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Review

Blockchain in the Energy Sector—Systematic Review

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Abstract: The article provides an overview of academic contributions to blockchain technology over the past three years. A large number of practical implementations are proving the versatility of blockchain across industries. Some of these areas are easy to deduce, but for some, the benefits of using blockchain technology may not be obvious. Real applications of blockchain can be found in sectors such as cyber security and the financial sector, but also in various categories of the public sector, healthcare, and industry. This paper focuses on the use of blockchain technology in the energy industry. The paper aims to present the current trends of blockchain in the energy sector and provide a summary of blockchain technology discussed in academia. The research questions are formulated to correspond to the basic goals of the energy sector today. The core of the paper forms a systematic review based on the PRISMA guidelines. The output of this systematic review brings an up-to-day insight into the issue and introduces potential areas for further research.

Keywords: blockchain; energy sector; PRISMA; renewable energy

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1. Introduction

Blockchain is a distributed, decentralized database of individual transaction records. These are structured data files with asymmetric encryption and a hash function, which is used to maintain data integrity. Data integrity is also enhanced by the very principle of blockchain, which is that it stores transaction data in blocks, which are chained using hash pointers. The cryptocurrency Bitcoin, one of the oldest applications of blockchain technology, is a typical example of the use of blockchain technology in general awareness [1–3]. In addition to theoretical concepts [4], the versatility of blockchain is already evidenced by a large number of practical implementations across sectors [5–7]. Some of these areas are easily derivable. The benefits of the use of a blockchain may not be obvious. The real applications of blockchain can thus be found in sectors such as cyber security [8] and the financial sector [9,10], but also governmental services [11], healthcare [12], tourism [13], industry, and others [14].

There are countless areas in business and non-business spheres [15] where blockchain can be used. With the development of this technology, there are more and more areas that can benefit from this technology by increasing efficiency and transparency or reducing fees. Another important topic in this area is the use of the Smart Contract protocol and its advantages, which enables the automation of the performance of simpler contracts [16,17].

Blockchain technology as a current, trendy, and promising phenomenon brings crucial changes. Its implementation affects various parts of the organization; it changes the established run of the organization, and its processes—it is not just a question of technology; it is a question of the whole concept. Nuryyev et al. [18] claim in their study that the implementation of blockchain technology faces organizational, institutional, and technological challenges.

This literature review deals with the utilization of blockchain in the energy sector. The implementation of this technology in the energy sector is proving to be beneficial [19]. As an example of the involvement in the issue of the European geopolitical platform, a technical report by the Joint Research Centre is given. It aims to provide evidence-based scientific support to the European policymaking process. Researchers investigated the applicability of blockchain technologies to the power sector from technical and legal perspectives, considering how the energy and distributed ledger technology integration could work in practice and how to manage legal compliance especially with data-protection-related policies [20]. It is crucial to find out how extensive the possible implementation of the blockchain in the energy sector is, what the costs of its implementation are, and what the benefits of this technology in the discussed area are. The paper assumes that the implementation of blockchain technology significantly affects the business processes themselves; moreover, it concerns not only the ICT department of the organization, but it is far-reaching, complex, and essentially global in scope.

We can summarize the current energy trends and goals into "3D". This 3D stands for decentralization, decarbonization, and digitalization [21,22].

The research question on this topic is whether the utilization of a blockchain can meet the three basic goals of the energy sector, which represent a desirable connection between technology and the environmental issues of our time. Decentralization, decarbonization, and digitalization can be understood in a broad and specialized sense relating explicitly to the energy sector. The difficulty to find consensus on a precise definition of key terms stems from the fact that each represents a concept that encompasses many technologies and applications [23].

The term "decentralized" refers to decentralized autonomous units without interaction with other units [23]. Decentralization means that households or other facilities, such as supermarkets or other commercial buildings, will become at least partially self-sufficient, using renewable sources such as photovoltaic energy in particular [21,24,25]. Sustainability is highlighted in the context of decentralized energy in academic papers [26]. The terms decentralized and distributed might seem to be used interchangeably, as they are interconnected, e.g., [27]. The explanation of these terms in the context of systems is given in [23].

Closely and intricately linked to this is another point, that is decarbonization. According to Collins dictionary "Decarbonization is the process of reducing and removing carbon dioxide output from a country's economy" [28]. Decarbonization is achieved via a reduction of the greenhouse gas emissions by the use of zero-carbon renewable energy [29]. Decarbonization also requires enhancing carbon storage in agricultural lands and forests [30]. An effort to reduce the share of coal power plants can be observed, which, however, faces a problem with how to replace coal. The ideal option would be to replace it with renewable sources, but this requires either the above-mentioned decentralization of energy or the creation of large-capacity storage facilities, which would be able to withstand a large surge of electricity and store it in case of subsequent attenuation. Until then, it is therefore an acceptable option to replace coal power plants with nuclear or gas [31]. Decarbonization is not feasible without digitization, which forms the third of the key trends or goals [32].

The third "D" represents both digitization in the sense of working with information and digitalization referring to processes. In this study, we use the term digitalization as a broader general term that includes both meanings. In order to achieve the objective of decarbonization and increase the decentralization of the energy system, digitalization may make a significant contribution in this area. What cannot be measured cannot be improved [33]. Digitalization is the use of technologies for data collection and mining, which can be beneficial for predicting consumption fluctuations or personalizing offers for customers [21]. The innovative aspect of metering, however, is not in the data itself, but in what we can do with them to improve the effectiveness of the system. It is feasible to evaluate large amounts of data and produce specific actions to save operating and maintenance expenses. This is made possible by technologies such as artificial intelligence and machine learning. The productivity, security, accessibility, and general sustainability of energy systems are all being enhanced by digitalization, which is transforming the energy sector [33]. It encompasses smart cities, smart grids, or smart metering concepts. Finally, this point also includes the possibility of better supply management, which is also linked to energy decentralization [21].

All three trends are interconnected. The utilization of blockchain technology allows for the creation of all these 3D objectives.

The main contribution of this research is to provide the first insight into blockchain technology in the energy industry. This will contribute to further specialized research, which will be focused on the analysis and modeling of business processes caused by the deployment of blockchain technology and their evaluation of the impact on the organizational structure of the organization. Another question is which areas of the organization would be affected by the implementation. Another area of possible further research is the security policy of the organization including information and cyber security, where it is mostly necessary to analyze risks, propose measures with asset values according to their categorization, and describe the threats associated with the risks. The risks depend on the assets of a particular organization, so the future output of the intended study aims to create a general model of the organization's security policy concerning the impact of the use of blockchain technology. High emphasis on cyber and information security and necessary or recommended certifications for the operation of this technology can also be expected.

The structure of the paper follows the standard pattern: The Introduction as a background to the issue supported by a narrative review, the Research Methodology with a stated aim, research questions, and the PRISMA 2020 guidelines for systematic reviews, and the core section Results and Discussion, bringing clear outputs with an illustrative diagram, tables, and answers to the stated research questions and a final section, the Conclusion.

2. Research Methodology

The paper aims to present the current trends of blockchain in the energy sector and provide a brief summary of this technology. The main question on this topic is whether the use of a blockchain can meet the three basic goals of the energy sector today.

In the research, we focus on defining changes in collected data from compared studies. The research questions follow:

- What other academic formats occur besides reviews? (Will there be any case studies, examples, or applications?)
- What new trends and ideas are emerging, and are some frequent or dominant?
- Who is involved the implementation of blockchain technology, the state or a commercial business?

As an entry into the research, a review was conducted because it enables one to figure out what the articles deal with and what categories and aspects are most often researched.

The paper itself is based on the PRISMA 2020 guidelines for systematic reviews [34]. The search was conducted on 21 June 2022. The articles were selected from the Web of Science (WoS), where the primary criterion was to search for articles where the Topic was stated as "blockchain AND energy sector". Then, records that were not an article or proceedings papers, not in English, not available as Open Access, and did not fall into the correct field were discarded. The following fields were selected as correct fields: Engineering Electrical Electronic, Energy Fuels, Computer Science Information Systems, Telecommunications, Green Sustainable Science Technology, Environmental Sciences, Environmental Studies, Economics, and Management. After excluding the papers automatically, the next step was a manual evaluation of the papers from the title and the abstract. Five articles were excluded from the review within this research phase. Two articles were not related to either energy [35] or blockchain [36]. Although three articles were related to blockchain in energy, they focused on a different aspect than the researched aspects, e.g., human resources [37], another region [38], or strictly focused on cryptocurrency [39].

The search process was worked out by the authors; it was partially automated using the Zotero citation software, which enabled the import of results from WOS, identification and automatic download of full papers, and then, the work with the citations. Due to the smaller number of articles, it was possible to conduct a full paper review of all papers and subsequent manual identification of keywords and topics in the articles, based on which it was possible to develop the main categories of this issue.

The process of shortlisting articles is recorded in the PRISMA flow diagram (see Figure 1), which determines the number of articles in each selection phase. For selected articles, the selected criteria and the results of the scientific work are examined in detail.

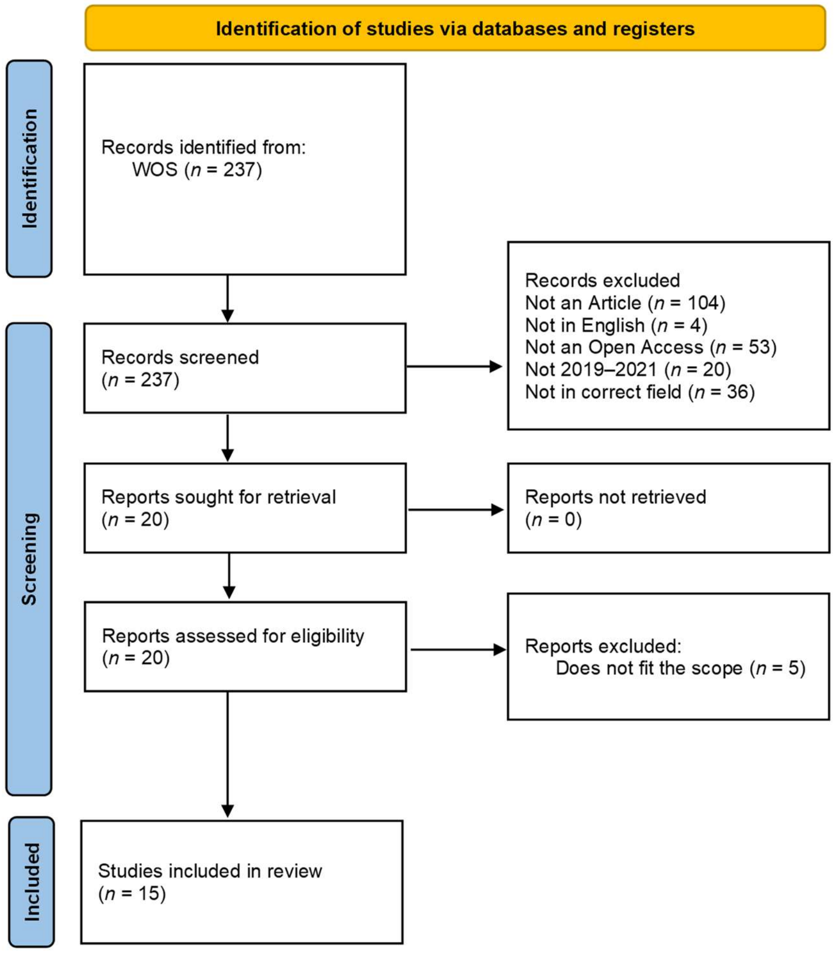

Figure 1. Flow diagram.

Searching and Selecting Relevant Papers

The criteria for selecting the relevant papers for this research were as follows:

- WoS database;
- Topic: blockchain; energy sector;
- Articles only;
- Language: English;
- Open Access;
- Published years: 2019–2021;
- Fields: Engineering Electrical Electronic, Energy Fuels, Computer Science Information Systems, Telecommunications, Green Sustainable Science Technology, Environmental Sciences, Environmental Studies, Economics, Management.

Twenty articles met these criteria. After the exclusion of the articles that did not completely correspond to the assignment, fifteen papers were selected.

3. Results and Discussion

According to the search strategy, the systematic review was made up of 15 articles that were selected from the Web of Science. The final set of articles consisted of 7 case studies, 4 desk research works, 3 reviews, and 1 survey. Quantitative research was conducted in 10 cases and qualitative research in 5 cases. Empirical studies predominated, of which there were nine. As for the theoretical studies, there were six of them. This distribution is visualized in Figure 2.

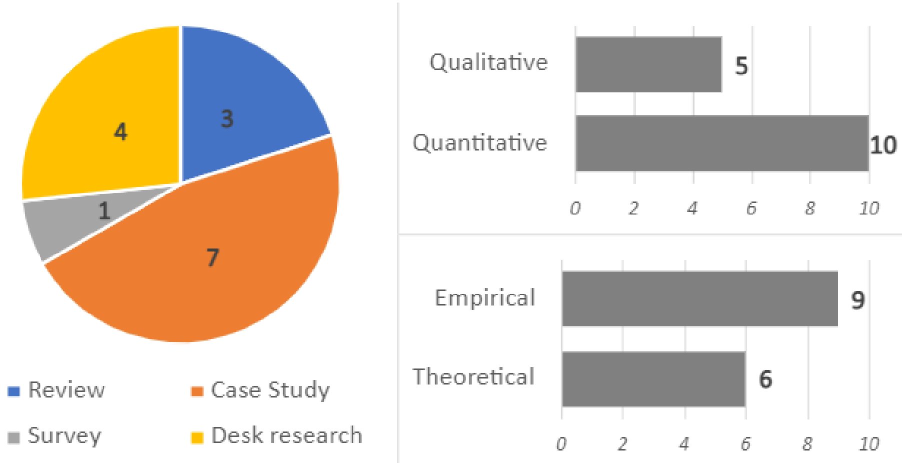

Figure 2. Distribution of articles according to various characteristics.

Selected papers were included in the following Table 1.

Table 1. Summary of papers.

Authors	Year	Name
Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., Mccallum, P., and Peacock, A. [19]	2019	Blockchain technology in the energy sector: A systematic review of challenges and opportunities.
Aoun, A., Ibrahim, H., Ghandour, M., and Ilinca, A. [40]	2021	Blockchain-Enabled Energy Demand Side Management Cap and Trade Model
Borowski, P. [41]	2021	Digitization, Digital Twins, Blockchain, and Industry 4.0 as Elements of Management Process in Enterprises in the Energy Sector.
Chaudhary, R., Jindal, A., Aujla, G., Aggarwal, S., Kumar, N., and Choo, K. [42]	2019	BEST: Blockchain-based secure energy trading in SDN-enabled intelligent transportation system
De Villiers, A., and Cuffe, P. [43]	2020	A Three-Tier Framework for Understanding Disruption Trajectories for Blockchain in the Electricity Industry
Diestelmeier, L. [44]	2019	Changing power: Shifting the role of electricity consumers with blockchain technology—Policy implications for EU electricity law
Fell, M., Schneiders, A., and Shipworth, D. [45]	2019	Consumer Demand for Blockchain-Enabled Peer-to-Peer Electricity Trading in the United Kingdom: An Online Survey Experiment
Karaszewski, R., Modrzynski, P., and Modrzynska, J. [46]	2021	The Use of Blockchain Technology in Public Sector Entities Management: An Example of Security and Energy Efficiency in Cloud Computing Data Processing
Khatoon, A., Verma, P., Southernwood, J., Massey, B., and Corcoran, P. [35]	2019	Blockchain in Energy Efficiency: Potential Applications and Benefits.
Masaud, T., Warner, J., and El-Saadany, E. [47]	2020	A Blockchain-Enabled Decentralized Energy Trading Mechanism for Islanded Networked Microgrids
Meeuw, A., Schopfer, S., Worner, A., Tiefenbeck, V., Ableitner, L., Fleisch, E., and Wortmann, F. [48]	2020	Implementing a blockchain-based local energy market: Insights on communication and scalability

Table 1. *Cont.*

Authors	Year	Name
Okoye, M., Yang, J., Cui, J., Lei, Z., Yuan, J., Wang, H., Ji, H., Feng, J., and Ezeh, C. [49]	2020	A Blockchain-Enhanced Transaction Model for Microgrid Energy Trading
Pop, C., Antal, M., Cioara, T., Anghel, I., Sera, D., Salomie, I., Raveduto, G., Ziu, D., Croce, V., and Bertoncini, M. [50]	2019	Blockchain-Based Scalable and Tamper-Evident Solution for Registering Energy Data
Wu, Y., Wu, Y., Guerrero, J., and Vasquez, J. [21]	2022	Decentralized transactive energy community in edge grid with positive buildings and interactive electric vehicles
Zeiselmair, A., Steinkopf, B., Gallersdoerfer, U., Bogensperger, A., and Matthes, F. [51]	2021	Analysis and Application of Verifiable Computation Techniques in Blockchain Systems for the Energy Sector.

Masaud et al. [47] discuss microgrids, which they consider to be the cornerstone of smart systems. The authors propose a two-tier business mechanism that is secure and based on a smart contract. In the second layer of this mechanism, they envisage the use of blockchain technology to ensure security. The authors performed simulations in the Python environment to validate this model. Okoye et al. [49] also deal with microgrids and their use in the power sector. They present a cyber-enhanced transactive microgrid model that uses blockchain technology.

Andoni et al. [19] claim in one of the most complex systematic reviews of the topic of blockchain technology in energy systems that purchasing energy using blockchain technology can be a way for customers who cannot afford to invest in renewable generation to have certified green energy.

De Villiers and Cuffe [43] present blockchain technology and its potential role in the energy industry. Zeiselmair et al. [51] discuss the decentralization of the energy system on how blockchain technology could provide a base infrastructure for the local market mechanism. They analyze applications in the blockchain environment and focus on energy-related applications.

Chaudhary et al. [42] present the BEST scheme, a blockchain-based secure energy trading scheme for electric vehicles, which is the subject of a case study confirming the deployment of BEST in energy trading.

The use of blockchain technology in power engineering is also investigated by Khatoon et al. [35]. They describe a system working together with Smart Contracts in two case studies. They cite scalability, standardization, cost, performance, complexity, and skills as challenges that continue to occur with this technology.

A possible connection of NoSQL databases, which would allow the registration of transaction fees, is researched. The prototype that Pop et al. [50] present should effectively balance energy fluctuations and, in terms of scalability, tampering, and throughput of energy data, also showed satisfactory results.

It is necessary to think about the socio-economic problems and challenges of this issue, which are addressed by Aoun et al. [40]. Besides other things, they address possible issues related to increased energy demand in the context of global economic growth and climate change. They address the issue of sustainable and eco-friendly power generation, which could be solved by the new Peer-to-Peer (P2P) trading model. The model they applied was tested on 200 households. They claim that this model can be beneficial to energy companies, as well as consumers.

P2P energy trading is also mentioned in Fell et al. [45], who conducted an online survey experiment with 2064 participants on customer demand for P2P energy trading schemes using blockchain technology. The respondents chose anonymity as the most important characteristic.

Meeuw et al. [48] in the context of the P2P energy market address the number of transactions that a blockchain can perform. In their paper, they show a simplified guide to P2P markets based on the Byzantine fault-tolerant system.

Wu et al. [21] emphasize the importance of the three pillars in energy (decarbonization, digitalization, and decentralization). They also present a systematic review of the positive roles of buildings in establishing sustainable energy. Karaszewski et al. [46] also discuss a reduction in carbon footprint. They considered cloud computing for the use of blockchain in the energy sector, which could reduce costs, but could also have a positive effect on environmental impacts, namely the reduction of the carbon footprint.

Digitalization and Industry 4.0 in the context of energy and blockchain are addressed by Borowski [41], who see in this area the potential for a change in energy distribution that would lead to a more economic, environmental, and social approach in the energy sector.

Diestelmeier [44] perceives the issue from the point of view of policy and law, who recalls the indispensable role of the EU and the legal consequences of the utilization of blockchain in the energy sector.

Table 2 summarizes the main topics and keywords that appear in the selected articles.

Table 2. Summary of topics and keywords.

	Andoni et al. [19]	**Aoun et al. [40]**	**Borowski [41]**	**Chaudhary et al. [42]**	**De Villiners and Cuffe [43]**	**Diestelmeier [44]**	**Fell et al. [45]**	**Karaszewski et al. [46]**	**Khatoon et al. [35]**	**Masaud et al. [47]**	**Meeuw et al. [48]**	**Okoye et al. [49]**	**Pop et al. [50]**	**Wu et al. [21]**	**Zeiselmair et al. [51]**
P2P Energy trading	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Renewable energy	x	x	x		x	x	x		x	x	x	x	x	x	x
Smart grid	x	x	x	x	x	x				x	x		x	x	
Smart contracts	x	x			x				x	x		x	x	x	x
Consumer	x	x	x			x	x		x	x		x	x	x	x
Energy efficiency	x		x			x		x	x				x	x	
Internet of Things	x		x		x			x	x	x	x	x	x	x	
Microgrid	x	x	x		x		x			x	x	x		x	x
Prosumer	x		x			x	x		x	x	x	x	x	x	x
Cryptocurrency	x			x	x		x		x					x	
Electric Vehicles	x		x			x	x		x	x			x	x	x
Shared economy	x			x		x				x			x		

3.1. Answers to Stated Research Questions

All the articles point to the possibility of connecting and achieving the 3D energy goals using blockchain technology:

- What other academic formats will occur besides reviews? (Will there be any case studies, examples, or applications?) Case studies prevailed, namely, there were 7 case studies, followed by 4 desk research articles, 3 reviews, and 1 survey (see Figure 2.).
- What new trends and ideas are emerging, and are some frequent or dominant? Naturally, all the articles dealt with peer-to-peer energy trading. Most of the articles discussed directly renewable energy, renewable resources, or green energy [19,21,35,40,41,43–45,47–51]. The smart grid [19,21,40–44,47,48,50,51] forms other frequently researched and de-

scribed ideas. However, energy efficiency was addressed by less than half of the articles [19,21,35,41,44,46,50]. In contrast to the above, the connection of blockchain in energy with electric vehicles was given in nine articles [19,21,35,41,44,45,50,51]. Many articles also used the term Prosumer [19,21,34,35,41,44,45,48–51], i.e., the combination of the words producer and consumer.

- Who is involved in the implementation of blockchain technology, the state or a commercial business?

Commercial implementation seemed to dominate. Commercial implementation was introduced in Meeuw et al. [48]. Even the articles that did not contain an implementation were aimed more at the commercial sphere than use in state institutions. The only implementation not aimed at commercial business was from Karaszewski et al. [46], who described the implementation of the local government in a Polish city.

Further research aiming at understanding and exploring this issue will require work and research on the functioning living system itself, for which it is necessary to obtain cooperation with the company/companies.

AI and blockchain technologies offer exciting opportunities to accelerate global decarbonization. As with the implementation of any technology, prior to deployment, companies will need to undertake privacy and data assessments to ensure they have the correct consent and approvals required to undertake the intended data collection and use. Similarly, consumers adopting such technologies should educate themselves about what data will be collected about them and how it may be used (including considering the potential for misuse) before electing to adopt them.

As shown in Table 2, many trends are associated with this topic, and some, despite not always being explicitly mentioned, such as renewable energy, are inherently associated with this topic.

3.2. Limitations

We are aware that a significant limitation is the choice of only Open Access articles, which lowered the number of articles in the systematic review. Openness and building on the work of others have always been the fundamental tenets of science. Since it is the best option and serves the interests of all parties involved in the process, Open Access is practically unavoidable in the long term. Academics easily adapt to Open Access as readers. It facilitates their job and allows them to access pertinent literature that would otherwise be behind paywalls [52]. The benefits of using open access are: visibility, transparency, availability, interdisciplinary research, collaboration partners [53,54].

The topic of blockchain in the energy sector is appealing for the non-academic sphere. There are several start-up initiatives, e.g., Powerledger [55] or LO3 Energy [56], which often do not have much funding to search among paid academic resources. We made the decision to conduct a search among Open Access articles in order to compile significant publications that are accessible to this group. Even with a topic that is so current and open, there are not many Open Access publications. This reveals that academics tend to contribute to traditional, paid journals and databases. We wish to emphasize the importance of cooperation between the academic and corporate sectors by including another Open Access article to this issue.

3.3. Possible use of Blockchain in Energy—Summary from the Review

We indicated in the beginning that, by using blockchain, it is feasible to achieve (or at least begin to achieve) the primary 3D goals of the energy industry. It might not be stressed enough how these objectives relate to the use of blockchain technology. In this part, we provide the possibilities of using blockchain in energy, which were discussed in the reviewed articles in the context of these goals.

3.3.1. Decarbonization

The blockchain application makes it possible to distribute electricity even among individual households. As a result, it makes it feasible to use renewable energy sources more widely since surplus energy may be distributed directly via the grid [40]. The implementation of a low- or zero-emission economy (decarbonization) is made possible by blockchain and other technologies, such as digital twins, for instance by building virtual power plants, increasing the use of renewable energy sources, and increasing the participation of Prosumers in the energy mix [41]. The deployment of renewable energy technologies such as photovoltaic solar power, which may be incorporated as residential or business rooftop systems, is another potential avenue for power system decarbonization. Blockchain technology may make it feasible to build a network that would allow these Prosumers to address energy shortages and surpluses [48]. Another application that could be beneficial in achieving this goal could be digital notarization for ownership and carbon credit tracking [43]. The process of digitalizing documents itself can assist in reducing the carbon footprint [46].

3.3.2. Decentralization

Due to the immutability of the blockchain record and the consensus processes used to authenticate information appended to the chain, the blockchain is a popular choice for safe transactions in decentralized networks [47]. Since the blockchain is a decentralized distributed database, it is built on the updates of several nodes that must approve the operation. How blockchain can decentralize an area can be seen in the banking sector and Bitcoin. It makes it possible to eliminate all intermediaries and create a system where peer-to-peer trading is possible [35,40,43,45,47,48,51]. The same model can also be used directly in energy distribution. Thus, it would be possible to decentralize not only payment and information transmission, but also energy distribution itself [40]. Decentralized storage systems that allow for the storing of extra energy will also be conceivable to develop [41].

3.3.3. Digitalization

Blockchain has the ability to speed up the development of smart grids and may be employed in the energy sector to improve grid monitoring [40]. A completely digital system based on cryptocurrency billing could be a valuable tool for energy wholesalers looking to speed up the payment process [43]. Documents related to the energy sector can also be stored in the blockchain, ensuring their digitalization [46].

4. Conclusions

The benefits and gains of using this technology are extensive. A blockchain model that would be capable of achieving the 3D goals in the energy sector on a society-wide level is still quite a futuristic idea, as these technologies are still under development and significantly influenced by sociological and economic factors. For these reasons, it seems appropriate to deeply analyze these concepts and create a theoretical model that could serve to further understand this area, which could then be applied on a small scale to validate the concept.

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