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Blockchain for smart grid

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ABSTRACT

The demand for electricity increases rapidly along with the advancement of the industrial age. To ensure efficient distribution of the electricity, maintain low losses and high level of quality, and the security of electricity supply, the smart grid concept was proposed. The concept enables a small, individual scale to generate electricity and sell it to the grid. However, the concept adds complexity to the existing system, such as how a transaction between these generators and consumers are conducted, verified and recorded. This paper proposes the blockchain as a tool to manage transactions in the smart grid. Transactions are performed with smart contracts, and the network acts as a transaction verifier. The blockchain provides immutability of the transactions, which ensure every transaction between generators and consumers will always be executed. It also provides immutability to transaction history, which can be used for audit or solving a transaction dispute.

1. Introduction

The discovery of electricity marked the beginning of the second industrial revolution. For nearly 150 years, the industry has been growing rapidly, along with the need for electricity. In 2015, worldwide electricity consumption reached 21,153 TWh, almost tripled in 30 years (Fig. 1). Depending on the power source and consumer demand, electricity has a broad range of prices. In 2015, the price ranges from US$0.01 per kWh in Argentina to US $0.33 per kWh in Germany (Statista: The Statistics Portal).

For years, there are limited sources to generate electricity, mostly from fossil fuel. The equipment to generate electricity was very expensive and it was not economical for small scale or personal use. Customers brought their electricity from power plants; have their electricity delivered by the power grid, and pay for what they consume. However, advancement in technology has changed the way people generate and distribute electricity. Automation leads to mass production, which leads to cheaper power generators. Inventions made possible to generate electricity from the sun, wave, geothermal, and other alternative sources.

Altogether, they made it possible for a community, family, or even individual to generate their electricity. When people generate more than they consume, they sell it to other people, so they act as alternative power sources. Table 1 shows the shifts in the electricity industry, which are accelerated by the shifting paradigm in the global industry (Hermann et al., 2016).

The smart grid offers more security in terms of electricity supply. However, the concept adds complexity to the existing electrical industry. On the transaction level, how to make sure generators will deliver the electricity after the consumer has paid. With multiple generators and consumers exist in the network, it also raises concerns about who will validate the transaction, and how the process is carried out.

The main goal of this paper is to propose the use of a blockchain network to manage transactions in the smart grid. In the proposed architecture, all entities involved in the smart grid acted as a node, and transactions are written in smart contracts. A mobile application is developed as an interface between the system and the users.

The rest of the paper will be divided as follows. In Section 2, we describe a definition and overview of Industry 4.0 and the smart grid, followed by an overview of the blockchain technology and its components. Section 3 discusses the implementation of blockchain in the smart grid. Finally, conclusions are drawn in Section 4.

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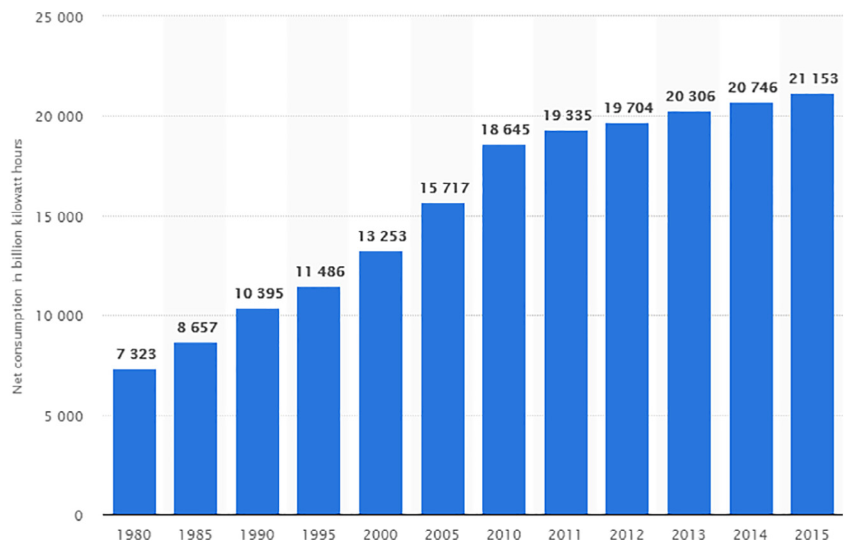

Fig. 1. Worldwide energy consumption (Statista: The Statistics Portal).

Table 1
Shifts in the electricity industry.

Entity	Traditional model	Smart grid
Generators	Centralized: industry scale power plants	More decentralized: industry scale power plants, home/small size power generators
Power source	Mostly hydrocarbon (natural gas, coal, oil) (Whitehorse City Council, 2007)	More portion of renewable energy
Transaction	Consumers bought power via energy companies (one direction)	A direct transaction between generators and consumers (multi direction)
Pricing	Determined by government or power company	Every generator can set their price
Billing (Goldman, 2010)	Periodic billing (postpaid)/pay as you need (prepaid)	Prepaid

2. Related works

This section presents a brief introduction related to the smart grid. We also present more detail on the blockchain, such as its concept, structure, node, ownership, how a transaction recorded in the blockchain, consensus mechanism, and smart contract to execute transactions between entities.

2.1. Industry 4.0 and the smart grid

Industry 4.0 is the fourth industrial revolution concept introduced in 2011 (Kagermann et al., 2011). There are four main principles in Industry 4.0; the interconnection of the machines through the internet; data processing trough information transparency to make a better decision, support system, and intelligent entities able to make decisions and perform the autonomous task (Hermann et al., 2016). In the Industry 4.0 contexts, a smart grid uses advanced information and communication system to connect power generators, distribution stations, and consumers. Advanced data processing allows the processes of electricity distribution to be more efficient, decentralized, flexible, reliable, and secure (Faheem et al., 2018). A smart grid also integrates the use of renewable energy sources into the existing power grid, to supply electricity demand (Faheem et al., 2018). Additional entity and functionality bring challenges for the existing grid, not only to the infrastructure but also on the transactional level.

A smart grid is defined by an electricity grid, which integrates the behavior and actions of all entities connected (Fig. 2). There are three types of entities; generators, which generate electricity; consumers, which consume electricity; and those which can do both. Together, these entities create a peer-to-peer network to ensure efficient distribution of the electricity; maintain low losses and high level of quality, the security of electricity supply (European Technology Platform, 2010). A peer-to-peer network eliminates intermediaries and trusted entities in trading, giving the buyers and sellers the freedom of preferences, choices, and prices (Otjacques et al., 2018). Previous research demonstrates the possibility of a blockchain with a smart contract capability to enable energy trading without a trusted entity (Hahn et al., 2017; Munsing et al., 2017). A peer-to-peer energy transaction project also being developed by TransactiveGrid in Brooklyn, USA. It utilizes permissioned blockchain as a transaction platform between entities on a residential scale (Broklyn Microgrid).

Although the character is also existing in today's grid, the smart grid should be capable to solve more complex problems effectively and efficiently, through intelligent monitoring, control, communication and self-healing technology (EU Commission Task Force for Smart Grids, 2010). One of the challenges in the smart grid proposal is how to deliver communication infrastructure consists of millions of entities to operate and trade in the single market (European Technology Platform, 2010). Energy traceability also become a concern. Blockchain was used to optimize energy transactions in microgrids. In this case, a green certificate is used to indicate that the energy was generated from renewable energy sources (Imbault et al., 2017). Blockchain can be also implemented to address fraudulent issues by utilizes a reputation system among the entities (Khaqqia et al., 2018).

2.2. Blockchain

Blockchain is a technology, which enables a community to maintain trust. Blockchain can also be defined as a distributed net-

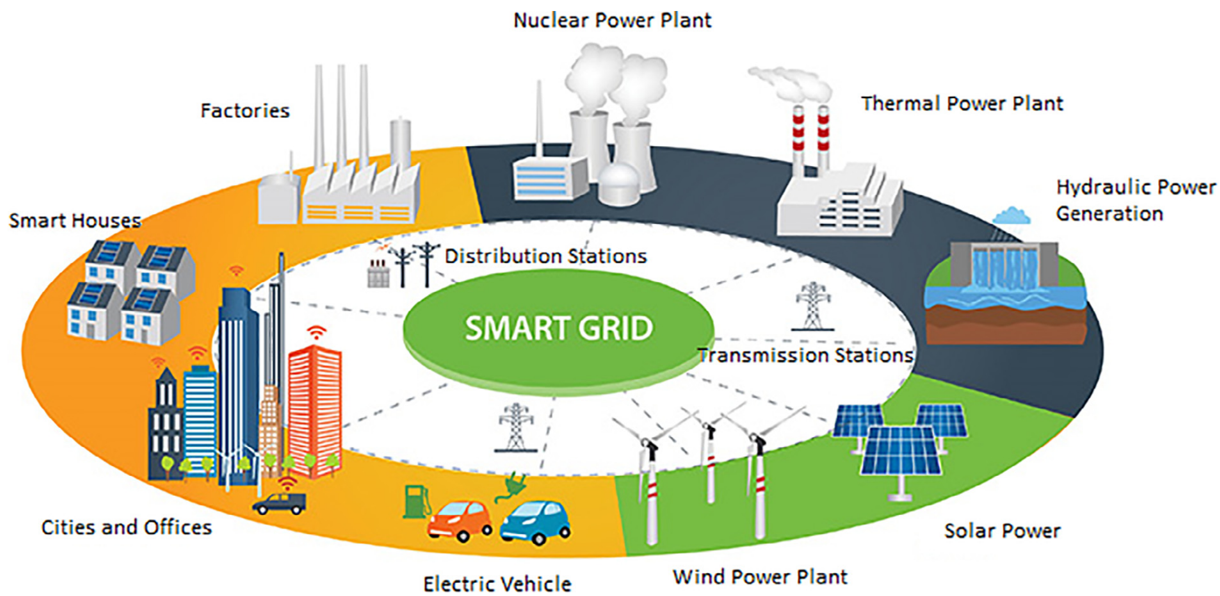

Fig. 2. Smart grid (eolas Magazine).

work, maintaining an immutable database. Satoshi Nakamoto proposed the concept of blockchain, and it was implemented in the bitcoin, a cryptocurrency (Nakamoto, 2008). There are two types of cryptocurrency, one with their blockchain platform, and the other which utilize existing platform (Wu et al., 2018). The first type is called coin while the other is called token. The blockchain, however, not only limited in cryptocurrency. Relevant proposals of the blockchain implementation include in the financial sectors (Knezevic, 2018), automatic transaction settlements (Liu et al., 2018), and traceability (Sander et al., 2018; Jansson and Petersen, 2017).

Previous research mapped and used essential data on the smart grid and utilized RainbowChain technology to manage transactions. The blockchain uses Proof of Work and capable to execute the smart contract, to record and executes transactions (Kim and Huh, 2018). A study conducted by PwC for German Consumer Advice Center (Verbraucherzentrale) pointed three critical aspects of blockchain technology to be succeeded in the energy sector, (1) user-friendly, easy to use and effective application, (2) cost efficiency verification process, and (3) value-added offered by the blockchain (PwC Global Power & Utilities, 2016).

2.2.1. Concept

The blockchain concept originally proposed as a solution for the double-spending problem in digital money without any central authorization or the decentralization of power. In a conventional transaction, when a buyer purchases something, the payer transfers the money (paper or coins) physically to the payee. In the digital world, money exists as data, which can be copied precisely with minimal effort. A payer can easily copy the money, spend the original, and spend the other copy, which is known as the double-spending problem (Chiu and Koeppl, 2007).

To overcome the problem, someone trustful is needed as an intermediary. It checks the balance of the payer, deducts the balance of the payer according to the bill, and added the balance of the payee according to the bill. Nakamoto argues in his paper, that this intermediary will raise transaction fee for the service, and eventually limiting small transactions. The intermediary is also needed to mediate a dispute between parties. Another concern is that this intermediary can reverse the transaction that occurred by force, which is not desirable for a non-reversible transaction, such as in the service industry. The condition will make merchants wary of their customers, gathering more information than they would need, risking the identity of the customers. Blockchain eliminates the intermediary, and the transaction written in a blockchain is immutable.

The blockchain can be implemented further in many industries. Outside the cryptocurrency, transactions could be any data representing the change of ownership of any asset, including electricity.

2.2.2. Structure

A blockchain consists of blocks, which ordered in a time-sequential manner, secured and linked using a hash function, as illustrated in Fig. 3. The block is timely stamped so it cannot be backdated. A block consists of a bundle of transactions. In bitcoin, a transaction is the change of ownership of the money. However, in our case, this can be substituted with the transaction of electricity. A hash function is a mathematical one-way function that produces fixed output, given any input. A slight change in the input will produce significant changes in the output (Shahzad and Crowcroft, 2019). The hash is also one way, which means, given the input, it is easy to calculate the output, but not otherwise. When a block is full or it is time to create a new block, the block is hashed with a specific hash function, H(x), where x is the number of the current block. The hash is then stored in the next block, creating a 'chain'. The process repeated itself until the last block, so a slight modification to a block could be easily notified because the hash will be invalid.

An owner of a certain amount of bitcoin can change the ownership of his coin to another person, or transfer the money to the other. However, instead of real-life identity, both the previous and the next owner is represented by a unique identifier called address. The address is derived from the public key of a private–public key. This way, the network could easily verify the authenticity of the coin owner. Since a blockchain records all the transaction history, the transaction can be traced back to the moment of its creation, eliminating the double-spending problem.

2.2.3. Node

A node is an entity, which connects to a blockchain network and performs various actions. Nodes can join or leave the network any-

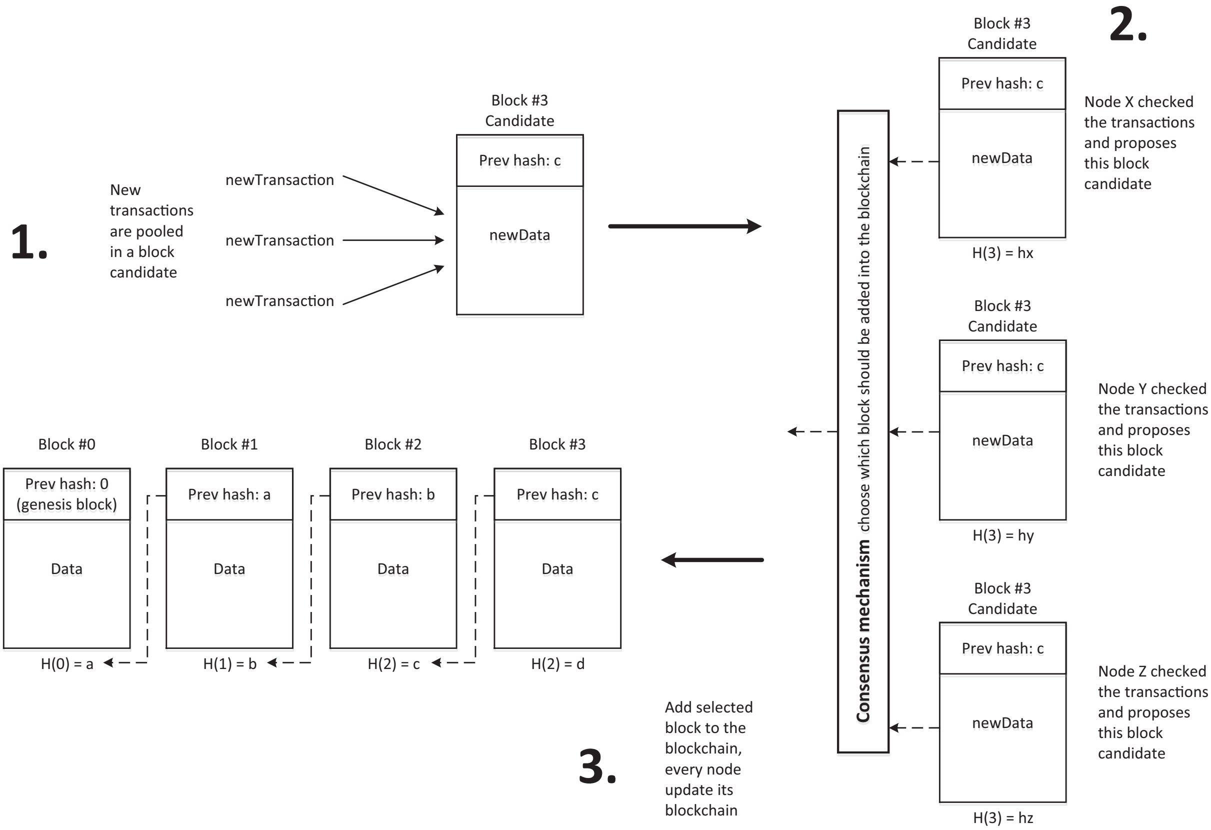

Fig. 3. Block insertion in the blockchain.

time they like. In a bitcoin blockchain network, there are two main nodes (Xu et al., 2017).

- Full nodes, which hold a copy of the blockchain on its storage, and its main tasks include verifying the transactions and maintain the consensus among other full nodes. Initially, nodes that create blocks fall into this category. Holding a complete copy of the blockchain may be inconvenient for most of the users. For example, for ten years in operation, on April 1st, 2019, the bitcoin blockchain was 205 GB in size (Blockchain Luxembourg).
- Light nodes, which able to run on a limited resource, such as mobile phones or laptops, are used in daily transactions. They use Simple Payment Verification (SPV) to validate transactions. They do not hold the complete copy of the blockchain, so they depend on full nodes.

2.2.4. Ownership

In general, there are three models of blockchain ownership (Turner et al., 2018). Ownership will determine who can participate in the network, such as become a node, verify the transaction, and perform transactions.

- Permissionless blockchain, also called public blockchain, is open to anyone who wishes to participate as a node. Every node keeps a copy of the blockchain in their storage, and work together consensually to maintain the blockchain. Bitcoin blockchain is an example of this model.
- Permissioned blockchain, also known as a private blockchain, has limited access to a certain entity. As opposed to the main concept of the blockchain, certain people or organization controls a permissioned blockchain. Sample of permissioned blockchain includes Quorum, an Ethereum based distributed ledger created by J.P. Morgan (Morgan Chase, 2018), and Hyperledger by The Linux Foundation (2018). To participate, a node must be validated by the blockchain owner or by a set of rules declared by the blockchain owner.
- Hybrid blockchain, also known as semi-private, or consortium blockchain. The main concept is to connect the private and public blockchain. In this blockchain, some part is private while the other is public. The public blockchain is connected with a private blockchain. The sample of hybrid blockchain is XDC by XinFin, a Singaporean company (XinFin, 2018; XinFin Organization, 2017). The concept of blockchain is to decentralize power to build trust between untrusted parties. The private blockchain will give full power to one party and could raise trust problems.

2.2.5. Transaction

When someone initiates a transaction, it is pooled in a block candidate (Fig. 3, process no. 1), and nodes in the network validate the transaction (Fig. 3, process no. 2). There will be many versions of block candidates since every node adds its address into the block candidate, but there must be only one block candidate added to the blockchain at a time. Here, a consensus mechanism chooses which block to be added (Fig. 3, process no. 3).

Depending on the mechanism, the node in which block is selected may or may not be rewarded. The cycle is then repeated over time. Once the data entered the blockchain, the data cannot be deleted. If someone made a wrong transaction, then it must be corrected by reverse transaction, leaving the previous transaction intact. This way, a blockchain maintains traceability of an asset and it is good for auditing. Table 2 illustrates how to reverse a transaction in a blockchain.

Every block is hashed. The hash is then stored in the next block, and so on (see Fig. 3). To change the data in a certain block, some-

Table 2
Illustrations of a reverse transaction.

No.	Origin	Destination	Asset involved	Description
100	Alice	Cindy	1 token	Alice wanted to send Bob 1 token, but mistakenly send it to Cindy
101	Cindy	Alice	1 token	Transaction no. 100 cannot be deleted, instead, Cindy reverse (send back) the token back to Alice
102	Alice	Bob	1 token	Alice initiates the correct transaction

one must recalculate the hash of that block, change the stored hash of that block in the next block, and so on until the last block. However, the network consists of nodes, and every node maintains a copy of the blockchain. Changing one copy of a blockchain will not 'convince' the network and they would easily reject the tampered blockchain. To successfully 'fooled' the network, someone must have the power to change at least 50% plus one blockchain stored in all nodes, simultaneously. Thus, the data recorded in a blockchain is not 'unchangeable', but it is very impractically to change the data, or immutable. Hence, as long as there is more honest node operating, the network will be secured.

2.3. Consensus mechanism

The consensus mechanism consists of a set of rules, which is used to achieve an agreement on single data value, such as determining whose block candidate will be accepted as a block and added into the blockchain. There are some popular consensus mechanisms in the blockchain. By the time the research was conducted, the Proof of Work was used by 505 coins, followed by the Proof of Stake by 393 coins, and the Proof of Service by 175 coins (Cryptoslate). A blockchain may implement one or many mechanisms. Here are some of them.

- Proof of Work, also known as mining, is a concept that to be chosen, a node must prove its contribution to the network by solving a mathematical, hash equation, in the process of creating a new block. To maintain constant block creation time, the equation's difficulty is adjusted every certain period (Nakamoto, 2008). If a node possesses more processing power, it will have more chances to solve the equation. Problems with this mechanism are miners can combine their hash power in a mining pool, dominating the hash distribution, and the process consumes a lot of energy (O'Dwyer and Malone, 2014; Agung et al., 2019). Another problem, sometimes miners contribute only to the reward and easily leave when the mining process is not profitable.
- Proof of Stake, also known as staking, is a concept that the more someone holds an asset, the more the contribution he makes, thus having more priority to be chosen as a block creator (King and Nadal, 2012).
- Proof of Service, also known as a masternode, is the second layer of service provided by a certain node. To be a masternode, a node must lock certain assets as collateral (Duffield and Diaz, 2014). This mechanism is complementary to the two former mechanisms above, and cannot run by itself.
- Proof of Importance, also known as harvesting. The concept was introduced by NEM. Instead of processing power or wealth, it identifies a node's overall contribution to the network. This includes vesting (deposit), net transactions over time and the number and size of transactions in the last 30 days (NEM Technical Reference 1.2.1).

2.4. Smart contract

A smart contract is a set of condition, which agreed by interested parties, and stored in the blockchain. It scans the blockchain and it automatically performs the predefined actions, once the conditions are fulfilled. Once written in the blockchain, a smart contract has also become immutable, and will always be executed (Szabo, 1997; Buterin, 2015). In a transaction, a smart contract acts as a trusted escrow service.

3. Result and discussion

In this section, we present how a blockchain implemented to manage transactions in the smart grid, which consists of electricity generators, consumers and nodes which can do both. An architecture is proposed, and a mobile application is developed as an interface between users and the system.

3.1. Proposed architecture

Fig. 4 shows the proposed architecture. In this scenario, cluster A consists of a government-owned power plant, cluster B consists of residential buildings, cluster C and E also consist of buildings, but some of them capable to generate their electricity. Cluster D consists of privately-owned power plants, and cluster F consists of a public electric outlet. Grid storages store excess electricity on the grid.

Utilizing the existing electric grid, consider every entity as a node (Fig. 4). A small computing device is placed as a light node, generates an address and maintaining the balance of that address. The device connects to or replaces the existing electricity meter. A full node is added at the existing distribution point, such as in the step-down transformers before the distribution lines to the customers.

Full nodes validate transactions, maintaining consensus, also perform routing to the network, determine an efficient route to deliver the electricity, especially when a certain electricity producer is out of service. This will provide the security of electricity supply. In the cryptocurrency model, this node also similar to the masternode.

Every producer and consumer is set as a light node, to reduce complexity and expensive hardware requirement. Table 3 summarizes entities involved in the proposed architecture.

Fig. 5 shows an example architecture of a producer/consumer node. A house with a solar panel has primary electricity from the distribution line, through a bidirectional meter (A). The power is distributed throughout the house (red lines).

For a producer, secondary power source, for example, a solar panel (B) generates power, store the electricity in the batteries (D). The batteries connected to an inverter and connected back to the bidirectional meter (A). Should the owner decided to use the previously stored power, it is directed back to the inside lines, but should the owner decided to sell it, the power is sent back to the grid. Users can monitor and maintain the process using devices connected through the internet.

3.2. Blockchain platform and smart contract

The blockchain operation of the proposed architecture is provided by computational nodes (computers). The blockchain platform for the research is Ethereum. The blockchain and smart

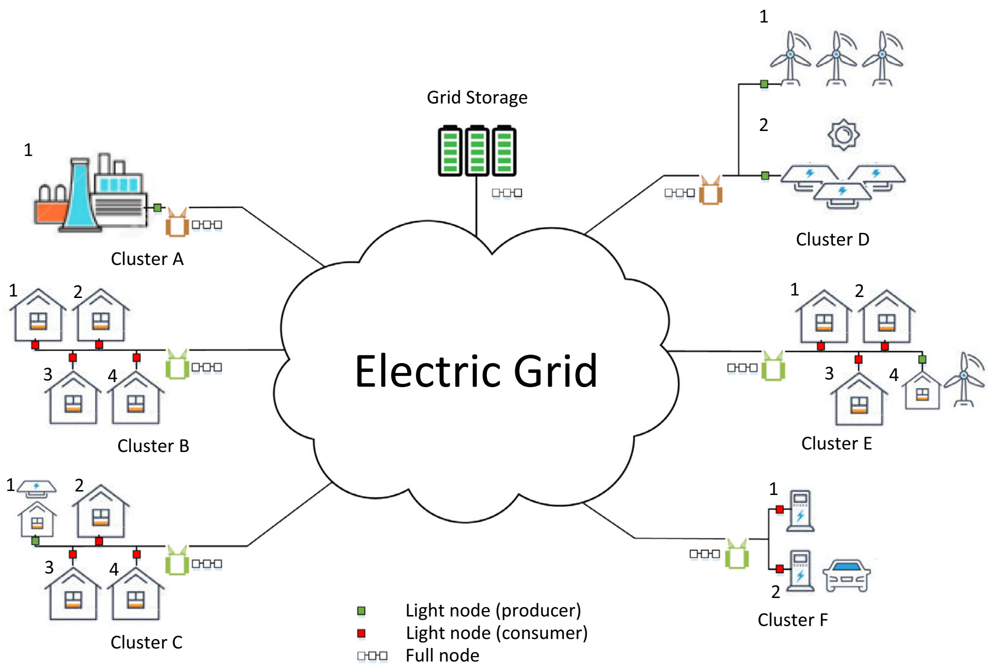

Fig. 4. Proposed architecture.

Table 3
Entities of smart grid and their actions.

Nodes	Actions	Example
Producers	Create and sell the token	Power plants (Fig. 4, Cluster A, D)
Consumers	Purchase and consume the token	Buildings (Fig. 4, Cluster B, C2, C3, C4, E1, E2, E3), electric outlets (Cluster F)
Both	Create and sell token; purchase and consume the token	House with an alternative power source (Fig. 4, C1, E4)
Distribution point	Acts as a full node, maintaining consensus, verifying transactions, perform routing	Step down transformers at every cluster

contracts for this research run on the test network. Deploying a smart contract in a real network requires real Ether to spend as a fee. This will require developers to buy Ether with fiat money. The blockchain uses the Proof-of-Work consensus mechanism (Buterin, 2015) and provides a platform for the smart contract, which is used to execute transactions between producers and consumers.

Every node has a private key and address generated. The key is unique and is used as a node identifier, while the address is used for transaction purposes. Rules of the transactions are coded in smart contracts, which are automatically executed when a certain condition is fulfilled. The processes are as follows.

- A producer node generates electricity. As a node, it generates a token with the corresponding value.
- If a producer wishes to sell its electricity, it places the sell order of the corresponding token in the network. The system checks the electricity availability and locked it before the sell order is published.
- A consumer who needs electricity could buy a token with the corresponding value. The system checks the consumer's balance and locked it before the buy order is published. When a sell order met a buy order, a transaction based on a smart contract is created.
- As a consumer consumes the electricity, the token with the corresponding value is burned. More explanation of burning the token will be explained in the Transaction chapter.

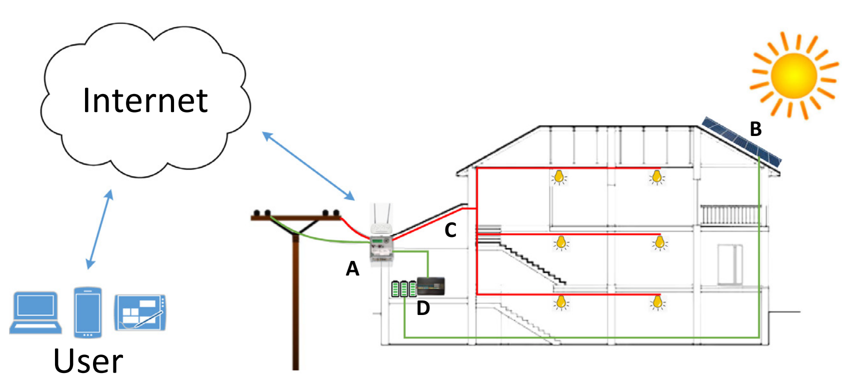

Fig. 5. Producer/consumer node.

Miners then verify the transaction, as follows.

- New transactions are included in a block candidate.
- Miners verify the transactions,

o

Check the producer's and consumer's account address,

o

Trace the consumer token ownership, whether the consumer is the proper owner of the tokens. Since the blockchain records complete transaction history, the chain of ownership of the token could be traced back.

o

Check whether a producer possesses enough electricity to be sold in the market.

- If the transaction is verified, the block candidate is added to the blockchain and broadcasted to all nodes in the network. The smart contract is then executed.

The smart contract itself acts as a digital protocol, which automatically performs predefined actions once the requirements are fulfilled by the previously agreed parties. In this case, the smart contract is used to ensure the electricity is delivered to the consumer once the consumer pays the previously agreed price to the producer. Because the smart contracts are written as code and committed to the blockchain, it also inherits the immutability of the blockchain, which means no one could modify the agreed contract. The contract logic would be as follows.

- Read the conditions (price, amount, source, destination, etc.)
- Check the requirements (payment)
- If the requirements have been verified then
  - o Grant access to an electric source,
  - o Record consumption.
- If consumption is reached, revoke access.

3.3. Transactions

In the energy market, electricity is a valuable and tradeable commodity. From that point of view, consider electricity as an asset, which represented by a token in a blockchain. Then consider the three entities in the smart grid concept (generators, consumers, and entities which can do both) as nodes, as described in Table 3. In cryptocurrency, a node joins and contributes to a blockchain network to get a reward. In our approach, it is mandatory for a node to join and contribute to the network, in order to consume and/or sell the electricity. A node may be rewarded for its positive contributions to the network, as will be explained in the reward mechanism chapter below. To maintain the infrastructure, or when a node uses additional service, such as using public grid storage, transaction fee can be added to the network.

For this research, consumers pay the electricity they need in advance. Producers provide electricity to the grid. They generate tokens, which they can sell at the network at a certain price. Consumers buy electricity on the market and receive a token worth the money. The token, then deducted when they consume electric from the grid. Instead of buying from a single producer, they can see all the offers from each producer. When the amount of electricity is consumed, the represented token is burned. Token burned indicates that the electricity represented by it has been consumed.

Burning a token is to transfer it to an irrecoverable address, so it cannot be used again. In the proposed architecture, this address is predefined and coded into the protocol. The token sent there would be irrecoverable, but everyone can see how much they have spent (how much they have transferred tokens to that address/burnt).

For this research, electricity generated by the government power plant was hedged to IDR.1467 per one kWh. This price is regulated by the government power plant (*Perusahaan Listrik Negara*/PLN) and adjusted over time. Other producers may raise or lower their price, but at their scale and the nature of the electricity market in Indonesia, they could only provide a limited amount of electricity. One advantage of having a government-owned plant in the grid is they can interfere with the price. When the price goes up, the government plant can sell its price at a lower price to lower the market price.

Fig. 6 shows a sample of transactions conducted in the research. These are simplified transactions, which do not include a transaction fee.

- A1 generates eight kWh and sells it to F2 (1 kWh), B1 (4 kWh), and C1 (3 kWh). The transaction is saved in Tx-100.
- Later, F2 consumes its one kWh of electricity, so F2 burns the token (Tx-200).
- B1 consumes three kWh, leaving one kWh at its balance (Tx-201).
- C1 generates one kWh from its solar panel. It consumes two kWh, so it burns two kWh. Instead of saving the rest, it decides to sell the two kWh to B4 (Tx-202).
- At the end of transactions, the balance for each account can be traced back from the beginning. For example, the C1 balance is now 2 kWh; 3 kWh bought from A1 (Tx-100) – 2 kWh consumed + 1 kWh generated (Tx-202).

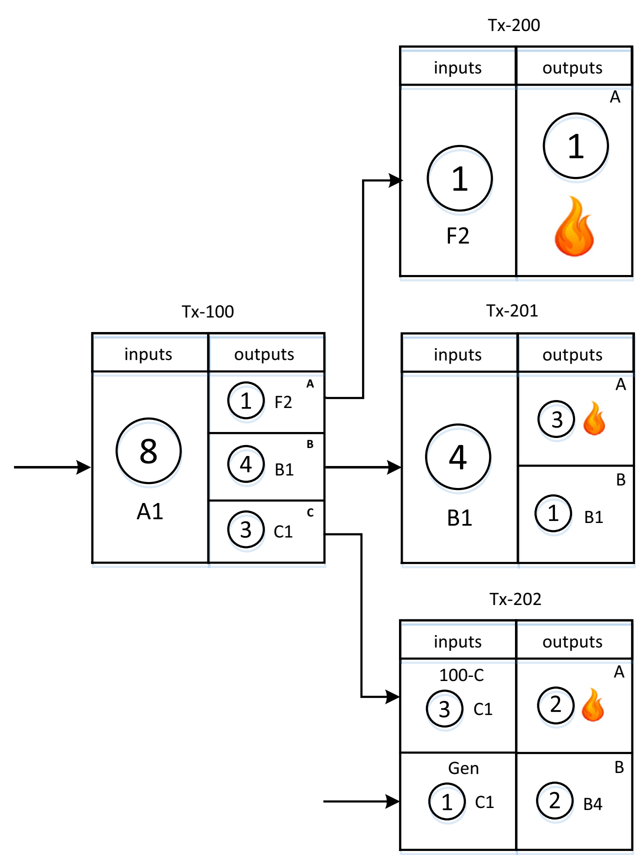

Fig. 6. Example of electricity transactions in the blockchain.

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To ensure all parties perform actions as they were supposed to, every transaction in the grid is stored as a smart contract. The asset locking mechanism acts as an escrow mechanism. All transactions are carried out successfully. The smart contract is capable to handle transactions between a generator and consumer and successfully burned the token after the consumer has consumed the corresponding electricity.

3.4. Client-side application

For the client, a mobile application is developed as an interface for users. The application connects to the blockchain via an API, which enables access to the smart contract that transacts on the blockchain, along with reading and writing transaction records into the blockchain. Variables such as electricity prices and cur-

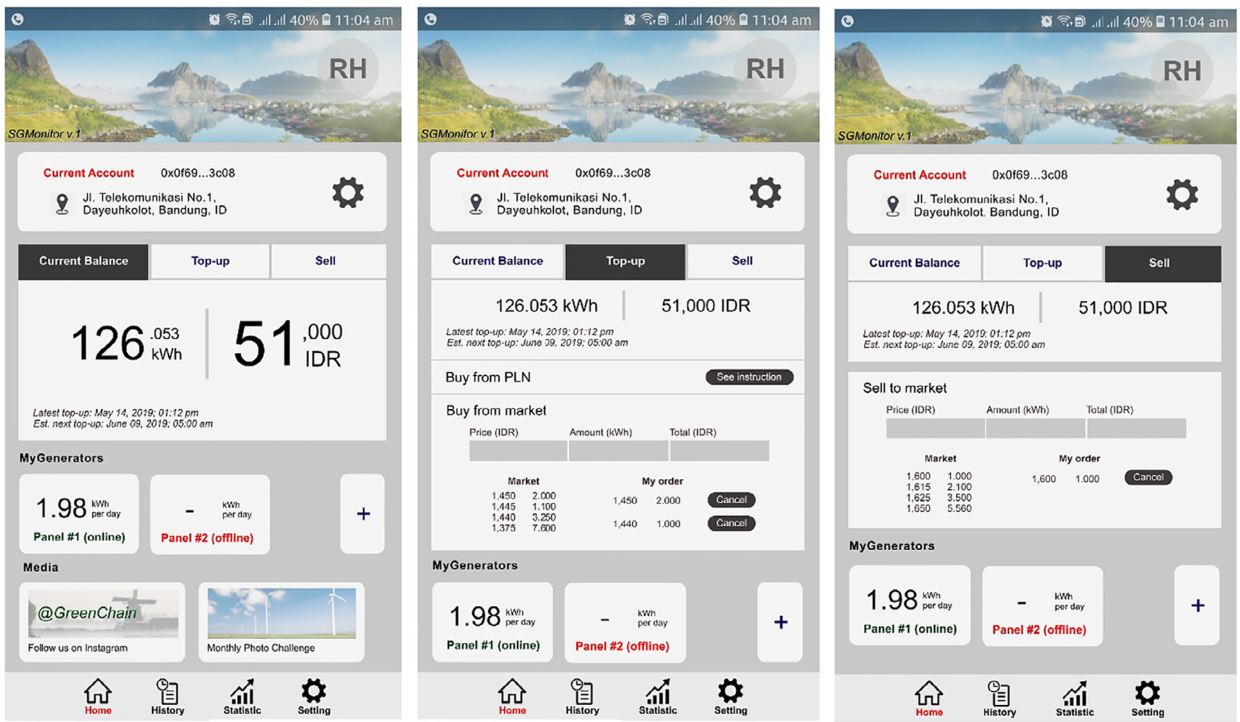

Fig. 7. Application interface (main functionality).

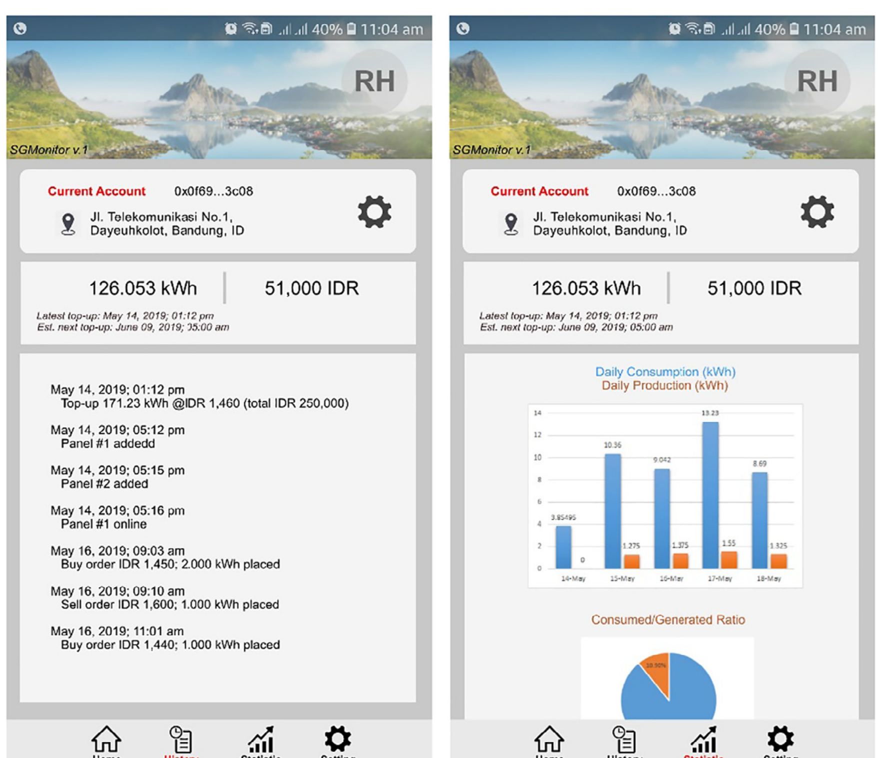

Fig. 8. Application interface (history and statistic).

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rency are set to Indonesia's national standard. The application then performs functionalities as proposed in Table 3, which are created and sell electricity (as a producer), and purchase and consume token (as a consumer). Below are some screen captures of the application.

Fig. 7 shows the main functionality of the application as proposed in the research. The left figure shows an account of the user, which consists of the blockchain and physical address of the user. The interface also shows the balance of the respected address, which divided into the remaining power in kWh and currency in IDR. Transactions, however, will be conducted in kWh and utilizing token, as visualized in Fig. 6. If a node acts as producer, the generator and its power is visible in MyGenerator section. Here the node has two solar panels, but only one is active and it generates 1.98 kWh per day.

The center image of Fig. 7 shows a top-up section when a user wishes to purchase electricity. Here a user can purchase from the government-owned power plant, or purchase from the market. Users can view offers available in the market. A user can put buying order at currently offered price or make his/her offer (in the example, the user place two offers, a 2.000 kWh at IDR.1450 and a 1.000 kWh at IDR.1440).

The right image of Fig. 7 shows the interface when a user wishes to sell the excess power. Here a user can view other sell orders in the market, and place his/her offer.

The left image in Fig. 8 shows the history of user transactions, while the right side shows statistics about the account, such as daily consumption, daily production (if the node also a producer), and other related information.

4. Conclusions and future works

The integration of blockchain into the smart grid allows the community to maintain transactions in the system in a consensus manner. Transactions are performed with smart contracts. Transaction history is stored in the blockchain and duplicated to all full nodes. The blockchain provides immutability to the smart contracts and transaction data, by restricting a record to be changed or erased. Therefore, a smart contract between a generator and a consumer will always be executed, providing certainty that a producer will always deliver the electricity when a consumer has paid. The immutability also provides traceability, which is good for audit or solving a transaction dispute. The Ethereum blockchain runs on Proof of Work consensus mechanism, so transactions are verified by miners around the world, including nodes running the full node.

Although the proposed system is capable to manage transactions in the smart grid, there are some points to be considered for future research.

- The Ethereum blockchain currently capable to process up to fifteen transactions per second, a limitation hard-coded in the protocol. The limitation would be a challenge if implemented in a full-scale smart grid.
- In public blockchain, the price will be based purely on supply and demand, and very sensitive to speculation. For example, the Ethereum reached the price of US$1432.88 on January 13, 2018, and fell to US$477.49 on June 13, 2018 (CoinMarketCap). This condition is not desirable, and the token price should be pegged to a fiat currency. Such a method is used by Tether, a cryptocurrency pegged to the USD. This is achieved by implementing Proof of Reserves, which creates token only in exchange for fiat money.
- The system cannot forbid people from selling electricity produced by dirty (but cheap) energy. People also tend to buy cheaper electricity regardless of its source. The blockchain records all transaction history. If a device capable to detect how the electricity was generated is presented, pricing can be adjusted based on this condition, promoting green energy and limiting electricity generated from the dirtier source.
- In public blockchain, transactions and balances of each address are public. For example, there is a web publicly list all Ethereum accounts and its balance (Etherscan). In our case, an account address corresponds to a node, and the node exists as a building or a house. To ensure all node truly exists in the real world, the government should have the mapping of these addresses, along with the owner's identity. The downside is, with the account provided in the web, criminals can target the wealthy account and track the owner. Transaction history can be made public but should be separated from the owner's identity. This can be achieved by implementing hybrid blockchain, which separates transactions and identities. In a hybrid blockchain, participation is open, but hosting and block creation can be set to trusted nodes only, making the network more secure (Muhammad Asad Khan et al., 2018).
- The proof of work consensus mechanism is resource extensive. In public blockchain, a person (or group of persons) with high-performance computing devices could dominate the system. A possible mechanism for future research is to use a consensus mechanism that considers a node's overall contribution to the system to choose the eligible nodes to add a block in the blockchain, such as the Proof of Importance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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