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Implementing Distributed Ledger Technology for Advanced Supply Chain Optimization in the Renewable Energy Sector: A Comprehensive Examination

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

Blockchain, also known as a distributed ledger, is a novel technological advancement that is currently gaining prominence in several sectors and industries worldwide. Various interest groups, including energy businesses, small and medium-sized enterprises (SMEs), start-ups, information technology developers, financial institutions, national authorities, and the academic community, have shown interest in this matter. The enhancement of daily corporate operations is projected to be achieved by several means, such as the decentralization of authority in transactions, installation of the Internet of Things (IoT), and utilization of smart contracts. Digitalization is already prevalent in several solutions within the energy sector, including smart grids, smart meters, and electric vehicles. Furthermore, the academic literature has developed a novel idea known as the Internet of Energy (IoE). This article examines the degree of trust and maturity associated with the use of

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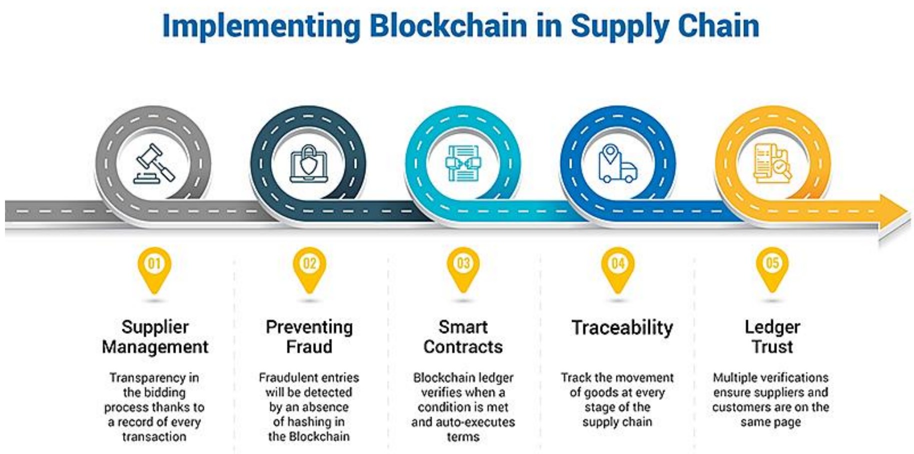
Blockchain technology. The authors have developed the Blockchain Maturity Questionnaire to assess these factors. The database comprises replies obtained from experts in high management positions within the renewable energy sector. The report provides an overview of the current understanding of Blockchain technology, highlighting its primary advantages and challenges in implementation. Additionally, it examines the extent to which firms are inclined to use this technology into their future operations. The valuable input from industry professionals facilitated the development of a comprehensive plan, referred to as the "Roadmap for Blockchain Adoption," which outlines the integration of blockchain technology into forthcoming energy systems.

Keywords: Block chain; renewable energy; ledger technology.

1. INTRODUCTION

The present energy systems are progressively integrating higher proportions of renewable energy sources (RES) [1]. The transition described, which is guided by the sustainable triple-bottom-line principle of creating value through the economic, environmental, and societal achievements of energy businesses, has been additionally enhanced by privatization, as well as incentives stemming from financial and energy policies [2,3]. In the year 2020, the proportion of renewable energy sources in Finland had a notable increase, reaching an approximate level of 40%. This achievement marks a significant milestone as it surpasses the combined share of fossil fuels and peat, a first in the nation's history [4]. Nevertheless the integration of renewable energy sources (RES) poses challenges in terms of their inconsistency, unpredictability and susceptibility to weather conditions, hence complicating the administration of power systems [5]. The advent of distributed energy markets necessitates innovative technological solutions to facilitate the exchange of energy and information. Therefore, as a result of the decentralized and sporadic characteristics of renewable energy sources, the use of pioneering technologies becomes imperative in order to propel their growth to a higher stage [6, 7]. Hence, the implementation of certain flexibility measures becomes imperative in order to bolster grid stability. These measures encompass the timely deployment of supply and demand response mechanisms, as well as the adoption of energy storage technologies. The proliferation of smart meters worldwide has led to assertions that energy systems are poised to undergo a digital revolution. The current centralized energy markets pose a significant obstacle to the realization of this revolution, since they lack the necessary information-sharing capabilities provided by ICT. Novel energy markets, often localized, offer various benefits such as enhanced energy efficiency, improved environmental sustainability, and socioeconomic performance. However, to enhance their effectiveness in managing peer-to-peer energy trading, these markets necessitate decentralization and digitalization solutions that enable greater proactivity by involving a broader range of actors [8,9].



Picture 1. Implementing blockchain in Supply Chain

Blockchain technology can potentially address these challenges by leveraging its inherent features, such as decentralization, to facilitate transactions without the need for central authorities. It can alternatively be characterized as a distributed ledger technology (DLT) or Internet of Value that securely records and facilitates the sharing of digital transactions, eliminating the need for centralized management [10,11]. This architectural framework facilitates the automated implementation of intelligent contracts within decentralized peer-to-peer trading systems. Blockchains can be conceptualized as a worldwide database that facilitates the participation of various users in the modification of the ledger. This is achieved by the automatic propagation of these modifications, wherein multiple copies of the updated records are generated and incorporated into the chain. In contrast to management systems that are centralized and governed by a single authority, the approval of modifications in this network is contingent upon consensus processes among users [12]. This characteristic renders the network transparent, safe, and devoid of the need for trust. In order to enhance resistance against human-related misconduct and errors, the preservation of user anonymity is achieved by the utilization of cryptographic techniques throughout the process of linking new transactions to the pre-existing ones within a block. The existing body of literature indicates that significant technical advancements need the development of novel business models and a reevaluation of prevailing technology paradigms [13].

1.1 What Actually DLT Is?

Distributed ledger technology (DLT) refers to a digital system that enables the recording, sharing, and synchronization of data across multiple participants or nodes within a network. Distributed ledger technology (DLT) refers to a digital framework designed to record asset transactions, wherein the transactions and their associated information are simultaneously recorded in many locations. In contrast to conventional databases, distributed ledgers lack a centralized data repository or administrative capabilities [14-16].

DLT, short for distributed ledger technology, pertains especially to the technological framework and protocols that facilitate the concurrent access, validation, and modification of records that define distributed ledgers. The system operates within a distributed computer network that spans across various entities, locations, or nodes. In a distributed ledger system, every node undertakes the task of processing and verifying each individual item, resulting in the generation of a comprehensive record for each item and the establishment of a consensus regarding its authenticity. A distributed ledger has the capability to record both static data, such as a registry, and dynamic data, such as financial transactions. Blockchain is widely recognized as an exemplar of a distributed ledger system. The decade after the introduction of Bitcoin in 2009 witnessed a substantial surge in the level of enthusiasm surrounding distributed ledger technology. Bitcoin, a cryptocurrency that operates on blockchain technology, played a pivotal role in showcasing the functionality, scalability, and security of this technology [17,18].

Subsequent to that period, other businesses across different industries conducted trials and tests to explore the potential applications of Distributed Ledger Technology (DLT) inside their operational frameworks. The financial services, healthcare, and pharmaceutical sectors emerged as pioneers in adopting supply chain management as a prevalent application [19, 20].

It is imperative to acknowledge that the notion of a distributed ledger is not novel. Historically, organizations have engaged in the practice of collecting and storing data in several locations, utilizing either physical paper or segregated software systems. The consolidation of this data into a centralized database has typically occurred at intermittent intervals. In the context of an organization, it is possible for various divisions to possess distinct sets of data, wherein each division contributes its respective data to a centralized ledger only when necessary. In a similar vein, it is common for multiple organizations to maintain their respective datasets and subsequently share them with a central ledger that is under the jurisdiction of an authorized entity, but only upon request or necessity. One notable progress of Distributed Ledger Technology (DLT) lies in its capacity to mitigate or eradicate the frequently protracted and error-prone procedures required for reconciling diverse contributions to the ledger. Additionally, DLT guarantees universal accessibility to the most up-to-date version, while instilling confidence in its accuracy [21-26].

1.2 What is the Operational Mechanism of Distributed Ledgers?

Distributed Ledger Technology (DLT) operates on the fundamental concepts of decentralization. In contrast to conventional centralized databases, Distributed Ledger Technology (DLT) functions within a peer-to-peer (P2P) network, wherein numerous nodes collectively store, validate, and update the ledger concurrently. This obviates the necessity for a central governing body and mitigates the potential vulnerability associated with a singular point of failure [27, 28].

The procedure commences with the reproduction of digital data throughout the network of nodes. Every individual node in the system is responsible for maintaining an exact replica of the ledger and autonomously handles the processing of new update transactions. In order to achieve consensus, all nodes that are involved in the process utilize a consensus algorithm that is responsible for determining the accurate version of the ledger. After a consensus has been achieved, the revised ledger is distributed to all nodes, thereby ensuring synchronization and correctness. Distributed Ledger Technology (DLT) employs cryptographic techniques to ensure the secure storage of data, while utilizing cryptographic signatures and keys to restrict access only to individuals with proper authorization. The technology also facilitates the establishment of an immutable database, wherein information, once stored, becomes unalterable, and any subsequent modifications are permanently documented for future reference [29-31].

The presented architectural design signifies a notable paradigm shift in the process of gathering and disseminating information. It involves the relocation of record-keeping activities from a centralized authority to a decentralized system, wherein all pertinent entities possess the ability to access and edit the ledger. Consequently, the ledger's users and modifiers are visible to all other entities. The openness inherent in Distributed Ledger Technology (DLT) engenders a significant degree of confidence among participants and effectively mitigates the possibility of fraudulent activity taking place within the ledger. Therefore, distributed ledger technology (DLT) eliminates the necessity for entities utilizing the ledger to depend on a trusted central authority that governs the ledger or an external third-party provider to fulfill that function and serve as a safeguard against manipulation [32-34].

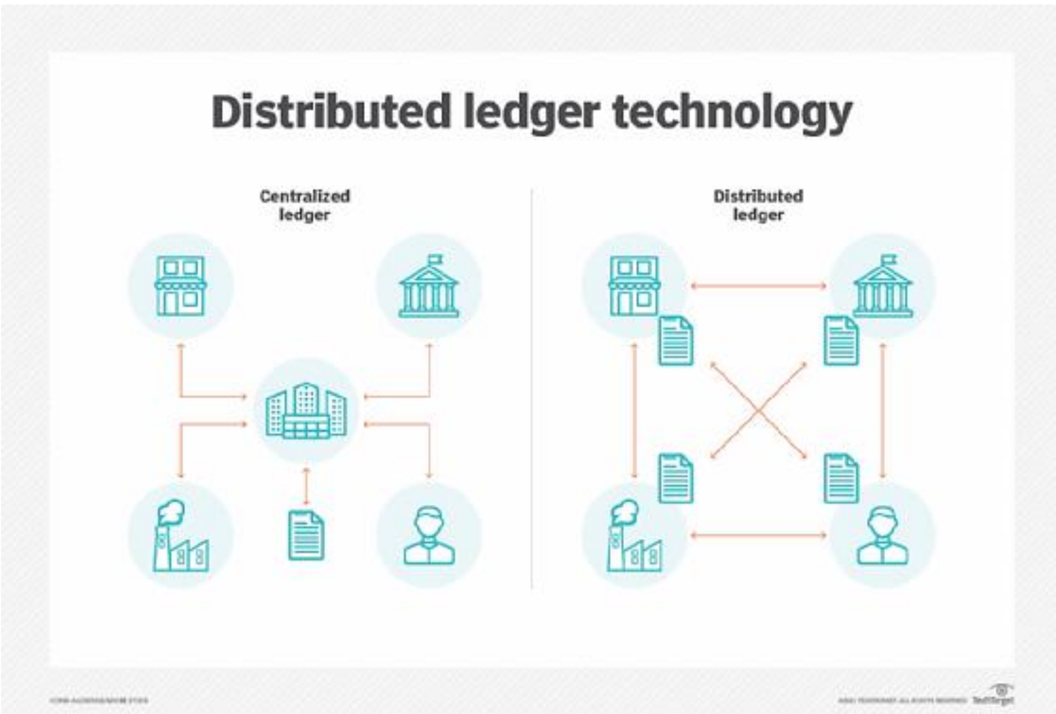


Fig. 1. Distributed ledger technology

The origins of ledgers can be traced back to ancient civilizations, where they were used as a means of recording financial transactions. For centuries, ledgers have served as a fundamental means of documenting transactions and related information, traditionally in the form of physical paper records. The process of digitization commenced throughout the late 20th century with the advent of computers, albeit digital ledgers predominantly replicated the content that was previously documented on paper. Throughout history, the use of ledgers has necessitated the presence of a central authority to verify the legitimacy of the transactions documented inside them. As an illustration, financial institutions are required to authenticate the financial transactions they undertake. The advent of 21st-century technology has facilitated the progression of record-keeping through the utilization of cryptography, sophisticated algorithms, and enhanced processing capabilities. Consequently, the distributed ledger has emerged as a progressively feasible method of maintaining records [35-37].

This advancement is occurring during a period of high demand for such technologies. Throughout history, economic activity has consistently entailed the involvement of several individuals, while commerce has consistently transcended various authorities and borders. However, contemporary corporate networks encompass a larger number of members across multiple areas, necessitating the recording of data for their individual purposes and to meet the requirements of other network participants. The utilization of traditional ledgers has been subject to significant strain, resulting in increased maintenance costs and heightened susceptibility to errors, computer breaches, manipulation, and tampering [38-44].

2. WHICH INDUSTRIES EMPLOY DISTRIBUTED LEDGER TECHNOLOGY?

The utilization of Distributed Ledger Technology (DLT) extends across several sectors and is fundamentally transforming many established procedures. The prevailing applications of Distributed Ledger Technology (DLT) encompass the subsequent domains [45].

2.1 Banking and Finance

The field of banking and finance encompasses various aspects related to the management of financial resources within the banking industry. The banking and finance sector has emerged as a leading adopter of distributed ledger technology. An exemplary application can be observed in the integration of smart contracts within the realm of trade finance. Smart contracts enable the efficient execution and settlement of trade transactions, thereby minimizing inefficiencies and obviating the necessity for middlemen. Moreover, distributed ledger technology (DLT) facilitates expedited cross-border financial transactions, improves the efficiency of Know Your Customer (KYC) procedures, and offers robust digital identification solutions [46-48].

2.2 Supply Chain management

Supply chain management refers to the strategic coordination and oversight of the various activities involved in the production, distribution, and delivery of goods and services from suppliers to end consumers. The utilization of Distributed Ledger Technology (DLT) is widely recognized as a crucial application in the field of supply chain management. Distributed ledgers facilitate the monitoring and authentication of products' movement within businesses, thereby safeguarding their legitimacy and mitigating the risk of fraudulent activities. This technological advancement facilitates instantaneous monitoring of supply chain processes, mitigates the need for physical documentation, and diminishes operational inefficiencies. One potential application of a distributed ledger solution is the ability to monitor and trace the origin of goods, thereby promoting ethical sourcing practices and bolstering consumer confidence [49-51].

2.3 Health Care Department

The utilization of Distributed Ledger Technology (DLT) in the healthcare sector has demonstrated significant potential in enhancing patient data management, optimizing operational operations, and fortifying security measures. The utilization of Distributed Ledger Technology (DLT) enables the secure storage and sharing of medical records, hence ensuring the preservation of data privacy and integrity. Furthermore, the implementation of smart contracts has the potential to streamline insurance claim processes by automating them, resulting in less administrative workload and enhanced operational effectiveness. Distributed Ledger Technology (DLT) also facilitates secure and transparent clinical trials, thereby safeguarding the integrity of data and bolstering trust in the research process [52-54].

2.4 Real Estate

Distributed ledger technology (DLT) holds promise for strengthening the real estate sector through streamlining property transactions, minimizing administrative documentation, and bolstering security measures. The utilization of smart contracts enables the automation of property transfers, thereby guaranteeing precise and unalterable documentation of ownership. Blockchain platforms that utilize distributed ledgers have the potential to establish property registries that are both visible and auditable. This has the advantage of mitigating the risk of fraud and conflicts, while also eliminating the necessity for expensive intermediaries. Moreover, distributed ledger technology (DLT) has the potential to facilitate the division of ownership in real estate, so creating novel avenues for investment and enhancing market fluidity [55, 56].

2.5 Various Sectors

Distributed Ledger Technology (DLT) has use in diverse sectors beyond its primary applications. In the energy industry, distributed ledger technology (DLT) has the potential to facilitate peer-to-peer (P2P) energy trading and enable the implementation of decentralized renewable energy systems. Within the realm of the entertainment sector, the implementation of Distributed Ledger Technology (DLT) has the potential to bring about a significant transformation in the management of royalties, thereby guaranteeing equitable remuneration for artists. Furthermore, Distributed Ledger Technology (DLT) finds utility in other domains such as voting systems, intellectual property rights management, gaming, and numerous other areas. Distributed ledger technology (DLT) encompasses a range of applications that facilitate decentralized and transparent record-keeping. This technology has gained significant attention in recent years due to its potential to revolutionize various industries. Several notable examples of DLT include blockchain. There are several types of distributed ledger technology that are presently being utilized, which encompass the following [57-60]:

- The concept of blockchain has gained significant attention in recent years. The most widely recognized kind of Distributed Ledger Technology (DLT) is blockchain, which involves the grouping of transactions into blocks that are subsequently linked together and disseminated to the various nodes within the network. It serves as the underlying technology that enables the functioning of Bitcoin and other cryptocurrencies.
- The term "tangle" refers to a situation or condition characterized by a complex and intricate Tangle, an alternative kind of Distributed Ledger Technology (DLT), is specifically designed to cater to the requirements of internet of things (IoT) ecosystems. The Tangle EE Working Group was established through a collaboration between the Eclipse Foundation and the IOTA Foundation. Tangle has been characterized as a decentralized ledger system that operates without the need for permission or fees. It is designed to provide secure and efficient transmission of data and currency between both human and machine entities.

3. BLOCKCHAIN AND ENERGY SECTOR

Blockchain, also known as distributed ledger technology (DLT), is a technological innovation that facilitates the dissemination of digital information inside a communal database. This database maintains a perpetually growing record of transactions, organized in a sequential manner based on their chronological occurrence. In essence, the blockchain is a distributed ledger that facilitates the sharing of digital transactions, data records, and executables among participating agents in the network. Blockchain technology is characterized by four primary attributes that differentiate it from other existing information systems: decentralization, security, verifiability, and smart execution. The technology in question is a product of extensive research and development spanning over a period of ten years, conducted by a distinguished collective of computer scientists, cryptographers, and mathematicians [61-64].

The fundamental process within blockchains is organized in the following manner. The agent initiates the creation of a novel transaction that is intended to be incorporated into the blockchain. The transaction that has been recently generated is disseminated across the network for the purposes of authentication and audit. Once the transaction has been authorized by the majority of nodes according to predetermined and mutually agreed-upon procedures, it can be appended to the blockchain as a new block. The transaction is securely kept in distinct distributed nodes to guarantee the overall system's security [66-68].

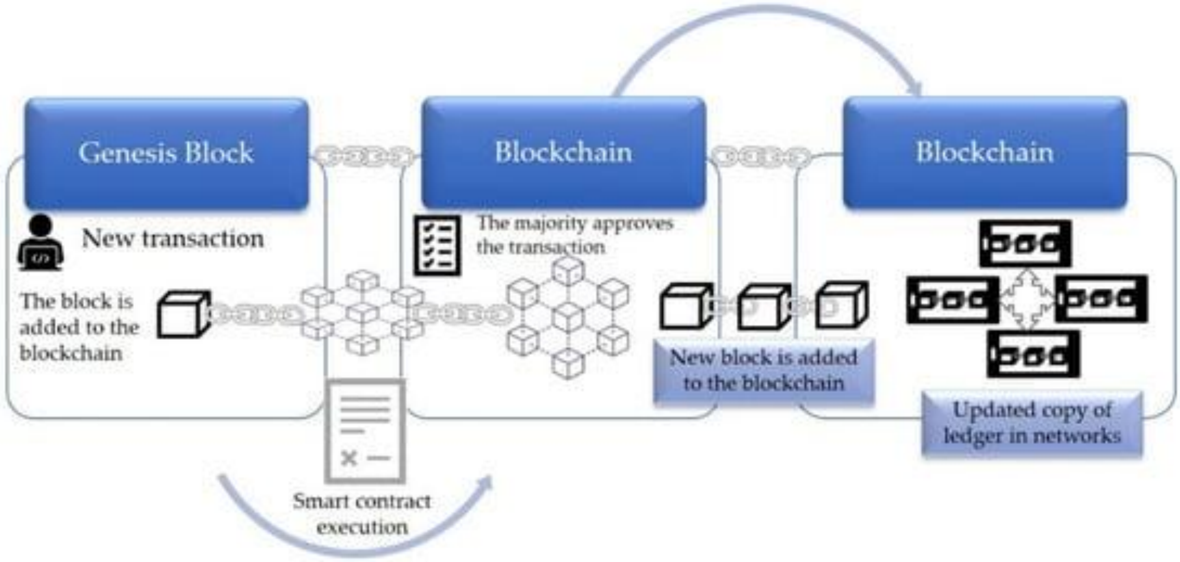


Fig. 2. Basic Steps in blockchain technology [65]

3.1 Features and Applications of Blockchain Technology

Decentralization is a prominent attribute of blockchain technology that substantially enhances the credibility of information. The inefficiency, high costs, and increased vulnerability to hacking, fraud, and major errors associated with the accumulation, updating, or deletion of information in centralized information systems are well-documented. The utilization of blockchain technology enhances the level of trust in transactions by establishing decentralized systems for sharing information. This eliminates the need to assess the dependability of intermediaries or other participants in the network. Furthermore, the data stored on the blockchain is easily accessible and can be verified without difficulty. The application of blockchain technology brings about an important advantage in the form of decentralization, which in turn enhances the transparency of information while ensuring the anonymity of participants. This is achieved through the utilization of cryptography systems, for instance. Furthermore, its architecture facilitates the reduction of human, social, or behavioral misconduct, such as fraudulent activities or sluggishness, hence ensuring the security and integrity of the network [69,70].

The architecture of blockchain might vary depending on the specific technology application, with the establishment of public ("permissionless") or private ("permissioned") data systems and ledgers. Both public and private blockchain systems exhibit characteristics of decentralization and distribution among their users, enabling the tracking of peer-to-peer transactions without relying on traditionally trusted intermediaries for validation. In the context of private or closed blockchains, it is important to note that participants have the ability to identify one another, so eliminating the element of anonymity. Consequently, the inclusion of certifiers becomes imperative, as they have the responsibility of authenticating network members and upholding the integrity of these private systems. In contrast, public or open blockchains employ cryptographic mechanisms to establish trust among several anonymous participants, enabling them to access the network and engage in operations inside it [71, 72].

To further explore this contrast, let us engage in a thoughtful analysis of the key distinguishing factors. Initially, it is worth noting that private blockchains exhibit enhanced transaction processing rates in conjunction with a reduced number of permitted participants. Therefore, a reduced timeframe is required to attain network consensus, enabling a higher volume of transactions to be processed within a certain duration. In contrast, public blockchains exhibit restricted transaction processing capacities. Consensus techniques, such as Bitcoin's Proof-of-Work (PoW) employed in public blockchains, necessitate the attainment of a collective agreement within the network regarding the present state of transactions. Furthermore, the unique characteristics of public blockchains make them more susceptible to risks associated with data privacy. In contrast, private blockchains provide robust data security frameworks wherein any alterations may only be implemented with the unanimous approval of all nodes, as facilitated by a consensus mechanism [73,74].

Simultaneously, the utilization of blockchain technology enables the development of transactional apps that enhance trust, transparency, and auditability. These applications are facilitated by the execution of smart contracts. Smart contracts are software-based solutions designed to facilitate the storage and enforcement of principles and regulations during the process of negotiating terms, conditions, and activities among participants. These systems function to autonomously validate whether predetermined rules and conditions have been met, and subsequently, if confirmed, carry out transactions. Smart contracts have the potential to mitigate informational asymmetry and foster welfare and consumer surplus by facilitating improved access and competitiveness. However, the dissemination of knowledge through consensus construction may lead to increased complexity [75,76].

3.2 Block Chain for Renewable Energy Technology

Blockchain technology has garnered significant interest in the energy sector, where it has already made notable contributions to the developing idea known as the Internet of Energy (IoE). This concept facilitates the establishment of transparent and decentralized networks of energy prosumers, including platforms for energy trading. Numerous instances of blockchain implementation in the energy sector have proven to be effective. This technology has facilitated advancements in the energy transition and circular economy initiatives. Examples include innovative approaches to electric e-mobility, energy democratization, peer-to-peer energy trading platforms, demand-response mechanisms, smart metering, smart grid management, automation of green certificates issuance, and carbon trading. According to Wang and Su, blockchain technology offers significant advantages to the energy sector. These advantages include decentralized energy trading and supply, efficient automation of energy and storage control through smart contracts, and the establishment of secure records for all business activities within the energy industry [77, 78].

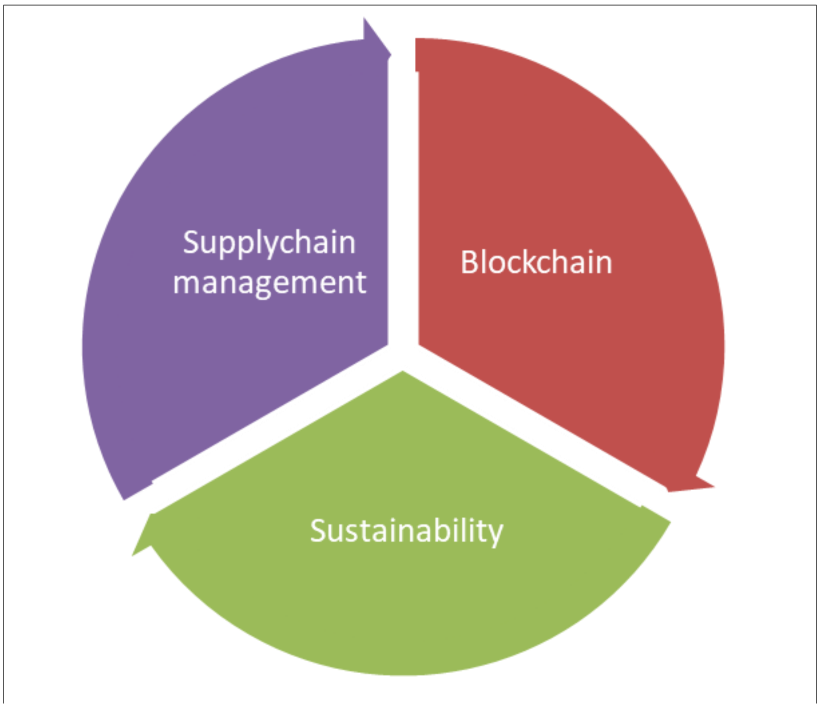


Fig. 3. Relationship of supplychain, blockchain and sustainability

3.3 Cryptocurrencies and Energy Tokens

The prevailing body of foundational knowledge regarding blockchain technology commonly associates distributed ledger technology (DLT) with digital currencies, such as Bitcoin or Ethereum. Hence, given its widespread recognition, the energy business is witnessing the emergence of novel cryptocurrencies and tokens as prominent applications of blockchain technology. Cryptocurrencies have the potential to function as a motivating factor for the production of low-carbon energy. Consequently, certain cryptocurrencies serve as a form of compensation for adhering to socially and environmentally responsible behaviors within the system. As a result, these cryptocurrencies have the capacity to stimulate investments in clean energy. In addition, cryptocurrencies have the potential to facilitate the tokenization of resources, thereby enabling the development of new marketplaces and innovative business models that are founded on the concept of asset division and ownership. It is noteworthy that a considerable number of organizations are currently employing cryptocurrencies as a means to attract prospective investors and facilitate supplementary avenues for financing, exemplified by the use of Initial Coin Offerings (ICOs). There exist numerous instances of the creation of novel cryptocurrencies and energy tokens with the objective of promoting investments in the Internet of Things (IoT), sustainable energy, and renewable energy. Prominent examples include SolarCoin, EverGreenCoin, EECoin, EcoCoin, and NRGcoin, among others. Additionally, a multitude of Ethereum-based tokens and platforms also contribute to this domain [79-81].

3.4 Enabling IoT and Asset Management

The utilization of cutting-edge information and communication technology (ICT) solutions, such as the Internet of Things (IoT), has the potential to yield a multitude of advantages for energy organizations. The exponential proliferation of intelligent devices, including but not limited to smart meters and information and communication technology (ICT) tools, facilitated by automated processes and the effective management of large-scale data, has the capacity to fundamentally transform the value chain within the energy sector. The implementation of novel digital assistance has the potential to enhance the overall performance of the energy system and facilitate resource analytics. This, in turn, may enable enterprises to reduce operational expenses. Smart technologies have the potential to improve network efficiency in the context of power generators. This is achieved through the implementation of billing automation, optimization of demand control mechanisms (such as aggregation and response), and the transformation of existing supply chains. Furthermore, the implementation of cutting-edge digitalization solutions such as the Internet of Things (IoT) and/or Information and Communication Technology (ICT) and blockchain-based technologies can serve as a catalyst for organizations to explore new avenues of innovation and revolutionize their existing business models. According to the existing literature, the digitalization of the energy sector necessitates a reevaluation of current structures and business models. This is primarily attributed to the decentralization of authority, the emergence of entirely virtual markets, and the development of new local markets that prioritize self-sufficiency. Additionally, these changes are expected to foster increased consumer engagement and participation [82-86].

IoT solutions are predominantly linked to smart automation technologies encompassing hardware and software components. These technologies include sensors, meters, cloud connectivity, and control tools. By using these technologies, smaller-sized renewable energy technology (RET) enterprises can potentially achieve notable reductions in maintenance and management expenses. The utilization of smart grids has the potential to enhance grid management and stability by leveraging smart devices. This technology enables real-time coordination and modification of energy demand, supply, and electricity prices in response to current power consumption levels. It is worth emphasizing that blockchains have the potential to significantly facilitate the advancement of IoT-based solutions. This is primarily due to their ability to serve as a robust technological foundation for the establishment and maintenance of IoT platforms. Moreover, blockchains offer the advantages of reciprocity and interoperability in the realm of IoT operations [87-89].

3.5 Smart Metering and Smart Grid Management

The utilization of blockchains has the potential to significantly enhance the efficiency and automation of metering and billing processes, primarily driven by the increasing adoption of smart meters. The primary advantage derived from the implementation of automation lies in its capacity to reduce administrative expenses within the grid and market. In addition, this technology offers enhanced visibility and traceability of the energy produced and utilized, thereby imparting knowledge to consumers regarding the origin, cost, and authenticity of the specific energy provided to them (referred to as renewable energy tracking). This, in turn, has a beneficial impact on market competition and promotes public consciousness regarding the environmental dimensions of energy. In addition, blockchain technology has the capability to safeguard sensitive personal and company data by implementing robust data security measures, hence providing enhanced privacy and protection against potential cyber threats. An additional dimension pertaining to perilous occurrences such as power outages and trash management can be addressed through the utilization of blockchain technology's smart contracts throughout the establishment of a novel smart grid system [90-94].

One of the early applications of blockchain technology in the energy sector involved the integration of cryptocurrencies as a means of payment for electricity and energy invoices. In contemporary times, there is a growing trend among companies to accept cryptocurrency as a form of payment for their services. This includes energy companies, with BAS Nederland being recognized as a frontrunner in this domain. BAS Nederland enables customers to settle their energy bills using Bitcoins, the widely recognized and globally popular cryptocurrency. This pioneering move has subsequently been emulated by other companies such as German Enercity and Japanese Marubeni [95-97].

The utilization of blockchain technology in the energy sector offers a multitude of advantages through the implementation of smart meters and smart contracts. An additional noteworthy illustration of a potential avenue for enhancement is the implementation of an automated and decentralized grid management system utilizing smart grids. The implementation of a smart grid management approach, utilizing the fundamental characteristic of blockchain technology known as smart contracts, has the potential to enhance various aspects of energy management. This includes improving supply and demand balancing, coordinating distribution systems, verifying and ensuring visibility of grid assets. Smart contracts enable efficient control of the energy network by operating according to predetermined rules in an automated and dependable manner [98,99].

3.6 Green Certificates and Carbon Trading—Automation

Significantly, blockchains have the potential to play a crucial role in the energy transition towards renewable sources by enabling and encouraging the exchange of cleaner energy and the reduction of carbon emissions. DLTs have the potential to facilitate novel methods of financing renewable energy by introducing tokens representing green energy or other digitally tradable assets in the energy market. Additionally, DLTs can enable the development of peer-to-peer energy trading platforms that provide transparent and accessible information regarding the origin of the energy source and the allocation of funds. This is made possible due to the transparency and interoperability offered by blockchain technology. Small-scale energy producers face significant challenges in participating in carbon credit operations due to the intricate nature and substantial expenses associated with claiming these credits [100,101].

Blockchains have the capability to automate the issue of green energy certificates, establish international and transparent markets for trading green assets, and reduce transaction costs by preventing instances of double-spending. These benefits are not contingent on the trading quantities involved [102].

3.7 Fostering Electric Transportation

Electric e-mobility is widely advocated as a prominent strategy for addressing the detrimental consequences of climate change and fostering a greener transportation sector. Furthermore, the process of digitalization serves as a key distinguishing element between traditional vehicles that rely on fossil fuels and electric transportation, leading to its significant promotion and advancement [103,104]. Hence, the forthcoming progression of electric vehicles (EV) necessitates enhancements in cost-effectiveness and vehicle performance, with a particular emphasis on charging speed, user convenience, availability, and shared charging infrastructure, among other factors. The decentralized character of contemporary transportation trends, such as on-demand automobile renting or automated mobility applications like Uber, renders blockchain a fitting solution for this domain. Indeed, the application of blockchain technology in the energy sector shows great promise, particularly in the context of electric vehicle (EV) charging and shared charging infrastructure. The utilization of blockchains has the potential to facilitate transparency for electric vehicle (EV) owners in terms of charging prices and the choosing of energy sources. In addition, the utilization of blockchain microgrids could enable local grid operators and energy suppliers to determine charging pricing. In addition, the integration of blockchain wallets could be employed to streamline payment processes at charging stations. One of the key distinguishing features of blockchain technology is its capacity to provide a distinctive validation and communication platform that is universally applicable regardless of geographical location. This characteristic makes blockchain particularly well-suited for facilitating cross-border mobility. In addition, blockchains have the potential to offer a market-driven method for optimizing management and coordinating electric vehicle charging. The utilization of blockchain technology by charging station operators has the potential to enhance the user experience for electric vehicle (EV) owners, streamline infrastructure administration, bolster system security, and facilitate the promotion of the shared energy idea. In conclusion, blockchain technology has the potential to ensure the integrity of vehicle security and protect autonomous vehicles from unauthorized access, addressing a significant apprehension associated with the deployment of self-driving automobiles. The provision of a safety guarantee has the potential to enhance the adoption of electric and automated vehicles, leading to a substantial decrease in fuel consumption and greenhouse gas (GHG) emissions within the transportation sector [105,106].

3.8 Contribution to the Circular Economy

As previously said, blockchains have the potential to significantly contribute to the renewable energy technology (RET) industry by offering a range of advantages. Consequently, they may play a pivotal role in enhancing the energy transition and fostering the adoption of more sustainable practices within the energy sector. A study conducted by Upadhyay asserts that blockchains have the potential to support the circular economy by enabling the reduction of transaction costs, enhancing performance and communication in supply chains, safeguarding human rights protection, ensuring healthcare patient confidentiality, promoting welfare enhancement, and reducing carbon footprints. Blockchains have the potential to optimize time and resources by facilitating automated transactions that are permanent and verifiable. This capability can efficiently mitigate operational disorganizations and reduce production waste. Ghisellini et al. (year) assert that the primary objective of the Circular Economy framework is to facilitate the adoption of environmentally sustainable industrial practices, the integration of renewable energy technology, and the development of efficient strategies and procedures. The utilization of blockchain technology has the potential to contribute to the realization of these goals by facilitating the development of more environmentally sustainable business transaction processes. Additionally, it can aid in the achievement of a balanced and harmonious relationship between the economic, environmental, and societal aspects of sustainability [107-110].

The decentralized nature of blockchain technology has the potential to significantly influence the field of supply chain management. One potential application of blockchain technology involves its utilization for the purpose of monitoring and validating the provenance of raw materials, production sites, transportation entities, warehousing facilities, and retail establishments involved in the procurement and sale of goods. Furthermore, the implementation of blockchain technology facilitates the effective monitoring and enhanced visibility of faulty and substandard products. Additionally, it is beneficial to ascertain the origin and sustainability practices associated with a product, specifically in relation to the presence of deceitful and unethical labor practices. Blockchains have the potential to be employed in manufacturing processes for the purpose of tracking spare parts and monitoring equipment status. Additionally, they can be utilized for automating shipping procedures, hence enhancing time efficiency and reducing operational and repair expenses [111].

The implementation of blockchain technology has the potential to facilitate and advance circular economy principles, encompassing the reduction of resources and waste, the reuse of products, and the process of recycling. The incorporation of traceability and transparency elements results in a reduction of operating expenses and the potential for waste reduction. The utilization of blockchain technology has the potential to encourage the adoption of novel behaviors through the verification of social sustainability assertions, the tokenization of sustainable transactions, and the establishment of innovative frameworks for pricing and trading. In addition, the implementation of blockchain technology's transparency can contribute to the promotion of sustainable practices and the regulation of contractors to prevent instances of human rights violations, child labor, inhumane working conditions, and corruption [112,113].

Within the framework of the circular economy, blockchain technology can be viewed as a social tool for facilitating coordination. This is due to its capacity to integrate and synchronize many decentralized databases, enabling immediate updates that are accessible to all participants within the network. This proposal introduces a decentralized convention for value generation and circulation, which has the potential to reshape the existing notions of value creation and value appropriation. The inherent characteristics of Distributed Ledger Technology (DLT) have the potential to greatly contribute to the realization of circular economy principles. DLT's properties of decentralization, distributiveness, and tamper-protection, along with its compatibility with smart contracts and tokenization, make it particularly well-suited for this purpose [114].

4. BENEFITS OF DLT IN RENEWABLE ENERGY SUPPLY CHAIN [115-118]

4.1 Transparency

Distributed ledger technology (DLT) facilitates transparency by securely documenting each transaction on an unalterable ledger. Stakeholders possess the capability to ascertain the source of renewable energy, authenticate its legitimacy, and monitor the trajectory of Renewable Energy Certificates (RECs).

4.2 Traceability

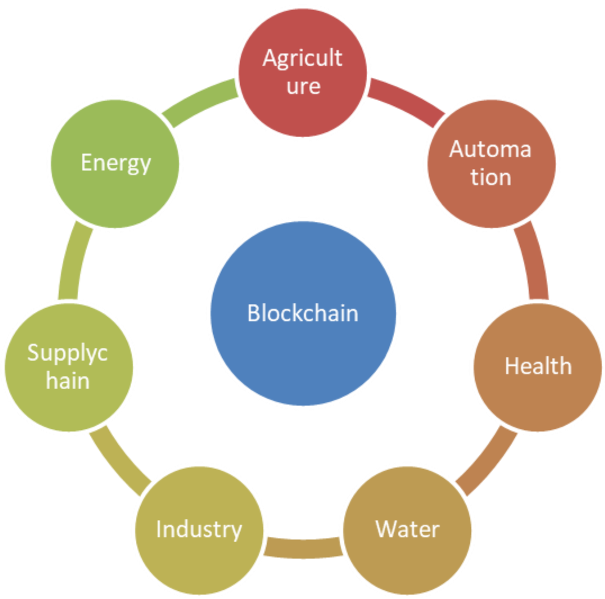
The incorporation of traceability mechanisms for renewable energy and Renewable Energy Certificates (RECs) serves to bolster accountability and mitigate the potential for fraudulent activities. Ensuring compliance with regulatory mandates and upholding the veracity of assertions pertaining to renewable energy are of paramount importance.

4.3 Efficiency

The implementation of automation via smart contracts The implementation of streamlined processes aims to achieve several benefits, including the reduction of administrative costs and the minimization of the time required for energy transactions and payments.

4.4 Improved Financing

The process of tokenizing renewable assets has the potential to appeal to a wider spectrum of investors, including those with limited financial resources, as it facilitates fractional ownership and provides simplified entry into the green energy market.



Picture 2. Improved financing

5. BARRIERS AND LIMITATIONS

Despite the great development potential for the renewable energy sector, the deployment of blockchain technology remains linked to several technological, sociological, and economic risks and challenges. The primary technological obstacles pertaining to decentralized energy trading encompass the scalability and speed of transactions allowed by blockchain, the relatively low levels of early digitalization, and the need for innovation in grid infrastructure. Social issues encompass several factors such as data protection, limited knowledge, and inadequate legal compliance or supportive policies. These factors significantly impede the advancement of innovative applications of blockchain technology, which have the potential to pave the way for hesitant stakeholders to embrace its adoption. The primary economic limitation pertains to the substantial expenses associated with electricity consumption for executing consensus algorithms like proof-of-work, as well as the expenditures associated with infrastructural advancements required for enhancing blockchain technology [119-123].

5.1 Scalability

As the renewable energy sector continues to expand, DLT networks have the problem of effectively managing a substantial influx of transactions and data.

5.2 Regulatory Compliance

Navigating complex regulatory environments, especially regarding RECs and tokenized assets, requires careful consideration and compliance.

5.3 Data Privacy and Security

Protecting sensitive data while maintaining transparency is a delicate balance. Privacy-preserving DLT solutions should be explored.

5.4 Interoperability

Interoperability between different DLT platforms and legacy systems may pose challenges for seamless integration into the existing supply chain.

6. CONCLUSION

The integration of Distributed Ledger Technology (DLT) into the renewable energy sector presents significant advantages in terms of enhanced transparency, traceability, efficiency, and improved financing. Nevertheless, the utilization of this technology presents certain difficulties pertaining to scalability, adherence to legal requirements, safeguarding of data privacy, and the capacity to seamlessly interact with other systems. In order to fully realize the promise of Distributed Ledger Technology (DLT) inside the renewable energy supply chain, it is imperative to foster collaboration among various industry players, technology specialists, and regulatory bodies. By implementing appropriate strategies and solutions, Distributed Ledger Technology (DLT) can assume a crucial role in propelling the renewable energy sector forward and expediting the shift towards a sustainable energy future.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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