Blockchain-Based Energy Trading in Electric-Vehicle-Enabled Microgrids

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***Abstract*—This article presents a blockchain-based scheme for energy trading between electric vehicles (prosumers) and critical load (consumer) in a logical network. Unlike traditional wholesale energy markets where retailers sell energy to consumers, our proposed model directly connects prosumers with consumers to meet temporary energy demands. We exploit blockchain technology to establish a trusted energy trading ecosystem and develop an application to remotely monitor energy trading activities between trading entities. Experimental results illustrate that the energy trading system is effective in finding, associating, and routing prosumers to consumers, while protecting privacy of entities. Numerical results show a favorable performance of our optimization model in comparison to traditional frameworks.**

Domestic energy production in the UK is not sufficient to address peak demands, with 7.2% of electricity supplied from net imports in the second quarter of 2019.[1] With the rising penetration of electric vehicles (EVs), domestic energy production will struggle to satisfy the ever-increasing energy demand. Vehicle-to-grid (V2G) offers a promising alternative to address demand–supply mismatch.[2] Additionally, EVs can also be deployed to meet the temporary demands of critical loads such as pop-up hospitals built during the Covid-19 pandemic, which may not be met by regular supply.[3] A major challenge is the wholesale

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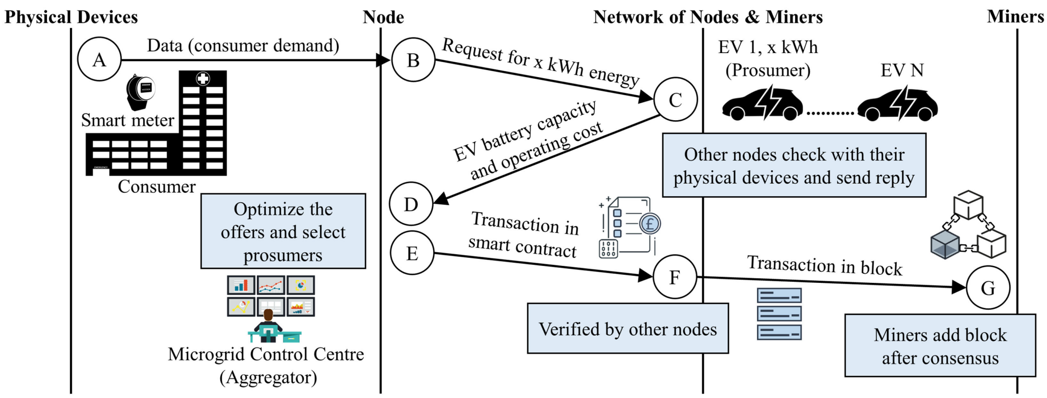

Figure 1. Interactions between various stakeholders in the P2P energy trading network.

energy distribution in traditional energy markets, where energy is sold to consumers by retailers. These retailers own a tiny percentage of the grid infrastructure and only manage services such as usage metering and billing. Supplementing retailers and connecting trading entities directly unlocks a more efficient and competitive energy market. However, this transition would need a robust platform that enables increased distributed influence and provides a trusted environment for energy trading.

Blockchain is an emerging technology in which the aforementioned platform could be based.[4] First developed as the backbone technology behind Bitcoin,[5] it has since grown to become a multipurpose technology for a variety of applications, including peer-to-peer (P2P) energy trading. Blockchain-enabled programs can create a trusted environment for trade between different entities.[6] For example, consortium Blockchain has been exploited in the article by Kang *et al.*[7] to achieve trusted energy trading between EVs. A blockchain-based scheme for demand response management is proposed in the article by Jindal *et al.*,[8] to facilitate energy trading between a static entity and EVs.

In this article, we propose a blockchain-enabled architecture to facilitate energy trading between EVs (prosumers) and critical load (consumer) in a microgrid. We then develop an energy trading prototype, based on the electric vehicle as a service (EVaaS) framework in the article by Umoren and Shakir,[3] to remotely monitor energy trading activities between trading entities, using graphical user interface (GUI).

EVAAS ENERGY TRADING SYSTEM

In this section, we will describe our proposed blockchain-based energy trading system and clarify some myths on the use of blockchain in this area. We present the blockchain architecture as it applies to our proposed system. A more detailed study on blockchain and its various applications can be found in the literature.[9,10]

Blockchain-Based Energy Trading Platform

Blockchain is an immutable distributed database made of blocks where each block is made of transactions and the hash of previous block. In the energy trading prototype, the transactions are the amount of transferred energy and the price paid for it. Each transaction will be broadcasted, and then added to the block after being validated. This way, the participants are not able to double-spend their money or double-sell their energy. The block will be added to the blockchain after a consensus among the miners. Miners are normally powerful computers hosted by the stake holders. Blockchains can be public, private, or hybrid. In this article, we propose a private blockchain-based energy trading platform. In Figure 1, we present the players in this platform and the data/message exchange among them. In addition to physical devices like smart meters that provide information about the energy level and raw data, our proposed platform has three types of blockchain nodes.

Light Nodes Blockchain nodes that have limited storage and processing power are called light nodes. In our model, EVs are examples of light nodes. These nodes can initiate transactions, but due to their limited data storage they cannot store the whole blockchain, and therefore, they are not able to verify transactions. Moreover, light nodes, are not able to add blocks to blockchain because this task requires complex and energy hungry computations.

Full Nodes The nodes that have sufficient storage to store the entire blockchain are called full nodes. In our model, smart homes with high-capacity data drives connected to the network or microgrid control centre (MGCC) are examples of full nodes. These nodes can initiate transactions and verify other transactions. We assume the MGCC is a full node in our proposed platform, thus, taking up the responsibility of verifying transactions.

Miners/Validators In *public Blockchains* adding blocks to a Blockchain will be done by nodes that are called miners. Miners do not need to store the entire Blockchain. However, miners with high volume of data storage can store the entire Blockchain and become full nodes too. Similarly, full nodes with high computational power can act as miners too. In *private Blockchains* like our proposed platform, proof of work algorithms are not used and, therefore, miners become validators. These validators run algorithms like Practical Byzantine Fault Tolerance or Federated Byzantine Agreement, which require much less processing power. In our platform, MGCCs are the validators and responsible for adding blocks.

Peer-to-Peer Network

Blockchain works on a P2P network basis; however, it is a logical network and it does not mean that the nodes need to have direct physical connection links with each other. Moreover, it is considered that the transaction is P2P without intervention of any central body. However, the transaction must be verified by other peers to be inserted in a block and the block will be added to Blockchain. Thus, there are more entities active in this procedure than the two parties at sides of the transaction. It must be noted that Blockchain service is not free and the miners/validators will be paid for the service they provide. Therefore, each transaction that is made has a cost for consumer and prosumer. This is the reason that the common myth on eliminating the middle man makes the transaction *free of charge* is not true.

Energy Trading Mechanism

For simplicity, we choose a centralized optimization mechanism, which is performed by an entity called aggregator. Based on the mathematical framework in the article by Umoren and Shakir,[3] the aggregator tries to associate optimum prosumers with consumer such that minimal operating costs are realized, while satisfying consumer energy demand and charging station constraints. The operating cost here is the sum of the energy, transportation, and (Blockchain) transaction costs. The transaction cost is fixed depending on the reward that is paid to full nodes for verifying the transactions and miners for adding a block to the chain. A detailed formulation of the optimization mechanism can be found in the article by Umoren and Shakir.[3]

EVAAS ENERGY TRADING PROTOTYPE

Prototype Development

EVaaS energy trading prototype is an application that makes use of GUI for remote monitoring of energy trading activities between prosumers and consumers. It is designed according to the energy trading mechanism introduced in the "EVAAS Energy Trading System" section. A variety of tools have been selected for the prototype development, which is influenced by various factors such as target operation system platform, integrated development environment (IDE), programming language, and required functionalities.[11] Android Studio SDK, Java, and Firebase were the selected IDE, programming language, and database, respectively. We have used several application programming interfaces (APIs) in the prototype development including Google Maps, Google Directions, Google Places Autocomplete, and GeoFire.

Energy Trading Process

Mode Selection Key players remotely access the application server to select between consumer and prosumer modes. Consumers will be able to specify energy demand and location, while prosumers will be able to set their available energy, operating costs, and location. Firebase authentication services are utilized to create new user account and authenticate existing user accounts.

Peer-Discovery and Optimization Consumers initiate energy trade request. The aggregator discovers the identities and information about energy availability of prosumers within proximity. The varied energy and transportation costs from prosumers are optimized. The optimum prosumers are selected and presented to the consumer for confirmation. Conditions for energy trade, which includes amount of energy to be transferred and price to be paid, are entered and after simple preprocessing (availability of the funds in consumer's account and energy in prosumer's battery), a transaction will be generated. The transaction will then be sent to the private blockchain and will be processed as explained before.

Energy Transfer and Payment Once an agreement has been reached between prosumers and consumers, the agreed price will be locked on the consumer's account. After the agreed amount of energy has been transferred in accordance with the transaction, prosumer receives payment in cryptocurrency. Being a private Blockchain, our proposed framework does not introduce a new cryptocurrency, and is flexible in using any cyrptocurrency like Ether (ETH) with the market value. The process is recorded to the Blockchain and it is validated across the network. Throughout the process, random pseudonyms are assigned to prosumers and consumers to preserve privacy. The barter of energy is achieved without leaking any personal information about the entities.

Optimization Algorithm

We present a greedy algorithm (GA) that is designed to solve the optimization problem. The strategy here is to select the prosumers with minimal operating cost. A detailed explanation of the optimization algorithm is provided in the article by Umoren and Shakir.[3]

We introduce two optimization schemes, which will be used later to study the performance of our proposed algorithm. In the first, the aggregator sorts the costs in a nondescending order

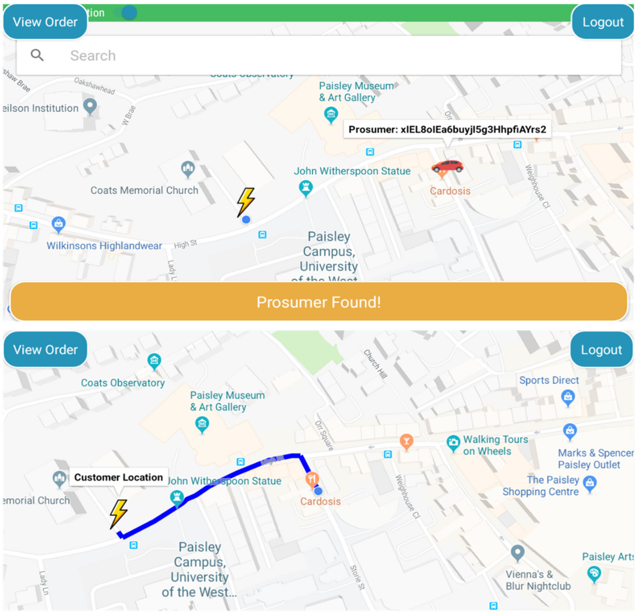

Figure 2. Consumer (top) and prosumer (bottom) activity pages based on the real map of Paisley.

and associates prosumers using knapsack algorithm (KPA).[12] In the second, the aggregator sorts the distances between consumer and prosumers in the nondescending order and associates prosumers that are closer to the consumer using a first-come first-served (FCFS) scheme.

Prototype Verification and Evaluation

The prototype depends heavily on leveraging the database to provide users with a real-time environment required for energy trade. When requesting for energy, consumers can either use their current location or the search text box, which returns place predictions as user's type. As soon as prosumers log into the system, their location and available energy are sent and stored in the database. The prototype uses information of the consumer and available (logged in) prosumers to run the optimization. It is to be noted that the application database is different from the Blockchain. This database is kept at the aggregator and prosumers or consumers do not have access to it. Figure 2 presents the consumer and prosumer activity pages for the prototype based on a real map of Paisley. From the consumer activity page, location of associated prosumers can be monitored on the map and prosumers are assigned random pseudonyms to protect their

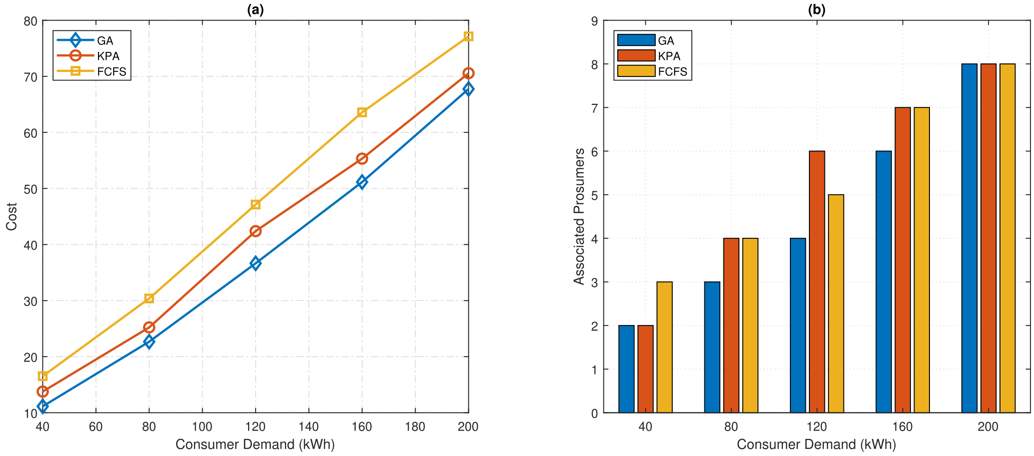

Figure 3. Costs and associated prosumers for consumer demand in different scenarios.

privacy. Similarly, from the prosumer activity page, the best route to the consumer is displayed to prosumers. Once the agreed amount of energy has been transferred, the prosumer receives payment as discussed earlier. When prosumers logout of the application, their information is removed from the database.

Java MessageDigest has been used to generate a unique hash for blocks by providing details (list of transactions and time stamp) of the previous block. These values are used to generate a hash for that block, so any changes in any of these fields will alter the hash of the block. This validates the blocks in blockchain and prevents records tampering. These blocks are then added to the blockchain. Users can download the updated blockchain on their devices.

Numerical Results

We consider a microgrid that consists of 20 prosumers and a consumer distributed within a 4 km $\times$ 4 km area. Energy demand between 40 and 200 kWh is uniformly allocated to the consumer, while energy capacity between 15 and 38 kWh is randomly assigned to prosumers. Energy and transportation tariffs between 0.08 and 0.46 cryptocurrency/kWh and 0.12 and 0.25 cryptocurrency/km, respectively, are randomly assigned to prosumers. We have assumed energy and transportation tariffs for simulation purposes. We have also assumed the transaction cost to be fixed; hence, it is negligible in the optimization model. Considering prosumer and consumer data, the parameters for prosumer-consumer association are calculated and passed to the optimisation algorithms to find the best association between consumer and prosumers.

We compare the performance of our optimization algorithm with the traditional mechanisms introduced earlier. Based on the algorithms, association has been derived for different consumer demand. We considered different scenarios for energy trading, and for each scenario, the abovementioned parameters are used to compute the total operating cost. The numerical results in Figure 3 show that our algorithm (GA) outperforms KPA and FCFS scheme. Figure 3(a) shows the operating cost of associated prosumers for different consumer demand, while Figure 3(b) shows the number of prosumers associated by the different algorithms. As the energy demand of the consumer increases, so does the number of associated prosumers. However, GA associates fewer prosumers than FCFS scheme and KPA in all scenarios, thus, achieving better battery capacity utilization of prosumers. The GA produces a 19% and 32% reduction in operating costs for a consumer demand of 40 kWh compared to KPA and FCFS scheme, respectively, as shown in Figure 3(a). Similarly, GA reduces operating costs by 14% and 22% for a consumer demand of 120 kWh compared to KPA and FCFS scheme, respectively. Prosumer–consumer association by GA reduces the cost in every scenario by at least 4%. Overall, we can observe that our optimization algorithm achieves reduced operating costs and better system efficiency.

CONCLUSION

This article has presented an energy trading system where prosumers and consumers trade energy with respect to demand–supply mismatch. Blockchain technology has been exploited to establish a trusted environment for energy trading and develop a prototype that associates prosumers with consumers directly. Experimental results based on a real map demonstrate the effectiveness of the trusted energy trading prototype, and numerical results show that our trading scheme achieves lower energy costs and better battery capacity utilization of prosumers.

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