

Blockchain Technology for Sustainable Management of Electricity and Water Consumption [†]

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Abstract: Electricity and water are vital resources, but the current management systems face challenges due to growing demand and regulatory complexities. To address this, we introduce a novel blockchain-based solution for managing electricity and water services. Our proposed system connects various entities through smart contracts on the blockchain, automates processes, and ensures transparency. Customers can easily view and pay bills, track consumption, and enjoy secure online transactions while preserving their privacy. The shared digital ledger enhances trust among entities and promotes transparency. Additionally, our system contributes to environmental sustainability by reducing paper usage, incentivizing energy-saving devices, and efficiently managing electricity and water consumption. Finally, a meta-analysis of the related work is conducted to highlight the importance of our solution.

Keywords: blockchain; smart contract; water management; electricity management; distributed ledger; environmental sustainability



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1. Introduction

Blockchain is more than a technology; it represents a paradigm shift and a transformation of some sectors [1]. The United Arab Emirates (UAE) Government targets achieving a sustainable environment and infrastructure [2]. This should preserve the environment and balance between social development and economic growth. In this paper, we focus on supporting three goals: lowering the water scarcity index, raising the online services index, and enhancing the networked readiness index [3,4]. Achieving environmental sustainability is not only limited to using recycled products, reducing waste, or developing green products. It can also be achieved through the inclusive green way of thinking [5]. The current electricity and water management system is facing difficulty in keeping up with rising demand and regulatory complexity [6,7].

Blockchain technology is a decentralized system of numerous nodes communicating with one another. The blockchain acts as a shared and immutable ledger for keeping track of transactions [8]. In other words, a blockchain is a series of blocks arranged chronologically, with each block functioning as a single page in a ledger. New transactions are stored in a new block; then, the blockchain minors append new blocks to the existing blockchain. Blockchain allows parties who do not have complete trust in one another to maintain a set of global states. The blockchain is reproduced and propagated throughout a network of linked computer systems. The ledger, like the one used for Bitcoin, can be un-permission and open to the world. It can, however, be a permission, private, and prioritized one, like the one used for business [8]. We implemented the permissioned blockchain in this research work.

Blockchain technology is adopted in the finance sector, government sector, Internet of Things (IoT), cybersecurity applications, cloud storage, smart property management, notary, real estate, smart contracts, identity management, smart cities, medical image watermarking, and vehicular networks, to list a few [8–13]. The integration of transactions into blockchain technology is reported to improve transparency, mitigate cyber threats, and improve trust in the public sector [14].

One of the primary motivations for implementing blockchain is to protect consumers' information and reduce the likelihood of security threats. Businesses can monitor transactions and products back to their source via the blockchain, which is another advantage in the workplace. The UAE government started implementing blockchain in its services and transactions in 2018 [15]. The estimated savings will be 77 million annual work hours, \$400 million annual hard copy documents, and three billion US dollars of transactions and document processing. It also aims to transform half of the governmental transactions by 2023 [15].

This work aims to utilize blockchain technology in managing electricity and water consumption. The blockchain ensures immutable and secure storage of bills, consumption records, and online transactions. Thus, this work reveals to practitioners and researchers the benefits of using a blockchain-based solution in managing electricity and water consumption. Furthermore, we propose a blockchain-based management system that consists of three layers. The Hyperledger Fabric is managed in the data layer. The application layer includes a database and other servers to communicate with the Hyperledger Fabric. Finally, the presentation layer includes the user applications.

The rest of the paper is structured as follows: blockchain background and recently reported work are presented in Section 2. Our proposed blockchain-based solution is discussed in Section 3. Finally, the conclusions and future work are explored in Section 4.

2. Background

For e-governments, blockchain is an innovative technology that can be used to improve data security. It also provides a framework for resolving interoperability issues across various entities [16].

To make consumer resources and information easier to access, a blockchain-based authorization community energy management system was developed [17]. Different communities participate in the monitoring and coordination of resource usage, which guarantees safe data access and storage. Virtual assets for sharing energy and water resources were presented in an auction, which improved global consumption efficiency and resource preservation [17]. On the other hand, the term “energy internet” describes a collection of distributed energy storage and gathering devices, power networks, information technology, intelligent management, and advanced power and electronics [18]. The energy nodes were intelligently interconnected to form a network of energy reciprocal exchange and two-way energy flow. Blockchain and big data were used to develop an energy grid pricing and transaction model. It offered free trade between producers and consumers and a market-oriented pricing model [18].

The term prosumer refers to a person who can be a consumer and producer at the same time. Another study investigated prosumers' concerns about smart contracts and information transparency, as well as their perceptions of blockchain in the energy sector. It also investigated the legal implications of smart contracts. The paper concluded that users have concerns regarding information transparency that should ensure a fair and secure market [18]. To promote green energy, a decentralized electrical power system was designed using sensors, blockchain, and smart contracts. The paper also proposed a power grid model that combined the IoT, blockchain, and smart contracts to produce green energy [6]. Local Energy Markets (LEM) are decentralized markets that allow members to exchange energy via a trading platform. In [7], a decentralized peer-to-peer (P2P) Local Energy Market based on private blockchain was suggested to increase the local production of energy from renewable sources. To improve energy use and reduce electricity costs, a

home energy management system was implemented. Further, the smart contracts of energy trading were secure against cyber threats [7]. To handle power imbalances in power grids, an Ethereum smart contract-based solution for managing large-scale residential energy storage systems was developed [19]. It ensured that shared storage unit owners were selected and fairly and transparently compensated [19].

In [20], the use of blockchain technology for the development of digital business models was explored. The paper recommended the use of peer-to-peer trading based on decentralized renewable energy services. In [21], the consumer demand for a decentralized blockchain-based peer-to-peer energy trading scheme to address electricity management issues was explored. The paper concluded that any solution should be able to meet the participants' energy needs and function at the regional level [21]. Another work targeted the big industry energy market by proposing a more accurate market structure. The proposed method addressed the user's optimal load management challenges and modelled the cost of proof-of-work [22].

Another work integrated the existing water management system with a smart contract agreement system to automate work processes [23]. A research team proposed a novel "Energy Internet"—a dynamic network enabling real-time, two-way exchange of energy, data, and financial transactions. Their model integrated small-scale renewable energy consumers, storage units, and electric vehicles via advanced technologies like the Internet of Things, vehicle-to-grid, and blockchain, promoting efficient power transfer [24].

The authors of [25] implemented a blockchain-based distributed monitoring system that offered a secure real-time control operation of node transactions that was used to manage power transfer and mitigate energy power failure [25]. Another work proposed a solution to provide small farmers with alternate irrigation systems [26]. It watered agricultural lands based on green energy generated from photovoltaic panels. The smart contracts were used to monitor the system's performance, and energy demand, and automate daily operations [26].

Another work utilized blockchain technology to propose a fully decentralized business model for the management of the electricity and energy market [27]. The proposed system integrated renewable energy devices offered peer-to-peer energy trading, and increased consumer engagement levels [27]. A feasible blockchain-based consensus method with parallel computing was introduced to offer an efficient and secure peer-to-peer transaction service model with application in the renewable energy field [28]. The proposed solution improved the system's stability, node reliability, and performance [28]. To handle massive data, a new distributed electrical market trading platform, based on blockchain, was suggested. A search engine was developed, utilizing smart contracts, to help the electricity purchasing and selling nodes in selecting the final delisting plan [29].

In [30], consortium blockchain and game theory were used to develop a peer-to-peer distributed energy trading scheme. The proposed system reduced operating costs and improved the security of transactional data. In [31], a permissioned blockchain system was proposed to manage renewable energy microgrids. The proposed energy trading platform offered a low-cost solution and utilized smart contracts and IoT to automate business processes [31]. In [32], a water waste management system was proposed based on IoT and blockchain technology. The proposed system effectively managed and monitored the medical water waste for healthcare operations [32]. In another work, a blockchain-based energy management and power trading system was proposed that utilized IoT, artificial intelligence, and blockchain technology to manage and monitor green power transactions between commercial buildings [33].

We also performed a meta-analysis of previous work to establish ground for our proposed solution. In this regard, we analyzed 25 different proposed methods and solutions, their challenges, energy management approach, privacy and security concerns, and environmental sustainability aspects [6,7,10–12,15–34]. We show 10 papers in Table 1 as a sample. About 75% of the 25 explored papers addressed electricity consumption via blockchain,

33% addressed water consumption via blockchain, 25% addressed privacy concerns, 83% addressed security concerns, and 33% addressed environmental sustainability.

Table 1. Experimental data Summary.

Method	Challenges	Energy Management	Privacy and Security	Environmental Sustainability
A blockchain-based authorization energy management system [6]	High latency, computational and storage overheads, 51% of attacks may succeed and control the network	Electricity and water resources	Secure data access and storage and delegation of controller functions among householders. It ensures the privacy and trustworthiness of all transactions	Not addressed
Decentralized energy using blockchain and data analytics to optimize pricing and transaction [7]	A possibility for contract breach, lack of in-depth discussion	Energy resources	The management platform ensures information security	Not addressed
A power grid model that combined the IoT, blockchain, and smart contracts to produce green energy [10]	The scalability of blockchain can be improved. The time can be further reduced	Centralized model of electrical energy production	Connected sensors encrypt data and verify device identities to ensure privacy and security	Decrease the environmental problems
A decentralized peer-to-peer LEM based on a private blockchain [11]	Penalty policy is not incorporated, issues in the creation of rebound in off-peak hours	Minimize electricity costs.	Security vulnerability analysis is used to ensure an energy trading smart contract platform	Reduces the environmental crisis and the energy losses as energy
Ethereum smart contract-based solution for managing large-scale residential energy storage systems [12]	The analysis needs to further explore the trade-offs between traditional auctioneers and smart contract-based systems	Renewable energy resources	Safeguard financial assets contingent upon the satisfaction of specified conditions	N/A
A new and more accurate market structure for big industrial users [15]	Targets only big consumers. Lacks scenarios for multiple consumers	Electricity market platforms and pumping load of a water supply plant	Network security is maintained	N/A
Integrated an existing water management system with a smart contract agreement system to automate work processes [16]	More intensive robotization of the water supply networks, with full accountability and transparency	Water management system	Guarantee secure and transparent financial transactions with consistent, tamper-proof data for all economic actors	Address some of the sustainability challenges
Blockchain-based distributed monitoring system to manage power transfer and mitigate energy power failure [18]	Private network-based permissions architecture	Distributed Power Systems	Leveraged blockchain to tackle security and privacy concerns plaguing distributed renewable energy systems, fostering trust and transparency in energy transactions	N/A
Smart contracts are used to monitor the system's performance, and energy demand, and automate daily operations [18]	Targeted small farmers only	Energy supply from national electricity system, smart water metering solution	Smart contract functions to improve security, Remix Ethereum to test security	Innovative and sustainable solutions for agro-power-problems
Fully decentralized business model for the management of electricity and energy market [19]	The study laid the theoretical groundwork for a fully decentralized P2P energy market, exploring its mechanisms and potential ramifications	Expands the four dominant archetypes of business models in the energy and electricity market	Reduces dependability and improves security of electrical grids	N/A

Although blockchain is employed in a variety of applications, it is still a relatively new technology. This is because blockchain technology must handle several difficulties, including efficiency, privacy, security, energy consumption, interoperability, regulatory concerns, scalability, and environmental sustainability [34].

3. Proposed Blockchain Solution for Water and Electricity Management

In this paper, a blockchain-based mobile application is developed to manage electricity and water consumption services across the following four entities. Our proposed solution uses smart contracts and keen agreements to integrate the different entities to automate and secure business processes. The participants or members of the blockchain solution are:

- Abu Dhabi Distribution Company (ADDC): a local energy distribution corporation that plans, runs, maintains, and owns network distribution assets for water and electricity [35].
- Fazaa: provides services and discounts to customers interested in purchasing energy-saving devices.
- Bin Moosa & Daly: sells energy-saving devices and provides solutions to reduce water and electricity consumption.
- Customer: any resident inside the UA

The major transactions and business services of the proposed solution can be summarized as follows:

- A customer orders an energy-saving device from Ben Moosa & Daly. Ben Moosa & Daly should get approval and authorization to sell the device(s) from the Abu Dhabi distribution company.
- The Ben Moosa & Daly changes the status of an order to submitted, pending, in progress, or accepted.
- The ADDC prepares and sends the new water and electricity bill to the associated customer. After that, the customer views and pays the bill.
- Customers can purchase or subscribe to a Fazaa card to receive a discount when purchasing energy-saving devices.

The participants of the proposed blockchain-based solution can use the following applications:

- EnergyBlockchain app: customers purchase energy-saving devices, view and pay electricity and water bills, track orders, and monitor use.
- BenMoosa Dashboard: customers search and place orders for energy-saving devices, and use Fazaa card to get discounts.
- Fazaa Dashboard: customers buy or renew Fazaa subscriptions.
- ADDC Dashboard: employees check customer consumption details, generate new bills, verify bill payments, and verify Fazaa card validity before applying a discount.

Figure 1 shows the redemption point transaction workflow between three entities. Sally, the customer, requests to use her redemption points, which she gained from buying energy-saving devices, to get a discount. The transaction goes to Bin Moosa & Daly to check Sally's balance. If Sally has a balance, Bin Moosa & Daly deducts the suitable amount of redemption points and approves Sally's request. Next, the ADDC approves the use of redemption points and applies a suitable discount on the bill. Finally, Sally pays the discounted bill.

As another example, Figure 2 shows the transaction workflow of purchasing an energy-saving device between four entities. Sally submits a request to the blockchain to buy an energy-saving device. Next, Emma from Bin Moosa & Daly checks their inventory and approves the purchase request. After that, Hamdan checks the ADDC dashboard to verify that the requested energy-saving device is listed on their approved list and then authorizes the request. Next, Omar checks Sally's subscription status using Fazaa's dashboard and then approves a suitable discount rate. After that, Sally finalizes the payment. Finally, Emma issues an order to the inventory to ship the device to Sally.

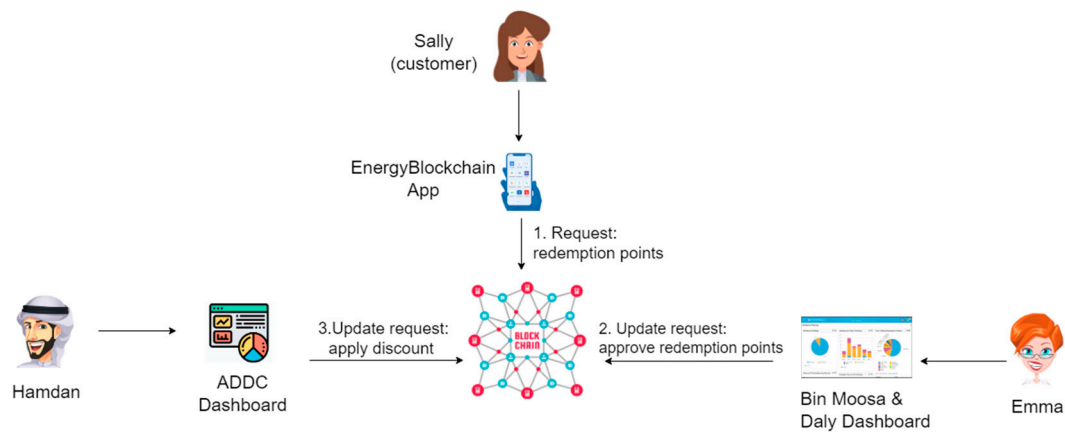


Figure 1. Redemption points network diagram.

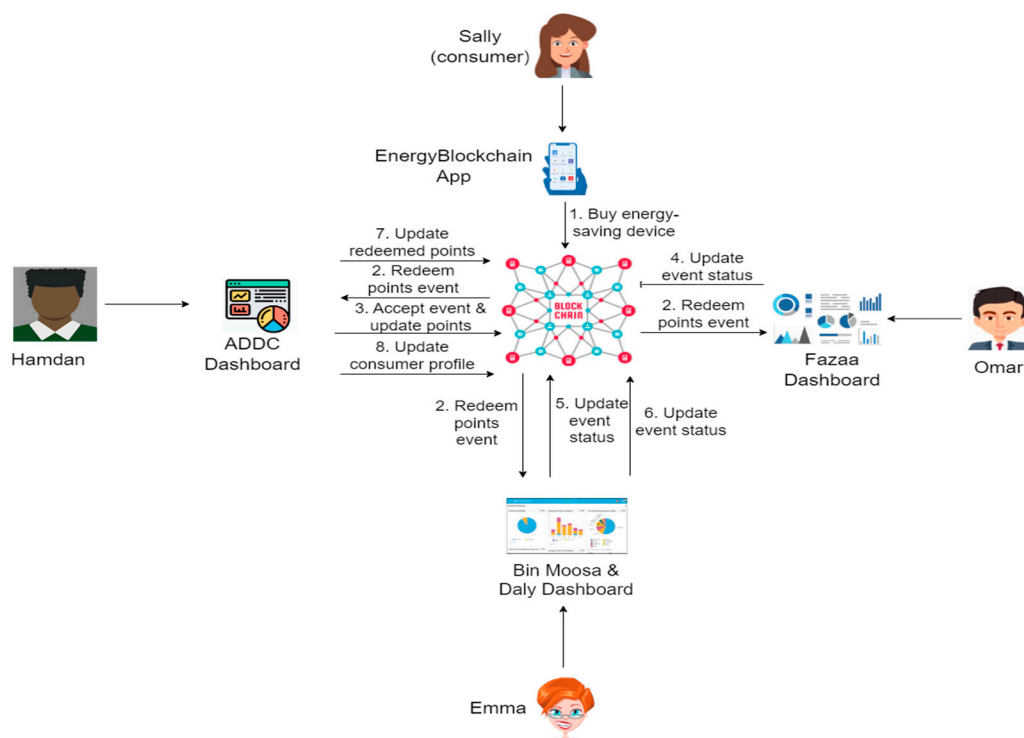


Figure 2. Buying energy-saving device network diagram.

4. Implementation Details

Figure 3 illustrates the implementation steps of the proposed solution. The network layer is implemented using the Hyperledger Fabric, an open source for developing cross-industry blockchain technologies [36]. We used the IBM Blockchain Platform extension to create the business logic (smart contract) and package it for deployment, connect to any instance of the Hyperledger Fabric, run and debug the smart contract, submit transactions, and generate functional-level smart contract tests [37]. The IBM Blockchain Platform extension combines simplicity, scalability, security, and enterprise-grade support, making it an appealing choice for blockchain development. It also enables developers to build robust, scalable, and secure blockchain applications while seamlessly integrating with existing enterprise systems [37].

The following subsections provide examples of the proposed blockchain-based solution for electricity and water consumption management.

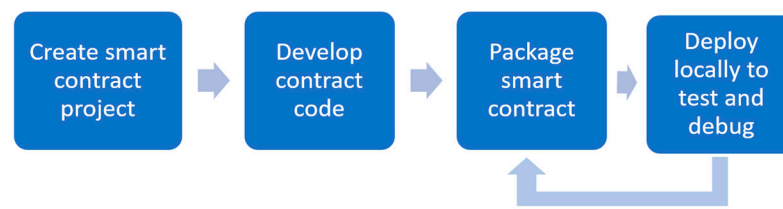


Figure 3. Proposed solution implementation steps.

4.1. Asset Modelling

To model the different assets of the blockchain business network, we used TypeScript [38]. For the sake of simplicity, in this section, we define one asset. It is worth mentioning that the entire code is developed by the authors. Figure 4 illustrates the definition of the asset energy device as an object. As shown in line 1, we imported the *Fabric-contract-API* to provide the contract interface, which is a high-level API to implement smart contracts [39]. It is worth mentioning that the data utilized in our solution comprises synthetic data about assets and transactions.

1. Import the Object and Property from the 'fabric-contract-api' library.
2. Create a class called 'EnergyDevice'.
3. Declare a public property called 'DeviceID' of type string.
4. Declare a public property called 'DeviceDescription' of type string.
5. Declare a public property called 'DeviceMake' of type string.
6. Declare a public property called 'DeviceModel' of type string.
7. Declare a public property called 'DeviceOwner' of type string.
8. Declare a public property called 'DevicePrice' of type string.
9. Declare a public property called 'OrderId' of type string.

Figure 4. Energy device asset definition.

4.2. Smart Contract Function Development

As shown in Figure 5, before starting the development of the smart contract logic (functions), it is essential to import the *Fabric-contract-API* and the assets of the blockchain business network and then extend the Contract class.

Step 1: Import the necessary libraries and modules

```

import {Context, Contract, Info, Returns, Transaction from 'fabric-contract-api';
import {EnergyDevice} from './energy-device';
import {Order, OrderStatus_ from './Order';

```

Step 2: Create a class that implements the Contract interface

Figure 5. Importing required objects.

The next step is to prepare the logic of the smart contract. The functions provided in Figures 6–9 are examples related to the energy-device asset, which was introduced in the previous section. Each function in the smart contract has “ctx” as its first parameter, which provides smart contract creators access to various Fabric APIs and enables them to carry out tasks linked to complex transaction processing [40]. The function *energyDeviceExists* in Figure 6 is used to check for an asset’s existence in the ledger. This function does not change the status of the ledger (read-only). Line 2 uses the API *getState* to read an asset based on its ID from the ledger and assign the value to a buffer. Lines 3–5 return true if the asset exists or false if not. The overall complexity of the given function can be approximated as $O(1)$, indicating constant time complexity. This implies that the execution time of the function does not significantly increase with the size of the data or the number of private assets in the collection.

```

1. FUNCTION energyDeviceExists(ctx, energyDeviceId)
2.   buffer <- ctx.stub.getState(energyDeviceId)
3.   IF (buffer.length > 0)
4.     RETURN TRUE
5.   ELSE
6.     RETURN FALSE
7.   END IF
8. END FUNCTION

```

Figure 6. Energy device asset existence verification.

```

1. FUNCTION CreateEnergyDevice(ctx: Context, energyDeviceId: string, deviceDescription: string, deviceModel: string, devicePrice: string,
   deviceOwner: string, orderId: string)
2.   EXISTS <- EnergyDeviceExists(ctx, energyDeviceId)
3.   IF (EXISTS) THEN
4.     ERROR('The energy device already exists')
5.   ELSE
6.     eg <- new EnergyDevice(energyDeviceId, deviceDescription, deviceModel, deviceModel, DevicePrice, deviceOwner, energyDeviceId)
7.     buffer <- Buffer.from(JSON.stringify(energyDevice))
8.     ctx.stub.putState(energyDeviceId, buffer)
9.   END IF
10. END FUNCTION

```

Figure 7. Energy device asset creation.

```

1. FUNCTION queryEnergyDevice (ctx: Context, energyDeviceId: string)
2.   exists <- EnergyDeviceExists(ctx, energyDeviceId);
3.   IF exists = false
4.     THEN throw ERROR('The energy device does not exist');
5.   buffer <- GetState(ctx.stub, energyDeviceId);
6.   eg <- ParseJSON(buffer);
7.   return eg;
8. END FUNCTION

```

Figure 8. Energy device asset search.

```

1. FUNCTION queryEnergyDevice (ctx, energyDeviceId, devOwner)
2.   exists <- EnergyDeviceExists (ctx, energyDeviceId)
3.   if (exists = false)
4.     Throw ERROR ('The energy device does not exist')
5.   buffer1 <- GetState (ctx, energyDeviceId)
6.   eg <- Parse (buffer1.toString()) as EnergyDvice
7.   eg.DevcieOwner <- devOwner
8.   buffer2 <- buffer.from (JSON.stringify (eg))
9.   PutState (ctx, energyDeviceId, buffer2)
10. END FUNCTION

```

Figure 9. Energy device asset owner update.

The function in Figure 7 is used to create an asset energy device. This function updates the ledger. Line 2 calls the function *energyDeviceExists*, which was already explained in Figure 6, to check if the asset already exists or not; if yes, an error message will be issued (lines 3–4); If not, line 5 creates an instance of the asset. Finally, lines 6–7 update the ledger.

The function in Figure 8 is used to search for an energy device asset. However, this function does not update the ledger. Line 2 calls the function *energyDeviceExists* to check if the asset already exists or not; if not, an error message will be issued (lines 3–4); If yes, then, lines 5–7 retrieve the asset in the correct format. The overall complexity of the given function can be approximated as $O(1)$, indicating constant time complexity.

The function in Figure 9 is used to update the owner of the asset energy device. This function updates the ledger. Line 2 calls the function *energyDeviceExists* to check if the asset already exists or not; if not, an error message will be issued (lines 3–4); If yes, then, lines

5–6 are to retrieve the asset in the correct format (converting JSON object to Utf8 String). Line 7 is used to update the owner, while lines 8–9 are used to convert the energy device from the string into a JSON object and update the ledger. The overall complexity of the given function can be approximated as $O(1)$, indicating constant time complexity.

4.3. Packaging and Instantiating the Smart Contract

The purpose of packaging a smart contract is to create a deployable artefact that can be deployed to a blockchain network. The IBM extension provides a graphical interface to package your smart contract code into a format compatible with the blockchain framework (such as the Hyperledger Fabric Chaincode package). After packaging the smart contract, it must be deployed to the blockchain network (business network). The IBM Blockchain extension provides tools to configure and deploy the smart contract to the business network (channel).

4.4. Testing the Smart Contract

In this section, we test the smart contract by invoking its functions. For each function, there are two options: evaluate the transaction and submit the transaction, as shown in Figure 10. Two functions can be used to update the ledger: *createEnergyDevice* and *updateEnergyDeviceOwner*. Once a function is selected, the submit transaction option should be used. The *evaluate* transaction option.

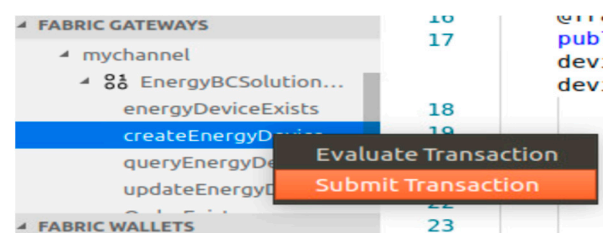


Figure 10. Testing the smart contract.

To create a new asset of energy device, the *createEnergyDevice* function is used with suitable parameters, as shown in Figure 11.

```
[4/24/2022 12:10:17 PM] [INFO] submitTransaction
[4/24/2022 12:10:45 PM] [INFO] submitting transaction createEnergyDevice with args ed1,company X,it is a desc.,M12,Jon,333,o1
[4/24/2022 12:10:47 PM] [SUCCESS] No value returned from createEnergyDevice
```

Figure 11. Creating a new asset of energy devices.

To check if the energy device asset with the id “ed1” exists or not, we invoke the function *energyDeviceExists*(“ed1”) as shown in Figure 12.

```
[4/24/2022 12:12:04 PM] [INFO] evaluateTransaction
[4/24/2022 12:12:34 PM] [INFO] evaluating transaction energyDeviceExists with args ed1
[4/24/2022 12:12:34 PM] [SUCCESS] Returned value from energyDeviceExists: true
```

Figure 12. Verifying energy device existence.

To return an asset from the ledger, the function *queryEnergyDevice* (“ed1”) is invoked, as shown in Figure 13.

```
[4/24/2022 12:15:09 PM] [INFO] evaluateTransaction
[4/24/2022 12:15:54 PM] [INFO] evaluating transaction queryEnergyDevice with args ed1
[4/24/2022 12:15:54 PM] [SUCCESS] Returned value from queryEnergyDevice: {"DeviceDescription":"it is a desc..", "DeviceID":"ed1", "DeviceMake":"company X", "DeviceModel":"M12", "DeviceOwner":"Jon", "DevicePrice":"333", "orderId":"o1"}
```

Figure 13. Returning an asset from the ledger.

In 2020, the Dubai Electricity and Water Authority (DEWA) joined the blockchain network to improve customer experience by automating bills and contracts [41]. One year later, in 2021, all tenancy contracts were integrated into the blockchain network where DEWA receives 2000 daily contacts to be verified and signed through the blockchain. Per the latest research in this field and up to the authors' knowledge, no blockchain-based solution has been developed for water and electricity management [42].

5. Conclusions

Water and electricity have traditionally been regarded as important resources in any country. The current power and water management system is experiencing challenges because of increasing demand and regulatory complexity. In this paper, blockchain is used to handle all transactional electricity and water consumption services. The developed system includes three dashboards that can be used to automate, secure, and improve trust and transparency, and as a shared digital ledger between the different entities. Further, the mobile application was developed to be used by users to view and pay electricity and water bills, track consumption records, improve trust and privacy, and as a secure management solution. Finally, environmental sustainability is supported by minimizing paper consumption and rewarding the use of energy-saving equipment.

Future work includes improving the smart contract and creating indexes to improve the performance of queries. We also plan to investigate the use of the machine learning (ML) framework on top of our blockchain-based application to enhance customer services. Finally, we plan to evaluate the scalability of our blockchain solution to ensure that it can handle the increasing volume of transactions without excessively straining energy resources, which is vital for sustainable long-term adoption.

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