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RESEARCH ARTICLE

# Blockchain-Based Distributed Renewable Energy Management Framework

**SHIKAH J. ALSUNAIDI**[1] **AND FAKHRI ALAM KHAN**[1,2]

[1]Department of Information and Computer Science, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
[2]Interdisciplinary Research Centre for Intelligent Secure Systems, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Corresponding author: Fakhri Alam Khan (fakhri.khan@kfupm.edu.sa)

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**ABSTRACT** Most of the world's countries are concerned with reducing harmful gas emissions. Some governments have made considerable attempts to address this problem. Saudi Arabia, for example, has taken significant steps to utilize renewable energy (RE) sources in addition to oil and gas. Consumers are encouraged to build small RE systems. These small grids will help people meet their daily electrical energy requirements. They can sell the excess to other customers. One of the major issues is managing the distribution and sale of RE. Blockchain-based peer-to-peer (P2P) networks can help overcome several obstacles to the implementation of a distributed RE management system (DREMS). However, several impediments may still stand in the way of its execution. Scalability and productivity are two of the most important considerations. The number of transactions made to the Blockchain network will increase in lockstep with the number of energy consumers. This will result in a significant lag in response. Understanding the renewable distributed energy system will aid in minimizing the effects of these roadblocks. Therefore, this research identifies the RE systems installation approaches, and how Blockchain technology can be utilized. It provides the solution requirements of any DREMS. Moreover, it proposes a new Blockchain-based framework for DREMS. And designs selective protocols of the proposed framework. It provides a comparative analysis to assess the proposed protocols' ability to meet the identified requirements.

**INDEX TERMS** Blockchain, distributed management, microgrid, renewable energy.

## I. INTRODUCTION

Population and economic growth in the world in general, and in Saudi Arabia in particular have been accompanied by an increase in energy consumption, whether in the form of fuel, electricity, or water desalination. In order to preserve current resources and achieve balance and economic development, Saudi Arabia has taken significant steps to benefit from renewable energy sources (RESs) such as solar and wind, in addition to oil and gas, as part of the National Renewable Energy Program [1], one of the initiatives of Vision 2030 for Saudi Arabia. One of the program's objectives is to maximize Saudi Arabia's share of renewable energy production, in addition to reducing carbon dioxide emissions.

Renewable energy is energy derived from naturally renewable sources. It is also known as green energy or clean energy. Unlike fossil fuels, RESs are inexhaustible. However, they generate a specific amount of energy per unit of time [2]. Saudi Arabia has a high capacity for solar energy production due to its geographical location within the global sunbelt. Saudi Arabia has one of the highest rates of sun irradiation in the world [3]. Recently, interest in distributed energy generation based on RESs has increased, because it does not emit pollutants into the atmosphere. The lower cost of wind turbines and solar panels has also increased their acceptance in small grids and smart homes. However, the amount of energy produced from renewable energy sources is affected by environmental factors such as wind speed and the amount of sunshine shining on solar panels, which makes them unreliable and makes connecting consumers to the main grid mandatory [4].

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Traditional energy systems are managed by a trusted central authority. This central agency is responsible for managing the distribution and sale of energy to customers. Renewable energy units used in home or in small grids can generate excess energy than they need. The central entity purchases excess energy from consumers to resells it to other consumers. With the increase in the number of consumers, the overheads, and costs on the central authority increase. This increases the need for a secure and reliable distributed energy management solution [5]. Employing Blockchain technology in a distributed energy management system can overcome these challenges [5], [6]. Blockchain will also contribute to building reliable and secure peer to peer (P2P) energy trading systems [4], [5]. For example, Brooklyn microgrid, the Blockchain-based power trading project in New York [7].

### A. PROBLEM STATEMENT

The Kingdom of Saudi Arabia seeks to contribute to reducing carbon emissions by relying on renewable energy to produce electricity instead of fossil fuels [8]. The Saudi's Vision 2030 has adopted a number of promising plans and renewable energy projects to achieve this goal [9]. The residential sector in Saudi Arabia is the highest in terms of electrical energy consumption at 44.5% based on the 2019 annual statistics of the electricity and water desalination industry [10]. Despite the community's awareness of the benefits of employing renewable energy systems and relying on them to generate electricity [11], the initial installation costs and long-term benefits make their adoption a challenge for the residential sector [11], [12]. Residential photovoltaic (PV) installations are expected to contribute to generating more than 80% of the electricity needs [13], which calls for finding effective solutions that encourage their adoption in the residential sector.

### B. OUR APPROACH AND CONTRIBUTIONS

Blockchain technology has a vital role in managing renewable energy distribution. It can assist in overcoming a lot of challenges. For example, selling the surplus energy produced by small and home grids, maintaining the privacy and anonymity of subscribers, tracking transactions in a secure manner. However, there are still some obstacles that may hinder its implementation [14]. Scalability and productivity are two of the most crucial. The number of transactions submitted on the Blockchain network will grow in tandem with the number of energy consumers. This will cause a noticeable delay in response. Understanding the renewable distributed energy system by addressing the following questions: 1) what data should be stored in the Blockchain, 2) what processes should be traced, and 3) who will utilize the system will help to mitigate the consequences of these obstacles. Even though there are various Blockchain-based energy distribution management systems in the literature, they do not provide clear answers to these questions.

The main contributions of this study can be summarized as follows.

1) Solution requirements identification that must be achieved in any distributed renewable energy management solution.
2) A design of the main protocols of the proposed Blockchain-based distributed renewable energy management approach.
3) Comparative analysis of the proposed approach with the state of the art.

### C. ORGANIZATION

The rest of this paper is organized as follow. Section 2 explains terms that are frequently mentioned in the paper. Section 3 reviews existing solutions of renewable energy distribution management. Section 4 identifies solution requirements. Section 5 introduces the proposed framework and its main protocols. Section 6 provides the discussion and analysis. Section 7 concludes the paper and provides the future work.

## II. BACKGROUND

This section explains a number of terms that are used frequently in different sections of this paper.

### A. BLOCKCHAIN

Blockchain is a peer-to-peer network-based transaction mechanism. It enables secure transactions to be carried out without the requirement for a trusted third party [15]. It is built on a shared database or "ledger" that is stored on several nodes in various locations. The ledger keeps track of all transactions or "blocks" and expands continually as new blocks are added, establishing a sequence of interconnected blocks with verifiable data. Because there is no central location, manipulating the information stored in the numerous nodes is challenging. Blockchain is classified into three types: public, private, and consortium or (permissioned) [16]. Furthermore, Blockchain is primarily based on consensus algorithms [17], which govern how transactions are approved in the Blockchain network. Blockchain offers several security features that make it suited for improving a variety of applications in energy sector [5], [18]–[20].

### B. RENEWABLE ENERGY MANAGEMENT SYSTEM

There are three approaches for installing renewable energy systems, namely on-grid, off-grid, and hybrid [21]. As shown in Fig. 1, the on-grid approach connects the renewable energy system (RES) with the electrical grid. The RES feeds the facility with the necessary energy and the shortage is compensated by importing it from the electricity grid. The excess energy produced by the RES is sent to the electrical grid, as the smart meter operates in two directions. The surplus is accumulated in the user's balance to be used in the following month when needed. At the end of the year, the surplus is purchased from the user if it is not used [22].

In the off-grid approach, the RES is not connected to the electricity grid, instead contains a battery to store excess electricity for use at night or when it's cloudy. In this approach, the user is not affected by any interruptions or damage to

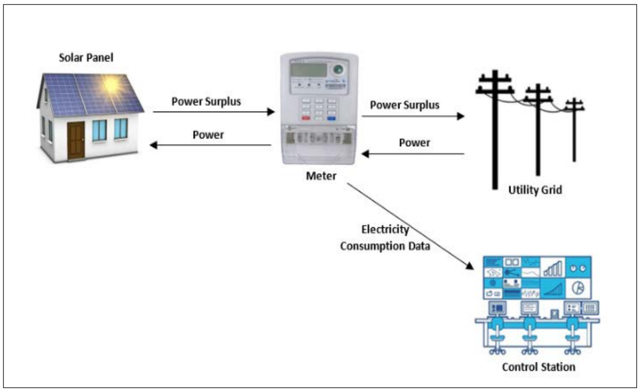


**FIGURE 1.** Existing solar energy framework in saudi arabia. (On-grid approach.)

**TABLE 1.** Renewable energy systems installation approaches.

| | On-grid | Off-grid | Hybrid |
|---|---|---|---|
| Connected to the distribution system | ✓ | × | ✓ |
| Contains battery | × | ✓ | ✓ |
| Protected from distribution network malfunctions | × | ✓ | ✓ |

the public electricity grid, but on the other hand, its costs are considered high compared to the on-grid method due to the need to provide sufficient storage units to cover the user's electricity needs [21]. Hybrid approach can combine the advantages of both on-grid and off-grid systems. It connect the RES to the electricity grid and contains a battery that used to store excess electricity [21], [23]. Table 1 compares the three RES installation approaches.

The Saudi Electricity and Cogeneration Regulatory Authority has developed the regulatory framework for small-scale solar PV systems (SSSPV). The framework defines the controls and provisions for linking SSSPV systems to distribution system. The on-grid approach is followed, the surplus energy for residential and non-residential consumption can be sold to the distribution system at 7 and 5 Halalah/KW/H, respectively [22]. The other two methods can be installed, but there is no way to invest in the surplus energy produced and the only consumer of it is the owner.

## III. LITERATURE REVIEW

This section introduces and discusses the existing RES management Blockchain-based approaches found in the literature.

### A. MONITORING AND MANAGING THE DISTRIBUTION OF RENEWABLE ENERGY

Although renewable energy grids are very affordable to create, and their sources are generally available, there is still a need for effective technologies to monitor and manage energy distribution especially for small and home grids. To that end, several Blockchain-based approaches have been proposed. For example, Wang *et al.* [24], proposed an off-grid energy management system based on the permissioned Blockchain. Only eligible participants can join the microgrid, as the entity mapping is used with a unique identity to identify each enterprise, person, and device. The system relied on direct point to point communication between any two parties to avoid delays resulting from centralization. The user registration method relies on a zero-knowledge proof mechanism that enables anonymous user identity distributed registration.

Plaza *et al.* [25] have designed a Blockchain-based prototype solution to manage solar energy exchanges between energy community in France. The solution allows for the redistribution of energy among the participants based on the energy community's rules. It benefits from the smart metering infrastructure that were installed by Distribution System Operators (DSO) that considered a trusted party of the energy data. Smart meter measures the produced energy then send it to the Blockchain system through IoT devices. The smart contract is used to calculate the appropriate allocation of the produced energy to each participant based on pre-defined rules. Several requirements were considered in the solution which are: 1) Security and trust as the data must be tamper-proof. 2) Confidentiality because energy measurements are personal data that must be protected. 3) Reliability and data integrity. 4) Robustness and resilience. 5) Auditability. 6) Execution performance of the IoT device. 7) System flexibility. 8) Scalability. 9) The system's energy efficient. However, the system regularly calculates the consumption amount for each subscriber to estimate the amount of energy required, resulting in increased computing costs and communication overheads.

Wu *et al.* [26] studied the use of Blockchain to machine-to-machine (M2M) interaction in the context of an energy. They investigated the possibility of using smart contracts for storing transaction data and automatically transferring assets. The system consists of a number of power generator nodes and the power management center (PMC). PMC forecast the power flow and publish offers. Each generator node can read the offer to make a decision; Either accept the offer and serve the transaction or reject it. Since the system contains a single PMC, the performance will degrade as energy demand increases, making system scalability a challenge.

### B. RENEWABLE ENERGY TRADING MANAGEMENT

Conventional energy markets rely on several energy producers who sell energy to consumers. With the trend towards distributed renewable energy resources such as solar and wind energy, traditional energy consumers are becoming prosumers (they can produce or consume energy), giving them the opportunity to participate in energy trading markets [27]. However, most of the current energy trading markets are one-sided and depending on traditional energy providers, who sell energy to consumers at a higher price while buying energy from prosumers at a lower price [28], [29]. Therefore, number of researchers have studied and investigated the possibility of employing Blockchain technology and smart contracts in the field of P2P energy trading [4], [7], [30]–[32].

Brooklyn microgrid in New York was the first P2P Blockchain-based power trading system [30]. This platform allows prosumers to sell their surplus energy directly to their neighbors using Ethereum-based smart contracts and the Practical Byzantine Fault Tolerance (PBFT) consensus algorithm. Smart meters are used to measure energy surpluses, which are then converted into tokens that may be traded on the local market. The microgrid's users interact with the platform by stating their individual pricing preferences to purchase or sell electricity. Energy prices are displayed on the platform by location and real-time. Users can manually design the sales contract that is stored on the Blockchain [7]. The ledger records the contract terms, transaction parties, amount of energy produced and consumed, and the transaction time. The platform lacks many features that are planned to be added in the future, including setting the maximum purchase price and percentage of the energy that the consumer wants to buy, assigning buying/selling priority, for example to neighbors and relatives, and allocating locally produced energy to the highest bidders [30]. Moreover, the increases in the number of users have a negative impact on the system's performance.

Gorski *et al.* [32] have introduced an energy supply management system based on Blockchain and smart contracts. It helps in monitoring and recording information about the incoming and outgoing energy from the power grid. The system can be managed using two different methods which are automatic and manual. Automatic management helps to increase the profits of energy producers, as energy is sent directly to the grid when the energy price is higher than the normal profitability ratio. The trusted Power-Stock Exchange entity is responsible for approving each transaction as well as confirming the energy price. Continuous monitoring of electricity consumption in addition to calculating the expected profit margin regularly increases computation costs and communication overheads.

Khalid *et al.* [4] proposed a P2P model to implement an efficient and low-cost hybrid energy trading marketplace. They proposed three various smart contracts. The first for registering the members and storing transaction information, it is the main smart contract that market members interact with, it is the one that calls other smart contracts to be processed. The second for managing local trading of the market. The third manages the prosumer to grid electricity transactions. To minimize potential energy loss, physical distance is considered for energy exchange between peers. The proposal aided in lowering electricity costs and peak to average ratio (PAR). When a customer wants to buy energy, all offers from the vendors are studied and the lowest price and closest in terms of distance is selected before the energy is sold to the customer. Therefore, the system response is expected to become slower as the number of users increases.

Han *et al.* [31] introduced a private Ethereum-based smart contract approach that relies on a double auction method. They created a smart contract with four fundamental algorithms, with the consideration of reducing gas usage and ensuring security. It allows P2P energy trading for 25 users at a time, with more than six miner nodes. It can reflect market quotations and balance player profits. The system relies on a proof-of-work consensus algorithm, which requires complex calculations, and the response speed of the system is expected to decrease with the increase in the number of users.

### C. RESEARCH GAPS

There are several contributions in the literature to enhance distributed renewable energy management systems, Table 2 highlights the main characteristics of the solutions reviewed in this paper. There are still several gaps that have not been adequately addressed in previous works and require additional attention from researchers, including the following.

1) Most of the current studies are concerned with the field of energy trade and overlooking the management and control aspect, which is a requirement for the governance of the renewable energy distribution process.
2) The requirements for an optimal solution for Blockchain-based distributed energy management are not clearly defined.
3) When compared to other methods, the on-grid installation approach is considered cost-effective for the residential sector and ensures energy stability; nevertheless, not enough studies have been found to enhance the power distribution management for this strategy.

## IV. SOLUTION REQUIREMENTS AND CHALLENGES MAPPING

Through the literature review conducted in the Section 3, we found many challenges that could hinder or reduce the efficiency of the distributed renewable energy management systems (DREMS). We, therefore, propose a number of requirements, illustrated in Fig. 2, the fulfillment of which will help improve the efficiency of DREMS. The rest of this section summarizes the challenges found in the literature and maps them with the proposed solution requirements.

### A. FUNCTIONAL REQUIREMENTS

Table 3 introduces two main functional requirements that are required to address several challenges found in the literature.

### B. PERFORMANCE REQUIREMENTS

Three requirements shown in Table 4 must be met to achieve acceptable system performance.

### C. SECURITY REQUIREMENTS

Three requirements shown in Table 5 must be achieved to ensure the system's security.

## V. DISTRIBUTED RENEWABLE ENERGY MANAGEMENT PROPOSED FRAMEWORK

This section introduces the proposed framework for the distributed renewable energy management system (DREMS) in the Saudi Arabia. We propose to integrate the permissioned

**TABLE 2. Summary of the main characteristics of existing studies.**

TABLE II
SUMMARY OF THE MAIN CHARACTERISTICS OF EXISTING STUDIES

| Ref | Aim | Country | Functions/ Protocols | Users | Type of energy | Blockchain infrastructure | Smart contracts | RES installation approach | Define solution requirements |
|---|---|---|---|---|---|---|---|---|---|
| [4] | Hybrid electricity trading market system | N/F | 1. Member registration and storage of transaction information. 2. Local market trading management. 3. Grid electricity prosumer transactions management. | A smart homeowner (consumer & prosumer) | Electricity | Ethereum/ Private | ✓ | Hybrid | × |
| [7] | Enable P2P energy trading | Brooklyn | 1. Local market trading management. 2. Users can state their pricing preferences to purchase or sell electricity. | Energy producers and consumers | Renewable energy | Ethereum/ Private | ✓ | Hybrid | × |
| [24] | Privacy-preserving P2P energy management system | N/F | 1. Register and permit a new power generating unit. 2. Users create new power dispatch instructions. 3. Search and extract historical information. | Power producers, suppliers, users | Renewable energy | Hyperledger Fabric/ consortium | ✓ | Off-grid | × |
| [25] | Manage energy exchanges based on the energy community's regulations | France | Compute the appropriate allocation of the produced energy to each participant based on pre-defined rules | Energy producers and consumers | Renewable energy (Solar) | Hyperledger Fabric/ Consortium | ✓ | On-grid | ✓ |
| [26] | Manage demand side of smart grid | N/F | Forecast the power flow and publish price offer | Power management centre, generator | Electricity | MultiChain/ Private | ✓ | Off-grid | × |
| [31] | Enable P2P energy trading and management | N/F | 1. Register the sale contract's parties. 2. Local market trading management. | Producers, consumers, and distribution system operator | Renewable energy | Ethereum/ private | ✓ | Off-grid | × |
| [32] | Manage and store information of inbound/outbound energy | N/F | 1. Monitor inbound/outbound energy. 2. Compute energy production costs. 3. Monitor energy stocks and send electricity to the grid when economically profitable. | Producers, buyer, trusted power stock exchange entity | Renewable energy | Corda platform/ Consortium | ✓ | Hybrid | × |

**Note:** Renewable Energy Systems (**RES**), Not Found (**N/F**)

Blockchain network into the existing system as shown in Fig. 3. This will provide a secure distributed network that will allow energy tokens to be exchanged between multiple parties without the need for a third party. As shown in Fig. 4, the proposed framework consists of two main models are the Data Collection Model, and the Data Utilization Model. The rest of this section introduces these two proposed models and describes their proposed protocols.

### A. NOTIONS

Table 6 explains several notions utilized in the description of the proposed distributed renewable energy management framework as well as its protocols. Also, it should be noted that the terms "client" and "user" are used interchangeably in this paper to refer to the term "customer".

### B. DATA COLLECTION MODEL

This model is responsible for gathering the primary data about the system's consumers as well as the solar panel that they own. As shown in Fig. 5, it consists of two protocols, which will be discussed in the next subsections.

#### 1) CUSTOMER REGISTRATION PROTOCOL

We assumed that all power utility companies (PUCs) are authorized by a third party. Each PUC is responsible for registering any new customer who does not have a record in the Blockchain system (BS). Registering customers on the BS allows them to easily switch from one power utility company to another when seeking better services. This protocol will be performed once for each customer, which helps in managing storage and reducing the system overheads resulting from having duplicate records for a single customer. Fig. 5 (a) illustrates the steps involved in registering a new customer to the BS, which are briefly discussed in follow.

$$\textbf{Step 1}: C \rightarrow PUC : R = Enc_{PK}(C_{id}, S_{id})$$

In Saudi Arabia, all customers whose facilities are linked to electric power utilities have accounts registered in the service provider's e-system, helping them to carry out many electronic transactions. It is possible to add a new service to this e-system that allow the user to request joining the renewable energy management Blockchain system (REMBS). To participate in the distributed energy trading process, the customer ($C$) must make a request ($R$) to the power utility company ($PUC$) to create a new account for him/her in the BS. R includes the customer identifier ($C_{id}$) and the service identifier ($S_{id}$). To avoid data tampering attack, the request will be encrypted using the PUC public key ($PK$) which can

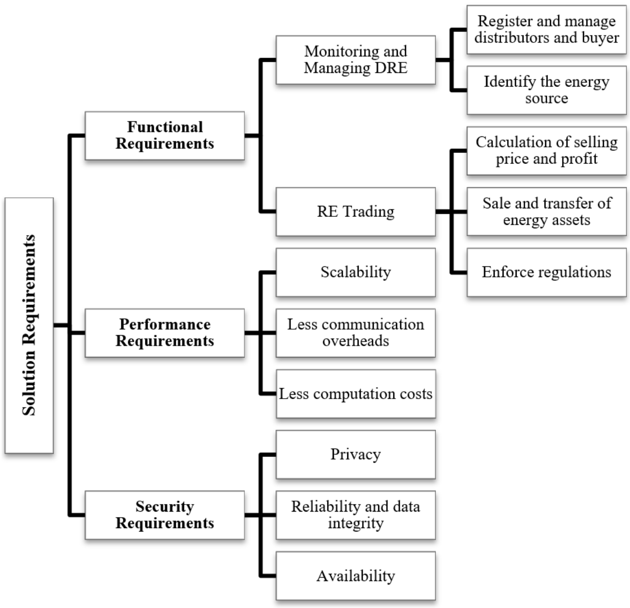


**FIGURE 2.** Solutions requirements.

be found in the digital certificate of the PUC's website.

$$\textbf{Step 2}: PUC \to BS : CR = Sig_{PUC}(C_{id}, CC)$$

PUC will check the received request ($R$), and if it contains valid information, a customer credential ($CC$) will be generated, and a new record for the customer ($CR$) will be added to the $BS$. $CR$ is signed digitally using the $PUC$ private key, and it contains the customer identifier ($C_{id}$) and $CC$. It is known that Blockchain nodes will verify the transaction before adding the record on the system, later storing the transaction in a new block linked to the previous block of the chain. After completing this step, the user will be notified. To simplify the system, the user will be able to log into the REMBS using the same credentials they have to access the PUC's system.

The request will be dropped in two cases. First, if PUC check the request and found that it contains with invalid information. Also, if the Blockchain nodes agree that the Blockchain transaction is invalid after the verification process.

### 2) METER REGISTRATION PROTOCOL

In Saudi Arabia, the Distribution Service Provider (DSP) is responsible for developing, establishing, operating, and maintaining the distribution system [22]. It is an entity licensed by the Electricity and Cogeneration Regulatory Authority (ECRA). In our proposed framework, the DSP is responsible for link the bidirectional meter identifier to the customer identifier, updated the distributed database, and record this transaction on the Blockchain ledger. Fig. 5 (b) illiterates the steps of linking the bidirectional meter identifier to the customer identifier, which are briefly described in follow.

$$\textbf{Step 1}: C \to DSP : R = Enc_{PK}(C_{id}, S_{id})$$

**TABLE 3.** Mapping of functional requirements to the challenges.

| | Requirement | Remark | Challenge |
|---|---|---|---|
| 1 | Monitoring and Managing the Distribution of Renewable Energy | | |
| 1.1 | Register and manage accounts of distributors and buyers | The system must be able to manage accounts in a transparent, flexible, and reliable manner. | Increasing users of renewable energy systems will make it more difficult to manage the system [14]. |
| 1.2 | Identify the energy source | The system must be able to compute the distance to the energy source before purchasing it, as the distance might affect the cost and increase the energy consumption as well. | The greater the physical distance between peers exchanging energy, the greater the waste of energy [4]. |
| 2 | Renewable Energy Trading | | |
| 2.1 | Calculation of selling price and profit | The system should be able to set prices based on predetermined conditions as well as calculate profits for the owner of the energy source. | There must be regulatory rules [6]. |
| 2.2 | Sale and transfer of energy assets | The system must provide a reliable means of selling and transferring energy assets between the parties. | There must be a party responsible for managing disputes between the transaction's parties [6]. |
| 2.3 | Enforce regulation | Monitor and control the amount of renewable energy produced and balancing supply and demand. | Increased energy self-sufficiency may result in lower income, while expenses associated with the operation and maintenance of the power grid system may rise [30], [33]. |

Execution of this protocol begins when the customer ($C$) submits a request ($R$) to the $DSP$ to install the solar panels in his facility. The request contains the customer identifier ($C_{id}$) and the requested service identifier ($S_{id}$). To protect the request information from tampering attack, it is encrypted using the DSP's public key ($PK$), which is obtained from the digital certificate of the DSP's website.

$$\textbf{Step 2}: DSP \to BS : MR = Sig_{DSP}(M_{id}, M_{loc}, C_{id})$$

$DSP$ will check and verify the received request ($R$) before processing it. $DSP$ will then install the solar power system (SPS) at the customer's facility. A bidirectional meter is a key component of SPS, which is responsible for measuring the photovoltaic (PV) energy generated by the solar panel and the energy consumed by the customer. Each bidirectional meter has a unique identifier ($M_{id}$). In this step, $DSP$ will send a request to the $BS$ to add a new record $MR$. The record contains the meter identifier ($M_{id}$), its location ($M_{loc}$), and

**TABLE 4. Mapping of performance requirements to the challenges.**

| | Requirement | Remark | Challenge |
|---|---|---|---|
| 1 | Scalability | The system must be capable of adding an unlimited number of energy distribution points, users, and transactions. | The number of energy consumers is constantly increasing, which will lead to an increase in the number of transactions that take place on the distribution network [14]. |
| 2 | Less communication overheads | The system must be able to provide its services with the least amount of delay. | Increasing the number of users of renewable energy systems will increase the number of system transactions which may increase response time and reduce network performance [14]. |
| 3 | Less computation costs | Operating costs must be considered while designing the system. | Employing modern technologies such as Blockchain may increase operating cost due to some storage requirements and consensus algorithms [30]. |

**TABLE 5. Mapping of security requirements to the challenges.**

| | Requirement | Remark | Challenge |
|---|---|---|---|
| 1 | Privacy | Authorized data should be accessed only by authorized users. | Most current P2P power energy solutions are based on traditional/centralized database systems, where ensuring data privacy and integrity is a challenge [31]. |
| 2 | Reliability and data integrity | The system must be able to detect misleading operations and manipulations. | Unauthorized modification of data is prohibited [6]. |
| 3 | Availability | The system must always perform well. | The energy sector is a vital sector, and many daily and basic services depend on it. Any disruption in the energy distribution system will negatively affect many other sectors. |

the customer identifier ($C_{id}$). *MR* is signed digitally using the *DSP* private key. It is known that Blockchain nodes will verify the transaction before adding the record on the system, later storing the transaction in a new block linked to the previous block of the chain. After completing this step, the amount of produced power will be available on the distributed network and the user can manage its distribution. If the Blockchain nodes agree that the Blockchain transaction is invalid following the verification process, the request will be rejected.

### C. DATA UTILIZATION MODEL

This model allows access to the data collected by the first model. This data can be used for monitoring supply and demand, energy distribution management, and energy trading. In this paper, we have proposed only one protocol for this model, but any other protocols can be implemented to benefit from the collected data. We propose a protocol that manage energy distribution between two users, the rest of this section describes this protocol.

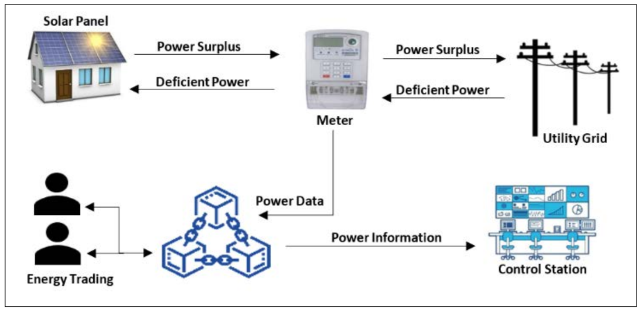


**FIGURE 3. Proposed renewable energy distribution management framework.**

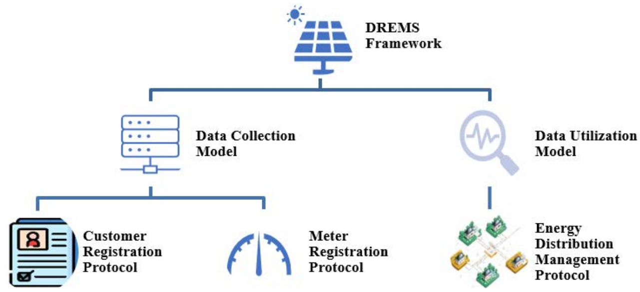


**FIGURE 4. Models of the proposed DREMS framework.**

**TABLE 6. Notions used in the description of the proposed framework and its protocols.**

| Notion | Description |
|---|---|
| BS | Blockchain System |
| DS | Distribution System |
| PV | Photovoltaic |
| PUC | Power Utility Company |
| DSP | Distribution Service Provider |
| C | Customer |
| R | Request |
| PK | Public Key |
| PR | Private Key |
| id | Identifier |
| S | Service |
| CR | Customer record |
| CC | Customer credentials |
| $\mathbf{Enc_K}$ | Encryption process using key K |
| $\mathbf{Sig_K}$ | Digital signing process using key K |
| M | Meter |
| loc | Location |
| MR | Meter record |
| T | Token |
| No | Number |
| SC | Smart contract |
| A | Agreement |

#### 1) ENERGY DISTRIBUTION MANAGEMENT PROTOCOL

This protocol enables nearby consumers in the same distribution network system to trade energy depending on the rules

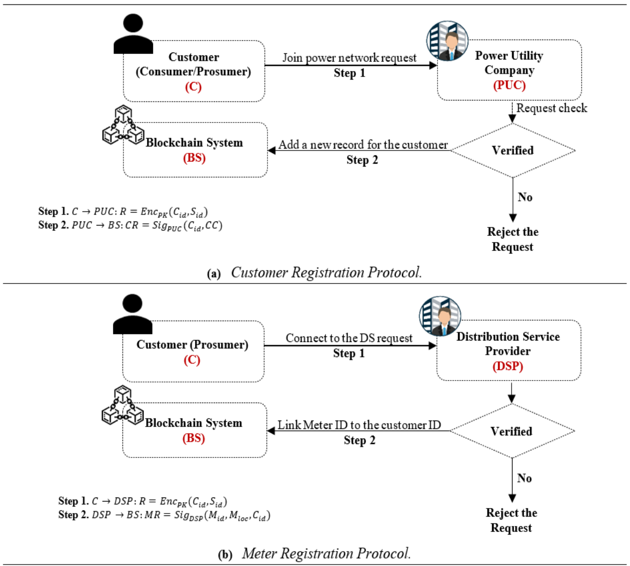


**FIGURE 5.** Protocols of data collection model.

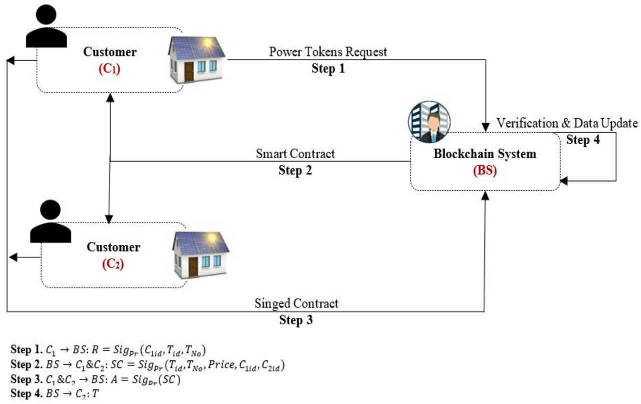


**FIGURE 6.** Energy distribution management protocol.

of the agreed-upon smart contract. The smart contract handles the energy trading process, for example, it defines the amount of energy to be transferred and the selling price. In order for the energy exchange to take place, both parties must electronically sign the contract. The steps of this protocol are illustrated in Fig. 6, with each step being briefly discussed in follow.

$$\textbf{Step 1}: C_1 \rightarrow BS: R = Sig_{Pr}(C_{1id}, T_{id}, T_{No})$$

When a customer ($C_1$) wants to buy energy tokens from another customer ($C_2$), they will send a request ($R$) to the Blockchain system ($BS$). The request contains the customer identifier ($C_{1id}$), the token identifier ($T_{id}$), and the amount of the needed tokens ($T_{No}$). For authentication purposes, the request will be signed by the private key of $C_1$.

$$\textbf{Step 2}: BS \rightarrow C_1\&C_2: \quad SC = Sig_{Pr}(T_{id}, T_{No}, Price, C_{1id}, C_{2id})$$

Blockchain nodes will verify the received request ($R$) and the availability of the requested tokens. If $R$ can be processed, then an elected node of $BS$ executes a smart contract program to generate the required sales smart contract ($SC$). The $SC$ contains the number and identifier of token to be transferred, the selling price, and the identifiers of the transaction's parties ($C_{1id}$ and $C_{2id}$). The BS node digitally signs the contract for authentication purposes and then sends it to the transaction's parties.

$$\textbf{Step 3}: C_1\&C_2 \rightarrow BS: A = Sig_{Pr}(SC)$$

The transaction's parties check the contract ($SC$) when they receive it, and if approved, digitally sign it using the transaction party's private key and then send it to the BS. Otherwise, it will be dropped.

$$\textbf{Step 4}: BS \rightarrow C_2: T$$

Blockchain nodes will verify the received signed agreements ($A$) from the transaction's parties ($C_1\&C_2$). If the signatures are valid, the agreed power tokens ($T$) are transferred to the customer who ordered them. Otherwise, the process will be terminated.

## VI. DISCUSSION AND ANALYSIS

This section provides a comparative analysis of the proposed framework and other existing solutions in terms of meeting the solution requirements, and this comparison is summarized in Table 7.

### A. FUNCTIONAL REQUIREMENTS

Since our proposed solution aims to increase revenues and reduce operating costs of renewable microgrid while ensuring the stability of the energy supplied to the facilities, it is directed to the on-grid installation approaches. As shown in Table 7, it can meet all the proposed functional requirements, although some of the existing solutions could only meet a portion of them.

We proposed a data collection model with two protocols, the client registration protocol, and the meter registration protocol. These two protocols must be performed in order for the customer to purchase and distribute energy. The model aids in detecting the energy source that has been overlooked by numerous solutions [24]–[26], [31], [32]. Identification of the power source assists in verifying its type as well as increasing the likelihood of purchasing from the nearest supplier to avoid power leakage.

The designed data utilization model allows the implementation of any protocol to access the collected data, assisting in meeting the functional requirements for renewable energy trading. As shown in Table 7, not all solutions were able to meet these requirements. Our designed energy distribution management protocol enables the sale and distribution of power based on predefined rules in a smart contract. The sales price and profit can also be calculated using the data collected, for example by designing a machine learning based application.

**TABLE 7.** A comparison between the existing solutions and our proposal in terms of meeting the solution requirements.

| Requirements/Ref | | Renewable Energy Systems Installation Approach | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Off-grid | | | Hybrid | | | On-grid | |
| | | [24] | [26] | [31] | [4] | [7] | [32] | [25] | Our |
| Functional Requirements | | | | | | | | | |
| 1. | Monitoring and Managing the Distribution of Renewable Energy | | | | | | | | |
| 1.1. | Register and manage accounts of distributors and buyers | ✓ | × | × | ✓ | ✓ | × | × | ✓ |
| 1.2. | Identify the energy source | × | × | × | ✓ | ✓ | × | × | ✓ |
| 2. | Renewable Energy Trading | | | | | | | | |
| 2.1. | Calculation of selling price and profit | × | ✓ | ✓ | × | ✓ | ✓ | × | ✓ |
| 2.2. | Sale and transfer of energy assets | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 2.3. | Enforce regulations | × | ✓ | ✓ | × | ✓ | ✓ | ✓ | ✓ |
| Performance Requirements | | | | | | | | | |
| 1. | Scalability | ✓ | × | × | × | × | ✓ | ✓ | ✓ |
| 2. | Less communication overheads | ✓ | × | × | × | × | × | × | ✓ |
| 3. | Less computation cost | ✓ | ✓ | × | × | × | × | × | ✓ |
| Security Requirements | | | | | | | | | |
| 1. | Privacy | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 2. | Reliability and data integrity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| 3. | Availability | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |

### B. PERFORMANCE REQUIREMENTS

Energy demand may be viewed as a real-time application that does not tolerate delays since it is one of life's essentials; hence, the performance of the power distribution system is important to the system's acceptance or rejection. As shown in Table 7, most of the solutions failed to fulfil the performance requirements. It is evident that most studies seek to employ Blockchain technology to tackle security issues while overlooking the performance aspect; low-performance apps cannot be deployed in the real environment, especially real-time applications. For instance, in [25], the system analyzes the consumption amount for each subscriber on a regular basis in order to estimate the amount of energy required, resulting in higher computational costs and communication overheads. In [32], continuous monitoring of electricity consumption, in addition to predicting the profit margin regularly, increases computation costs and communication overheads.

Some systems, like [4], [7], [26], and [31], function well with a small number of users but degrade as the number of users increases. In [4], when a consumer needs to buy energy, all vendor bids are analyzed, the lowest price and nearest in terms of distance are chosen before the energy is supplied to the client. As a result, as the number of users grows, the system's response time is likely to degrade. Because the system in [26] has a single power management center, performance will degrade as energy demand rises, making system scaling a challenge.

Blockchain technology is primarily relied on consensus algorithms to process transactions; however, some of these algorithms involve significant computation costs, such as proof of concept [17], which has an impact on the overall performance of the system. For example, in [31] the response speed of the system is expected to decrease as the number of users increases.

To achieve the performance requirements, we considered the flaws identified in the literature as well as the characteristics of the renewable energy distribution management system. To achieve the scalability requirement, users are only registered and linked to the system once, and this is done by trusted parties. In addition, only the data necessary to exchange energy is recorded, which includes the user identifier, location, and meter identifier. Moreover, there are only two steps for each protocol of the proposed data collection model. We assigned the user registration and meter registration tasks to two authorized entities, namely power utility companies and distribution service providers, respectively. In Saudi Arabia, power utility companies already collect utility grid customers' data while distribution service providers are responsible for installing and connecting customers' renewable energy systems. It assists in the minimization of communication overheads and computation costs.

The power distribution management protocol begins with the receiving of the power purchase request; if the request can be completed, the smart contract program is performed and transmitted to the two parties of the sale for approval, after which the ledger is updated. This procedure has no complex computations and is consists of only four steps. Other computations, such as predicting energy needs, calculating surplus, and estimating profit margins, can be performed using the collected data without the need for periodic readings, as stated by these studies [25], [32].

### C. SECURITY REQUIREMENTS

It is clear from Table 7 that all solutions are able to fulfill the security requirements since Blockchain technology naturally offers a number of security features. As shown in Table 2, the solutions utilize either a private or consortium Blockchain network, which aids in data privacy protection and restricts users' access to system resources. The data integrity criteria have been satisfied since all transactions' digital signatures and hash values are checked before they are committed in Blockchain. The data in the Blockchain network is kept in a distributed ledger, which ensures its availability even if one of the copies is broken.

## VII. CONCLUSION AND FUTURE WORK

Despite the community's awareness of the benefits of utilizing and depending on renewable energy systems to generate power, the initial installation costs and long-term benefits make their adoption challenging for the residential sector. Residential PV systems are estimated to contribute to more than 80% of total power generation. Involving home users in the energy trade via a distributed renewable energy management system (DREMS) may encourage them to help reduce reliance on fossil fuels to generate power. There are several challenges that may hinder the deployment of DREMS; consequently, these challenges are identified in this paper. Also, a set of requirements that must be met to address each challenge were introduced. Furthermore, the DREMS framework was introduced with the design of three main protocols, namely, the user registration protocol, the counter registration protocol, and the energy distribution management protocol. The framework was also analyzed and compared to other solutions in terms of the fulfillment of the solution requirements. It is recommended that further studies be conducted to improve the framework by adding more features such as predicting each customer's energy demands and determining peak periods and the expected shortage in energy production due to weather changes.

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## REFERENCES

[1] S. Jurgenson, F. M. Bayyari, and J. Parker, "A comprehensive renewable energy program for Saudi vision 2030," *Renew. Energy Focus*, vol. 17, no. 5, pp. 182–183, Sep. 2016.

[2] M. Mohsin, H. W. Kamran, M. A. Nawaz, M. S. Hussain, and A. S. Dahri, "Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental Nexus from developing Asian economies," *J. Environ. Manage.*, vol. 284, Apr. 2021, Art. no. 111999.

[3] Y. H. A. Amran, Y. H. M. Amran, R. Alyousef, and H. Alabduljabbar, "Renewable and sustainable energy production in Saudi Arabia according to Saudi vision 2030; current status and future prospects," *J. Cleaner Prod.*, vol. 247, Feb. 2020, Art. no. 119602.

[4] R. Khalid, N. Javaid, S. Javaid, M. Imran, and N. Naseer, "A blockchain-based decentralized energy management in a P2P trading system," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jun. 2020, pp. 1–6.

[5] J. Wu and N. Tran, "Application of blockchain technology in sustainable energy systems: An overview," *Sustainability*, vol. 10, no. 9, p. 3067, Aug. 2018.

[6] J. Xie, H. Tang, T. Huang, F. R. Yu, and R. Xie, "A survey of blockchain technology applied to smart cities: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2794–2830, 3rd Quart., 2019.

[7] E. Mengelkamp, J. Gärttner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn microgrid," *Appl. Energy*, vol. 210, pp. 870–880, Jan. 2018.

[8] A. G. Abo-khalil, "Seeking sustainable development: Prospects for Saudi Arabia's transition from oil to renewable energy," *Global J. Res. In Eng.*, vol. 21, no. 1, pp. 49–74, 2021.

[9] F. R. Alharbi and D. Csala, "GCC Countries' renewable energy penetration and the progress of their energy sector projects," *IEEE Access*, vol. 8, pp. 211986–212002, 2020.

[10] Water & Electricity Regulatory Authority (WERA). (2019). *Annual Statistical Booklet for Electricity and Seawater Desalination Industries*. Accessed: Mar. 19, 2022. [Online]. Available: https://www.ecra.gov.sa/en-us/MediaCenter/doclib2/Pages/SubCategoryList.aspx?categoryID=5

[11] K. Alrashoud and K. Tokimatsu, "Factors influencing social perception of residential solar photovoltaic systems in Saudi Arabia," *Sustainability*, vol. 11, no. 19, p. 5259, Sep. 2019.

[12] H. G. Lopez-Ruiz, J. Blazquez, and M. Vittorio, "Assessing residential solar rooftop potential in Saudi Arabia using nighttime satellite images: A study for the city of Riyadh," *Energy Policy*, vol. 140, Jun. 2020, Art. no. 111399.

[13] A. A. Imam, Y. A. Al-Turki, and R. S. Kumar, "Techno-economic feasibility assessment of grid-connected PV systems for residential buildings in Saudi Arabia—A case study," *Sustainability*, vol. 12, no. 1, p. 262, Dec. 2019.

[14] T. Wang, H. Hua, Z. Wei, and J. Cao, "Challenges of blockchain in new generation energy systems and future outlooks," *Int. J. Electr. Power Energy Syst.*, vol. 135, Feb. 2022, Art. no. 107499.

[15] B. Singhal, G. Dhameja, and P. S. Panda, *Beginning Blockchain*. Berkeley, CA, USA: Apress, 2018.

[16] I.-C. Lin and T.-C. Liao, "A survey of blockchain security issues and challenges," *Int. J. Netw. Secur.*, vol. 19, no. 5, pp. 653–659, Sep. 2017.

[17] S. J. Alsunaidi and F. A. Alhaidari, "A survey of consensus algorithms for blockchain technology," in *Proc. Int. Conf. Comput. Inf. Sci. (ICCIS)*, Apr. 2019, pp. 1–6.

[18] H. A. Khattak, K. Tehreem, A. Almogren, Z. Ameer, I. U. Din, and M. Adnan, "Dynamic pricing in industrial Internet of Things: Blockchain application for energy management in smart cities," *J. Inf. Secur. Appl.*, vol. 55, Dec. 2020, Art. no. 102615.

[19] Q. Wang and M. Su, "Integrating blockchain technology into the energy sector—From theory of blockchain to research and application of energy blockchain," *Comput. Sci. Rev.*, vol. 37, Aug. 2020, Art. no. 100275.

[20] J. Bao, D. He, M. Luo, and K.-K.-R. Choo, "A survey of blockchain applications in the energy sector," *IEEE Syst. J.*, vol. 15, no. 3, pp. 3370–3381, Sep. 2021.

[21] U. Subramaniam, S. Vavilapalli, S. Padmanaban, F. Blaabjerg, J. B. Holm-Nielsen, and D. Almakhles, "A hybrid PV-battery system for on-grid and off-grid applications—Controller-in-loop simulation validation," *Energies*, vol. 13, no. 3, p. 755, Feb. 2020.

[22] *Regulatory Framework for Small-Scale Solar PV Systems*, Water Electr. Regulatory Authority, Riyadh, Saudi Arabia, 2019.

[23] U. T. Salman, M. A. Abdulgalil, O. S. Wasiu, and M. Khalid, "Energy management strategy considering battery efficiency for grid-tied microgrids during summer in the kingdom of Saudi Arabia," in *Proc. 8th Int. Conf. Renew. Energy Res. Appl. (ICRERA)*, Nov. 2019, pp. 422–427.

[24] L. Wang, S. Jiao, Y. Xie, S. Mubaarak, D. Zhang, J. Liu, S. Jiang, Y. Zhang, and M. Li, "A permissioned blockchain-based energy management system for renewable energy microgrids," *Sustainability*, vol. 13, no. 3, p. 1317, Jan. 2021.

[25] C. Plaza, J. Gil, F. de Chezelles, and K. A. Strang, "Distributed solar self-consumption and blockchain solar energy exchanges on the public grid within an energy community," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/ICPSEurope)*, Jun. 2018, pp. 1–4.

[26] X. Wu, B. Duan, Y. Yan, and Y. Zhong, "M2M blockchain: The case of demand side management of smart grid," in *Proc. IEEE 23rd Int. Conf. Parallel Distrib. Syst. (ICPADS)*, Dec. 2017, pp. 810–813.

[27] D. Thomas, M. Iain, and G. Dale, "Virtual power plants leveraging energy flexibility in regional markets," *CIRED Open Access Proc. J.*, vol. 2017, no. 1, pp. 2939–2943, Oct. 2017.

[28] E. Sorin, L. Bobo, and P. Pinson, "Consensus-based approach to peer-to-peer electricity markets with product differentiation," *IEEE Trans. Power Syst.*, vol. 34, no. 2, pp. 994–1004, Mar. 2019.

[29] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-peer energy trading in a microgrid," *Appl. Energy*, vol. 220, pp. 1–12, Jun. 2018.

[30] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, ''Blockchain technology in the energy sector: A systematic review of challenges and opportunities,'' *Renew. Sustain. Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.
[31] D. Han, C. Zhang, J. Ping, and Z. Yan, ''Smart contract architecture for decentralized energy trading and management based on blockchains,'' *Energy*, vol. 199, May 2020, Art. no. 117417.
[32] T. Gorski, J. Bednarski, and Z. Chaczko, ''Blockchain-based renewable energy exchange management system,'' in *Proc. 26th Int. Conf. Syst. Eng. (ICSEng)*, Dec. 2018, pp. 1–6.
[33] M. F. Zia, E. Elbouchikhi, M. Benbouzid, and J. M. Guerrero, ''Microgrid transactive energy systems: A perspective on design, technologies, and energy markets,'' in *Proc. 45th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Oct. 2019, pp. 5795–5800.

**SHIKAH J. ALSUNAIDI** received the B.S. degree (Hons.) in computer science from King Faisal University (KFU), Dammam, Saudi Arabia, in 2009, and the M.S. degree in information security from Imam Abdulrahman Bin Faisal University (IAU), Dammam, in 2020. She is currently pursuing the Ph.D. degree with the Department of Information and Computer Science, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia. She has more than eight years' experience in the IT domain, training, and management. She obtained many international certifications and qualifications from Microsoft and Cisco. Her research interests include network and communication, network security, smartphone security, authentication approaches, the IoT, blockchain, and biometrics.

**FAKHRI ALAM KHAN** received the M.Sc. degree from Quaid-i-Azam University, Islamabad (www.qau.edu.pk), in 2005, the Ph.D. degree (Hons.) in computer science from the University of Vienna, Austria, in 2010, and the Ph.D. degree from the Vienna University of Technology, in 2017.

He is currently serving as an Associate Professor with the Department of Information and Computer Science, King Fahd University of Petroleum and Minerals (QS Ranked 163). Before joining KFUPM, he worked for more than ten years in different capacities such as an Associate Professor, an Assistant Professor, a Coordinator of BCS, a Coordinator of BSSE, and a Coordinator of B.S. degree in data science at the Institute of Management Sciences (IMSciences), Peshawar, Pakistan. He played a pivotal role in designing the B.S. (Data Science) Program at the IMSciences. He has worked at the Central Bank of Pakistan (State Bank of Pakistan, www.sbp.org.pk) as an SBOTS Officer. He has published several research articles in various reputed peer-reviewed internationally recognized journals and has supervised numerous M.S. and Ph.D. students. His research interests include the IoT, data analytics, scientific workflows provenance, energy efficiency in WSN, multimedia technologies, and nature-inspired metaheuristic algorithms.