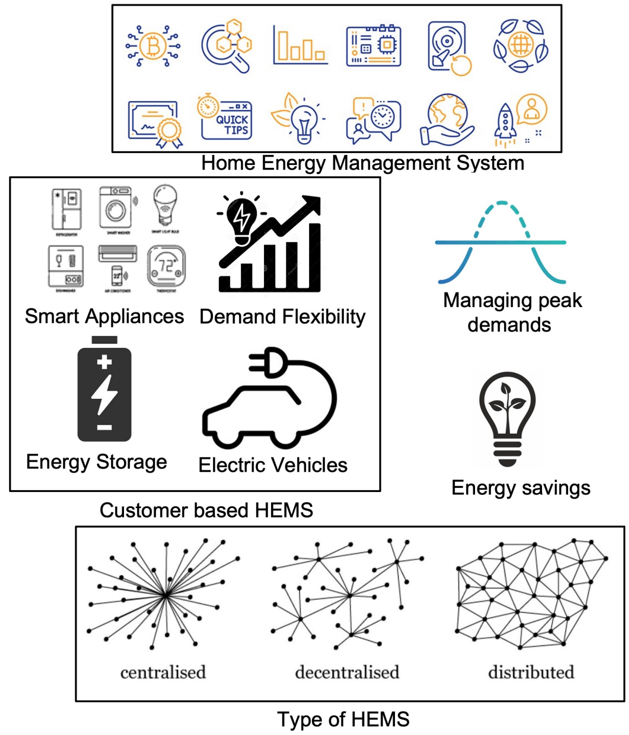

Fig. 1. Home Energy Management System.

transparent to all the nodes/users (consumers and prosumers) in the network [15]. This transparency allows consumers and prosumers to have a network where users in the network can settle transactions without having trust on each other. With a self-executing and self-enforcing program, also referred to as the ‘smart contract’, blockchain can facilitate and verify the transactions.

The smart contract is a set of self-executing transaction protocols which are intended to run with respect to the terms of nodes present in the network directly written into the codes. Smart contracts exists in a distributed, decentralized blockchain network. First, the validity of each user is checked by the smart contract. When a user sends a request to trade energy, the smart contract checks for the surplus and deficit energy of that user. When a prosumer sends a surplus energy request, the smart contract calls for the seller function. The seller function stores the prosumer data, such as, surplus energy, selling price, geographical location of the prosumer, and the lowest selling price available in the network. Similarly, when a consumer sends an energy demand request, the smart contract calls for the buyer function. The buyer function stores the consumer data, such as, deficit energy, buying price, geographical location of the consumer, and the highest buying price available in the network. When bidding ends the trading price/market clearing price is calculated using a clear market function. To further extend the scope and harness the potentials of microgrid with blockchain innovations in fostering the clean energy transition, challenges, approaches, and future directions are presented in [16] from the technical, social, and economic dimensions. [17] developed a cost analysis method for blockchain-based peer to peer energy trade systems by examining the tradeoffs between the cost of the blockchain network, the appropriate throughput required for the blockchain, and profit from a user low energy price provided to another prosumer.

III. Home Energy Management Model

A. Control levels of Microgrid

Microgrids are cluster of loads and DER coordinated and operated by a third party or the main grid. Grid connected and isolated/stand alone are two type of microgrids. Microgrids are controlled by three levels of hierarchical structure: Primary, Secondary and Tertiary are illustrated in Figure 2. Primary level includes output control stage that tracks voltage, current and power imbalances. Smart meters in primary level uses smart bi-directional power flow for providing information. Secondary level is HEMS controls the economical operation and management of DER. Tertiary level is responsible for the coordination between the third party/ community aggregator/ main grid and the user. The community aggregator is responsible for coordination between the residential users in the microgrid and providing data to the blockchain platform.

HEMS is used to control, monitor and schedule smart appliances, extract energy generated information, while meeting the customers requirement. HEMS receives data like energy demand, foretasted weather details, real time prices, ToU prices from the community aggregator. Smart appliances can be divided into critical loads and schedule loads. Loads like air conditioner can be shifted to non peak hours by changing the thermostat level. Other high demand loads like washing machine, dish washer are also considered as time shiftable loads.

B. Double auction based Trading Algorithm

In Double Sided Auction (DSA), multiple consumers and prosumers gets an opportunity to trade energy simultaneously at a single time interval. According the bidding price of both the players, DSA mechanism provides efficient market scenario. DSA market asks consumers to submit the bid price i.e., the maximum price they are willing to pay and prosumers to submit sell price i.e., the minimum price they want to receive for selling surplus energy. The auctioneer(aggregator) collects the data from both the players, sorts the price and pairs consumer's bid price to prosumers selling price. It allows single consumer to buy energy from multiple prosumers to complete its demand and similarly, single prosumers can sell the surplus energy to multiple consumers in the network. Here all the users are in equilibrium, which is the state in which all the users find their required optimal energy while meeting all the user preferences. Once all the users are in equilibrium state, no user can further improve its utility by deviating from its current position. Nash Equilibrium is a state where no user can improve the revenue by changing its current positions, with respect to other users. In this section, a trading algorithm is proposed, that allows users to trade energy from

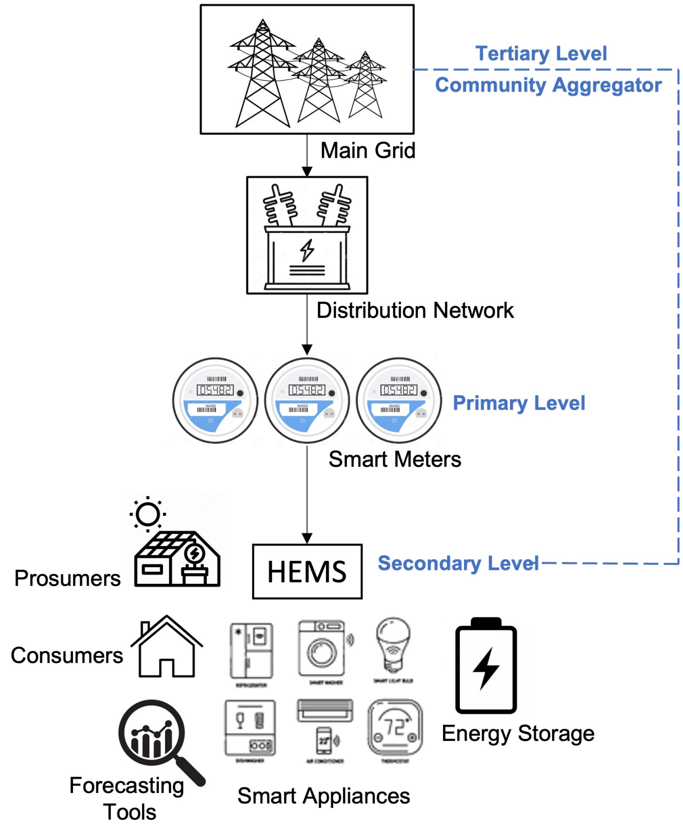

Fig. 2. Control levels of a microgrid.

each other using double auction mechanism. At each time interval (iteration), a user (U) chooses its best strategy to fulfill its energy demand and sell the surplus energy.

This trading algorithm presented in Algorithm 1 will run for two cases: Summer and Winter. Smart meters connected with blockchain network will send information regarding energy demand, surplus energy, and price to the community aggregator. The collaboration algorithm of DSA and blockchain will run as follows:

Step 1: Smart meter connected with the blockchain network will send the information regarding energy generated, surplus energy available to trade, and energy demand.

Step 2: Community aggregator will announce real time energy prices, energy load status on the grid or any other incentive that can help to low or high the load on electricity grid.

Step 3: The aim of the community aggregator is to maximize the use of solar rooftop generation to complete energy demand and minimize the energy imported from the main grid. Community aggregator will commit such incentives (including price of electricity) using the offline channel network.

Step 4: End users may update their energy use preference to the HEMS. The user have an option to take energy from the grid, or to trade from other users, or be a part of demand response.

Step 5: The HEMS will collaborate as optimal electricity consumption plans will be generated via computation offloading to edge servers. HEMS will match and make pairs to trade energy within users.

Step 6: Data from smart meters will be used to validate end user compliance with planned energy consumption.

Step 7: Finally offline channel network will be used to share the incentives among the end users(such fund or token may be kept on the home energy device or smartphone of the user).

Algorithm 1: HEMS algorithm

```
For T=5 minutes
Initialization: Energy demand and energy generated, Input
buying price and selling price
Check status of consumers and prosumers
function peak hours () {
        Announce real time energy price for peak  hours
for grid and Trade }
function non-peak hours () {
        Announce real time energy price for non-peak
hours for Grid and Trade }
function clear market () {
        HEMS does matching and call calculated users to
distribute energy }
function match bid () {
        Exchange energy with paired user }
Function sell energy () {
        Calculate Trading price
        Send price to blockchain }
Calculate incentives
Send incentives to the blockchain network
    End procedure
```

Fig. 3. HEMS using double auction algorithm.

IV. Blockchain Architecture

We will use Blockchains and decentralised data storage to execute the auction-based energy trade. We will use a permissioned blockchain with prosumers, Distribution System Operator (DSO), utility companies, and miners as the participants. We will use Inter-planetary File Systems (IPFS) as a decentralised data store. Figure 4 shows the overview of the proposed decentralised method:

1) The regulator (for example DSO) will store Hashes of a set of keys in the blockchain by creating a transaction with these hashes in the data field of the transaction.
2) The HEMS will ask the DSO for encryption keys (symmetric encryption).
3) DSO will verify the identify of the HEMS (possibly by its public key) and send a set of keys (hashes of these keys are kept a transaction in the blockchain).
4) HEMS will send information regarding bids/ asking price and amount of energy to be traded to the auctioneer. It will also send the Hash of a key which will be used to encrypt energy consumption data by the HEMS.
5) The Auctioneer will announce the outcome of the auction and HEMS.

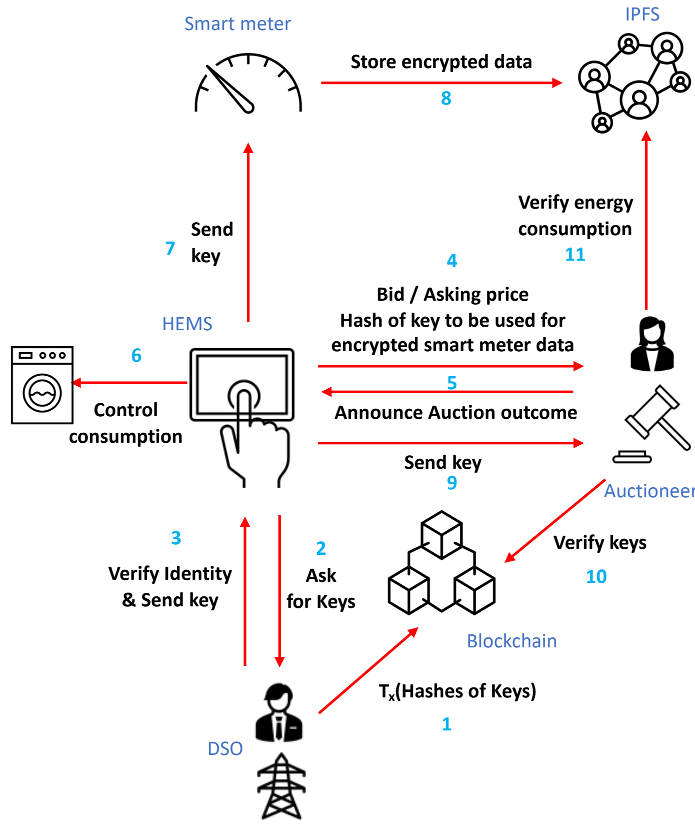

Fig. 4. Blockchain architecture.

6) HEMS will control its energy consumption according to the outcome of the auction.
7) After the energy consumption the HEMS will send the key (which it got from the DSO and reported Hash of it to the auctioneer) to encrypt smart meter data.
8) Smart meter will store will use this key to encrypt electricity meter reading and store it to the IPFS. It will get the ID of this information from IPFS and inform the ID to HEMS.
9) HEMS will send this ID and key used to encrypt the meter reading to the auction.
10) Auctioneer will verify the validity of the key by searching transactions created by the DSO.
11) Auctioneer will verify compliance with outcome of auction by decryption of the smart meter reading in the IPFS.

V. Simulations Results and Discussions

In this section, a microgrid is considered and simulated. To demonstrate this proposed trading algorithm, let us consider a microgrid consisting of N = 100 users, where 25 users have solar rooftop and 75 users are customers over a period of 288 time slots of 5 minute intervals. The trading simulations has been modeled and solved using MATLAB 2022. The energy transactions are blockchain based double auction mechanism proposed in this paper. The designed blockchain based HEMS

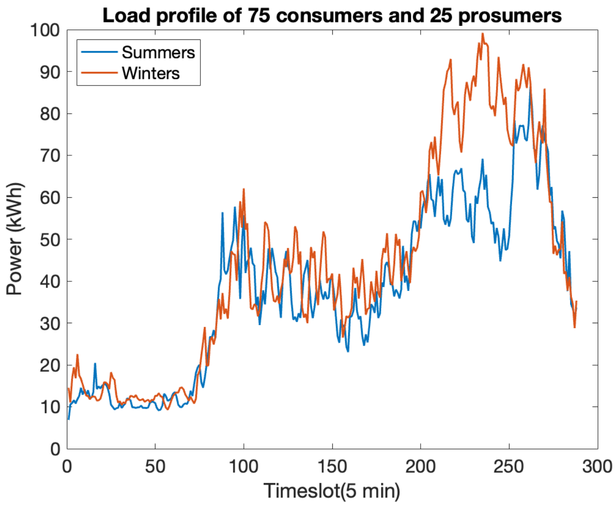

Fig. 5. Load profile for summer and winter for a microgrid with 75 consumers and 25 consumers.

for a microgrid is tested on low voltage network data having summer and winter load analysis and generation. For this simulation, an update time interval is chosen as 5 minutes, which is suitable with the intermittent nature of renewable sources and can collect fluctuations as well. Therefore, every 5 minutes the HEMS action is triggered by blockchain, and trading algorithm is solved according to the real time prices and the preferences of the users. Using 5 minutes time intervals, the entire horizon results in 288 time slots and incentives are distributed for each slots using blockchain. In this paper, data for 24 hours is used for summer and winters for the HEMS problem. Thus, smart meters captures energy generated and demand of the user and provide real time prices for trading.

The load profile of microgrid in summer and winter is shown in Figure 4. We can see that the peak hours are mostly during the night time. The peak load can be shifted to the non-peak hours either by shutting down schedule loads or shifting the loads to non-peak hours according to the real time prices. The Real time prices of Ireland is shown in Table 1 below. The electricity cost for day and night in winter and summer are shown in Table 1.

TABLE I
REAL TIME PRICES FOR SUMMER AND WINTER

	Summer	Winter
Day price	€0.18/unit	€0.2255/unit
Night price	€0.0924/unit	€0.1113/unit

For comparison purposes, the trading energy algorithm is run for two cases: summer and winter. In summer analysis, the solar generation is high and energy demand is fulfilled by energy generated by solar rooftop. However, during winter, energy demand is high, and solar rooftop is not able to fulfill the energy demand of the microgrid. Figure 5 and 6 show the trading price for both the scenarios. The ToU tariff for peak hours as shown in Figure 3 lies between 0.16€ to 0.2€ and

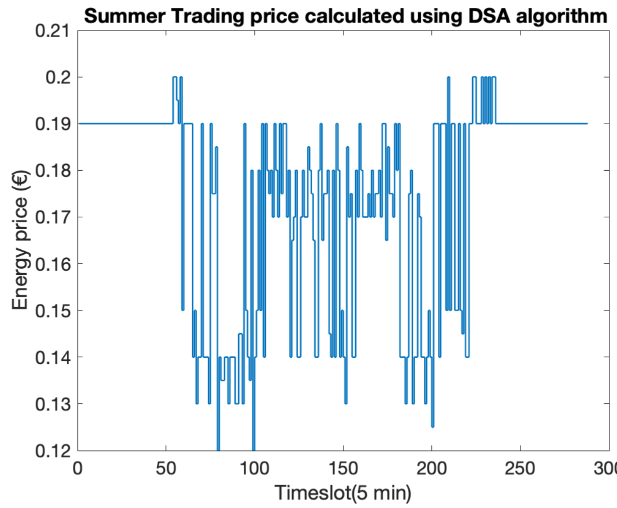

Fig. 6. Trading price in summer.

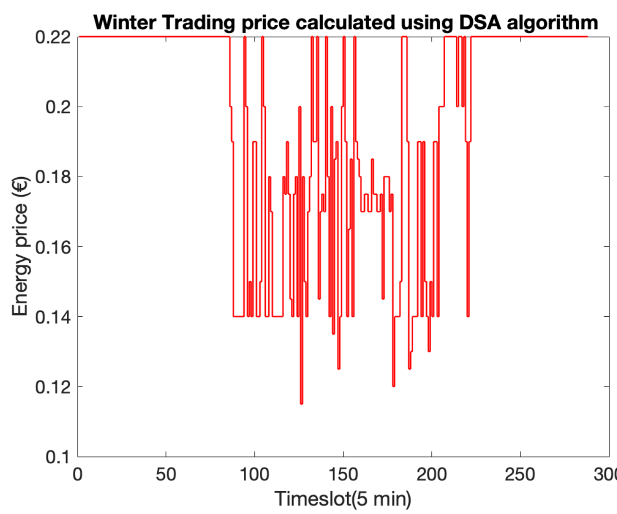

Fig. 7. Trading price in winter.

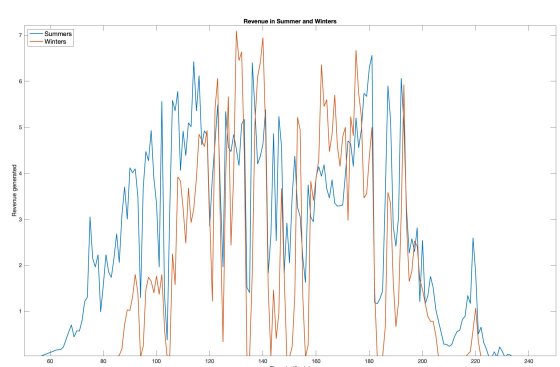

Fig. 8. Incentives distributed by blockchain.

for no-peak hours it lies between 0.09€ to 0.15€. The trading price is calculated as the average price of the asking price and selling price of the pair selected for trading. In Figure 7, the comparison of incentive generated in both, summer and winter scenario is presented. In the day time, the sum of incentive generated in summer is higher than in winters. The average revenue generated by the microgrid is 1175 Euros in 24 hours.

The total simulation time of this trading algorithm is 76 sec for 288 iterations of the HEMS, thus yielding an average computational time of 0.26 sec per iteration, making it suitable for real time price and smart appliances.

VI. Conclusions

This work has shown the modelling of integrated blockchain based on HEMS where users are able to trade energy, save their electricity bill, generate revenue, and shift from peak hours to non-peak hours. Type of pricing mechanism and importance of decentralized HEMS are introduced in this study. Microgrids are controlled by three levels of hierarchical structure: Primary, Secondary and Tertiary. HEMS is used to control, monitor and schedule smart appliances, extract energy generated information, while meeting the customers requirement. A trading algorithm is proposed in this work, that allows users to trade energy from each other using double auction mechanism. We used Blockchain and decentralised data storage to execute the auction-based energy trade. A test-bed is constructed with 100 users, with 25 houses with 3kWp rooftop PV. The simulations are done for two seasons: winter and summer. Different case studies and scenarios are carried out to show the proposed model's effectiveness. The results show that blockchain-based trading algorithms can impact individual users to manage energy consumption with high incentives. In future, we will provide a detailed formal security analysis of the blockchain-architecture of the energy trade. Moreover, the proposed work will be compared with other HEMS available to check its effectiveness.

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