A Blockchain-Powered Energy Monitoring System

A. Swain, K. P. Swain, G. Palai, and M. N. Mohanty

1 Introduction

Smart grid technology is emerging at a rapid pace by leveraging various IoT technologies that increase the efficiency and accuracy of the systems as well as reduce the requirement of manpower. It adopts intelligent systems for energy production and consumption that can monitor and communicate with each other. For efficient utilization of energy, an energy monitoring system is used, in which a system of computer-aided tools is providing real-time digitally maintained energy records used by operators of utility grids to monitor, control, and optimize the performance of the generation and transmission system [1]. It provides real-time metering, utility bill tracking, energy audits, and carbon and sustainability reporting, in order to analyze the trend in energy consumption and identify cost-saving opportunities. Due to the increasing demand for energy consumption, it is necessary to come up with energy systems that can manage individual energy transactions between the consumers and the utility provider without any loss of information. To make information available instantly and securely to authorized users, these energy records can be shared through Energy Internet that integrates power technology, electronic technology, information technology, and intelligent

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management technology to achieve energy exchange more efficiently and cleanly with the least wastage.

However, there are many issues associated with the current system of energy monitoring and billing, of which some major ones are centralized control, tampering of data, the involvement of intermediaries, high transaction costs, privacy issues, consumer issues, the manual intervention of billing process, overdue bill payment, power theft, and lack of interoperability. The involvement of several processes, intermediaries, and third parties, such as banks, regulators, price reporters, exchanges, and logistics in typical energy commodity transactions, leads to an increase in operational and transactional cost, which sometimes paves way for erroneous transactions, intentionally or otherwise. Due to a centralized control, the entire process is controlled by one central entity, and thus, in case of data tampering or loss of data due to lack of security, the data cannot be retrieved, since there is only a single copy of the records.

With the emergence of modern power systems and new age technologies, the traditional energy markets are transforming into advanced markets that are adopting various mechanisms and business models to curb the issues associated with centralized systems and encourage distributed clean energy trading. At present, blockchain technology is emerging in various fields, including financial services, health care, cybersecurity, supply chain management, banking, etc., and it is growing at a rapid rate with each passing day. It has been a major area of research as it provides numerous benefits that can help overcome the challenges faced by centralized systems. Its application in the energy sector has increased over the recent years due to its distributed ledger technology and decentralized control over energy systems. The main advantage of blockchain-based energy systems is that it eliminates the involvement of intermediaries and third parties, such as banks, regulators, exchanges, logistics, price reporters, etc., that can lead to high transactional costs and delay in payment settlements. Due to the absence of central authority, the faster and cheaper transaction is achieved in the blockchain. Along with that, the personal information and identity of blockchain users are also protected, as these are not linked to the transactions.

1.1 Blockchain Technology

Blockchain is a highly secure and immutable distributed ledger system that holds transactional records in the form of blocks, as shown in Fig. 1. These blocks are created with every transaction and are verified and validated by network engineers before adding them to the existing ledger. They are linked to each other using cryptography, that is, a reference to the previous block's hash is present in the current block, which is time-stamped with a unique cryptographic hash [2]. Blockchain is also known as a consensually shared database that stores transactional records on the Internet, thus cutting the costs of buying servers. It provides a high level of transparency and security by providing a copy of the ledger to all the

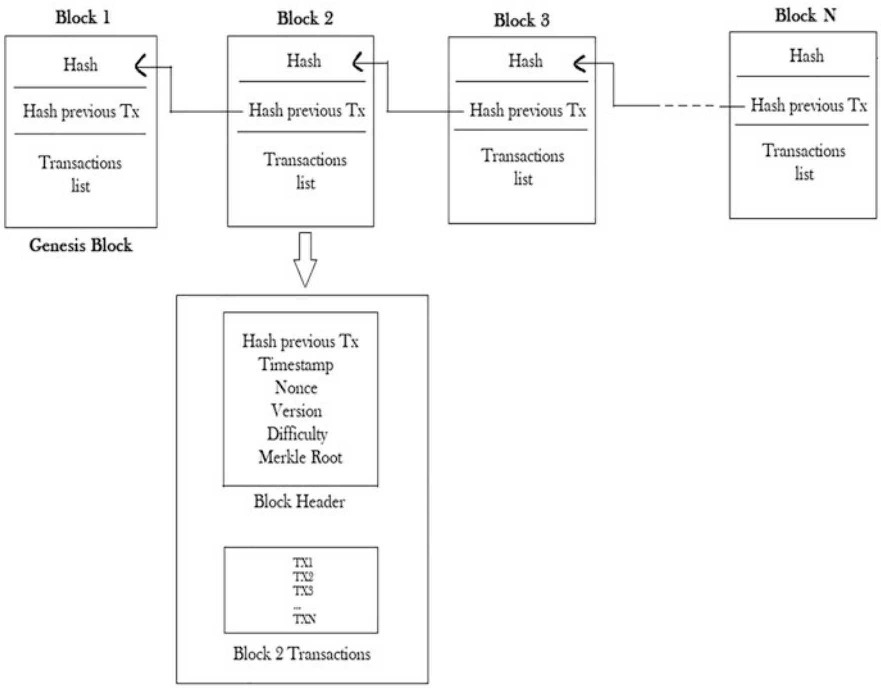

Fig. 1 Structure of a blockchain

nodes and achieving consensus among participating computers within a peer-to-peer network. Each participating node, also known as "miner," validates the transaction using certain mathematical calculations that are based on predefined rules. A block is considered verified when a consensus is achieved among at least 51% of network participants. This consensus protocol establishes system reliability and trust between unknown peers in a distributed computing environment. Therefore, in case of any malicious activity, that is, if someone tries to tamper the data in one node, the alternate transaction copies in other nodes will identify the invalid ledger and discard it and provide that node with a new copy of the ledger. Hence, the public distributed ledger is regularly updated at the same time in all the participating nodes in a blockchain network.

In Fig. 1, the "nonce" represents the resulting number that the miners are required to obtain by solving the consensus algorithm, and the term "difficulty" is the measure of the difficulty level for mining a particular block that represents the amount of computational power required to validate the block. This will make the network more secure against malicious attacks. The Merkle root is the hash of all the hashes of the transactions present in a particular block.

In a blockchain, each block is wrapped with a 256-bit hashing algorithm-based encryption, which is very difficult to decipher. Even if a particular block is altered, it will lead to an invalid ledger that will automatically get discarded, since modifying a single block will also modify the hash of that block and all subsequent blocks. Thus, it requires a huge amount of computing power to decrypt the blocks in a blockchain.

Blockchain is of three types – private blockchain, public blockchain, and consortium blockchain. The private blockchain is a permissible blockchain, in which transactions are private and are only available to authorized participants who are given access to join the network. They behave the same as centralized systems. Hyperledger is an example of a private blockchain. A public blockchain is a decentralized blockchain, also known as a distributed ledger system, which ensures a high level of transparency by providing a replica of the ledger to each blockchain node and perform verification and validation of data by a consensus mechanism. Examples of public blockchain are Bitcoin and Ethereum. Consortium blockchain behaves like a combination of both public and private blockchain as they provide only a set of pre-authorized nodes with high computational capabilities to allow them to access the ledger of transactional records and solve the proof-of-work consensus algorithm. This blockchain can enable faster transactions by reducing the overall power consumption. Corda, Quorum, and Hyperledger are few examples of consortium blockchain.

1.2 Ethereum

Ethereum is the first decentralized, open-source, public blockchain-based platform that supports smart contract [3]. It was released in 2015 by Vitalik Buterin, a cryptocurrency researcher. It enables smart contracts and distributed applications or DApps to be built and deployed on top of it, without any third-party interference. Smart contracts, which form the core of blockchain applications, are computer codes consisting of some predefined instructions that are implemented only upon meeting a particular set of conditions or certain specified actions. They are immutable, that is, once a smart contract is executed on a blockchain, its code cannot be updated like a normal application [4]. It uses Ether cryptocurrency for trading and running smart contracts for DApps. It assigns a cost called "gas" (unit – Gwei) for every execution of the task, which is a much smaller unit of Ether (1 ETH $= 10^{-9}$ Gwei), in order to drive the competition for transactions to be added successfully to the blockchain. The price of the cryptocurrency can also be predicted by LSTM (Long Short-Term Memory) algorithm of machine learning technology [5].

The Ethash algorithm-based encryption, which is a cryptographic hash function, is used to encrypt blocks in the Ethereum blockchain. It takes input data and yields an alphanumeric output of 64 characters or 256 bits. Every user in a blockchain network has two cryptographic keys to secure identities and to encrypt and decrypt the data – a public-key, which is like an email address of the user, and a private key, which is like a password or passkey used to sign the transactions and is always kept undisclosed with the user. In the blockchain, when the transactions contained in a transaction pool are considered verified and validated, a new block is added to the existing blockchain and the miner who solves the proof-of-work (PoW) consensus algorithm gets the reward in the form of Ethers coins for mining the block.

The rest of the chapter is organized as follows. Section 2 summarizes the related literature review. Section 3 describes the structure of the proposed work. Sections 4 and 5 shows the implementation and analysis of the proposed model. Finally, Sect. 6 concludes the work.

2 Literature Review

In the smart grid domain, blockchain technology delivers excellent features like distributed ledger facilities, smart contracts, compromise mechanisms for a secure transaction. The advent of blockchain expertise in the energy segment is the key market transformation that is implemented in [6, 7]. In these, the application of blockchain technology in the energy sector is discoursed by comparing it with the existing technology in South Africa and Russia. The references [8–11] highlight the employment of Bitcoin in the distributed energy system such as energy operating conditions, monitoring, sharing, trading, etc.

A systematic review on Blockchain technology over the energy sector is thoroughly discussed [12] by considering over 140 research articles and startups related to the same. In this, it is found that blockchain technology is one of the promising technologies that can be implemented in the energy sector as it exhibits a tamper-proof, secure, and transparent system that leads to a novel business solution. It also focuses on the challenges and market barriers of the technology while implementing it in the real world. Another review is proposed in the reference [13] where the integration of blockchain technology is discussed in the energy sector by considering the related works of literature from 2014 to 2020 available in the Scopus database. In this assessment, the authors have pointed out the rapid progress of the technology in the energy sector especially in the fossil energy sector where blockchain technology can solve the bottleneck problem of existing technology. The use of cryptocurrency in the energy sector is realized [14] with some proof of works using a technical example. The reference [15] highlights some possibilities of blockchain technology in the electricity market with a review of all prospects and threats. Primarily, this work focuses on the decentralized energy sector with all sustainable configurations by using Bitcoin.

A trusted communication between the electric grid and the consumer is projected in reference [16] where the billing system is implemented via smart contact through blockchain technology. It also proposes a mathematical model to schedule the use of electric appliances for the optimum uses; according to the price, distributed energy system, and smart contract to monitor the trading of the electricity transaction system. A flexible, decentralized smart grid system is proposed in reference [17] using blockchain technology where both Bitcoin and Ethereum are implemented. A ledger is utilized for every transaction for each demand response in a very trusted manner using blockchain technology. A billing system for the electrical network is proposed [18] by using blockchain technology and IoT devices where trust and privacy are maintained. The smart contract using Blockchain technology for securing the Internet and IoT with challenges and the research associated with this technology are revealed in the references [19, 20]. IoT data sets that are meant for the research fraternity are addressed in [21] by analyzing the IoT-based research papers published in English since Jan 2016. Here, seven IoT-related research potential threats are highlighted pertaining to IoT security. The performances of IoT are analyzed [22] by adapting blockchain technology in which, the several ways of integration of blockchain with IoT, challenges, benefits are discoursed by comparing the existing blockchain-IoT platform. An assessment is also realized for the shake of the practicability of blockchain nodes with IoT devices. The integration of Blockchain technology in smart logistics with regard to the information, transport, finance, and management are discussed in [23]. The blockchain technology-based smart grid system is reviewed in the reference [24, 25] where different parameters are thoroughly discussed. It also focuses on a variety of blockchain technology applications for smart grid and other industrial applications with a standard procedure for future expansions. In addition to IoT, a combination of blockchain and big data is realized in [26] for smart city projects to reduce the carbon emission intended for a green environment.

A Blockchain technology-based smart grid system is demonstrated [27] where the database is implemented more securely. In this, a customer can monitor the uses of power on a real-time basis. Blockchain technology-based smart grid is discussed in [28] for the protection of data flow in the different layer network where a consumer can sell their individual renewable energy back to the grid. A peer-to-peer electricity exchange network is discussed in [29] with proof of benefits to attain minimum power fluctuation without any intermediate party. The reference [30] proposes a blockchain-managed smart grid system where all the transactions are managed with a smart contract. This technology ensures that each transaction must be an immutability transaction with a history of transaction which is beneficial for audit. Secure communication is achieved [31] between a service provider and a user having a smart meter through blockchain technology under a keyless signature decentralized scheme. Furthermore, blockchain technology-based cybersecurity architecture is proposed in [32], where all the cloud computing technology is implemented to improve the efficiency of the smart metering system. The integration of blockchain technology in smart logistics with regard to information, transport, finance, and management are discussed in [33]. A case study of a smart model related to blockchain for the supply chain is proposed in [34] for storing the entire transaction. The case study has been carried out in Nigeria to implement mobile voting system which averts illegible person from casting their votes using blockchain technology [35]. The complete work along with literature is well presented for reader's interest as in [36].

Keeping the view of the above literature, we propose in this work, a blockchain-powered energy monitoring system that provides the solution to the issues associated with a centralized system and addresses major challenges in utility grids such as delayed electricity bill payment, the manual intervention of the process, unethical practices in a centralized system and illegal tapping of power in transmission lines. Furthermore, the blockchain technology is implemented in Advanced Metering Infrastructure (AMI) to monitor the energy usage and send data to a decentralized Web application that is developed using an Ethereum smart contract for supervising and automating the billing process.

3 Proposed Structure

In order to overcome the challenges of a centralized system, this paper presents a blockchain-powered energy monitoring system in which Blockchain technology is integrated with advanced metering infrastructure, which, in general, comprises various software and hardware equipment, that gather energy usage information from the smart meter and transfer it to the control center equipment via a two-way communication network in near real time as shown in Fig. 2.

Initially, a smart meter will be installed in every house registered on a given network, which will send meter readings to a blockchain at regular intervals. A decentralized Web application or DApp will be used that records the cost of energy usage of each house in terms of Ether for households to pay their monthly electricity bills. This Web application is powered by a smart contract that fetches unit usage of meter from the blockchain and secures the transactions by permitting genuine and accurate data transfers among the smart meters and supervisory nodes and reports if any illegal and malicious tampering of data has occurred. Once the required amount is paid, the smart contract will verify and record the transaction on a payment blockchain and send a permit signal to the smart meter for the next month. If a household fails to pay the bill in the required time, the smart contract will not send a permit to the smart meter, resulting in the meter automatically tripping the connection of the house. Hence, the entire process is automated without the need

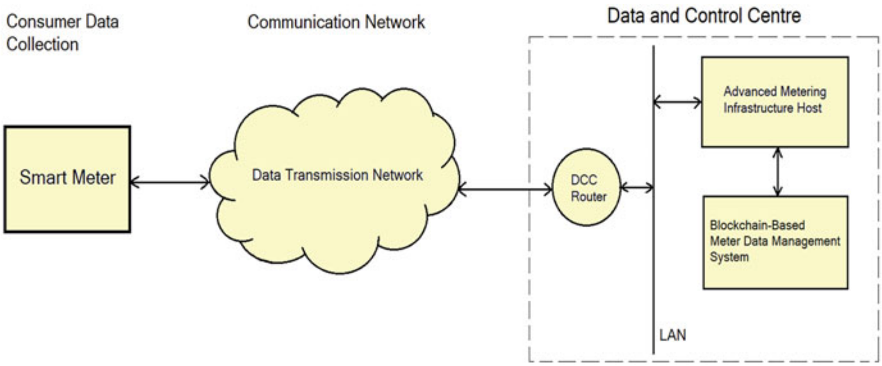

Fig. 2 Advanced metering infrastructure

for any manual intervention. This process of automated and regulated billing is illustrated in Fig. 3.

4 Implementation

The prototype for a blockchain-powered energy monitoring system is implemented by developing a Web application that can be used for enabling protected transactions of Ethers and storing energy records securely. Blockchains, like general Web servers, execute an application code and host a database. Generally, with a Web application, we can access a web page on our Web browser. All the front-end codes (written in HTML, CSS, JavaScript) for the website are stored on a central Web server, which interacts with the back end (written in PHP, JavaScript, or python), which then interacts with a database in order to render the web page. However, a blockchain application works differently. We can access our blockchain Web app with an Ethereum browser that interacts with a normal front-end website, but instead of interacting with a back-end Web server, this website will interact directly with the blockchain. Hence, the blockchain acts as a back end that hosts all the codes and data for our decentralized system.

4.1 Model of Blockchain Web Application

The blockchain Web application has a user interface for users to interact with a smart contract and a blockchain that stores information for peer-to-peer payments. For building the user interface, a client-side website is created using HTML5 and JavaScript along with web3.js and react.js libraries. The web3.js libraries are used to connect to the Ethereum network and interact with a smart contract through an inter-process communication (IPC) connection. The Ethereum smart contract is developed using Solidity programming language and deployed to the blockchain. The model of this Web application is illustrated in Fig. 4.

This application is implemented on Intel Core i5-7200U 2.50GHz Processor with 8 GB RAM and Windows 10 Pro 64-bit operating system. To develop and run dynamic Web applications, Node.js is used, which is a JS runtime environment on Chrome used to execute JavaScript codes outside a Web browser. The codes for smart contracts and client-side websites are written on Sublime Text. To build, test, and deploy the Web-based DApp, the Truffle framework is used, which provides multiple functionalities. It compiles the smart contract codes to byte codes that can be run on Ethereum Virtual Machine. It enables automated testing of the smart contract using Mocha and Chai testing frameworks. It helps in connecting to both public and private blockchain networks to run the applications. The Truffle ecosystem also provides a personal Ethereum blockchain known as "Ganache," where smart contracts are deployed. Ganache blockchain can be used instead of

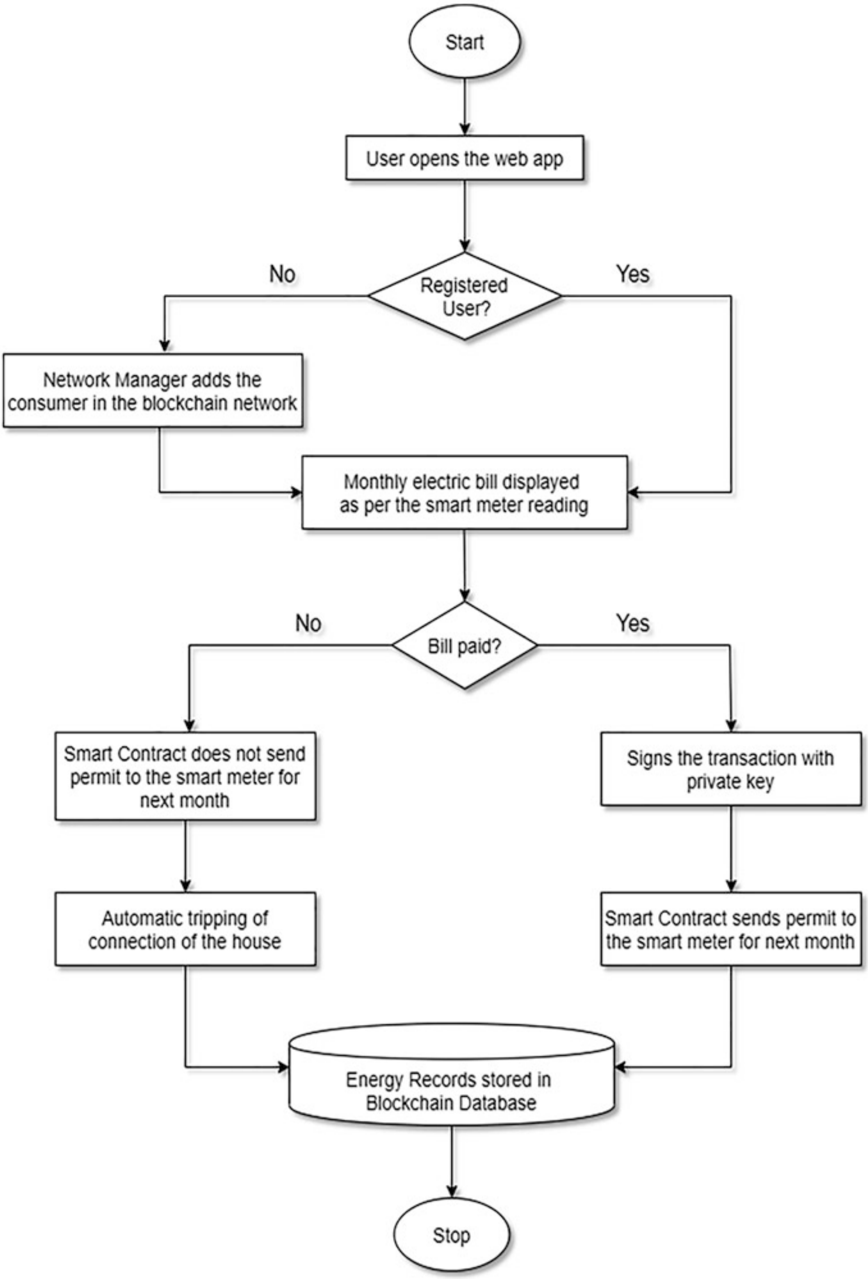

Fig. 3 Workflow overview

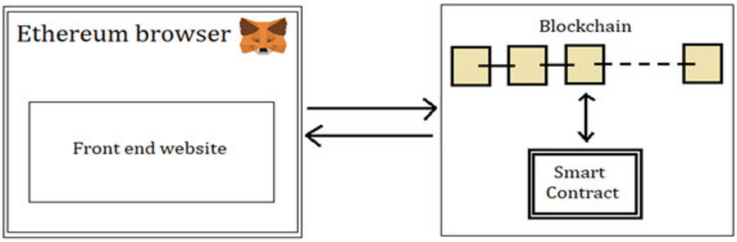

Fig. 4 Web app model

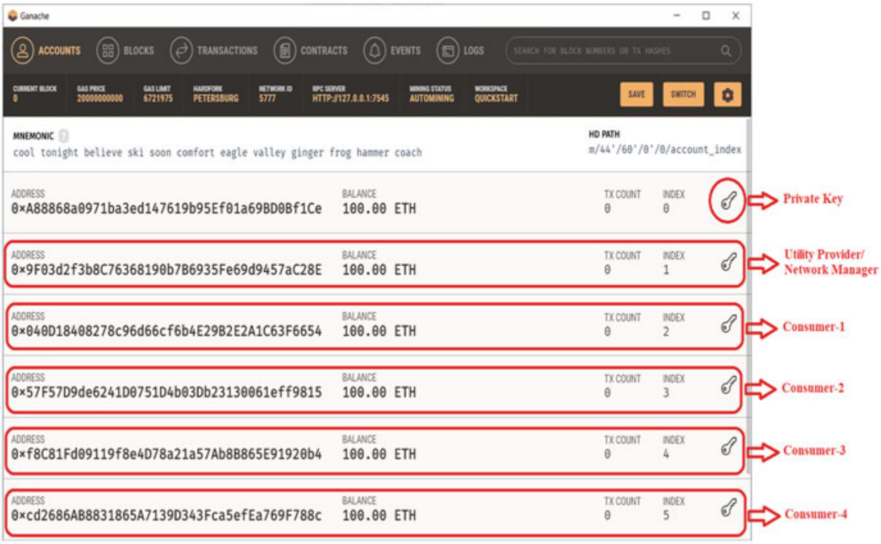

Fig. 5 Ganache console

a real Ethereum blockchain as it behaves the same as a public blockchain but won't cost us any real money. It enables us to develop, deploy, and test our DApps in a safe and deterministic environment. The user interface of Ganache is shown in Fig. 5. Its UI has a list of user accounts with different public and private keys, and each account is credited with a balance of 100 Ethers.

In order to interact with Ganache blockchain from the Web app, we need to use MetaMask browser extension, which converts regular Web browser (e.g., Chrome, Firefox) into Ethereum blockchain browser and allows us to run Ethereum DApps without having to download and run an entire Ethereum node consisting of more than 10GB blockchain on to our computers. To connect our Web app with Ganache, we need to import all Ganache accounts into the MetaMask wallet using the private key of each account and change the default main Ethernet network of MetaMask to Localhost 7545. The Ether balance of each user is now visible in the MetaMask wallet of each account.

Using this model, a decentralized application is built that allows registered consumers to pay electricity bills on the website with Ethereum cryptocurrency and uploads energy transaction data on the Ganache blockchain. It also allows new houses to be added to the group of registered consumers in the power grid network through the Web app.

4.2 Front End of Web Application

The front end of our Web app is the user interface through which consumers can directly pay their monthly electricity bills online. The front end, also known as the client-side application, is shown in Fig. 6. It consists of two sections, the admin's section and the consumer's section. The admin's section has a field for the admin to add new consumers to the network by entering their usernames and the bill amount as per their smart meter reading. The monthly bill amount will be in Ethers. It is assumed that the smart meter reading will be regularly updated on the web page by the AMI. However, in this prototype, we will manually add the readings on this Web app. These readings are then uploaded on the blockchain along with the information of new consumers in an encrypted manner. The consumer's section contains the bill payment status of all the consumers as per their blockchain transaction records. It includes the usernames of consumers, their monthly bill amount in Ether, and their public-keys in the "account number" section. It also contains the link in the form of

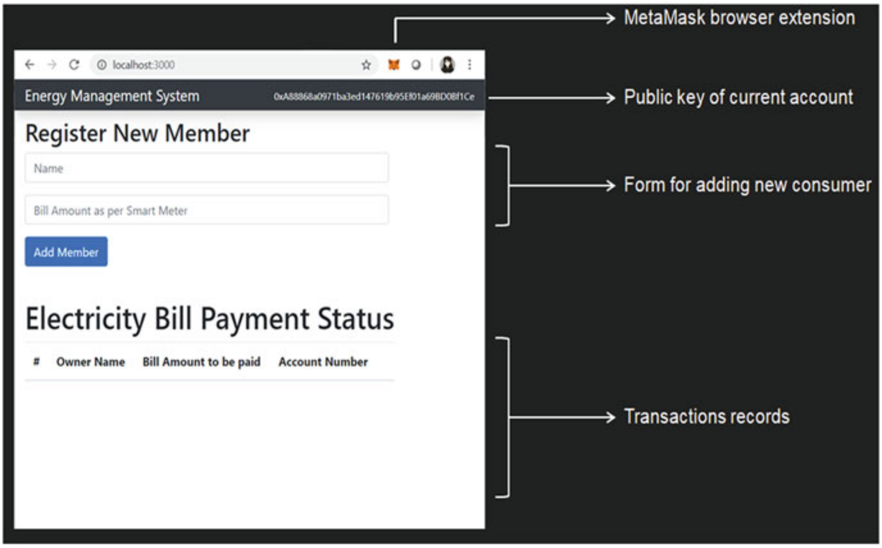

Fig. 6 Client-side web page in MetaMask browser

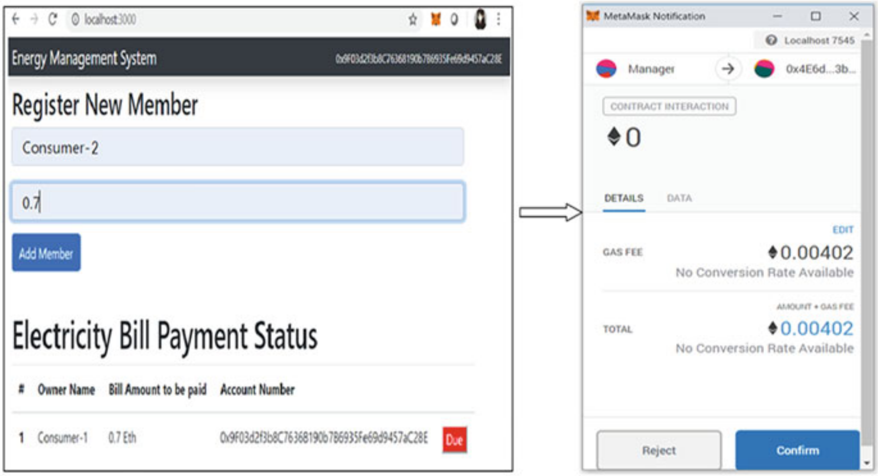

Fig. 7 MetaMask confirmation for adding new participants to the network

a button to pay their respective bills online, which will be added once a consumer record is created.

4.3 Role of Admin

The admin is an independent entity whose role is to only add new consumers in the blockchain network, who are willing to purchase energy from that particular grid network. To add new consumers, the admin has to fill the "Name" field and the "Bill Amount as per Smart Meter" field and click on the "Add member" button on the webpage, after which a MetaMask confirmation will be generated for signing the transaction initiated due to the interaction with a smart contract, as shown in Fig. 7. Thus, a new block will be created and added to the Ganache blockchain, and a new transaction record will be created in the consumer's section, as shown in Fig. 7. In this record, the account number is the public-key of the user, and the red "Due" button indicates that the bill has not been paid yet. Currently, this record has the public-key of admin in the account number section, since Consumer-1 is newly added to the Ethereum network. This key will change into the consumer's public-key only after the payment of the first month's electricity bill, which indicates the transfer of ownership of energy from the admin to the consumer.

The smart contract is written in a way that restricts the admin to pay the consumer's bill. If the admin tries to pay any consumer's bill, the smart contract will throw a transaction error in the MetaMask notification, which means the transaction will not be successful. This can help in checking unethical selling of power units by the electricity board.

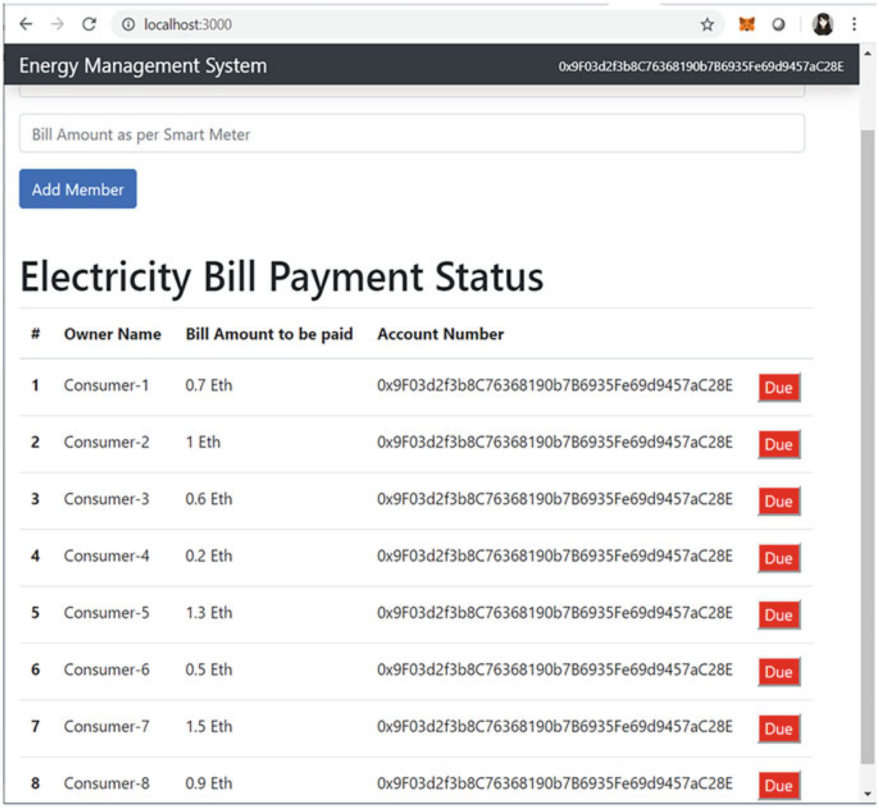

Fig. 8 Consumer's payment status

4.4 Role of Consumer

The consumer's section on the web page is a list of energy records of all the registered consumers, which contain only the username, the bill amount as per the smart meter reading, and the public-key of consumers, as shown in Fig. 8. This ensures that the personal information and identity of users are hidden. In these records, a payment link is also present in the form of "Due" button, which redirects to the MetaMask wallet once it is clicked by the respective consumers to pay their bills.

It is assumed that the energy usage of a house is constantly monitored by the AMI and the bill amounts in the record are updated at regular intervals by the blockchain. It is also assumed that each consumer record is marked "Due" at the end of the month, indicating that the monthly electricity bill is due the current month and the payment portal will remain active till the end of the month, exceeding which the smart contract will not send any permit to the smart meter that will eventually trip

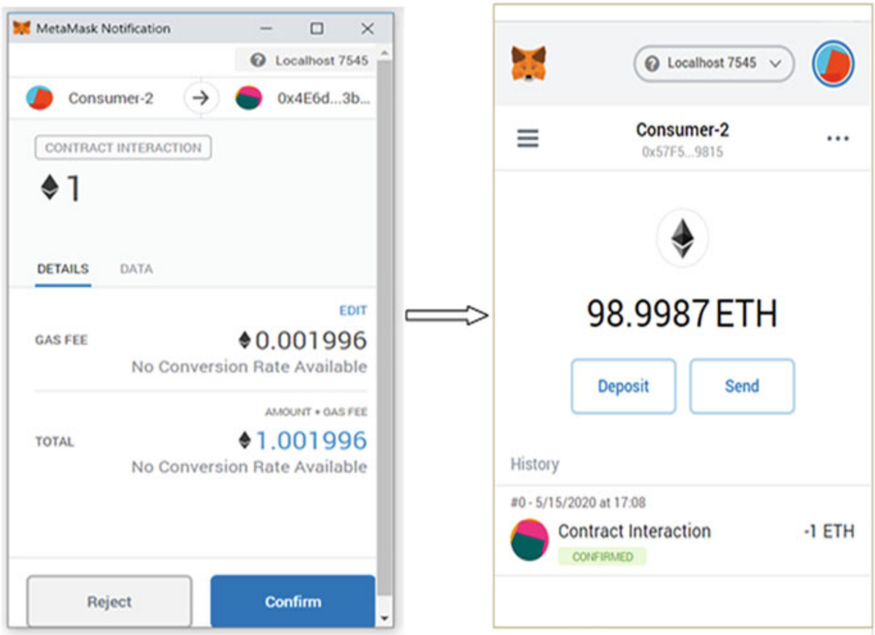

Fig. 9 MetaMask confirmation for consumers

the power flow to the house. On clicking the respective "Due" button, a MetaMask confirmation will be generated, where the consumers have to sign their transactions using their private key in order to complete the payment process and create a block, as shown in Fig. 9.

The MetaMask notification contains a detailed summary of a transaction, which contains the Ether value of bill amount along with the gas fee, and it is generated by the smart contract to let the users sign or confirm their transactions. As soon as the contract interaction is confirmed in MetaMask, a block will be added to the Ganache blockchain, and the red "Due" button automatically changes to the green "Bill paid" mark, as seen in Fig. 10, which signifies successful transaction of Ethers from the consumer's account to admin's account.

At the end of the month, the client-side UI will appear as shown in Fig. 10. The consumers who have paid their electricity bills are now easily distinguishable from the ones who have not and will get a permit for the next month in their smart meter from the smart contract. Consumers who have passed the due will get their connection automatically tripped by the smart meter as it would not receive any permit from the smart contract. This way, our Web application is able to monitor all the bill payments from the consumers by listing out the users who have paid and who have not, respectively, at the end of the month.

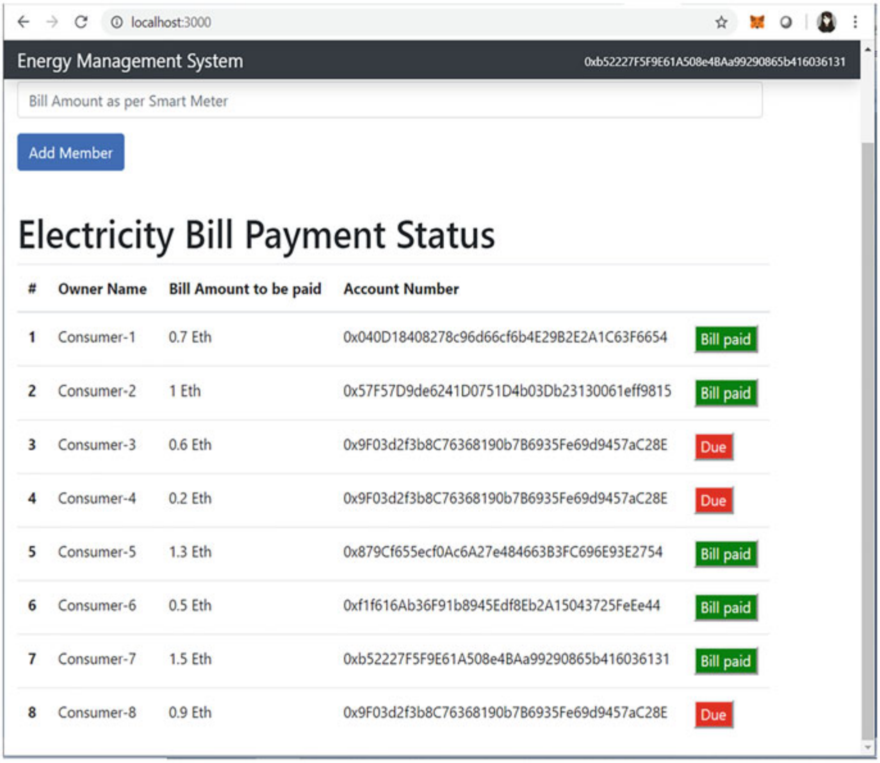

Fig. 10 Resulting database after bill payment

4.5 Creation of Blocks in Ganache

In the Web app, a transaction is initiated either when the admin adds new consumers to the blockchain network or the consumers pay their monthly bills. Blocks are created and mined every time a transaction is initiated and added to the Ganache blockchain, as shown in Fig. 11. Each transaction block is verified and validated during mining, which requires a certain amount of gas fee to complete the process. Thus, the blocks contain different time stamps on which they are added to the ledger, along with the amount of gas fee spent during the process of mining.

In the Ganache console, we can find the list of blockchain transactions in the transaction section of Ganache, which is shown in Fig. 12.

All the transaction details stored in the blocks are encrypted using the 256-bit hash algorithm known as Ethash, which is very difficult to crack. This will prevent data tampering due to cyberattacks and also protects the personal information of the user. The transactional information of each user is converted into a transaction hash, as shown in Fig. 12. Along with transaction hash, the gas amount and the public-key of the sender and receiver are also present in the block.

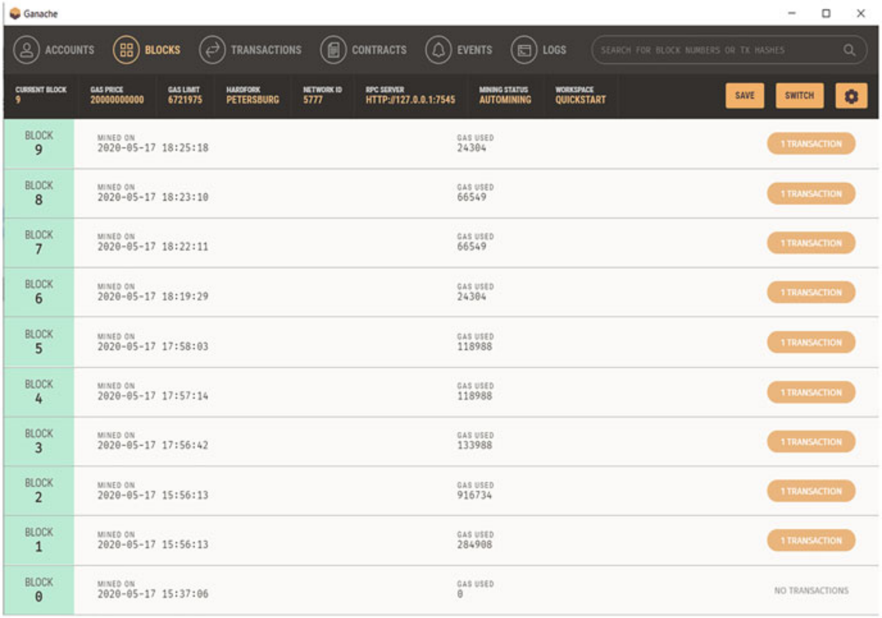

Fig. 11 Blocks in Ganache

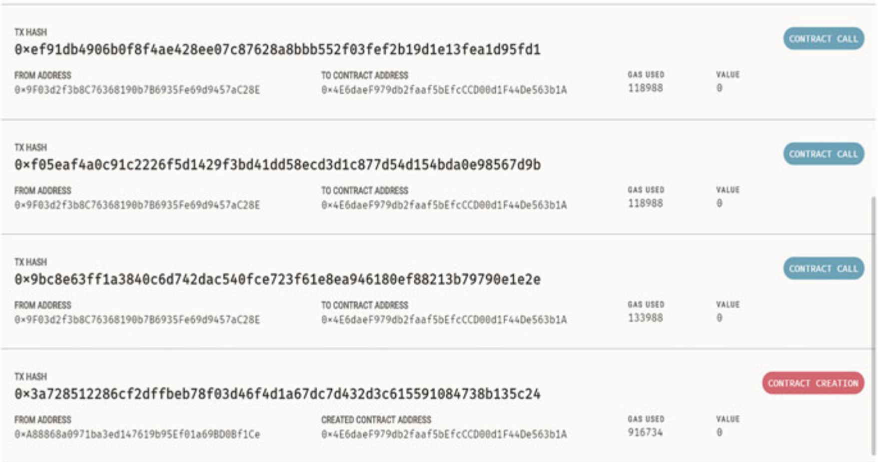

Fig. 12 Transactions in Ganache

5 Analysis

It is evident from the proposed system of a blockchain application that it is capable of executing the smart contract functionality in automated billing and storing transactional data in the blockchain. This prototype can be used in large-scale applications for monitoring energy usage in real time and tracking the electricity billing process. Along with ease in payment process through the Web app, this will also ensure payment settlements in real time through consensus among all the nodes in the network. The automated tripping of electricity connections in a house by the smart contract will prevent manual interventions and other problems arising due to delays in bill payments. In our DApp prototype, the Web app is hosted on the "LocalHost 7545" network since we are implementing our prototype on the Ganache blockchain, which is present in our local machine. We can also implement the proposed system on a public blockchain network such as the "Kovan Test Network," where we have to pay with real Ethereum cryptocurrency. The households can pay directly through the Web app if they are connected to a given public blockchain network for energy transactions of the power grid.

The power generated in power stations passes through large and complex networks, such as transformers, overhead lines, cables, and other equipment, and reaches the end users. It is a fact that the unit of electric energy generated by the power station does not match with the units distributed to the consumers. Some percentages of the units are lost in the distribution network. This difference in the generated and distributed units is known as transmission and distribution loss. Transmission and distribution losses are the amounts that are not paid for by users. Distribution lines account for nearly 15% loss of the total power produced. However, in the case of illegal tapping of power, the sum of electricity usage by individual houses and power generated from transformers/power plants after eliminating the losses will not be equal, i.e., losses will be greater than 15% of the total power generated. Therefore, in order to detect power theft, transformers can be connected to the blockchain on which their electricity transactions are uploaded regularly. So, if there is an illegal tapping at any instant, then the net power available to the consumers will be less than 0.85 times the total power generated by power plants. This change will be evidently identified by the blockchain networks due to the transparency in the transactions of all the consumers.

6 Conclusion

In this work, a system is proposed successfully by using blockchain as a medium to reserve energy transactions and user accounts. With the help of the Internet and the encryption technique in blockchain, the proposed system provides a better solution for a smart grid system that is decentralized, interoperable, and secure. As seen in the proposed system, the decentralized application offers numerous benefits over centralized systems, such as immutability, security, transparency, reduction in transactional cost, faster transactions and prevention of unethical access, data tampering, and single point of failure. Due to the abovesaid advantages, the corresponding institutions will find easy and cost-effective solutions to implement in their system. The projected blockchain system will be highly favorable for both the customers and service providers to make profitability in the business.

Currently, there is a high potential for blockchain-based systems and applications in the energy sector. It aims to provide the solution for real-time energy monitoring and faster, secure, and efficient energy transactions. However, it faces major obstacles, which have prevented its optimal usage. Blockchain technology is still in its nascent stage of development, and applications are still in the pilot stage, due to limited research work. Lack of guidelines, laws, and regulations is also there. Future work can be done to integrate a blockchain-based energy monitoring system with the current system and include incentives for users. Possible long-term consequences are the creation of an Internet of Value and decentralized society and organizations. This could be a future energy market with a decentralized and unified energy grid, efficient and secure P2P transaction platform, interchangeable roles between prosumers and consumers, automated billing and logistics, energy flexibility, and competitive and cost-efficient market.

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