

Article

Blockchain-Enabled Smart Grids for Optimized Electrical Billing and Peer-to-Peer Energy Trading

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Abstract: This research investigates the integration of blockchain technology into smart grids, focusing on optimizing both electrical billing and peer-to-peer energy trading between producers and consumers. Using blockchain smart contracts, the system automates and secures energy consumption recording, bill calculation, payment processing, and energy transactions. In the electrical billing framework, a blockchain-based approach was developed to model these functionalities, utilizing an EnergyBilling smart contract to calculate bills and an EnergyPayment smart contract to ensure payment accuracy. Validation using actual consumption data from Sinoma Handan's project site confirmed the system's accuracy and reliability when cross-verified with mathematical models. Simultaneously, the study explores peer-to-peer energy trading, where producers (represented by Askari Cement Plant, Nizampur, Pakistan) and consumers (Sinoma Handan Ltd, Handan, China.) conduct automated, transparent transactions. Blockchain's decentralized nature ensures transparency, data immutability, and a secure, tamper-proof record of transactions. The system eliminates intermediaries, enhancing operational efficiency and reducing costs. Key outcomes demonstrate successful transaction execution with detailed settlements, ensuring financial accountability. Our research highlights blockchain's transformative potential in revolutionizing electrical billing and energy trading. It offers a secure, transparent, and efficient solution while acknowledging scalability, transaction costs, and regulatory hurdles. Future work could focus on real-world implementation, integration with IoT devices for real-time data collection, and scaling these technologies for broader industrial applications in global energy markets.



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Keywords: blockchain technology; smart contracts; electrical billing; energy management; peer-to-peer energy trading; decentralized systems

1. Introduction

Blockchain technology has introduced revolutionary changes across various sectors, particularly in financial transactions, data management, and energy. This decentralized, immutable ledger system ensures data integrity, transparency, and security, making it a promising solution for many industries. Blockchain integration offers new possibilities in the energy sector, especially smart grids and peer-to-peer (P2P) energy trading. As the global shift towards decentralized energy systems continues, blockchain enhances energy transactions' transparency, security, and efficiency by enabling direct interactions between producers and consumers. This promotes a more resilient and flexible energy market, transforming how energy is managed and traded [1–4]. This research investigates the role of blockchain technology in electrical billing systems and P2P energy trading, aiming to enhance transparency, automation, and efficiency within smart grids. By utilizing blockchain-based smart contracts, the study explores how key processes such as energy consumption recording, bill generation, and payment processing can be streamlined. Additionally, it emphasizes the importance of decentralized systems in advancing energy management. The research further examines blockchain's potential to revolutionize smart grids, fostering more sustainable and efficient energy systems.

2. Literature Review

Smart grids signify a significant leap from traditional electrical grids by integrating advanced digital technologies that enhance communication, automation, and data management. This upgrade allows for real-time monitoring and control of energy flows, supports the integration of renewable energy sources, and boosts energy efficiency [5,6]. Electrical billing systems are critical for both providers and consumers, requiring precise data recording and processing to ensure accurate billing. Traditional billing systems often rely on centralized databases, making them susceptible to errors, fraud, and delays in processing [7]. These issues can lead to disputes between energy providers and consumers, undermining trust and operational efficiency [8,9].

However, the decentralized nature of renewable energy sources like solar panels and wind turbines poses challenges to energy management and transaction security [9]. Traditional centralized systems often find it difficult to manage these distributed resources efficiently, leading to inefficiencies and increased costs [10]. Blockchain technology addresses these challenges by providing a decentralized, immutable ledger system that ensures data integrity and transaction security. This technology is particularly valuable for the energy sector in enabling P2P energy trading, where consumers can directly buy and sell energy without intermediaries. This feature enhances market efficiency and promotes the adoption of renewable energy by offering financial incentives for consumers to produce and trade excess energy [11,12].

Moreover, blockchain can improve the security and privacy of energy transactions by using cryptographic methods to safeguard sensitive information. This is particularly important in a smart grid setting, where the growth of connected devices expands the potential for cyber threats [13]. Additionally, blockchain's decentralized structure minimizes the risk of single points of failure, thus enhancing the resilience of the energy infrastructure [14]. Despite its potential, the application of blockchain technology in the energy sector encounters numerous hurdles. Issues such as scalability, interoperability, and regulatory compliance must be resolved to fully capitalize on this technology's advantages [15,16]. Furthermore, the energy consumption involved in blockchain mining, especially in proof-of-work systems, presents environmental challenges [17]. To comply with varying national regulations, our blockchain-based energy management system must adapt to diverse data privacy laws, financial transaction guidelines, and consumer protection standards. For example, the EU's GDPR mandates privacy safeguards like data anonymization. Additionally, financial regulations may require integration with traditional banking in regions with limited blockchain transactions. Successful implementations, such as Power Ledger in Australia and Brooklyn Microgrid in New York, demonstrate how blockchain enhances energy management through secure and efficient peer-to-peer trading. These examples highlight the system's potential to deliver similar benefits globally while ensuring regulatory compliance.

This research investigates the role of blockchain technology in electrical billing systems and peer-to-peer (P2P) energy trading, aiming to enhance transparency, automation, and efficiency within smart grids. By utilizing blockchain-based smart contracts, the study explores how key processes such as energy consumption recording, bill generation, and payment processing can be streamlined. Additionally, it emphasizes the importance of decentralized systems in advancing energy management. The research further examines blockchain's potential to revolutionize smart grids, fostering more sustainable and efficient energy systems.

3. Preliminaries

3.1. Traditional Grid and Smart Grid

The traditional electrical grid is designed for the generation, transmission, distribution, and trading of electricity, primarily moving power from large central plants to consumers through a one-way flow model. This approach has limitations, especially as reliance on fossil fuels and the demand for electrification—such as electric vehicles (EVs) and industrial

processes—increase. Traditional grids, built for unidirectional power flow, struggle to integrate renewable energy sources (RESs) and distributed energy generation, which can produce electricity at various points in the system. These grids are not well-suited to manage the dynamic, variable nature of renewable energy production, nor can they easily adjust to fluctuating energy demands. Additionally, conventional grids often face power quality issues, such as voltage fluctuations and frequency instability, due to the introduction of power converters and distributed generation [18,19].

Furthermore, the lack of advanced monitoring and control systems in traditional grids makes real-time analysis and response difficult, limiting their ability to efficiently balance energy production and consumption. To overcome these challenges, the electrical grid must be modernized with smart grid technologies that support the integration of renewable energy, enhance control systems, and adopt innovations such as energy storage systems and demand response programs. Transitioning to smart grids is crucial for addressing growing energy needs, accommodating renewable energy sources, and ensuring a more sustainable, resilient energy future [18]. The smart grid represents a significant advancement over the traditional electric power system by incorporating information and communication technologies (ICTs) to facilitate a two-way flow of both information and electricity. This modernized grid enhances the efficiency of power distribution and is widely regarded as the next generation of electrical infrastructure. Extensive research on smart grid applications is being conducted by governments and energy companies alike.

The National Institute of Standards and Technology (NIST) in the USA defines the smart grid as a modernized system that enables bidirectional energy flow and utilizes two-way communication and control capabilities, leading to new functionalities and applications [17]. Some authors define it as an electric system that integrates information, cyber-secure communication technologies, and computational intelligence across the entire energy spectrum, from generation to consumption [5]. The smart grid enables more efficient integration of renewable energy sources (RES), such as solar and wind, by employing digital technology that allows communication between devices—unlike traditional grids, which rely on mechanical devices that lack such capabilities. With the smart grid, power distribution from multiple plants and substations becomes feasible, aiding in load balancing, reducing peak-time strains, and minimizing power outages.

The presence of multiple sensors throughout the grid helps detect issues and reroute power as needed, thereby limiting interruptions. These smart infrastructures enable electrical companies to effectively control and monitor power distribution and consumption, with sensors capable of identifying transmission line issues and performing troubleshooting autonomously.

Figures 1 and 2 present an overview of a traditional grid and a smart grid.

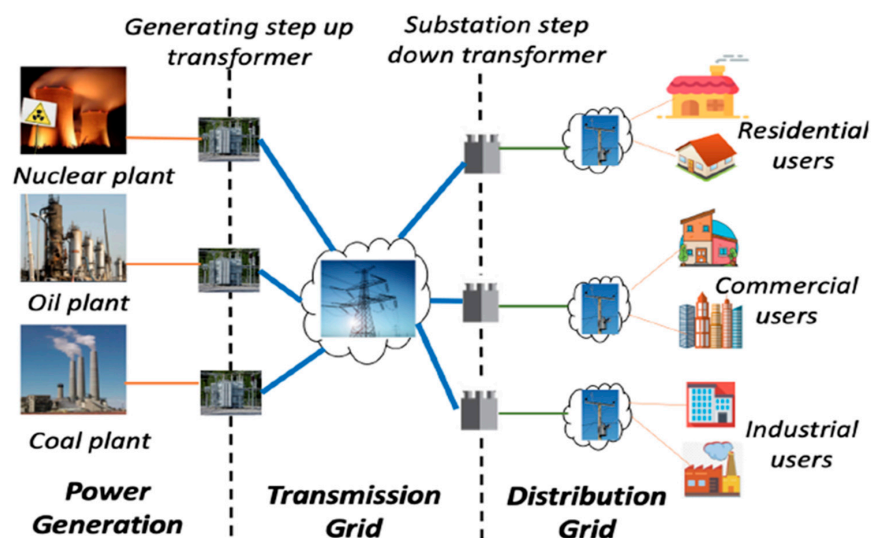


Figure 1. Traditional grid [18].

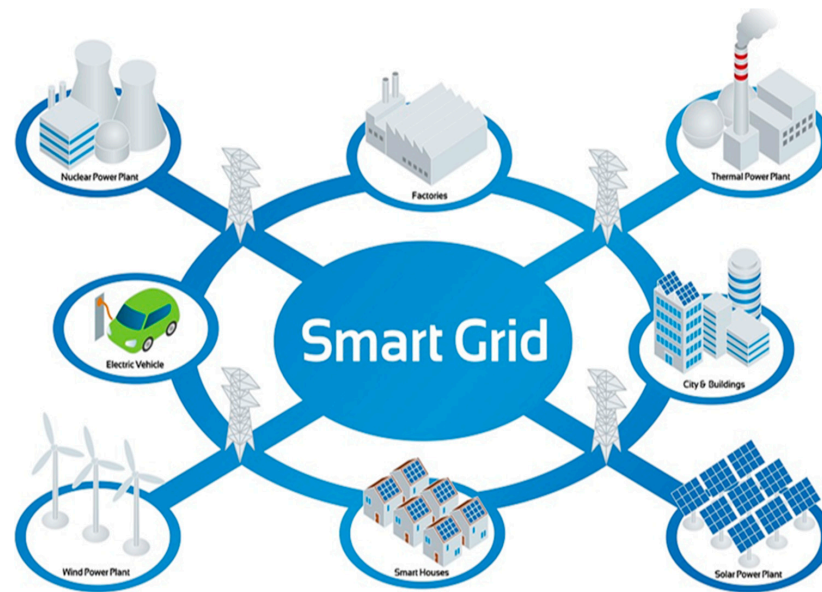


Figure 2. Smart grid [20].

3.2. Blockchain Technology

Blockchain is a form of distributed ledger technology (DLT) that securely logs transactions across a network of computers. Each block in the blockchain compiles a list of transactions and connects to the previous block, forming a continuous chain. This design guarantees that the data within the blockchain are immutable, meaning that once information is added, it cannot be altered or removed without the consensus of network participants. The security and transparency of the blockchain are upheld through cryptographic hashing and distributed consensus mechanisms like proof of work (PoW) or proof of stake (PoS) [1]. Although blockchain technology is primarily recognized for supporting cryptocurrencies such as Bitcoin and Ethereum, its applications are diverse and extend to sectors such as supply chain management, healthcare, and energy trading.

3.3. Blockchain Data Structure

Figure 3 depicts the architecture of a blockchain, where each block contains data and is linked to the preceding one, creating a secure sequence. The header of each block encompasses critical elements: the “Previous Block Address” (a hash that connects it to the previous block), a “Timestamp” (showing when the block was formed), a “Nonce” (a numerical value used in mining to safeguard the block), and a “Merkle Root” (a hash that encapsulates all transactions within the block). This interlinked structure guarantees that once data are entered into a block, they cannot be changed without modifying all following blocks, thus ensuring the security and permanence of the blockchain.

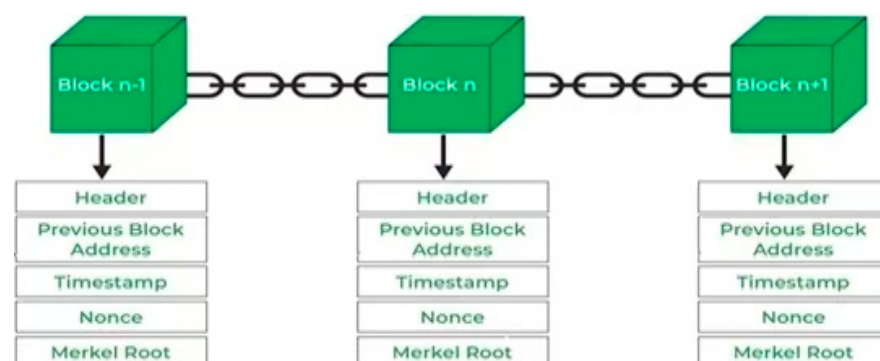


Figure 3. Blockchain data structure [21].

3.4. How Blockchain Works

Blockchain operates on a peer-to-peer network where each participant, or node, possesses a copy of the entire ledger. The process begins when a new transaction is proposed. This transaction is broadcast to the network and grouped with other transactions into a block. Before this block can be added to the blockchain, it must be validated by the network through a consensus mechanism [22].

3.5. Consensus Mechanism

In proof of work (PoW), miners compete to solve complex mathematical challenges to validate transactions and create new blocks. The first miner to solve the puzzle transmits the solution across the network, and other nodes confirm its validity. Once validated, the block is included in the blockchain, and successful miners are rewarded with cryptocurrency [23]. Although this process requires high levels of power, it ensures the security and integrity of the blockchain. Validators in proof of stake (PoS) systems use their tokens as collateral. They are responsible for creating new blocks and validating transactions in proportion to their stake. PoS is more robust than PoW and enhances security by encouraging honest behavior; any dishonest behavior risks the loss of their staked tokens [24]. Each block contains a unique cryptographic hash of the previous block, making any changes to that block detectable because such changes alter its hash and break the chain. This system creates a secure and tamper-proof record of all transactions [25]. Smart contracts regulate the terms of an agreement, reducing the need for intermediaries and the likelihood of conflicts [26]. They are particularly useful for streamlining business processes and enhancing transparency and trust between parties.

4. Materials and Methods

This research explores the integration of blockchain technology into the electrical billing system and peer-to-peer (P2P) energy trading processes. The blockchain-based approach leverages smart contracts to automate and secure various operations such as energy consumption recording, billing, and payment verification. The methodology involves simulating the billing and payment processes through MATLAB R2023b, demonstrating how blockchain and smart contracts can streamline energy management.

Figure 4 illustrates the integration of blockchain technology into the electrical billing system. Initially, energy consumption data are collected from various energy meters installed at different sites. These data are then integrated into a blockchain network, ensuring secure and immutable recording. The billing smart contract processes the energy consumption data to automatically generate bills based on a predefined rate, ensuring accuracy and efficiency. Subsequently, the payment smart contract facilitates the payment process, verifying payments against the generated bills and updating the blockchain ledger with payment information. The entire process is recorded on an immutable ledger, guaranteeing that all data and transactions are secure, transparent, and tamper-proof. This framework showcases how blockchain and smart contracts can streamline and secure the processes of data collection, billing, and payment in an electrical billing system.

The system illustrated in Figure 5 begins with a setup phase where global variables are defined to store transaction data and identify the producer and consumer. Askari Ltd. is designated as the producer, while Sinoma Handan Ltd. is the consumer. The unit rate for energy is set, which in this case is 30.1 PKR per kilowatt-hour (kWh). The process starts when Sinoma Handan Ltd. sets its energy demand for January 2022. This demand is stored in a structured format within the system, which initializes the transaction status and prepares for subsequent steps.

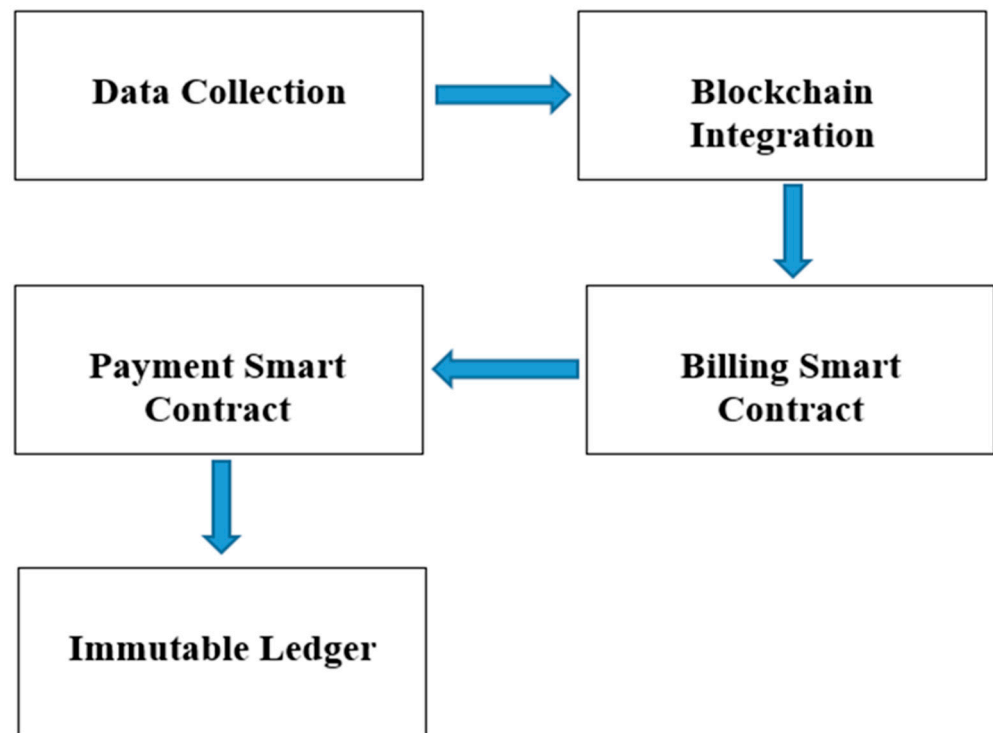


Figure 4. Block diagram for electricity billing.

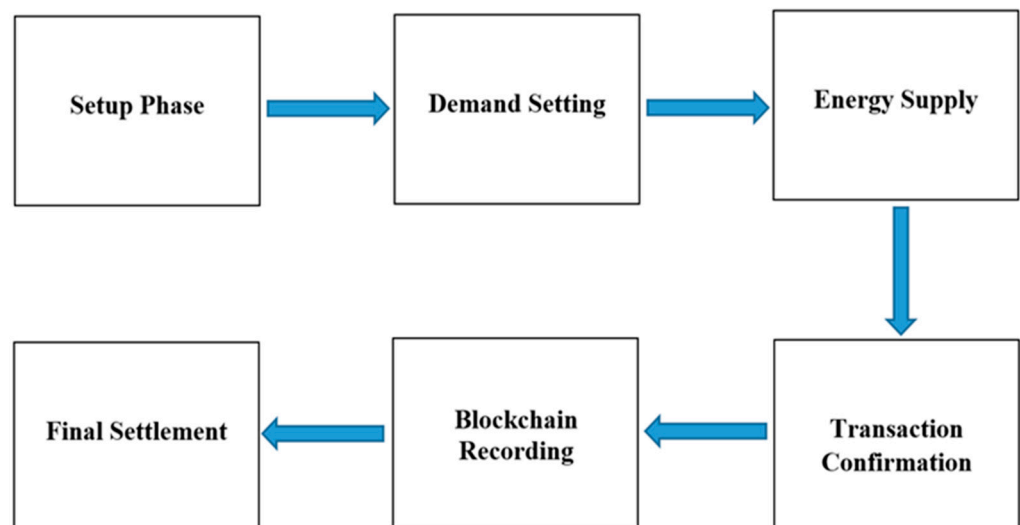


Figure 5. Block diagram for a smart contract-based energy trading system.

Following the demand setting, Askari Ltd. fulfills this demand by supplying the requested amount of energy. This action is simulated within the system, reflecting a real-world scenario where energy is delivered through a smart grid. The transaction requires confirmation from both parties: the consumer confirms receipt of the energy, and the producer confirms that the energy was supplied. This dual confirmation ensures that both sides agree on the transaction's details before it is finalized.

Once both parties have confirmed the transaction, it moves to the final settlement stage. During this stage, the system calculates the total cost based on the unit rate and the amount of energy supplied. The total cost is then communicated to both parties, providing transparency in the transaction's financial aspect. The system records these details, and the transaction status is reset, allowing for future transactions to be processed without interference.

Figure 6 illustrates the implementation of a blockchain-enabled energy trading system between two parties: Askari Ltd. (the producer) and Sinoma Handan Ltd. (the consumer). This system utilizes smart contracts to automate and ensure the transparency and accuracy of transactions.

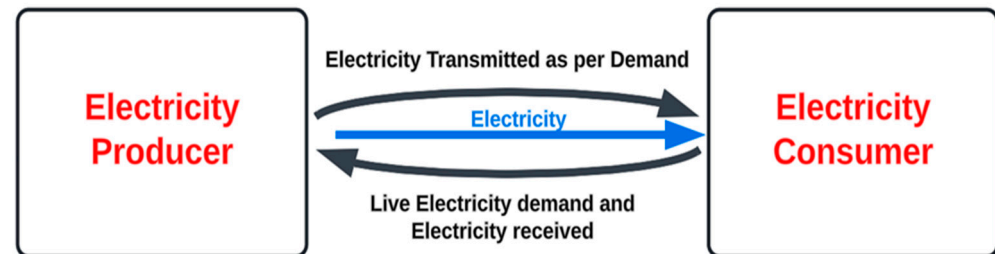


Figure 6. Smart contract energy trading [27].

In our research, we implemented a smart contract for energy trading directly in MATLAB, simulating the interactions between an energy producer (Askari Ltd.) and a consumer (Sinoma Ltd.). The code enables the automation of transactions and reduces the need for intermediaries.

Below are key details regarding the implementation.

Initialization: The simulation starts by initializing the balances of the producer and consumer, along with the energy production and consumption rates. For instance, the consumer begins with a balance of 500 pkr, while the producer's balance starts at 0.

Energy Trading Logic: The smart contract logic checks whether the producer has enough energy available for sale and whether the consumer has sufficient balance to make a purchase. If both conditions are met, the transaction proceeds, updating the balances of both parties accordingly. For example, if the consumer requests 100 kWh and the price is set at 0.15 pkr per kWh, the total transaction cost is calculated, and balances are adjusted to reflect the trade.

Event Display: Throughout the process, transaction details are displayed to provide feedback on the simulation's status. This includes successful transactions, energy traded, transaction costs, and remaining energy for the producer.

Data Simulation: In addition to the simple trading scenario, we expanded the model to simulate energy trading using real-world data. The MATLAB code processes energy consumption data from various meters, determining the total energy available and performing transactions accordingly. If the consumer's balance is insufficient for any meter, the simulation indicates a transaction failure, thus reflecting real trading scenarios.

Blockchain reduces transaction costs primarily by minimizing the need for intermediaries. In traditional energy markets, multiple intermediaries are typically involved in managing, validating, and settling trades, each charging fees that drive up transaction costs. With Ethereum, smart contracts allow for automated transactions directly between energy producers and consumers, thereby eliminating the costs associated with middlemen [28]. Furthermore, while Ethereum's gas fees fluctuate based on network demand, advancements like layer-2 scaling solutions (e.g., rollups) and the transition to Ethereum 2.0 aim to reduce these costs, making Ethereum more viable for high-frequency, low-cost energy trades [2,29]. Beyond cost reduction, Ethereum's blockchain provides immutability and transparency—key benefits in energy trading. Once transactions are recorded, they cannot be altered, enhancing security and minimizing disputes [30]. This immutability, combined with transparency, enables stakeholders to trust that all trades are accurately and fairly recorded, thereby reducing the need for costly reconciliations and attracting greater market participation [31]. Real-world implementations such as the Brooklyn Microgrid and Power Ledger in Australia further illustrate how blockchain-based energy systems can achieve cost-efficiency and transparency, ultimately creating a more secure and efficient energy trading framework [32]. Thus, by integrating references to empirical and theoretical

research, the claims regarding blockchain's impact on transaction costs, immutability, and transparency are well-supported and substantiated.

4.1. Accurate Recording of Demand and Supply Data

The accurate recording and real-time updating of demand and supply data are fundamental features of our MATLAB simulation.

Here is how this was achieved:

Dynamic Demand and Supply Tracking: The simulation continually tracks energy requested and supplied. Each successful transaction updates the producer's and consumer's balances, ensuring that all changes are recorded in real time. This approach mimics the functionality of blockchain technology, where every transaction is logged and verifiable.

Enhanced Demand Response: By simulating various consumer demands and the corresponding producer supplies, the MATLAB model demonstrates how real-time data can facilitate better demand response strategies. Producers can adjust their output based on the simulated consumption data, thus improving grid management and operational efficiency.

4.2. Data Collection

Table 1 contains the electricity consumption data for each meter installed by Sinoma Handan at various sites during the installation of Askari Cement Plant Line-3 at Nizampur, Nowshera, Pakistan. Sinoma Handan, a Chinese construction company, undertakes various construction projects both domestically and internationally. Askari Cement Plant Nizampur is a Pakistani cement production factory. Electricity consumption data for January 2022 were collected from various meters installed by Sinoma Handan at different sites. Each meter's data include the kilowatt-hour (kWh) consumption and the unit rate in Pakistani Rupees (PKR). These data were essential for generating accurate billing information and simulating the billing process.

Table 1. Electricity consumption readings by Sinoma Handan Ltd. for January 2022.

S. No	Meter NO	kWh
1	PT41613	11,240.4
2	PT41615	16,656
3	PT41635	4280.4
4	PT41638	10,359.6
5	Sr#160577	3196.8
6	CR9006171259	26,240
7	SR# 201510217941	8320
8	PT41614	7514.4
9	SR# 201704008626	1690
10	NO.90061712646	31,864
11	PT41633	818.4
12	PT-42154	64.92
13	PT-42086	2.45
14	PT-41313	51.57

4.3. Mathematical Model

The total bill for each meter is calculated by multiplying the energy consumption by the unit rate:

$$B_i = E_i \times R \quad (1)$$

E_i : Energy consumption for meter i in kilowatt-hours (kWh).

R: Unit rate in Pakistani Rupees (PKR) per kWh.

B_i : Total bill for meter i in PKR.

P_i : Payment made for meter i in PKR.

5. Results

Table 2 and Figure 7 show the total electricity consumption and corresponding bills for various meters installed by Sinoma Handan Ltd for January 2022. The table lists the meter numbers, the kilowatt-hour (kWh) consumption, the unit rate in PKR, and the total bill in PKR for each meter.

Table 2. Electricity bill by Sinoma Handan Ltd for January 2022.

S. No	Meter NO	kWh	Unit Rate (PKR)	Total Bill (PKR)
1	PT41613	11,240.4	30.1	338,336.04
2	PT41615	16,656	30.1	501,345.6
3	PT41635	4280.4	30.1	128,840.04
4	PT41638	10,359.6	30.1	311,823.96
5	Sr#160577	3196.8	30.1	96,223.68
6	CR9006171259	26,240	30.1	789,824
7	SR# 201510217941	8320	30.1	250,432
8	PT41614	7514.4	30.1	226,183.44
9	SR# 201704008626	1690	30.1	50,869
10	NO.90061712646	31,864	30.1	959,106.4
11	PT41633	818.4	30.1	24,633.84
12	PT-42154	64.92	30.1	1954.092
13	PT-42086	2.45	30.1	73.745
14	PT-41313	51.57	30.1	1552.257

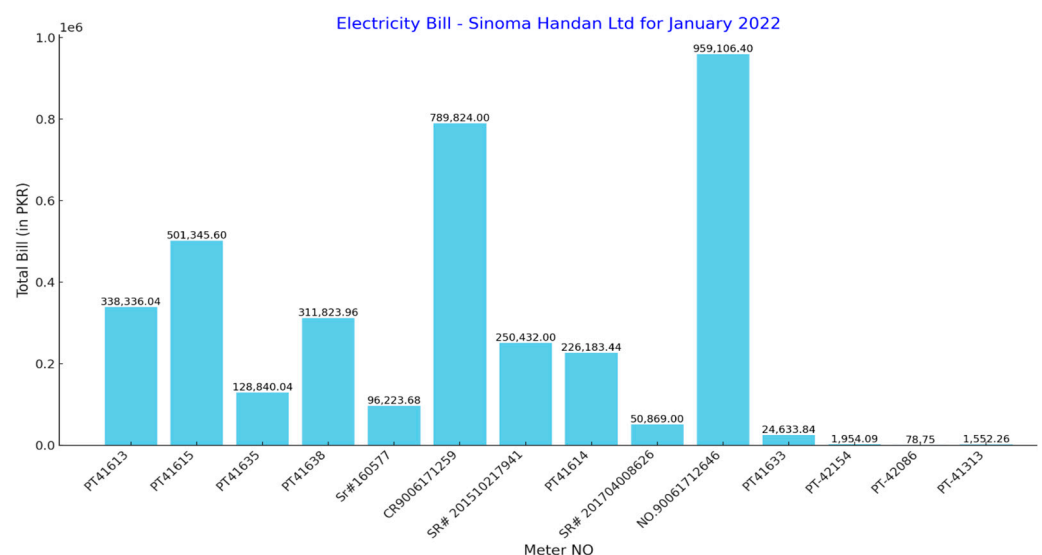


Figure 7. Electricity bills by Sinoma Handan Ltd. for January 2022.

The bar graph visualizes the total electricity bills for each meter for January 2022. The x -axis represents the meter numbers, while the y -axis represents the total bill in PKR. Each bar's height indicates the total bill amount for the corresponding meters.

Using Equation (1) and Table 2, we can verify the accuracy of both mathematical and blockchain-based smart contract models. The smart contract, designed for energy trading

within a blockchain-enabled smart grid, defines key parameters such as the producer (Askari Ltd.) and consumer (Sinoma Handan Ltd.) addresses, price per unit of energy, and the amounts of energy demanded and supplied. The contract includes functions for requesting and supplying energy, as well as managing user balances through deposits and withdrawals.

The simulation using Matlab involved generating transactions based on actual energy consumption data, with multiple nodes participating in the mining process. These nodes confirmed transactions while being compensated in a manner similar to traditional cryptocurrency implementations, ensuring robust participation and network security.

The values obtained from the Smart Contract Simulation Model closely align with the calculated values shown in Table 2, confirming the reliability of the simulation and illustrating a clear connection between the simulated data and their real-world counterparts.

Figure 8 shows the energy trading between the Energy producer (Askari Ltd.) and the Energy consumer (Sinoma Handan Ltd.). In January, Sinoma Handan Ltd. set an energy demand of 110,770 kWh, which was accurately recorded within the system, demonstrating its capability to handle and store energy demand data securely. Askari Ltd. fulfilled the demand by supplying the requested energy, with both parties confirming the transaction, showcasing the system's effectiveness in ensuring that the supply and receipt of energy are acknowledged to prevent disputes. The system then automatically calculated the total cost based on a unit rate of 30.1 PKR per kWh, resulting in an amount of approximately 3,332,177 PKR. This automated calculation provided a clear and transparent breakdown, essential for maintaining trust between the involved parties. Furthermore, all transaction details—including energy amount, confirmation status, and cost—were securely stored on the blockchain, ensuring that the data remain tamper-proof and accessible for future audits or reviews.

>> EnergyTradingContract

Demand set by Sinoma_Handan_Ltd: 110,770 kWh

Askari_Ltd supplied 110,770 kWh to Sinoma_Handan_Ltd

Transaction settled: Askari_Ltd -> Sinoma_Handan_Ltd for 110,770 kWh

Transaction finalized: Askari_Ltd supplied Sinoma Handan Ltd with 110,770 kWh at a total cost of 3,334,177.00 PKR

Figure 8. Blockchain-enabled energy trading contract.

6. Discussion

Integrating blockchain technology into electrical billing and energy trading systems has demonstrated considerable benefits, particularly in terms of transparency, security, and efficiency. Transparency is achieved through the immutable nature of blockchain, where all transactions are recorded on a public ledger, allowing all participants to verify and audit transactions in real time.

Security is enhanced through cryptographic techniques that protect transaction data and the decentralized nature of the blockchain, which reduces the risk of single points of failure or fraud. Additionally, the use of smart contracts automates processes and ensures that agreements are executed exactly as programmed, mitigating the potential for human error or manipulation.

Efficiency is reflected in the streamlined billing and payment processes enabled by blockchain, reducing transaction times and costs associated with traditional systems. For instance, our simulations demonstrated a significant reduction in processing times for energy trades compared to conventional billing methods. These findings are supported by [33–36], which highlight the advantages of blockchain implementations in similar contexts.

The blockchain-based smart contract for the billing process accurately modeled energy consumption and payment transactions. The validation of these results, through a compar-

ison between simulated and calculated values, confirmed the reliability and accuracy of the system. Using Equation (1) and Table 2, the simulated values were verified against the calculated ones in Table 3, showing a perfect match, which underscores the precision of the blockchain-enabled billing framework. The bar graph in Figure 7 further aids understanding by highlighting the consumption distribution across different meters, making it easier to identify potential areas for energy savings.

Table 3. Verification of blockchain-based smart contract model with a mathematical model.

Meter No.	Energy Consumption E_i (kWh)	Unit Rate R (PKR/kWh)	Calculated Total Bill B_i (PKR)	Blockchain-Based Smart Contract Model (PKR)
PT41613	11,240.4	30.1	338,336.04	338,336.04
PT41615	16,656	30.1	501,345.6	501,345.6
PT41635	4280.4	30.1	128,840.04	128,840.04
PT41638	10,359.6	30.1	311,823.96	311,823.96
Sr#160577	3196.8	30.1	96,223.68	96,223.68
CR9006171259	26,240	30.1	789,824	789,824
SR# 201510217941	8320	30.1	250,432	250,432
PT41614	7514.4	30.1	226,183.44	226,183.44
SR# 201704008626	1690	30.1	50,869	50,869
NO.90061712646	31,864	30.1	959,106.4	959,106.4
PT41633	818.4	30.1	24,633.84	24,633.84
PT-42154	64.92	30.1	1954.092	1954.092
PT-42086	2.45	30.1	73.745	73.745
PT-41313	51.57	30.1	1552.257	1552.257

Despite the promising results, future research needs to address several challenges. The system's scalability is crucial, particularly in larger grids with numerous participants. The transaction speed and associated costs on public blockchains, such as Ethereum, must also be optimized to handle high-frequency trading scenarios effectively. Additionally, regulatory and compliance issues related to energy trading and blockchain use require thorough exploration to ensure legal and operational alignment. Integrating Internet of Things (IoT) devices for real-time data collection and analysis could further enhance the system's efficiency and accuracy, paving the way for more advanced energy management systems. Overall, the research highlights the significant potential of blockchain technology in modernizing and optimizing electrical billing and P2P energy trading, making it a valuable tool for future energy markets.

7. Conclusions

The research on blockchain-enabled smart grids for optimized electrical billing and peer-to-peer (P2P) energy trading has demonstrated the transformative potential of blockchain technology in improving transparency, security, and operational efficiency. By leveraging blockchain-based smart contracts, the system effectively automated the management of energy consumption, billing, and transactions between producers and consumers. The integration of blockchain reduces the need for intermediaries, lowers transaction costs, and ensures the immutability and transparency of records, contributing to a more efficient and secure energy management framework.

While the results are promising, future research should address key challenges such as system scalability, transaction speed, and regulatory compliance. Additionally, integrating Internet of Things (IoT) devices for real-time data collection could further enhance system performance and provide greater optimization. This research underscores the potential of

blockchain technology to revolutionize energy trading and billing, promoting the development of decentralized and more democratized energy markets, and paving the way for more sustainable, transparent, and efficient energy systems.

Future work could involve pilot projects with energy firms to validate the blockchain-based system in real-world settings, particularly in automating billing and peer-to-peer energy trading. Collaborations with companies like Askari Ltd. or Sinoma Handan Ltd. would enable testing with actual data, revealing insights into system adaptability and cost efficiency across different regulatory frameworks. Additionally, pilot studies in high-density areas could assess scalability and transaction costs, identifying necessary adjustments for broader implementation. Engaging with regulatory bodies to ensure compliance across jurisdictions would also enhance acceptance, paving the way for future innovations in blockchain-powered energy management.

Author Contributions: The authors confirm their contribution to the paper as follows: conceptualization: J.D. and H.S.; methodology: J.D.; software, J.D.; validation: J.D. and H.S.; formal analysis: J.D.; investigation: H.S.; resources: H.S.; data curation: H.S.; writing—original draft preparation, J.D.; writing—review and editing: J.D. and H.S.; visualization: H.S.; supervision: H.S.; project administration: H.S.; funding acquisition: H.S. All authors have read and agreed to the published version of the manuscript.

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