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INTEGRATION OF BLOCKCHAIN AND ARTIFICIAL INTELLIGENCE IN SMART GRIDS: A COMPREHENSIVE REVIEW

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Abstract- Blockchain and artificial intelligence (AI) integration in smart grids offer a novel paradigm for operating contemporary power grids. Blockchain is a consistent and distributive ledger solution that brings a high level of security and transparency to methods of data recording that are preliminary beneficial for guaranteeing the reliability of grids. In that scenario, AI has various extra features in data processing, machine learning ability, robotization to have preemptive maintenance, smart electricity distribution, and security from cyber threats. This paper focuses on the viability of combining these technologies in smart grids. Further, it discusses how these technologies come into play in P2P energy trading, predictive maintenance, and demand response applications. It also discusses the issues related to the applications, such as scalability, interoperability, energy consumption, and regulatory issues. Examples from different parts of the world show how blockchain and AI work together to improve grid effectiveness, security, and environmental friendliness. However, the paper focuses on the fact that the execution of such technologies is flexible and, hence, calls for further research and development to overcome existing limitations that hinder the optimal execution of these technologies. The prospect of developing intelligent grids that employ blockchain and AI and make the energy supply more reliable and innovative is in the future; however, it is also in the process of becoming, and the only way to get what we envision as the future is through cooperation between different sectors such as industry, academia, and various agencies.

Keywords: Blockchain, Artificial Intelligence (AI), Smart Grids, Data Security, Predictive Maintenance, Cybersecurity, P2P Energy Trading, Machine Learning, Scalability

1. INTRODUCTION

Smart grids are a revolutionary advancement in the energy sector and involve the incorporation of digital technology in electric grid systems. Smart grids mean the improvement of conditions for managing power flows, increasing their efficiency and reliability, and decreasing their negative impact on the environment. The expanding demand for renewable energy brings about a shift from conventional power plants, better management of energy distribution, and a growing trend toward customer involvement in energy management [2]. Nevertheless, smart grids also present a number of issues, primarily related to security and data usage. Due to the integrated and complex characteristics of smart grids, they are even more vulnerable to cyber threats, leaking data, and even affecting the functioning of the system [2].

In response to these difficulties, new solutions, including blockchain and artificial intelligence (AI), have been considered to improve the effectiveness of smart grids. Ebenezer [3] has described how blockchain, an innovative technology based on a shared and unalterable record book, can provide an accurate method of transaction authentication. The third advantage of AI is its superior analytical features, such as the prediction of the next maintenance, the demand for electricity forecast, and the detection of any irregularity, all of which are very beneficial for the grid [4]. Thus, the purpose of this paper is to present a systematization of the existing literature on the use of both blockchain and AI in smart grids, discussing their applications, potential benefits, and emergent issues that have to be resolved to improve them.

2. LITERATURE REVIEW

Current literature reveals that the application of blockchain and AI in smart grid systems has widely discussed their capabilities in providing solutions to major functional problems. Deep learning and blockchain technology research to improve secure data sharing in smart grid systems are described by Srinivas, et al. [5]. They highlight how, through distribution, blockchain has a ledger that can help in providing the best ways of recording information, given that it has mechanisms to verify the integrity of data passed from one part of the grid to the other. These types of technologies not only provide more security for data but also make the data more manageable for these kinds of applications, which are crucial for the management of grids. Zhuang, et al. [6] also presented a detailed overview of the application of blockchain technology to enhance security in smart grids.

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Therefore, they explain that blockchain can significantly address risks in areas such as data manipulation or unauthorized access to the data due to the creation of an immutable ledger for transactions. The capability of data integrality is especially valuable within the framework of smart grids since unreliable and unstable data can lead to instabilities in stakeholders' trust in the grid's functioning. Furthermore, Gai, et al. [7] further discuss the integration of the two technologies, namely, blockchain and machine learning, to enhance the efficiency and protection of the grid system. They emphasize the importance of developing advanced structures to utilize these technologies as a means of improving energy distribution and forecasting the maintenance issues of smart grid systems.

Bera, et al. [8] have presented an access control protocol that is based on the blockchain concept and enhanced for IoT-supported smart grid networks. This protocol solves the security problems that arise due to the connection of numerous devices in smart grids and only allows devices that have the authority to exchange information. That is how their approach stresses the need to use effective protective measures for smart grid applications and systems. In addition, Hasan et al. [9] also provide a comparison of different ways of using the blockchain system for securing the smart grid and the demand for efficient and effective methods that may cover the high activities of modern energy systems. Taken together, these works substantiate the future applications of blockchain and AI integration with the smart grid, although the ongoing challenges and future directions for investigation have been identified.

3. BLOCKCHAIN IN SMART GRIDS

Originally, blockchain technology was created to serve as the setting for cryptocurrencies; however, it has found another successful application in increasing the security level of smart grids. Its most significant characteristic is distributed ledgers, which consist of transaction information without any specific center that manages all these transactions. This is important as it provides the decentralized nature of the smart grid and makes the system very hard to compromise, making it more secure [10]. Every transaction that takes place is chronicled and dependent on a network of participants to ensure its authenticity and unchangeability. This process not only increases openness but also improves trust among the users because all the transactions reflect history and cannot be modified without the approval of the network [11].

As applied to smart grids, the following are critical uses of blockchain technology: One of the main application areas is associated with updating data security and reliability. They also collect and use many data points, the primary of which are energy consumption reports, changing the status of the grid, and business transactions. Protecting and verifying this information is essential due to the critical role it plays in the functioning of the grid. Blockchain has been designed for such a purpose and stores the above data into a blockchain, and all the participants get assurance that the data stored is valid and is the same every time they access it [12]. This capability is very crucial in preventing fraud and unauthorized data manipulation, which have a great impact on grid operations.

In addition, P2P energy trading is another possible use case of blockchain in smart grids, in which prosumers can trade energy directly with each other. This structure of the consumers' market offers an opportunity to purchase and sell the remaining energy between themselves, provided through solar or wind energy sources. These transactions are conveniently made transparent by blockchain and are facilitated by smart contracts to execute and oversee the effect of the trade [13]. These smart contracts will only run once specified conditions have been met to facilitate fair business transactions without the help of intermediaries. It also saves costs and helps to harness renewable energy sources, and this is because consumers can also get direct benefits from the excess energy produced.

In the same regard, blockchain can also improve access control on smart grids. This means that there is an increase in the number of IoT devices connected to the grids, and therefore, more security measures have to be put in place to keep out intruders. This is based on the concept that blockchain can, in a decentralized nature, dictate the permissions of those who access special systems and data [14]. This application becomes more imperative in averting cyberattacks, especially in developing and interconnecting systems and frameworks.

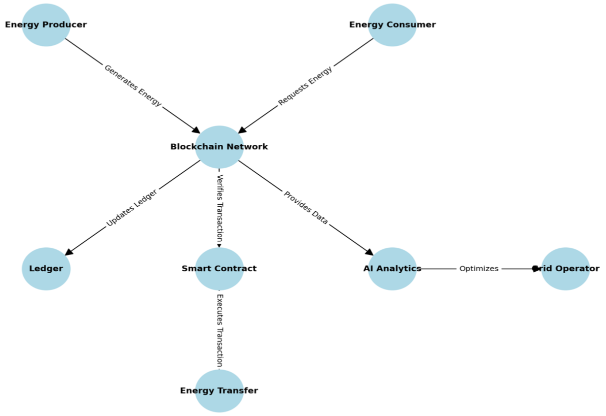

Figure 1. Blockchain-Enabled Secure Energy Trading in Peer-to-Peer (P2P) Networks

4. ARTIFICIAL INTELLIGENCE IN SMART GRIDS

The enhanced functionalities of smart grids would not be possible without the support provided by artificial intelligence technology because of its analytical capacity in processing data related to today's dynamic grid systems. AI consists of machine learning, neural networks, deep learning, and other factors that allow systems to be trained on data and make decisions regarding this data with as little human intervention as possible. AI is involved in the decision-making of different operations in smart grids, like energy distribution and scheduling of maintenance of the required components or systems within grids, which in turn makes smart grids efficient, reliable, and sustainable [15].

The most beneficial use case of AI within smart grids is proactive maintenance. Smart grids use numerous installations, such as transformers, generators, and transmission lines, that must be well maintained for efficiency. Conventional maintenance strategies that involve working to a calendar or detecting faults and arranging for repairs to be carried out are, therefore, expensive and not very effective. AI technologies, however, can capture data in real-time through different equipment that can be connected to sensors and predict possible failures [16]. For instance, using AI signals, trends in the wear of a transformer can be noted based on vibrations, temperatures, and electrical variables. This predictive feature enables utility companies to carry out maintenance when it is most essential, therefore reducing the time that the equipment is out of service and increasing the product's life cycle.

Another important use of AI in smart grids is in demand management, which is the ability of the grid to provide electricity according to the demand created by consumers in the market. It is crucial to maintain an equitable supply and demand rate with the help of precise forecasting, which can avoid power outages and help save energy. AI techniques can forecast energy consumption, the dynamics of consumption, and other factors based on historical data with relatively high accuracy [17]. These predictions help the grid operators closely monitor the electricity generation and, thus, balance supply and demand and avoid waste and extra expenses.

AI equally serves a critical purpose in increasing the cybersecurity of smart grids. The complexity of the intelligent grid, with many digital and IoT-connected devices, provides the system with new opportunities to be attacked and suffer critical structural and data damage. AI systems can constantly observe the grid for any changes that may indicate that something is awry or if there are attempts to breach the grid [18]. Since machine learning algorithms are applied, such systems can enhance the detection level over a certain period and provoke proper reactions in cases of threats. Its timely identification and prevention measures for external threats are of paramount importance to mitigate threats and protect the integrity of the grid to ensure constant electricity delivery.

Table 1. How to manage IA and blockchain security

AI Application	Description	Benefits
Predictive Maintenance	Uses machine learning to predict equipment failures	Reduces downtime, extends equipment life
Demand Forecasting	Analyzes historical data to predict future energy demand	Improves energy distribution efficiency
Fault Detection	Uses pattern recognition to identify grid faults	Faster response to outages, improved reliability
Energy Theft Detection	Applies anomaly detection to identify unusual consumption patterns	Reduces revenue losses, improves grid security
Renewable Integration	Optimizes the integration of renewable energy sources	Increases renewable energy utilization, reduces waste

5. APPLICATION OF BLOCKCHAIN FOR AI

Blockchain and the concept of smart grids, in combination with artificial intelligence, are revolutionary solutions to the present and future problems in the field of energy systems. Modern blockchain solutions are decentralized and have an irreversible record of transactions, making them suitable for data management and authentication. AI, in contrast, allows for more efficient data analysis, sophisticated mechanisms of machine learning, and automated management of grid operations. These technologies, combined, make smart grid systems more secure, reliable, and efficient, resulting in a more resilient power system.

5.1. Improved Data Processing and Protection

Investigating the integration of blockchain and AI highlights that the major advantage of such a solution is increased and secured data handling in smart grids. Blockchain makes all transactions permanent and permits no modification of data entries without the approval of the whole network, giving it the function of guaranteeing the authenticity of records. This feature is very important in ensuring data purity, and this is very necessary for monitoring and managing grid operations [19]. This information is secure, and AI systems can use the data for analysis, for example, forecasting the demand for energy, analyzing patterns and energy consumption, or detecting irregularities. For example, it is possible to use machine learning techniques to analyze past consumption data to make a prognosis of the future demand for energy in order to ensure efficient usage of the resources for utilities and avoid waste [19].

5.2. Smart Contracts and Automation

Investigating the integration of blockchain and AI highlights that the major advantage of such a solution is increased and secured data handling in smart grids. Blockchain makes all transactions permanent and permits no modification of data entries without the approval of the whole network, giving it the function of guaranteeing the authenticity of records. This feature is very important in ensuring data purity, and this is very necessary for monitoring and managing grid operations [19]. This information is secure, and AI systems can use the data for analysis, for example, forecasting the demand for energy, analyzing patterns and energy consumption, or detecting irregularities. For example, it is possible to use machine learning techniques to analyze past consumption data to make a prognosis of the future demand for energy in order to ensure efficient usage of the resources for utilities and avoid waste [19].

5.3. Smart Contracts and Automation

Engineering self-executing contracts that are coded with the basic conditions of the agreement is another major use case of blockchain on smart grids. These contracts also share complex transactions and business processes, such as energy trading, billing, and resource management, thus decreasing the requirement for intermediaries and lowering transaction costs [20].

The consequences of incorporating AI in combination with smart contracts can amplify their efficiency and changeability in terms of execution in response to the data processing results. For instance, it is important to monitor the grid load and generation capability and use it to recalculate the terms of power purchase and supply to fit the current conditions of efficiency and costs [20]. This automation benefits the entities as it increases efficiency while at the same time improving credibility and openness, as all transactions are permanently stored on the blockchain and may be inspected by the parties.

5.4. Security and Fraud Prevention

The use of blockchain and AI also provides major enhancements in terms of security and the possibility of fighting fraud. Due to the strong capabilities of an AI system, if, for instance, the smart grid has suspicious activity like high energy usage or hacking attempts, the system will immediately detect it [21]. Using machine learning methods, these systems can become more effective in their detection of threats or events that cause desired responses and improve with time. Any detected incidents will be on the blockchain, thus encrypted, and cannot be tampered with since the ledger is immutable [21]. Hence, the fortification of smart grids at both the cyber and physical levels make this critical infrastructure more capable of continued and dependable electricity delivery.

6. CASE STUDIES AND REAL-WORLD APPLICATIONS

The use of blockchain and AI in smart grids can be discussed in terms of various examples and specific instances that give valuable information on the real-life implementation of these technologies.

6.1. Grid Balancing and Demand Response in Europe

Multiple pilots on blockchain and AI to enable grid balancing and demand response have been initiated in Europe. These projects are to meet the aims of maximizing the distribution of electrical energy by addressing supply and variable demand. Prediction of demand patterns for load shifting or curtailment is the analysis of data from smart meters and other remotely placed sensors by the installed AI systems [24]. Blockchain technology helps to provide full records of transactions related to demand response and guarantees payments for consumers' participation in utilities. Thus, this approach not only contributes to the improvement of the grid's stability but also enables a better introduction of renewable energy sources since the supply fluctuation problem is also reduced [24].

These cases of implementation underscore the capability of the application of blockchain and AI in smart grids to make them optimally efficient, secure, and sustainable. At the same time, they also show that there is a need for greater efforts and research to adopt and optimize those benefits and solve technical problems.

6.2. Recent Trends in P2P Energy Trading in Australia

In Australia, a pioneering project has revealed the capacity of combining blockchain and AI to support P2P energy trading. This platform enables consumers with solar panels to sell excess power to their neighbors, hence eliminating the middleman, which is the electricity companies. Cryptographic processing is employed to ensure that transactions are stored securely and that all stakeholders can easily verify the authenticity of the pending trades [9]. In this system, real-time data processing is made possible by special AI algorithms that hinder energy production and consumption data, forecast market demand, and select appropriate buyers and sellers. Not only does this assist in the regulation of supply and demand, but consumers are encouraged to produce and sell any excess solar power generated [22].

6.3. North American Power Plants: Predictive Maintenance

Another interesting example is its usage in the sphere of anticipatory repair, including power stations in North America. One of the large utility companies adopted an AI predictive maintenance system with blockchain data management to maintain and improve the efficacy of its system [23]. The AI system collects data from the sensors placed on various essential units like turbines and transformers and informs about probable failure. It can predict when equipment or systems need maintenance so that there are minimal chances of failure and the total cycle use of the equipment is improved. It remains crucial to use blockchain technology to secure all of the maintenance activities' records and the equipment performance data for further analysis of the collected data [23]. This integration has also resulted in reduced costs and optimal performance, which are true implications of the integration of these technologies in critical settings.

7. CHALLENGES AND FUTURE DIRECTIONS

Consequently, several challenges need to be met to guarantee the proper implementation and management of blockchain and AI in smart grids.

7.1. Scalability and Performance

Based on the above analysis, one of the technical issues that has been noted is the scalability of blockchain networks. The processes of current real-world blockchains, especially those that are based on proof-of-work consensus algorithms, need help with the speed and throughput of transaction processing. This limitation could lead to high latency, high transaction cost, and low throughput, which are key quality parameters, especially in smart grid environments where the activity is fast [24]. To surmount these problems, there is a current investigation of other consensus algorithms, such as proof of stake, sharding, and the combination of the two models. Further, state channels and side chains are considered other layers, two solutions that help to move the transactions from the main blockchain in order to increase the capacity and reduce the traffic [24].

7.2. Interoperability and Standardization

One more important concern is the integration of blockchain and AI with smart grids and corresponding standards. Smart grids are multi-supplier systems that incorporate several pieces of equipment from different manufacturers, which may have different communication protocols and data patterns. These and other components have to function in coherence, and maintaining this level of interconnectivity and compatibility is the main goal of the grid [25]. Integration of blockchain and AI is not an easy process due to the fact that the two technologies have yet to be standardized. As the problem arises, proper resolution can be observed through the cooperation of several priority players in the industry, such as utility companies, technology suppliers, and regulatory agencies, in setting up common data exchange and communication protocols. These standards will arise, helping to incorporate the blockchain and AI within current systems and guaranteeing compatibility [25].

7.3. Energy Use and Emissions

The current usage of power for blockchain systems, particularly those that employ the proof-of-work consensus mechanism, is another major issue that takes into account the current trend toward more effective usage of energy resources and global ecological impact. The computational power needed for mining activities in the proof-of-work systems is power-intensive and is usually provided by non-renewable electricity; hence, it is different from the smart grids' aims of reducing carbon footprints and encouraging the use of clean energy [26]. To counter this problem, there is a trend towards the usage of new, more energy-efficient consensus algorithms, like, for example, proof-of-stake. Secondly, applying renewable resources in the process that takes place within the blockchain system can help to cope with the problem of environmental pollution. Scientists also try to make the basis of the blockchain structures or the algorithm of the blockchain less energy-consuming [26].

8. TECHNICAL ANALYSIS OF AI AND BLOCKCHAIN FOR GRID BALANCING AND DEMAND RESPONSE

This approach significantly contributes to grid stability and facilitates the integration of renewable energy sources by mitigating supply fluctuation issues. In this chapter, we explore the application of AI and blockchain technologies to further enhance grid stability and support demand response in energy systems.

AI is employed for accurate demand forecasting and optimization, while blockchain ensures secure and transparent transactions. Together, these technologies improve energy distribution efficiency and support the seamless integration of renewable energy sources. The following sections provide a detailed technical analysis of these approaches and compare their performance across various metrics.

8.1. Time Series Forecasting (AI Demand Prediction)

For time series forecasting using ARIMA, LSTM, and Prophet models, historical demand data is utilized. These models analyze past patterns to forecast future demand. The table below presents sample data for analysis using ARIMA, LSTM, and Prophet models [31].

Table 2. Result of analysis forecasting

Date/Time	Actual Demand (MW)	ARIMA Forecast (MW)	LSTM Forecast (MW)	Profit Forecast (MW)
2024-08-01 00:00	500	495	498	502
2024-08-01 01:00	480	478	482	485
2024-08-01 02:00	460	463	461	465
2024-08-01 23:00	520	515	518	523

To evaluate the accuracy of the models, the Mean Absolute Percentage Error (MAPE) can be calculated for each model using Equation (1):

$$MAPE = (1/n)\times \times\sum(|Actual\_t - Forecast\_t| / Actual\_t)\times 100 \tag{1}$$

8.2. Optimization for Load Shifting and Curtailment

Optimization techniques help balance energy production and demand while minimizing costs. The table below shows sample data for energy production, demand, and costs related to shifting and curtailment [32]. The total cost for each time interval can be calculated using Equation (2):

$$C = C\_production + C\_shifting + C\_curtailment \tag{2}$$

Table 3. Sample data for energy production

Time Interval	Production (MW)	Demand (MW)	Load Shifting (MW)	Curtailment (MW)	Production Cost ($/MW)	Shifting Cost ($/MW)	Curtailment Cost ($/MW)
00:00 - 01:00	500	520	10	10	50	30	40
01:00 - 02:00	480	470	5	5	45	28	35
02:00 - 03:00	460	440	10	10	48	29	36
23:00 - 00:00	520	540	15	20	55	35	45

Table 4. Sample for data with using Blockchain

Transaction ID	Timestamp	Energy Traded (MW)	Price ($/MW)	Condition Met (Yes/No)	Payment ($)	Hash (SHA-256)
TX001	2024-08-01 00:00	10	45	Yes	450	3e23a4d5e2...
TX002	2024-08-01 01:00	5	48	No	0	8f5c12d7a1...
TX003	2024-08-01 02:00	15	50	Yes	750	a94f12b3c9...
TX024	2024-08-01 23:00	20	55	Yes	1100	e4f8c9b12a...

Table 5. Comparison of performance metrics across different approach

Metric	ARIMA Model	LSTM Model	Prophet Model	LP Optimization	GA Optimization	Blockchain System
MAPE (%)	5.2	4.8	5.0	N/A	N/A	N/A
Total Cost ($)	N/A	N/A	N/A	50	48,5	N/A
Energy Shifting (MW)	N/A	N/A	N/A	100	120	N/A
Energy Curtailment (MW)	N/A	N/A	N/A	80	70	N/A
Smart Contract Execution Time	N/A	N/A	N/A	N/A	N/A	0.5 sec/contract
Transaction Processing Time	N/A	N/A	N/A	N/A	N/A	1.2 sec/transaction

8.3. Blockchain for Secure and Transparent Transactions

Blockchain technology ensures secure, immutable, and transparent records of energy transactions. The table below presents sample blockchain energy transactions, including the amount of energy traded, price, and payment execution.

8.4. Performance Comparison Across Models and Techniques

The performance of different models and techniques can be compared using metrics such as accuracy, cost savings, and execution time. The table below presents a comparison of performance metrics across different approaches [33].

9. REGULATORY AND ETHICAL CONSIDERATIONS

The adoption of a smart grid through the use of blockchain and AI technologies also has some regulatory and ethical issues. There is a need for regulators to set some specific guidelines for the management and safeguarding of data privacy and security to protect consumers. Concerning data ownership, consent, and the right to privacy have been more critical regarding their application with the use of AI since the development and functionality of AI require massive databases for training and execution [27]. Other factors, including the ethical effect, employment effect, and social effect, must also be taken into consideration. For example, the management of the grid and its operation and maintenance by AI would cause unemployment, and similarly, the implementation of smart contracts in energy trading through blockchain would cause an imbalance in the energy supply. As a result, decision-makers and representatives of industry sectors will have to cooperate to establish proper and fair regulations concerning the usage of these technologies [27].

10. FUTURE RESEARCH AND DEVELOPMENT DIRECTIONS

Further studies must aim to explore the technological and legal issues relating to the application of blockchain and AI technologies in smart grids. Some of the major and emerging research domains are the identification of novel blockchain protocols for efficient and sustainable cloud computing in hybrid AI technologies, the design and optimization of large-scale analytic solutions, and secure computing and network architecture.

Furthermore, field experiments and pilot projects are crucial to investigate these technologies in actual environments and to gather actual quantitative evidence concerning their efficiency, sustainability, and effectiveness. Innovative technologies to build the future need major partnerships between academia, industry, and government organizations for the development and deployment of new technologies to create more energy-sustainable and safer energy infrastructure.

11. CONCLUSIONS

Blockchain and artificial intelligence, as applied to smart grids, are the subsequent developments in advanced energy systems management and smart grids' optimization. Blockchain allows for keeping records of transactions and data that are safe and transparent, while AI helps handle the data for the grid intelligently, efficiently, and quickly. Altogether, these technologies can solve key problems in cybersecurity, data processing, and organizational productivity, thus contributing to the building up of a stronger and continually evolving energy system.

In the pieces that explain various case studies, the practical uses of blockchain and AI in the context of smart grids advocate for the emergence of new opportunities that can define the energy industry's future. Ranging from peer-to-peer energy transactions to predictive maintenance of equipment and efficient demand management, these technologies present novel possibilities to utilities and consumers. Still, to unlock the full potential of blockchain and AI within smart grid systems, several issues should be resolved, among which are scalability, interoperability, energy efficiency, and legal concerns.

The increasing application of blockchain and AI in the energy sector indicates that smart grid applications of these technologies are likely to continue developing in the future as the energy sector undergoes further innovation. Further development research should be devoted to the existing issues and the new opportunities. Thus, the potential of these technologies has to provide the actual creation of more efficient, secure, and sustainable energy systems. The formation of cross-discipline and multi-stakeholder global teams will be crucial to providing leadership and stewardship as to where, when, and how these technologies should be developed and implemented in a manner that fosters the creation of a wiser grid by focusing on fairness and sustainability.

APPENDICES

Appendix 1. Technical Analysis of Blockchain and AI for Grid Balancing and Demand Response

This annex provides a detailed technical analysis of the use of blockchain and AI technologies in grid balancing and demand response initiatives in Europe. The focus is on predictive algorithms, optimization techniques, and blockchain integration for secure and transparent transactions.

1) Demand Prediction Using AI

- Objective: Predict electricity demand patterns to enable load shifting and curtailment, ensuring efficient energy distribution.
- Time Series Forecasting: AI models like ARIMA (Auto-Regressive Integrated Moving Average), LSTM (Long Short-Term Memory networks), or Prophet can be used to predict future energy demand based on historical data. These models analyze past patterns to forecast demand peaks and troughs.

a) ARIMA:

$$Y(t) = c + \varphi_1 \times Y(t-1) + \theta_1 \times e(t-1) + e(t) \tag{3}$$

where, $Y(t)$ is the current value, φ_1 is the coefficient for the lagged value, θ_1 is the moving average coefficient, and $e(t)$ is the error term.

b) LSTM: LSTM networks are recurrent neural networks that are effective in capturing temporal dependencies. The key equations include:

Forget gate

$$f\_t = \sigma\left(W\_f \times \left[h\_(t-1),\ x\_t\right] + b\_f\right) \tag{4}$$

Input gate

$$i\_t = \sigma\left(W\_i \times \left[h\_(t-1),\ x\_t\right] + b\_i\right) \tag{5}$$

Cell State

$$C\_t = f\_t \times C\_(t-1) + i\_t \times \acute{C}\_t \tag{6}$$

Output Gate

$$o\_t = \sigma\left(W\_o \times \left[h\_(t-1),\ x\_t\right] + b\_o\right) \tag{7}$$

- Prophet model: A decomposition-based approach to time series forecasting, particularly useful when there are seasonality effects.

Prophet Model:

$$y(t) = g(t) + s(t) + h(t) + \varepsilon\_t \tag{8}$$

where, $g(t)$ is the trend function, $s(t)$ is the seasonal component, $h(t)$ represents holidays, and ε is error term.

2) Optimization for Load Shifting and Curtailment

- Objective: Optimize grid operations by balancing supply and demand through load shifting (moving energy consumption from peak to off-peak times) and curtailment (reducing energy usage during peak times).

a) Optimization Problem Formulation:

- Objective Function: Minimize the total cost of energy distribution while maintaining grid stability.

Mathematical Formulation:

- Minimize:

$$C = \sum(t = 1\ to\ T) \left[C\_production(t) + C\_shifting(t) + C\_curtailment(t)\right] \tag{9}$$

Subject to:

- Power balance constraint:

$$P\_production(t) + P\_import(t) - P\_demand(t) - P\_curtailment(t) = 0 \tag{10}$$

- Grid stability constraint:

$$V\_grid(t) \le V\_max \tag{11}$$

- Demand response constraint:

$$0 \le P\_shifting(t) \le P\_demand(t) \tag{12}$$

Table 6. Equation and paper references

Equation	Article Reference
Equations (1) and (2)	[8]
Equation (3)	[4]
Equation (4)	[8]
Equation (5)	[4]
Equation (6)	[6]
Equation (7)	[7]
Equation (8)	[2]
Equation (9)	[9]
Equation (10)	[3]
Equation (11)	[5]
Equation (12)	[10]

b) Algorithms

Algorithm 1. AI-based demand prediction and blockchain transaction process

```
# Python code for AI-based demand prediction and blockchain
transaction process
import numpy as np
from sklearn.linear_model import LinearRegression
from statsmodels.tsa.arima.model import ARIMA
import matplotlib.pyplot as plt
# Sample data for energy demand (in MW)
energy_data = np.array([100, 105, 110, 115, 120, 130, 125, 140, 135,
150, 160])

# ARIMA model for demand prediction
def predict_demand_arima (data, steps=5):
   model = ARIMA (data, order= (1, 1, 1))
   model_fit = model.fit ()
   forecast = model_fit.forecast (steps=steps)
   return forecast

# Predicting future demand
predicted_demand = predict_demand_arima(energy_data)

# Simulating load shifting and curtailment
def optimize_load_shifting (demand, threshold=140):
   shifted_demand = []
   ford in demand:
      if d > threshold:
         shifted_demand.append(d - 10)  # Simulate shifting by reducing
demand by 10 MW
      else:
         shifted_demand.append(d)
   return shifted_demand

optimized_demand = optimize_load_shifting(predicted_demand)

# Simulating blockchain transaction
class Blockchain:
   def __init__(self):
      self.chain = []
      self.create_block (proof=1, previous_hash='0')

   def create_block (self, proof, previous_hash):
      block = {'index': len(self.chain) + 1,
```

```
                'proof': proof,
                'previous_hash': previous_hash}
        self.chain.append(block)
        return block
    def get_previous_block(self):
        return self.chain[-1]
    def proof_of_work (self, previous_proof):
        new_proof = 1
        check_proof = False
        while check_proof is False:
            hash_operation = (new_proof**2 - previous_proof**2) % 100
            if hash_operation == 0:
                check_proof = True
            else:
                new_proof += 1
        return new_proof

    def hash (self, block):
        return hash(str(block))

# Creating a blockchain and simulating a transaction
blockchain = Blockchain ()

# Simulating a smart contract for payment
def execute_smart_contract (demand, condition=130):
    if demand < condition:
        return "Payment Executed"
    else:
        return "Payment Not Executed"
# Loop through the optimized demand and record transactions
for demand in optimized_demand:
    previous_block = blockchain.get_previous_block()
    proof = blockchain.proof_of_work(previous_block['proof'])
    previous_hash = blockchain.hash(previous_block)
    blockchain.create_block(proof, previous_hash)
# Execute smart contract
    result = execute_smart_contract(demand)
    print (f"Demand: {demand} MW - {result}")

# Plotting predicted and optimized demand
plt.plot(predicted_demand, label='Predicted Demand')
plt.plot(optimized_demand, label='Optimized Demand', linestyle='--')
plt.xlabel('Time Step')

plt.ylabel('Demand (MW)')
plt.legend()
plt.show()
```

- Linear Programming (LP): Solves the above optimization problem by minimizing a linear objective function subject to linear constraints.
- Mixed-Integer Linear Programming (MILP): Useful when discrete variables (e.g., on/off decisions for devices) are involved.
- Genetic Algorithms (GA): An evolutionary algorithm for solving optimization problems by mimicking the process of natural selection.
- Reinforcement Learning (RL): An AI approach where an agent learns to take actions in a way that maximizes a cumulative reward (e.g., minimizing costs while maintaining grid balance).

3) Blockchain for Secure and Transparent Transactions

- Objective: Use blockchain technology to ensure secure, immutable, and transparent records of energy transactions and guarantee payments to participants in demand response programs.

a) Blockchain Structure:

- Ledger: A distributed ledger that records every transaction related to energy trading and demand response events.
- Smart Contracts: Self-executing contracts that trigger payments when certain conditions are met (e.g., curtailment of energy usage during peak hours).
- Consensus Algorithms:
- Proof of Work (PoW): Participants solve complex cryptographic puzzles to validate transactions.
- Proof of Stake (PoS): Participants validate transactions based on the number of tokens they hold.
- Practical Byzantine Fault Tolerance (PBFT): A consensus mechanism that achieves agreement among participants even in the presence of some faulty or malicious nodes.

b) Blockchain Transactions:

- Let T_i represent the transaction associated with a demand response event i.
- Transaction Validation: T_i is added to the blockchain after consensus is reached among the validators.
- Smart Contract Execution: If the condition C_i (e.g., curtailment of X MW) is met, then the payment P_i is automatically transferred to the participant.

c) Security Considerations:

- Cryptographic Hashing: Ensures data integrity by representing the transaction data as a fixed-size hash H(T_i).
- Public/Private Key Encryption: Ensures secure communication between participants using asymmetric encryption.

4) Integration and Challenges

- Objective: Integrate AI and blockchain in the smart grid to achieve optimal efficiency, security, and sustainability.

a) Integration of AI and Blockchain:

- Data Flow: AI systems analyze data from smart meters and sensors to predict demand patterns. Blockchain stores the outcomes of these predictions and the corresponding transactions.
- Automation: Smart contracts on the blockchain automatically execute actions (e.g., payments, load adjustments) based on AI predictions.

b) Challenges:

- Scalability: The blockchain must handle a large number of transactions with low latency.
- Data Privacy: AI systems require access to sensitive data (e.g., energy consumption patterns) that need to be securely managed on the blockchain.
- Interoperability: Ensuring that AI models and blockchain platforms can communicate seamlessly within the grid infrastructure.

The combination of AI and blockchain technologies offers a robust framework for optimizing grid operations, enhancing energy distribution efficiency, and ensuring secure, transparent transactions in demand response scenarios. The effectiveness of these systems depends on the successful implementation of predictive algorithms, optimization techniques, and blockchain protocols, as well as overcoming challenges such as scalability and data privacy. Further research and pilot projects are needed to refine these technologies and maximize their potential benefits for smart grids in Europe and beyond.

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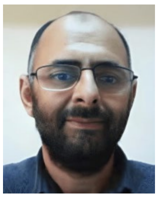

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