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The Convergence of Blockchain, Smart Microgrid, and Energy Market

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ABSTRACT

This paper reviews the integration of blockchain technology, smart microgrids, and the energy market, highlighting its potential to revolutionize the energy industry. The integration of blockchain technology into smart microgrids aims to address challenges related to energy efficiency, reliability, and sustainability. The paper provides an overview of blockchain technology, emphasizing its transparency, immutability, and decentralization characteristics. It explores the concept of smart microgrids, which enable efficient energy management and integration of renewable energy sources. The combination of blockchain and smart microgrids offers several benefits such as increased efficiency, reduced transaction costs, enhanced security, and improved grid reliability. One of the key advantages of this convergence is the ability to facilitate peer-to-peer energy trading. Blockchain technology allows for transparent and auditable energy transactions, enabling direct trading between energy producers and consumers. This empowers prosumers to actively participate in the energy market, promoting renewable energy adoption and democratizing energy access. However, some challenges need to be addressed, including scalability, interoperability, and regulatory frameworks. Ongoing initiatives, projects, and pilot studies are exploring the implementation of blockchain-enabled smart microgrids, and case studies provide real-world examples of successful deployments. In conclusion, the convergence of blockchain, smart microgrids, and the electrical energy market has the potential to transform the energy industry. Collaboration among stakeholders, including energy companies, technology providers, regulators, and consumers, is crucial to fully realize the benefits of this integration. By leveraging blockchain and smart microgrids, the energy industry can pave the way for a more efficient, sustainable, and decentralized energy future.
***Index Terms*—** Blockchain, energy efficiency, energy market, peer-to-peer trading, renewable energy, smart microgrid

I. INTRODUCTION

The first alternating current generating station can be dated as far back as 1886 in Great Barrington [1]. Since then, tremendous advancements have been made in the technology of electricity generation and transmission. This features elements such as conductors, transformers, switches, relays, and many others, which enable the safe delivery of electricity to end users. Traditionally, the power grid has a centralized topology, wherein energy is generated at a station and transmitted to various consumers; the generating station being the central point [2]. To improve the grid's reliability and overall efficiency, the development of real-time control, supervision, and monitoring systems with a smart protection system is essential to optimize the production and consumption of electricity.

A. Traditional Grid System

The major elements of the traditional electrical network are generation, transmission, and distribution.

Electrical energy is generated at generating stations and stepped up to high voltages for transmission. The bulk power generated is transmitted at a very high voltage to the distribution networks through interconnecting substations. The transmission system may include overhead lines and underground and underwater cables. Transmission can be done at a very high voltage alternating current (HVAC) or high voltage direct current (HVDC). Conventionally, HVAC system is mostly used; however, the HVDC is rapidly gaining popularity due to reduced losses and cost particularly over large distances. Underground cables could also be used for transmission and distribution of electric power [3]. Underground transmission line system construction normally

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costs 4 to 10 times that of an equal overhead line distance [4]. The transmission and distribution systems design is determined by the distance and the overall amount of power needed to be transmitted [5]. Distributed energy generation is lesser in cost compared to centralized energy. When distributed energy resource (DERs) replace the need to produce energy from another resource, they provide energy value, meaning that electricity consumers can accumulate greater savings under centralized coordination between 4% and 8% when operating without technology, by 3%-11%.

The last stage in the traditional power system network is the power delivery to the consumers through distribution networks. Delivery of power through the distribution network to end users is done by the use of cables either on utility poles or underground for some developed countries. In the distribution systems, high voltage from the transmission networks is stepped down to lower voltages by the use of step-down power transformers for less clearance.

The arrangements in power system distribution networks, namely could be radial, parallel feeders, meshed/interconnected, or ring connected, each have scenarios wherein they perform well [6, 7]. Some of the drawbacks of the traditional power network include transmission and distribution costs resulting from the robust nature of the networks, materials, and relatively long distance between the generation stations and bulk load demand centers; attempts to reduce losses in transmission and distribution; environmental implications of the traditional electrical networks solely because of the number of physical structures involved, which occupy space and cause some environmental disturbances; and others [3, 8, 9]. Fig. 1 shows basically what the traditional grid looks like. This paper is inspired to give insight into how energy transfer could be made reliably.

II. SMART MICROGRID TECHNOLOGY

The traditional main grid design is gradually being phased out as a result of the emergence of DER and distributed generation of renewable energy sources (RES) [10]. Microgrid is a cutting-edge technological innovation in power systems; it aims to improve energy sources and dependability, reduces carbon emissions, and reduces overall costs. A smart microgrid can be seen as a perfect approach to integrate renewable energy resources at the community level or within a locality [11]. A smart grid can be seen as a future grid involving a two-way communication link between the utility grid and the consumer. A smart grid is a growing network of communication, control, automation, computers, modern sensors, and new and improved technologies that work together to make the grid more efficient, reliable, secure, and environmentally friendly [12]. The massive infrastructure of today's grid and utilities can better communicate with each other to manage electricity needs by the use of a smart grid. One of the main aims of smart grids carried out by microgrids is the decentralization of the traditional power grid into smaller grids (microgrids) [13, 14]. With the use of smart microgrid, new technologies such as solar and wind energy or RES can be integrated [11].

A typical smart grid structure revolves around a certain architecture. The smart grid architecture gives the framework on how it works. It is broadly classified into:

- Generation/distribution: this is the utility grid, comprising a central generating source, coupled with transmission and distribution structures to make the commodity readily available for the end consumers [6].
- Storage system: includes advanced batteries like lithium-ion batteries, thermal batteries, sodium batteries, and lead acid batteries, which are incorporated with the microgrid. And it is used to buffer and smooth out the production of renewable energies to sustain a microgrid when the grid is not available [6, 15].
- Control/monitoring domain: advanced control systems like programmable logic controller (PLC), which can control multiple smart devices and interact with other building systems to provide a reliable and efficient electrical system [2, 13].
- Customer/market domain: this comprises consumers and customers with energy generators such as wind turbines, solar and bi-directional inverters, biogas, and more. The bi-directional inverters can sell excess energy back to the utility grid. Has the ability to synchronize with the local utility grid, and inverters can also isolate the microgrid from the main utility grid acting as an island [16]. This is shown in Fig. 2.
- Operations: this domain manages and controls the activities of all other domains, with a focus on the control domain. It communicates with the customer domain, utility system, and other intelligent devices. This domain is in charge of providing reports and supervision status on the network [16, 17]. Fig. 3 describes how the operation domain works.

Demand response concept has come to be a reliable solution to control load demand [18, 19]. The demand response program is a set of algorithms, with existing prerecorded data and interaction with the network to ascertain load demand behaviors of consumers, ascertaining peak-load on the grid, and customers are engaged in the wholesale market operation [2]. Consumers who are active can change the profile of the load by maximizing or minimizing the demand as per the generation instructions. This implies that the load will follow the generation rather than the generation following the load in the current energy paradigm [20]. The major drawback to designing this type of program is the large number of customers it attracts.

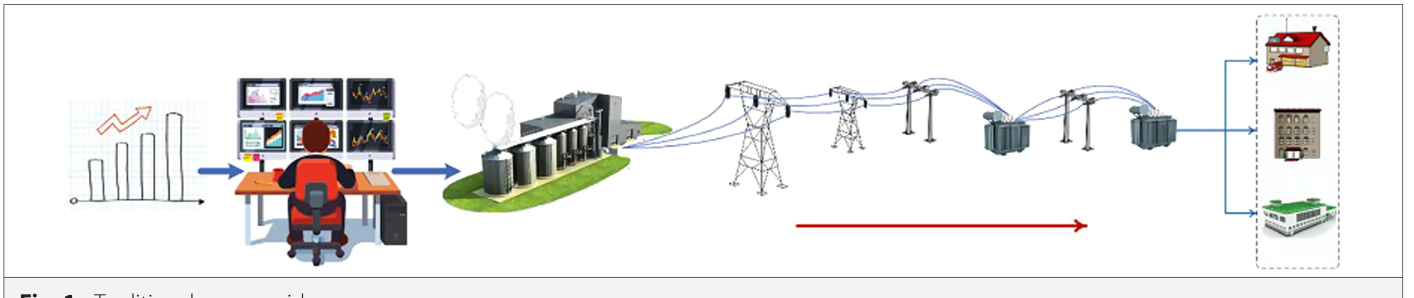

Fig. 1. Traditional power grid

Fig. 2. Customer domain of smart grid [16].

A. Smart Contract

Smart contracts were proposed in 1994 by an American computer scientist named Nick Szabo. Smart contracts can be seen as computerized transaction protocols that strictly follow the terms of a contract and executes it [20–22]. The primary aim of smart contract design is to satisfy specific conditions or terms outlined in a contract, without the need for a mediator or third party. Smart contracts improve the blockchain transaction process by making it more flexible and functional [21]. They consist of contract statements that automatically execute after meeting predefined conditions and requirements. Smart contracts improve the blockchain transaction process by adding more functionality to it. They consist of contract statements that are automatically executed after a set of predefined conditions and requirements are met [23].

In contrast to the traditional method, a digital, decentralized cyber stable security accounting ledger is deployed in this work for the storage of data, security, transparency, immutability, and validation of all energy transactions carried out on the network [24]. To achieve such a market, blockchain technology is utilized. The blockchain is the next revolutionizing technology to reinvent the way we live and work with the potential to replace economic transaction systems [25]. Apart from being utilized mainly in the financial sector, it has

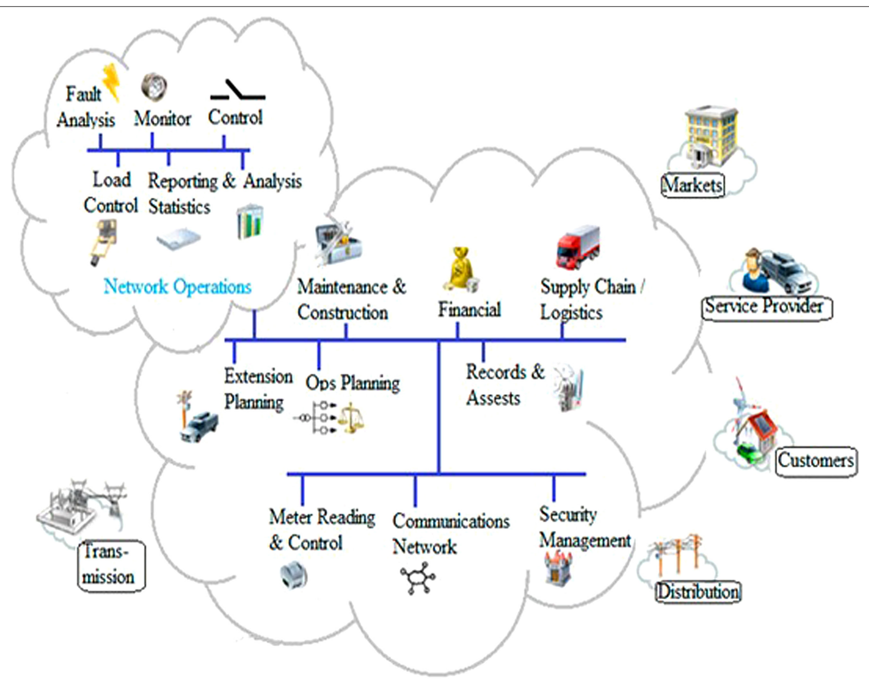

Fig. 3. Smart grid operations domain [16].

greater potential to create better heterogeneous business models in other sectors of the economy like the power and energy sector.

B. Smart Grid vs. Traditional Grid System

The smart grid technology emerged as an upgrade to the traditional grid system, to reduce the challenges and limitations of the latter earlier discussed in this paper [8]. A comparative analysis between smart grid and traditional grid technology is presented in Table I.

From the analysis presented in Table I, it no longer becomes far-fetched that smart grid technology will replace the very obsolete traditional grid and eliminate the existing market monopolies and limitations. In short, smart grid technology will contribute in the following ways:

- Smart grid helps to reduce overall long-term capital expenses and operating expenses. Traditionally, as demand increases, utilities must provide the required power to meet the peak loads, which results in extremely high-cost infrastructure. In the case of smart grid technology, the distributed energy resources and generation and demand side management schemes will account for the rising demands.
- Smart metering and real-time pricing, as advantages of smart grid technology, will drastically reduce dependence on traditional power plants. Though it has a high initial capital cost, the long-term return on investment makes it a far better technology to adopt.
- Smart grid provides better grid stability, encourages renewable energy integration, reduces environmental impacts, and these make it more efficient. Also, it promises growth in economic activities, providing research areas for researchers to venture into, creating jobs, and advancing in interdisciplinary development.

III. BLOCKCHAIN TECHNOLOGY

Blockchain is a decentralized data management system, which stores data in an encrypted block of chains and distributes the stored data in a peer-to-peer (P2P) network [25]. The blockchain concept was first integrated into the Bitcoin electronic payment system white paper proposed by Nakamoto Satoshi. They are called blockchains because the blocks are grouped in chains. Each block has a predefined size and stores a certain amount of data. Each block has two unique identifiers (hashes): the hash address of the current block and the hash address of the previous block [22].

The first block of such chains is called the “genesis block” [26]. Hence, blockchains are hash interlocked and cannot be broken because any attempt to create change inside a block will cause the hash of that particular block to change, leading to a break in the chain. The hash addresses of all blocks are located in a tree form, which in turn generates a root hash. Any unauthorized change in the blocks will lead to a change in the root of its hash, hence, it will be detected and averted during the block verification process by other participants [22].

Each node in a blockchain network has a public and a private key; thus, the participating peers can perform digital signatures on the performed transactions using the hash function and private key. All the participants of the network can verify the transactions by accessing the ledger they hold. Transactions without validations cannot be stored [27]. In the proposed model, each node in the blockchain represents a

TABLE I. COMPARATIVE ANALYSIS BETWEEN SMART GRID AND TRADITIONAL GRID TECHNOLOGY

Parameter	Traditional Grid	Smart Grid
Reliability	Prone to failures and outages	Higher level systems protection, fault sensing automation and prevention [9]
Security	Prone to security issues and cyberattacks	Little or no security issues, and user data privacy is ensured [8]
Scalability	Not scalable	Highly scalable, able to incorporate new technologies and fit into larger scales [2, 14, 42]
Self-healing capabilities	Inability to self-heal	Ability to self-heal, restoring after outages and fault conditions [9]
Communication	Vertical, one-way flow of electricity and communication.	Multiple communication and electricity flow [13]
Customer participation	Customers are restricted to the services provided.	Customers have a range of options and thus have active participation in the market [8]
Efficiency	Less efficient	More efficient
Control and monitoring	Traditional control and monitoring schemes are slow to response and erroneous	Smarted and more automated control methods are now being used, utilizing smart meters and sophisticated monitoring devices [13]
Generation of electricity	Centralized	Distributed and easily accessible
Pollution and environmental impacts	High pollution and adverse environmental effects	Reduced pollution rate, resulting from the adoption of alternative sources of energy especially renewable [9]
Technical losses	Higher reactive, transmission and distribution losses	Reduced losses, resulting from distributed generation [9, 43]
Demand response	Little or no ability to respond to changes in load demand, as it is done manually	Ability to respond rapidly to changes in energy demand [18, 44]
Complexity	Less complex and easy to install	Higher design and implementation complexity [19, 43]
Capital costs	Cheaper installation costs	More capital intensive

prosumer who can generate, sell, buy, and can trade energy through a P2P network without going through a central organization.

Blockchain is a decentralized and distributed digital book of records (database) which records data in encrypted form in blocks that are inextricably linked to each other and are cryptographically protected [28]. Copies of the records of transactions are possessed by all participants in the blockchain network. Data stored in a blockchain network is subject to constant synchronization and cannot be altered by a single participant without the consent of all other participants in the network, thereby making blockchain system suitable for managing immutable data [28]. Blockchain also provides authentication by all the participants for any change made in data, hence providing data security management, which is vital for the establishment of a secure system of trading [24].

Blockchain technology provides the following attributes which distinguish it from the centralized way of book-keeping far from its decentralized feature [24, 27, 29, 30];

- **Transparency:** In this technology, data is stored across multiple nodes rather than on a single central server. This approach ensures that every participant in the network has access to the data; thus, no single user has exclusive control over the data.
- **Immutability:** In the event that a new transaction is added to the blockchain, a cryptographic signature is assigned to it. This signature is a string of alphanumeric symbols. The parent block is linked to subsequent blocks in chronological order, thereby creating an unbreakable chain of blocks. Because of these multiple blocks that are chained together, it becomes difficult to alter the recorded data, without a consensus from the majority of participants.
- **Trustless trust:** The transparent nature of blockchain fosters trust among participants. Since no one entity has control over the entirety of the network, and transactions are visible and auditable, it becomes very difficult for participants to perform actions without being detected. This in turn builds trust and accountability of the network.
- **Authenticity and security:** The decentralized nature of the technology ensures that users have a copy of the entire blockchain, making it easy for only authentic information to be in the network. If counterfeit information is shared, and the assigned hash or cryptographic sign does not match with that of other participants, it is considered not genuine. Fig. 4 gives a simplified pictorial context on how blockchain works.
- **Privacy:** There are private blockchains where access to data is limited to only authorized participants. Also, while transactions are recorded in the blockchain, the assigned cryptographic signature or addresses are used to provide a certain level of privacy to participants, while making the transactions transparent.

A. Applications of Blockchain Technology

Blockchain technology, initially designed to underpin cryptocurrencies like Bitcoin, has evolved far beyond its original purpose [32]. It is now recognized as a revolutionary and transformative technology with a wide range of applications across various industries. At its core, blockchain is a decentralized and immutable ledger, enabling secure and transparent transactions without the need for intermediaries [33]. It has found its way into biomedical and health applications, government and politics, supply chain management, transportation and automotives, finance, energy market, internet of things, identity management, and many more [21, 25, 29, 34-36].

Blockchain technology in the energy market would contribute greatly to the existing systems. These are explained as follows:

- The technology will improve power system progress and reliability by causing a paradigm shift away from the energy market being dominated by a small number of major firms and toward a consumer- or prosumer-centric market. This can be accomplished by connecting the local community's electricity prosumers to build a microgrid network. A smart microgrid network can be created by integrating smart meters, IoT devices, and the web with the grid. To allow a network participant to freely sell energy with other network participants, an online trading platform built on smart contract can also be developed.
- This, if implemented, it will minimize the long-distance transmission and distribution line losses of the conventional power network as energy is generated and distributed within the same locality. Thus, the energy demand of each community can always be met by increasing the number of energy prosumers and also energy storage systems of the network. The distributed generation energy source is mainly from renewables such as solar, thus carbon emission in the environment are minimized drastically. It can serve as an alternative solution to rural electrification difficulties, mostly in remote areas with sunny weather. Also, grid overload is minimized as the smart microgrid will be independent of the utility grid network (islanded mode).
- The convergence will enhance peer-to-peer trading of energy in the smart microgrid using the smart meter, smart-contract concept, and blockchain. By means of automation, the smart meter controls all operations of transmission of excess electricity to the grid and also detects energy shortage in the node (household/orga nization/building), hence placing a request for purchase of power from the network. By means of a smart contract, all predefined conditions and terms are carried out without a third-party interference. The recording and storage of all the transactions are done by the blockchain. To ensure fairness of the market pricing, energy pooling is integrated to ensure a balance in supply and demand. A user interface is created to enable trading among the participants. In general, the overall system will provide a more decentralized energy trading that guarantees data security, transparency,

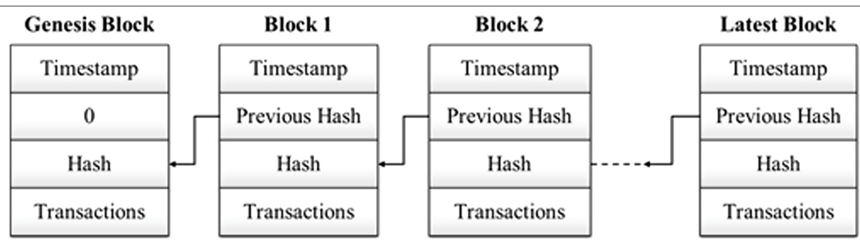

Fig. 4. Simplified representation of blockchain [31].

efficiency, reliability, immutability, and system stability as against the centralized schemes currently available.

B. The Convergence and Possible Frameworks

Given the endless possibilities of this concept, to achieve this, complete harmonization and sync is required to achieve convergence. A possible framework for achieving this is outlined below:

- Smart contracts for automated transactions: Blockchain facilitates the use of smart contracts, self-executing contracts with the terms of the agreement directly written into code. In the electricity market, smart contracts can automate and streamline various transactions, such as energy trading, billing, and settlements. This reduces the need for intermediaries, minimizes errors, and ensures quicker and more transparent transactions [21, 37].
- Decentralized energy trading: Energy being the commodity for exchange, needs a platform to facilitate this smooth exchange. A decentralized trading platform will achieve this. Producers of renewable energy, such as solar panel owners, can directly sell excess energy to nearby consumers without involving traditional intermediaries [9, 38].
- Grid management and optimization: Blockchain can improve grid management by enabling a decentralized and secure way to monitor and control energy flows. Through a distributed ledger, all participants in the network can have real-time visibility into the state of the grid, leading to better coordination, reduced energy losses, and improved overall efficiency. Developing technologies on machine learning and deep learning algorithms can be included in the system to help achieve a better demand response rate and curb the problem of energy losses due to excess supply [39, 40].
- Data security and privacy: The decentralized nature of blockchain enhances the security and privacy of data in the electricity market. Critical information related to energy transactions, customer details, and grid operations can be securely stored on the blockchain, protecting against unauthorized access and ensuring the integrity of the data.
- Tokenization of energy assets: Blockchain allows for the tokenization of energy assets, representing ownership or access rights to specific amounts of energy. This can enable more flexible and granular trading of energy, allowing consumers to buy and sell energy in smaller increments, optimizing usage based on demand and supply [41].
- Decentralized identity and authentication: Blockchain can provide a decentralized identity and authentication system for participants in the electricity market. This ensures that only authorized entities engage in transactions, reducing the risk of fraudulent activities and enhancing the overall security of the market [41].

IV. CONCLUSION AND RECOMMENDATION

A. Conclusion

The convergence of blockchain, smart microgrid, and energy market represents a transformative and promising trend in the energy sector. The integration of these technologies has the potential to revolutionize the way energy is generated, distributed, and consumed, leading to a more decentralized, efficient, and sustainable energy ecosystem. Through the application of blockchain technology, smart microgrids can facilitate secure and transparent peer-to-peer energy transactions, creating new opportunities for energy market participants and consumers alike. This convergence opens up new possibilities for optimizing energy resources, reducing greenhouse gas emissions, and enhancing energy resilience in the face of climate change and other challenges.

By combining blockchain's decentralized and tamper-resistant nature with the intelligence of smart microgrids, the energy market can become more efficient and cost-effective. The use of smart contracts enables automated, trustless interactions, removing the need for intermediaries and reducing transaction costs. This, in turn, empowers consumers to take a more active role in managing their energy usage and engaging in energy trading, fostering a more democratized and consumer-centric energy market.

B. Recommendations

In order to ensure the seamless transition and application of blockchain in the electricity market, it is important to note the following:

- Foster collaboration and standards: To fully realize the potential of this convergence, collaboration among stakeholders in the energy, blockchain, and technology sectors is crucial. Governments, regulatory bodies, utilities, startups, and research institutions should work together to establish interoperable standards, ensuring seamless integration of smart microgrids and blockchain solutions across different energy systems.
- Invest in research and development: Continuous research and development are essential to refine and optimize the technology and its applications. Funding should be directed toward exploring scalability, security, and energy efficiency improvements in blockchain-based systems. Additionally, supporting pilot projects and real-world deployments will provide valuable insights into the feasibility and benefits of this convergence.
- Regulatory frameworks: Policymakers should adapt existing regulations or create new ones to accommodate the unique characteristics of blockchain-enabled smart microgrids and energy markets. Regulatory clarity will encourage investment, innovation, and healthy competition while safeguarding the interests of all stakeholders and ensuring the stability of the energy infrastructure.
- Raise awareness and education: As with any emerging technology, educating stakeholders, including consumers, about the benefits and potential risks of blockchain and smart microgrid applications is crucial. Raising awareness will foster greater adoption and acceptance, enabling more individuals and businesses to participate actively in the decentralized energy market.
- Address security and privacy concerns: While blockchain technology offers robust security features, potential vulnerabilities and privacy concerns must be proactively addressed. Implementing advanced security measures and privacy protocols will enhance user confidence and protect sensitive information within the decentralized energy ecosystem.
- Incentives and reward mechanisms: Governments and utilities should consider implementing incentive programs and reward mechanisms to encourage energy conservation, renewable energy adoption, and active participation in peer-to-peer energy trading. These incentives can motivate consumers to embrace the new energy paradigm and further drive the transition toward sustainable energy practices.
- In conclusion, the convergence of blockchain, smart microgrid, and energy market holds great promise in revolutionizing the energy sector, paving the way for a more sustainable, decentralized, and consumer-centric energy future. However, realizing this potential will require concerted efforts from various stakeholders, including policymakers, researchers, utilities, and consumers, to address challenges, foster innovation, and create an enabling environment for the widespread adoption of these transformative technologies.

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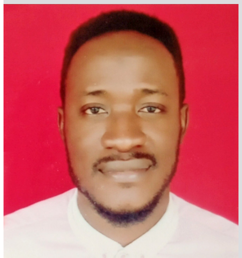

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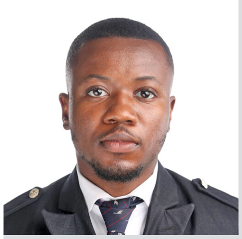

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