Review

Blockchain Technology Implementation in the Energy Sector: Comprehensive Literature Review and Mapping

Nadhira Khezami 1, Nourcherif Gharbi 2, Bilel Neji 1,⁎ and Naceur Benhadj Braiek 2

1 College of Engineering and Technology, American University of the Middle East, Egaila 54200, Kuwait; nadhira.khezami@aum.edu.kw
2 Laboratory of Advanced Systems, Ecole Polytechnique de Tunisie, Carthage University, Carthage 1054, Tunisia; nourcherif.gharbi@enicas.u-carthage.tn (N.G.);
naceur.benhadjbraiek@ept.u-carthage.tn (N.B.B.)
⁎ Correspondence: bilel.neji@aum.edu.kw

Abstract: Satisfying the world’s rapidly increasing demands in energy via the optimized management of available resources is becoming one of the most important research trends worldwide. When it comes to energy, it is very important to talk about decentralization, security, traceability and transparency. Thus, over the last few years, numerous research works have presented blockchain technology as the best novel business platform enabling a secure, transparent and tamper-proof energy management solution. In this paper, we conducted a systematic literature review (SLR) using the PRISMA framework of the different existing research studies related to the use of the blockchain technology in the energy sector, published between 2008 and 2021. We identified a total of 769 primary studies after intensive manual analysis and filtering, which we thoroughly assessed using various criteria to address six main research questions that covered the blockchain types, applications and platforms in the energy sector, the energy source types for which blockchain platforms are implemented, the emergent technologies that are combined to blockchain solutions, and the types of consensuses used in energy blockchains. Based on the collected survey data, we built a database to categorize the existing research works, identify research trends, and highlight knowledge gaps and potential areas for additional field study.

Keywords: systematic literature review; energy blockchain; energy management; sustainable energy; PRISMA

1. Introduction

Energy is the world’s primary industry and the main driving force for various applications. It plays an important role in social stability and economic development, with a global market value exceeding USD 6 trillion in 2020 (Source: https://www.trade.gov/energy-industry, accessed on 13 November 2022).

Overcoming the contradiction between satisfying the exploding world needs and the limited energy sources is a challenge that motivates an increasing number of studies on smart energies. The development of the energy sector needs efficient and sustainable intelligent solutions to face the encountered problems.

With the increasing need for reliable smart and digital solutions in the era of the fourth industrial revolution, blockchain technology is appealing to more and more interests within the scientific community and more precisely in the energy sector worldwide.

Blockchain is a digital platform of a shared, distributed ledger containing the history of all the transactions that have accrued within a business network over a period of time. These transactions, enveloped in digital blocks that are linked to each other cryptographically, can never be deleted, changed or tampered with and are endorsed and validated based on a consensus of a predefined group of participants, hence avoiding the use of a central point of authority. These interesting properties of the blockchain technology offer a promising
solution for the smart management of energy grids and sources in order to ensure the transition towards a more sustainable and secure energy system.

The blockchain technique appeared for the first time in 1991 with Stuart Haber and Scott Stornetta, who worked on a cryptographically secured chain of blocks to create a tamper-proof time-stamped system. The first blockchain application was in 2008 with the publication of a white paper by Satoshi Nakamoto about a new cryptocurrency called “Bitcoin”. The rise of Bitcoin and the different cryptocurrencies in general during the last few years was the real gain of relevance and the concrete proof of the reliability and efficiency of the blockchain technology that started interesting and appealing to many researchers and scientists around the world in different sectors and fields, especially after the appearance of smart contracts in 2015 with Ethereum [1].

Smart contracts are programmed based on predetermined business rules and conditions. When these conditions are met and verified, the smart contracts are executed automatically without any intermediary’s involvement. They can be used to send specific notifications, release funds to appropriate parties, register an asset that the ownership has changed, etc. The introduction of this autonomous operating model using smart contracts was a noticeably new driving force to blockchain technology, bringing more efficiency, accuracy, trust and time saving.

Nowadays, blockchain is one of the topmost in-demand hard skills of 2021. The need for blockchain experts and professionals is exponentially increasing from one year to another worldwide, which has made blockchain related jobs become among the highest paid jobs in the world in 2021. Only between the years 2017 and 2020 did the evolution of the blockchain global job market reach more than 2000%. This explains the huge amount of the estimated global blockchain market size, which is estimated to be more than USD 1.4 trillion by 2030, excluding cryptocurrency investments. When it comes to the energy sector, it is predicted that the global market value of the blockchain technology in the energy industry will rise from USD 200 million in 2018 to around USD 3 billion by 2025 (Source: Global Market Insights Inc.: https://www.smart-energy.com/industry-sectors/energy-grid-management/blockchain-in-energy-market-to-reach-3-billion-by-2025/, accessed on 13 November 2022).

In this paper, we are interested in all aspects of energy to which blockchain technology can be associated. We perform here a systematic literature review (SLR) with a full mapping by following The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 statement [2] and the protocol established by Kitchenham and Charters [3] to conduct systematic reviews. Furthermore, a study and analysis of the obtained data are conducted, and future orientations are proposed. SLRs are considered as a powerful tool used by researchers to deliver a clear and comprehensive overview on existing research works on a given topic, highlight the research concerns in the studied articles and identify the gaps in the scientific research for future orientations.

In today’s world, where technological development is a synonym of energy-intensive industries, it has become mandatory to ensure an optimized method for energy management and trading, leading to the eventual balance between an exponentially increasing demand and the decreasing availability of energy sources.

The energy sector has several limitations and challenges:

- Lack of transparency: the energy sector is one of the driving forces of economical, social and even political development. Its transparency and traceability are hence very important for society, politics, research, and industry. For this reason, it has been receiving much attention by the media, public, and politicians, who are demanding full transparency about current policies, sectoral and technological development, potentials and constraints of future market developments, and ecologic and economic effects of certain pathways, which is unfortunately not always the case, especially with the increasing complexity of the energy systems. This lack of transparency can give rise to the assumption of deliberate manipulation of the future of the energy supply [4].
• Corruption: In many countries around the world, the energy sector is usually associated with weak monitoring, low transparency, and inadequate civil service pay, which makes it a source of several opportunities and incentives for illicit gain. There is no denying that the energy industry has always been a significant source of economic rent generation through energy extraction, transformation, and use. As a result, corruption has always been a major problem in the sector, especially given how time-sensitive it is, how much capital is required, and how important government institutions are to its success. Corruption in the energy business can take many different forms, including paying people with bribes or other “facilitating payments” to deliver services or disobey the law. Because corruption is dependent on numerous intricate factors, measuring it is challenging. However, it is predicted that corruption in the energy industry may lead to an increase in expenses of 20 to 30 percent and a decrease in revenues for gas, coal, and electricity companies of a comparable proportion [5].

• High administration/centralization: Governments around the world have natural monopolies in the energy sector. Today, this centralized model has become inappropriate and is disputed for its inability to meet the new challenges and needs of energy transition. The energy supply chain, from energy extraction to transformation, involves complex infrastructure systems, numerous institutions and jurisdictions, and potentially a large number of end users. The centralized decision-making management model leads to a significant waste of time and rife, as well as numerous opportunities for bribes and corruption in general [6].

• Grid management: While the operating lifetime of power lines is not eternal, it is mandatory to talk about modernizing the energy grid and its management and increasing its capacity. This is challenging as it may need periodically huge investments. Since building new power grids or even renovating the existing ones could be very costly when talking about the country level, shifting into a decentralized energy production system seems to be the most adequate solution. This could be possible by including small local energy systems, even at the level of individual residential buildings, that ensure energy is consumed as close as possible to its source rather than using a few big power plants. This is about creating self-sufficient energy communities by using microgrids with their much easier and less expensive management. Modernized energy grids require the use of digital platforms and new emergent technologies such as the Internet of Things (IoT) through smart meters. However, it is very important to guarantee the security of the system and its invulnerability to cyber-attacks.

• Lack of renewable energy sources integration: The amount of green energy generated in 2019 represented only 27% (Source: International Energy Agency (IEA)) of the worldwide production. This rate is still very low compared to the goals of reducing CO₂ emissions by integrating more and more renewable energies. With today’s world’s awareness about environment protection and climate change, as well as the need to make an energy transition towards green energy sources and low-carbon energy, it is expected that 62% of produced energy will be generated from renewable sources by 2050 as per the International Energy Agency (IEA). However, connecting renewable energy sources with the grid is not as simple as it may seem as they are intermittent sources and their effectiveness is entirely dependent on weather conditions, which could affect the grid’s stability. Without an advanced management system, the renewable energy sources can cause serious grid imbalance and hence become a problem instead of a solution.

• Imbalance between energy demand and supply: There has to be a perfect balance in the electricity grids between production and consumption at any given moment. However, with the increasing integration of intermittent renewable energy sources (mainly wind or solar energy) that are difficult to predict, the complexity of the current energy systems (either the infrastructure itself or even the management and the decision-making environment), in addition to the limited data collection or its
randomness and subjectivity, this primary objective becomes challenging with a lot of uncertainty, especially when it comes to decision-making. Several incidents of blackout have been reported every year in different parts of the world, which could have been avoided with the edification of a robust system that reacts to changes in consumption and production at different levels of time.

- Lack of a fast-acting supply system: The incident of massive blackout that accrued in Europe in 2006, where the imbalance between demand and supply lead to a grid frequency drop, which caused the whole connected European grid to disconnect for hours, could have been easily avoided if there had been a fast grid frequency control as a result of the increasing power consumption [7]. Seeing that this scenario was repeated—or almost repeated—several other times (with the last incident in January 2021 [8]) offers proof that the integration of fast-acting supply and demand management is critical to provide stability and efficiency in the operation of the energy value chain.

Taking into consideration all these challenges in the energy industry worldwide, and based on early research initiatives, blockchain could be considered as a very promising tool to switch into a digital platform for the energy sector that is fully secure, transparent, immutable and reliable. The requirements of the future energy systems and the limitations of the existing ones could be addressed for the following main properties and characteristics of the blockchain [9–11]:

- Transparency: The blockchain provides a shared distributed and replicated ledger between the different participants of the business network that includes the record of all its transactions.

- Privacy: Dealing with sensitive data in the energy sector, cryptography is used to ensure that network participants can only see relevant parts of the ledger and that transactions are secure, authenticated, and verifiable. Furthermore, only permissioned participants can update the ledger or even join the network. The identities of participants are not linked to transactions, which preserves their confidentiality. It is important here to emphasize on the difference between transparency (where all participants must see and be aware of all the transactions taking place in the blockchain network) and the privacy (not the anonymity) of the participants’ data (where only pre-approved data of every participant are to be shown to the rest of the network’s members).

- Immutability: A blockchain is a chain of blocks organized in a ledger chronologically (the newest block is always added at the end) and linked to each other through a hash (each block includes the result of a hash function of the previous block). If someone tries to change or alter any detail in a transaction that is stored in a block, the hash of that block would be updated and thus would be different from the hash included in the following block, which compromises the integrity of the blockchain. Therefore, the change is rejected.

- Finality: “Finality of settlement ensures that transactions … will, at some point, be complete and not subject to reversal even if the parties to the transaction go bankrupt or fail” [12]. In a blockchain, the shared ledger is the only one place to determine the ownership of an asset or completion of a transaction.

- Provenance: Participants know where every asset in their business network came from and how its ownership has changed over time.

- Decentralization: In a blockchain, transactions are endorsed and validated by a predefined set of participants via a cryptographic software-driven consensus before being stored in the shared ledger. These endorsers are agreed on in advance by the business network, hence avoiding a centralized decision-making authority and making the validation process much faster.

- Scalability: Each business network has its own shared ledger, which means that each participant maintains a replica of the shared ledger for every business network to which it belongs. This setup promotes scalability because updating a shared replica
during a transaction is easier than maintaining one’s own separate ledger, which requires independent synchronization with multiple participants in the business network. Moreover, it is always possible to add new nodes to an existing network, which means new participants.

Only a handful of survey or review articles have addressed the use of blockchain technology in the energy sector. We have studied these articles and concluded that the presented results are not sufficient to fully implement an energy blockchain platform. A great number of important details about building a new blockchain platform for the energy sector were missing in the reviews we found in the literature, such as the consensus to adopt, the platform to use for building our energy blockchain, the energy applications that would be the most advised to build our blockchain platform for, etc.

Consequently, our study presents a comprehensive systematic literature review with a full mapping of energy blockchain applications, guidelines, recommendations and orientations to be used and considered by researchers in this field.

In [13], Andoni et al. talked about the challenges and opportunities of the blockchain technology in the energy industry. They conducted their SLR on 140 different existing startups and projects that were dealing with this subject and not with research papers, and they constructed a map of the potential of blockchain technology for energy applications. This review lacks a clear identification of the research questions answered on the SLR and a comparison between the different projects they worked on.

Another SLR that dealt with the use of blockchain technology in the energy sector is [14]. In this review, Wang et al. collected their primary studies between 2014 and 2019 in a single database: Scopus. This article was mainly about the use of blockchain technology in the expansion of renewable energies to reduce the need for fossil energies. However, the research questions that this SLR were addressing were not well defined, and the employed search methodology was not well clarified.

Some other SLRs dealt with a specific aspect of the energy blockchain, such as in [15], where Kirli et al. focused on the specific application of smart contracts in energy blockchains and showed the benefits and drawbacks of this technology for several use cases pertaining to the energy industry. In addition to that, in [16], Li et al. conducted a review on the use of blockchain technology in energy trading as one particular application of energy blockchains.

At the time we conducted this SLR, there was no survey in the literature addressing the overall aspects of building a complete energy blockchain platform as we did in this review. We have tried to make our SLR the most comprehensive and as complete as possible to serve as a good reference for future research works on this subject. Our SLR is different from the existing reviews in different aspects, starting from the search methodology that was used to the research questions that were answered and the representation of the results that were obtained. It goes through 769 high-rigour primary research studies published between 2008 and 2021, answering six different research questions that cover the different aspects of fully implementing a blockchain platform for the energy sector. The obtained results are clearly presented through visual bibliometric analysis using charts, histograms and maps. The analysis of the obtained results could be a guide for researchers in this subject to choose the appropriate aspects and parameters to implement an energy blockchain platform based on their applications.

To formulate the main research questions to be answered in this SLR, we went through the usual steps that any blockchain architect/engineer needs to follow and consider to build an energy blockchain. These steps go from identifying the access to the blockchain (blockchain type and platform), to the transactions to be considered in the blockchain (the applications), the participants and their roles in proposing and validating transactions (smart contracts and consensus), and the methods to optimize the performances and the management of the network (the emergent technologies to be associated with the blockchain), etc. These requirements, in addition to the aforementioned objectives, lead us to draw up the following research questions:
• RQ1: In which energy source types is blockchain technology used?
• RQ2: What are the applications of blockchain in the energy sector?
• RQ3: What are the types of blockchain used in the energy sector?
• RQ4: What are the blockchain platforms used in the energy sector?
• RQ5: What emergent technologies are associated with blockchain for the energy sector?
• RQ6: What are the types of consensus used in energy blockchain platforms?

The gaps and limitations we found in the existing reviews on the use of the blockchain technology in the energy sector, in addition to the urgent need for sustainable energy solutions that could be obtained with the use of the blockchain, were the main reasons for us to conduct this SLR and to make it as complete and comprehensive as possible to cover all the aspects that were lacking or missing (completely or partially) in the existing works. Through this SLR, we went through various electronic databases to identify and collect all the papers that are directly related to the field of energy blockchain, deeply analyzed and studied them, and then proposed future orientations to the research community and the practitioners in this sector to help them conduct further research works/applications on energy blockchain platforms. To conduct this study, we followed the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines and 2020 checklist [2] and the protocol established by Kitchenham and Charters [3] to conduct systematic reviews in order to ensure the quality and the validity of our SLR results. A final set of 769 studies published between 2008 and 2021 fulfilling the quality assessment criteria was identified.

This SLR contributes to the existing literature in the following ways:
• We present a comprehensive qualitative and quantitative synthesis reflecting the state-of-the-art in the use of blockchain technology in the energy sector with data extracted from the identified 769 high-rigor studies. Our synthesis covers the following themes: (1) energy source types that the blockchain technology is most often used with, (2) blockchain applications, (3) types, (4) consensuses and (5) platforms used in the energy sector, and (6) the emergent technologies that are associated with energy blockchain platforms. The results obtained on these six axes will be able to help researchers in the future build a complete energy blockchain and make the most appropriate and efficient decisions for their research purpose and their applications.
• Based on our findings and our SLR results’ analysis, we identified the research gaps in the existing works and suggested areas that require further investigations. We also proposed other research perspectives and future directions that were not adequately—or at all—covered by the researchers in the existing literature on energy blockchains.
• We have built—as an appendix to this paper—a website that includes all our 769 primary studies in dynamic tables, allowing the readers to easily extract all the details that they could need for their studies. The website also presents all our research questions with a bibliometric analysis.

The present study is structured as follows. Section 2 outlines the research methodology that we have followed and underlies the protocol that we have applied for this systematic literature review. We present the results that we have obtained from our 769 primary studies in Section 3 with bibliometric visualizations using maps, charts and histograms and a discussion of their outcomes. To ensure the quality of our systematic literature review, we assessed in Section 4 the threats to the validity of our results. Conclusions, in addition to an agenda for future impactful research works about the use of blockchain technology in the energy sector, are provided in Sections 5 and 6.

2. Research Methodology

In this SLR, we followed the systematic mapping process described in the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines and 2020 checklist [2]. We also used the guidelines presented in the protocol established by Kitchenham and Charters [3] to search for relevant papers [17]. We start in Section 2.1 by presenting the databases we considered and the search words we applied to extract as many relevant papers as
possible. In Section 2.2, we identify the criteria that we relied on either to exclude or to include a paper into our final set of studies. Based on the research questions formulated in Section 1, we propose in Section 2.3 a classification of our papers taking into consideration the possible answers to each research question. We apply some pre-processing steps for the data we collect—as described in Section 2.4—to guarantee its reliability and the validity of the results. Finally, in Section 2.5, we define the criteria we used to assess the quality of our results.

2.1. Literature Search Strategy

To extract as many relevant papers as possible, we needed to consider several scientific literature sources. The literature search was conducted by two authors in March 2022. The databases we used are described as follows:

- Citation Databases: Web of Science (formerly ISI Web of Knowledge), and Scopus.
- Citation Search Engines: DBLP and Google Scholar.

The definition of our search words was made around two main axes: “blockchain” and “energy” and was aiming not to exclude any possible relevant papers in our search phase, which lead to these two sets of keywords relative to each area:

- Set 1: blockchain, chain of blocks, distributed ledger, shared ledger;
- Set 2: electrical energy, renewable energy, smart grid, microgrid, micro grid, energy decentralization, energy trading.

For the search words related to “energy”, we wanted to be very specific so as to collect papers related to “electrical energy” only and avoid irrelevant papers, such as, for example, papers dealing with mining energy in blockchain platforms. We combined these keywords by the logical operators AND and OR as shown in Table 1 in order to collect all papers that include at least keywords from each set either in their title, or abstract or keywords.

Table 1. Final list of search strings.

<table>
<thead>
<tr>
<th>Group</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blockchain</td>
<td>blockchain OR chain of blocks OR distributed ledger OR shared ledger</td>
</tr>
<tr>
<td>AND</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>electrical energy OR renewable energy OR smart grid OR microgrid OR micro grid OR energy decentralization OR energy trading</td>
</tr>
</tbody>
</table>

Following a multi-stage model using the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA 2020) chart of methodology (as shown in Figure 1), we refined our collected papers step-by-step so as to keep only those that are directly related to our subject. This phase was conducted by two authors independently to be sure about the number of articles obtained and excluded at each step along with the total returned publications, as explained in Figure 1.

Below are the different steps that we followed in our systematic review:

- Step 1: Identification: We executed our search queries (as in Table 1) in the different databases we selected. A total of 3150 references were found. By excluding the duplicates (343 articles), we ended up with 2807 articles.
- Step 2: Screening: We applied our inclusion and exclusion criteria (explained in Section 2.2) to the 2807 papers resulted from the previous step, which made us automatically remove 1917 articles. In addition to that, a manual examination of the titles and abstracts (and even the body of the paper whenever necessary) was performed by all the authors to exclude any irrelevant paper. We also applied a study quality
assessment (which will be described in Section 2.5), which excluded 106 papers and reduced our set of candidate papers to 784 articles. Fifteen extra papers were removed from our list as they were not available online.

- Step 3: Included: At this step, we confirmed the final set of of 769 articles that we included in our study. It is worthwhile to mention that forward as well as backward snowballing were applied by two authors as recommended by Wohlin [18], and we found no additional papers to be added to our final list of 769 relevant articles.

Figure 1. PRISMA flowchart for the review process.

2.2. Inclusion and Exclusion Criteria

We drew up a set of criteria that we applied to confirm whether to include or exclude a paper in or from our final set of studies so as to keep only the most relevant references to our study.

2.2.1. Inclusion Criteria

For an article to be selected as a primary study to this SLR, it must satisfy all the following criteria:

1. Date range: We chose to start our paper selection from the year 2008—the year when the first blockchain application (Bitcoin) appeared—and end it at the year 2021, since this SLR was conducted at the beginning of 2022.
2. Subject area: We limited our selection to papers related to the computer science and engineering fields.
3. Language: We chose to only select articles that were written in English.
4. Paper types: Articles were selected from scientific journals, conference proceedings and books. If a conference paper had a journal extension with the same title, authors and abstract, it was considered a duplicate article, and only one of them was included.
5. Availability: We only included papers that were available in an electronic format in our final set of studies.
6. Quality assessment: Each selected paper was required to pass the quality assessment criteria that are elaborated on in Section 2.5 to be included in our final set of studies.

2.2.2. Exclusion Criteria

In this section, we formulated a set of criteria that excluded any article with at least one of them.
1. Publication stage: Any paper that was explicitly marked as “work-in-progress” was to be excluded from final set of articles so as to keep only mature publications.

2. Paper types: We excluded all papers that were published in workshops, symposiums or poster sessions only.

3. Paper length: We excluded papers that we considered “short”: having less than 5 pages of length.

4. Grey Literature [19]: We excluded all papers that were published in non-commercial or non-academic forms.

2.3. Study Classification

We conducted this SLR to address our research questions formulated in Section 1. Answering these questions would be of a big help to the future researchers in this subject to directly build an energy blockchain platform.

• RQ1: Types of energy sources in energy blockchain platforms:

  When we talk about energy source types, we mention three types as below:

  – Fossil energy: This includes all energies that were formed from the fossilization, over millions of years, of buried remains of plants and animals, such as coal, crude oil, and natural gas. This type of energy is currently considered the biggest part of the global electricity mix in 2021, with more than 60% of the share [20].

  – Fissile energy: This is the energy issued from the fission of fissile (or also called fissionable) materials, which are any species of atomic nucleus that can undergo a fission reaction, such as uranium. This type of energy is considered a clean energy yet a dangerous one, composing about 28% of the global electricity mix in 2021 [20].

  – Renewable energy: This includes all types of energies that are issued from sources that are naturally replenished and do not run out, such as the wind and sun.

• RQ2: Blockchain applications in the energy sector:

  As energy tightly touches almost all fields and sectors, there could be a very long list of potential applications in energy blockchains. From our studies, we enumerate here below the main energy applications where blockchain could be the most relevant and with the best added value:

  – Energy trading: This includes the different possible ways of selling energy: conventional existing systems or new peer-to-peer models. The use of smart contracts in blockchain platforms made trading—and energy trading in particular—faster (less transaction backlog), less costly (no intermediaries), and more reliable and auditable (transparent to all participants). In addition to that, with blockchain-enabled P2P energy trading, it is possible for individuals to sell their surplus electricity (mainly produced from renewable sources) directly to local consumers through the blockchain network without the need for a retailer. This gave energy trading a totally new and efficient aspect of mutual beneficial transactions.

  – Energy management: This can be seen in two different aspects: first, on the level of the energy providing company that has its energy practitioners working on different tasks of the network management such as monitoring the energy consumption and production to meet energy balance, improving the energy efficiency, and ensuring the energy procurement, including the energy imports and the procurement of renewable and alternative energy. The second level of the energy management is at the level of the energy consumers aiming to reduce their costs by controlling and reducing their building’s energy consumption, especially given that 20 to 25% of all operating costs in an office building are energy costs, and a good energy management system can reduce these costs by 15% [21]. The good thing about blockchain is that these two aspects of energy management and monitoring can be easily programmed in the same platform, making it more efficient and reducing the need for man power.
- Energy storage: This is one of the key elements of ensuring a stable and safe energy supply by an all-time perfect match between energy availability and consumption by storing excess electricity and releasing it when the demand is high. With the increasing penetration of renewable energies in the electric mix, storage is even more important. Renewable energies are considered as “unreliable” sources due to their intermittency and unpredictability, which could easily destabilize the grid. Having enough storage can help stabilise the electricity grid by creating flexible provisions. This provides ample scope for research in this area, and most particularly in the field of energy blockchains. The costs of the present energy storage systems are considered expensive worldwide. One of the potential viable solutions to this is the ability to share energy storage between individuals or entities within the same community. The feasibility of this idea of peer-to-peer energy storage sharing could be possible only by using a blockchain platform.

- Security: This is definitely one of the first and most important requirements for any energy platform that deals with potential millions of transactions worth billions of USD. It is important that the energy transactions between market players in a very competitive environment are evaluated through a secure infrastructure against cyber-attacks to enhance the power system’s reliability. The Ukraine blackout of 2015 that was due to data vulnerability and malicious events is one concrete example of this [22]. The blockchain transaction framework is one of the most (if not the most) reliable systems against hacking and cyber-attacks in general and in the energy sector in particular [23].

- Electric vehicle (EV): This is one of the most increasingly developing industries nowadays. In spite of their low penetration rate today in many countries, it is expected that the global EV volume will reach more than 30% of the global market share by 2030 due to the “2050 net zero emissions” plan put forth by the IEA (International Energy Agency) [24]. This increasing number of EVs will eventually have a strong impact on the power distribution grid because of the expected large number of EVs being charged simultaneously from the same distribution grid, taking into account the high power demand required for charging one EV [25]. For this reason, an EV’s battery capacity is considered a key element to balance the smart power grid in the future. To be able to maintain the balance of the electric grid, it is crucial to know when and where an EV is plugged into the power grid as well as what battery capacity is available. A typical example to cite here as a reference is about the Danish grid based on wind energy (almost 60% of the electric mix as per the Danish Energy Agency). The electricity production from wind turbines is often high at night when the demand for electricity is the lowest. As a result, the electricity price in Denmark is negative during about 300 h yearly (i.e., you get paid for using electricity). It is hence very profitable and convenient to be able to select the EV charging period with respect to electricity pricing, which creates a need for more intelligent EV charging stations that can communicate with the grid managers and the EVs owners (or the EVs through a machine-to-machine interaction). Here comes the role of the energy blockchain that could present an interesting solution with the use of the Internet of things [26–28].

- Carbon emissions: This is about meeting internal sustainability goals and regulatory requirements with respect to the “2050 net zero emissions” plan of the IEA. The U.S. Environmental Protection Agency estimates that more than 80% of greenhouse gases released are carbon emissions, primarily in the form of CO₂. This has lead to an increasing momentum of sustainability initiatives as organizations are becoming more and more interested in monitoring their business practices, and many companies around the world have started implementing sustainability solutions appreciated by both consumers and investors. The con-
The conventional method most companies use to calculate their carbon footprints is a manual and time-consuming process based on many approximations, which could lead to a lot of errors. One of the most efficient solutions that researchers found was the use of the blockchain technology combined with IoT sensors to accurately calculate the carbon emissions [29].

- **Smart Grid:** This is about the digitalization of the conventional electricity supply network with an advanced information and control infrastructure, allowing interoperability among various stakeholders and the efficient integration of renewable energies. With the upcoming fourth industrial revolution “Industry 4.0”, this transition towards a new intelligent power supply infrastructure became mandatory. What makes a grid smart is the use of advanced metering systems (IoT smart meters), a two-way communication infrastructure between the utility and its customers, a digital secure platform for bill payment, an efficient form of network supervision that allows a fast response in any change in the electric demand (quicker restoration of electricity after power disturbances, reduced peak demand leading to lower electricity rates, more efficient energy transmission, ...). With all the complexity that is added to the conventional grid, there is a significant need for a reliable, secure and efficient solution that could be found with blockchain technology [30].

- **RQ3:** Types of blockchains used in the energy sector:
  When implementing a blockchain, it is important to define from the very beginning the type of your business blockchain. This will mainly define how participants can join this blockchain. There can mainly be three different types, as explained here below:
  - **Public blockchain:** This is also called the “permissionless” blockchain. It is a completely decentralized open-source platform based on a fully trustless system that allows anyone to access the network without any verification of their identity, which is the case of the cryptocurrency blockchain platforms such as Bitcoin and Ethereum. Any participant can join, access or exit the blockchain network, and any node from the network can submit and participate in the validations of transactions without any restrictions.
  - **Private blockchain:** This is also called the “permissioned” blockchain. It is a closed network that requires the full knowledge of the participants’ identities. It offers limited/restricted access to data (read permissions), which provides a higher level of privacy to the participants and a certain degree of centralized control compared to the public blockchain.
  - **Hybrid blockchain:** It is a combination of both private and public blockchains, where accessibility to some part of the network is made public and visible to all participants and another part is made private. It provides a solution where data need to be accessed publicly but shielded privately. We included in this category some other specific types of blockchains: “federated blockchain” or “blockchain consortium” and “alliance”, which are types of a private blockchain that includes a public readability feature, hence re-establishing a more decentralized-type system compared to the private blockchains.

- **RQ4:** Blockchain platforms used in energy sector:
  Several blockchain platforms are found in the literature. However, it is worthwhile to mention that they are still in their early phases. The list below is not exhaustive. It only includes the platforms that we were able to find in our final set of primary studies related to energy blockchains, and we removed all those where our search for keywords gave zero results.
  - **Hyperledger:** This is an open-source blockchain multi-project hosted by The Linux Foundation since 2016 that consists of several tools and APIs. It is an umbrella project where different teams work together to develop distributed ledger technology (DLT). The Hyperledger Fabric is one of the most commonly
used blockchain platforms. It is mainly adopted by IBM (as a premier member of the Hyperledger collaborative project) in all their blockchain projects. That is why it is referred to “IBM blockchain” sometimes. The Hyperledger architecture includes a smart contract layer responsible for the processing and the validation of the transaction requests by executing business logic. The Hyperledger framework is used for private enterprise/business blockchains [31].

- Corda: This is an open-source permissioned blockchain platform for businesses designed to offer interoperability between applications. It offers high security to the network, which makes it ideal for financial markets. It uses a smart contract logic and supports the development of decentralised applications. R3 Corda derives from the Corda system and is an open-source permissioned platform developed by R3 in 2014. One of the biggest disadvantages of the Corda system is that there is not a single chain of blocks shared between all nodes. Instead, it has several ledgers where transactions are only added to those owned by the nodes that are directly involved in these transactions. This point does not meet one of the most primordial requirements of the blockchain technology [32,33].

- Ethereum: This is a second-generation blockchain introduced by Vitalik Buterin in 2014, and the Ethereum platform was launched in 2015 by Buterin and Joe Lubin. Ethereum is an open-source operating system with an extremely flexible platform in which one can build, deploy, and use decentralised applications and smart contracts using the native Solidity scripting language and Ethereum Virtual Machine. The goal of Ethereum is to create a secure digital technology that further advances blockchain use cases and enables more functionality than peer-to-peer payments. One of the major advantages of Ethereum is the Enterprise/Private Ethereum that was introduced to help enterprises adopt blockchain technology more easily and quickly. The proof-of-work consensus protocol is used by Ethereum. Some Ethereum testnets are switching to other consensuses—such as proof-of-stake and proof-of-authority—since PoW requires a lot of computational power [34–36].

- Polkadot: Polkadot was first announced by Wood in 2016. Similar to Bitcoin and Ethereum, Polkadot refers at once to a network protocol and to the primary public network that runs this protocol. Polkadot is intended to be an open-source blockchain platform and cryptocurrency. Polkadot is designed to be fast and scalable, and it provides interconnectivity and interoperability between blockchains, which allows incompatible networks (Bitcoin and Ethereum, for example) to exchange data, messages and value and even perform transactions between them easily and securely without the need for a trusted third party [37–39].

- Binance: Binance was launched in July 2017 by Changpeng Zhao and is currently considered the leading blockchain ecosystem in the world, with a product suite that includes the largest digital asset exchange in terms of daily trading volume of cryptocurrencies [40,41].

- Powerledger: Powerledger has created the first blockchain trading platform for renewable energy in the world. Powerledger was founded by Dr. Jemma Green and technologist John Bulich in Perth in 2016. Every kilowatt of energy produced outside the grid can be tracked, traced, and traded thanks to the company’s software. Renewable energy resource owners have the option of selling their excess energy within microgrids or through the distribution network at a specified price. Energy exchanged across the distribution network brings a revenue to the distribution system operators (DSO) [42]. PowerLedger utilizes both the public self-developed Ecochain with proof-of-stake (PoS) consensus and the private Ethereum blockchain with proof-of-work (PoW) consensus. Market trading and settlement are provided by the PowerLedger mechanism based on blockchain [43].
RQ5: Emergent technologies associated with blockchain in the energy sector: One of the best key elements of blockchain is its compatibility with so many other innovative emergent technologies. This combination of technologies has attracted a large number of researchers in order to propose the most effective and efficient solutions for the energy industry problems by using blockchain technology. We grouped these emergent technologies in four groups, as shown below:

– Internet of Things (IoT): This is one of the most important technologies of the 21st century. Its concept is about interconnecting machines (physical objects/things) to the internet and to other connected machines through embedded computing devices enabling them to send and receive data. This exchange of data has created a method of communication between these machines and people, processes or other machines with minimum human intervention. When associated with blockchain, IoT enables devices across the internet to send data to the blockchain network that can be used to validate transactions and stored as tamper-resistant records. For the energy blockchain, the use of IoT devices could be in the use of smart meters to directly communicate buildings’ power consumption to the blockchain, in the EV charging stations, which allows the real-time management of the EV charging status, in the EVs themselves to monitor their battery levels, in the renewable energy devices (wind turbines, solar panels, ...) either in the private sources (for peer-to-peer renewable energy trading) or in the parks (to optimize the penetration of these sources in the power grid), in the energy storage stations for a smart supervision of the energy storage, etc.

– Artificial intelligence (AI): This is a field of computer science that makes a computer system mimic or simulate human intelligence. The word “Artificial Intelligence” itself is a popular tech term frequently used today to describe intelligence in machines that could be using data science (which is about analyzing big data) and machine/deep learning (which is about extracting knowledge from data). With the new industrial revolution-baptised Industry 4.0, a new concept has been emerging recently: decentralized AI (DeAI). DeAI aims to incorporate intelligence into existent decentralized systems, thus promoting the development of AI toward distributed, secure and even personalized intelligence and intelligent problem solving [44]. This new concept of decentralized artificial intelligence makes a perfect combination with blockchain technology. Particularly in the energy blockchain platform, where data are collected from the different IoT devices connected to the blockchain, transacted and stored on the distributed ledger, the DeAI enables processing data and analyzing it and performing decision making on information that is trusted, securely shared and digitally signed.

– Decision support systems (DSS): These are defined as human–computer systems with the ability to process data and provide information based on computers [45], enabling the management of multi-criteria decision-making activities [46]. Stakeholders in the energy sector may encounter difficulties in transferring the explosive amount of information collected from the network into practical knowledge, which may lead to improper decisions about the management of the energy network. For this reason, DSS platforms are needed to assist them in making accurate and precise decisions based on evidence. This characteristic could marry them very well to blockchain platforms [47].

– Management information system (MIS): This is an automated system (with computer-aided tools) within an enterprise that collects data from various online systems or entities; it, thus, analyzes the information and further reports the analyzed data to business managers to aid in making appropriate decisions, especially in projects of high complexity [48]. In the energy sector particularly, the need for fast and accurate decisions based on reliable, well-analyzed data is very important and even mandatory for electric utility grids to monitor, control and optimize the performances of the grid in addition to reducing costs and
saving time. For this reason, energy management information systems (EMIS) are rapidly evolving, allowing energy practitioners and consumers to monitor, analyze and control the performances of their buildings or grids. Blockchain technology and MIS could be one of the best software combinations. In the blockchain ledgers, there is a huge quantity of data that is collected and stored securely, which could be efficiently analyzed by a management information system in order to help the different participants of the blockchain network make good, timely decisions.

- RQ6: The consensus used for energy blockchain platforms:
The consensus is an algorithm incorporated in the blockchain to verify the data inputs and to validate the transaction requests in the network. Its aim is that all the peers of the blockchain network reach a common agreement about the current state of the data and the transactions to be validated and stored in the distributed ledger, and this is what guarantees the decentralization of the decision in a blockchain network. There are numerous types of consensus known and used in blockchain platforms. We made a long list of them to search in our primary studies. We only present here the ones we found in our primary studies. We removed all the consensus methods that did not appear in any of our articles (such as: proof of benefit, proof of burn, and proof of elapsed time). We also tried to group together consensus from the same family; for example, we grouped federated Byzantine fault tolerance (fBFT), practical Byzantine fault tolerance (pBFT), Istanbul Byzantine fault tolerance (iBFT) and honey badger under the umbrella of Byzantine Fault Tolerance (BFT). We divided these consensus methods into three main categories based on the type of the blockchain:

  - Proof of work (PoW): this is one of pioneering consensus models serving as the essential foundation of the Satoshi Nakamoto-created Bitcoin blockchain. It was first edited by Dwork and Moni Naor in 1993, and Markus Jakobsson and Ari Juels formalized it in 1999 [49]. PoW is used in permissionless blockchain networks and in almost all cryptocurrency blockchains (such as Bitcoin, Ethereum, ...) in validating transactions and mining new tokens. It actually requires the blockchain network’s nodes to produce new blocks through the “mining” process of resolving—by the trial and error method—arbitrary challenging, asymmetrical mathematical puzzles, demonstrating proof of work. This method requires a lot of computational power, which makes the transactions’ validation process a bit slow when the network is big (as in the case of Bitcoin) [50–52].

  - Proof of stake (PoS): This retains the advantages of PoW while overcoming some of its weaknesses, such as the large amount of energy consumption, while maintaining network security and being more decentralized. The PoS algorithm randomly chooses validators from the blockchain network nodes for block creation in accordance with the amount/value of the crypto-assets they stake. Staking is when a participant pledges their crypto-assets/coins to be used to verify a transaction. One of the biggest disadvantages of this consensus algorithm is that it favors the selection of holders with larger amounts/values of native tokens. A validator loses some of their stake when they attempt to approve an invalid block and receives the transaction fees (reward) and their stake back when they approve a valid block [49]. To avoid any fraudulent blocks from being added, the stake amount should be greater than the total transaction fee. Another voting-based consensus called delegated proof-of-stake (DPoS) derives from the PoS protocol. DPoS adds a democratic element to the PoS consensus mechanism by outsourcing the validation process to a third party. These third parties, referred as “witnesses”, are in charge of reaching consensus throughout the creation and validation of new blocks. Rewards are shared between the witnesses and the stakeholders. The chosen witness node will not be permitted to participate in further voting processes if it is unable to produce a block. PoS and DPoS are
linked first to permissionless networks but many studies indicate that using PoS and DPoS is possible in permissioned networks [50–52].

- Byzantine fault tolerance (BFT): This method was originally created in 1982. BFT was named with respect to military tactics in a scenario where many Byzantine generals amass around an enemy city before invading it. Assuming that each general has their own army stationed separately in different locations around the city that they intend to attack, they must agree (reach consensus) whether to attack or to withdraw. Applying this tactic in blockchains, we represent each general by a network node, and the majority of the nodes needs to reach consensus on the present state of the system. The consensus can be reached either by having at least \( \frac{2}{3} \) or more reliable network nodes. The BFT approach aims to keep the system intact in case of a failure of one of the nodes (or generals) and to reduce the effect of malicious Byzantine nodes in the blockchain network. On the other hand, it has a major drawback consisting of the vulnerability of the system to attacks if the majority of the network decides to act maliciously (such as the 51% attack). Some researchers consider the BFT consensus family as a variant of proof-of-stake [53].

Many optimizations have been applied to BFT, giving these following consensuses:

- Practical Byzantine fault tolerance (pBFT): This method relies on replication between recognized parties and can tolerate up to one-third of the parties failing. An ordered list of transactions is created by the primary node—the elected leader—and broadcast to the other validating nodes. Following the completion of transactions, validating nodes compute the new block’s hash code, which is subsequently broadcast to their peers. The block is added to the node’s local copy of the blockchain if two-thirds of the incoming hash codes match.

- Istanbul Byzantine fault tolerance (iBFT): This method draws from the original PBFT, ensuring a single, agreed-upon ordering for transactions. It takes a model that is only partially synchronous. When there are \( N \) validating nodes in a network, the system can accept up to \( F \) faulty nodes, where \( N = 3F + 1 \). In an Ethereum network, for example, the IBFT consensus serves as an alternative to proof of work. IBFT provides additional advantages for businesses, such as settlement finality [54].

- Federated Byzantine fault tolerance (fBFT): This method seeks to address centralization issues with improved scalability. All participants’ identities are known in the BFT processes mentioned above, but, in fBFT, all nodes’ identities are not needed to be known. As a result, membership is open, and control can be decentralized. It only requires a subset of nodes to reach consensus, which makes fBFT viewed as semi-trusted. The majority of fBFT implementations allows nodes to select the other nodes they trust for information [50–52,55].

- Honey badger: Unlike other BFT alternatives, honey badger does not care about the timing suppositions or the synchronicity of the underlying network. It is an asynchronous BFT extension using sufficient computational resources to address the network’s bandwidth shortage. Transactions that have been saved in nodes’ buffers are verified [52,56].

- CHB/CHBD: The blockchain networks created by CHB consensuses are predicated on the same security assumptions as those in Bitcoin systems since they employ a consistent hash algorithm. The CHB consensus technique uses unique public-private key pairs generated by a certification authority (CA) rather than a random public-private key. As a result, it saves a significant amount of power without compromising decentralization or security. To create new blocks, nodes are selected randomly. In order to guarantee a stronger security than the CHB-consensus protocol, a modified variant of it—known as CHBD (the \( D \) denotes
“Difficulty”)—adopts two phases. First, a new block creator is chosen using the same procedure as CHB consensus; then, it is required to provide PoW by solving a hash puzzle with difficulty. The difficulty of the entire mining in the CHBD technique can be adjusted, maintaining the overall energy consumption lower than PoW [50,57].

- Kafka/Zookeeper: LinkedIn first suggested Kafka as a way to store user data in a distributed system [58]. There are three major components in Kafka: the producer, the consumer, and the broker. The consumers read the data from the producers through the broker nodes. The broker stores the data as a set of separated nodes for producers and consumers to write and read independently [59]. Kafka keeps at least one leader “orderer” node active in the system because it determines the generation of blocks. When the existing orderer node fails, Apache Zookeeper chooses a new leader [60]. Zookeeper manages brokers, keeps a list of them, helps in performing leader election for partitions and sends notifications to Kafka in case of changes (i.e., a new topic, if a broker dies, if a broker comes up, when deleting topics, etc.). Kafka v2.x cannot work without Zookeeper, but Kafka v3.x can work without it using Kafka Raft.

- RAFT: This method uses a state replication paradigm where all transactions are distributed among all involved nodes. It stops the creation of unnecessary vacant blocks and enables a leader node to construct the next block [56,61,62]. From RAFT Consensus derives KRaft (Kafka Raft) and BFT-Raft. Apache Kafka Raft (KRaft) was introduced to break Apache Kafka’s dependency on ZooKeeper for metadata management. By combining the management of metadata within Kafka itself rather than dividing it between ZooKeeper and Kafka, KRaft simplifies Kafka’s design. BFT-RAFT combines the advantages of both BFT and Raft, including fault tolerance and security features [63].

- Proof of Authority (PoA): This is a consensus algorithm for permissioned blockchains. Compared to the BFT algorithm, it replaces a more lightweight message-passing scheme, which leads to the superiority of this approach in terms of performance. In PoA, blocks and transactions are verified by trustworthy nodes called “validators.” Because there are so few validators required, the network has a high throughput, is very scalable, and almost has no processing fees. Additionally, unlike with PoS, a validator only needs to stake its own reputation rather than any of its assets, and this solves the main problem of PoS. PoA tends toward strong centralization due to the small number of actors, which makes this approach appropriate for consortiums [50,56].

The choice and implementation of a particular consensus protocol depend mainly on the kind of operation a specific blockchain network is expected to conduct. When it comes to permissionless networks, a large emphasis is typically placed on security. This would ensure that untrusted nodes can come to a consensus. On the other hand, permissioned networks sacrifice decentralization in favor of settlement certainty and higher transaction rates. The nature of the energy blockchain types (combining between permissioned and permissionless accesses) makes the choice of the most appropriate and adequate consensus algorithm a difficult mission. For this reason, a consensus comparison is made in Table 2 based on the following characteristics: type, participation, network timing, blockchain type, energy consumption, speed of transaction processing, transaction finality, scalability, and security, with some examples of blockchain applications. This comparison was made based on several research works: [11,49–51,64–72]. We define below the main nine characteristics taken into account to prepare this comparison between the different consensus algorithms used in the energy blockchains as per our SLR:

- Network Timing: This defines the level of coordination among all processes. The timing may be synchronous, asynchronous, or partially synchronous.
- Scalability: This refers to the capacity to expand both in size and functionality without affecting the system’s performance.
- Energy consumption: This indicates whether the algorithm (or the employing system) uses a lot of energy.
- Finality: This is essential for ensuring that blocks cannot be revoked after they are deployed in blockchain applications. Immediate and probabilistic finality are the two fundamental types of finality. In the case of immediate finality, a transaction is concluded immediately after it is added to a blockchain, whereas probabilistic finality suggests that a transaction is not concluded instantly, but rather that—as additional blocks are added to the chain—the possibility that the transaction might be undone reduces.
- Consensus participation: The number of nodes taking part in the validation of the proposed block.
- Transaction speed: This depends on two key factors: block confirmation time and transaction throughput. Block confirmation time determines how quickly a transaction is confirmed after it is added, while transaction throughput refers to the number of transactions the protocol can handle in a second.
- Security: This evaluates how well a consensus protocol confronts different attacks.
- Type of blockchain: Classes for blockchain network access are permissioned (private), permissionless (public) or a combination of the two (hybrid).
- Type of consensus: Consensus can be categorized into two main types:
  - Proof-based consensus: This is mainly used in large networks with a high number of nodes, which makes it very suitable for public blockchains (though it may also be used in private and consortium ones). The concept of this type of consensus is that only nodes with sufficient proof have the right to validate transactions and append a new block to the ledger, for which they will be rewarded. Among the several variants of the proof-based consensus algorithms, we find stake-based and reputation-based consensus.
  - The voting-based consensus: This is mainly used in small networks with only a limited number of nodes, which makes it more appropriate to be used in private and consortium blockchains (though it may also be used in public ones). A given transaction is validated through voting from the network’s nodes. It is important for the nodes to be known so that they can exchange messages more easily between them. Numerous alternatives to voting-based consensus include consensus protocol based on effort, consensus protocol based on wealth, consensus protocol based on resources, consensus protocol based on past behavior, consensus protocol based on representation, etc.
Table 2. Comparison of consensus algorithms’ characteristics and performance.

<table>
<thead>
<tr>
<th>Property</th>
<th>PoW</th>
<th>PoS</th>
<th>DPoS</th>
<th>BFT</th>
<th>PBFT</th>
<th>FBFT</th>
<th>IBFT</th>
<th>HONEY BADGER</th>
<th>PoA</th>
<th>RAFT</th>
<th>CHB/CHBD</th>
<th>Kafka/ZooKeeper</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Timing</strong></td>
<td>Synchronous/Partially synchronous</td>
<td>Synchronous</td>
<td>Partially synchronous</td>
<td>Partially synchronous</td>
<td>Partially synchronous</td>
<td>Partially synchronous</td>
<td>Partially synchronous</td>
<td>Asynchronous</td>
<td>Synchronous</td>
<td>Asynchronous</td>
<td>Synchronous</td>
<td>Asynchronous</td>
</tr>
<tr>
<td><strong>Consensus participation</strong></td>
<td>Entire nodes/Random</td>
<td>Entire nodes</td>
<td>Entire nodes/committee</td>
<td>Only designated nodes</td>
<td>Only designated nodes</td>
<td>Only designated nodes</td>
<td>Only designated nodes</td>
<td>Random</td>
<td>Only designated nodes</td>
<td>Only designated nodes</td>
<td>Only designated nodes</td>
<td>Entire nodes/Random</td>
</tr>
<tr>
<td><strong>Blockchain Type</strong></td>
<td>Permissionless</td>
<td>Permissioned/permissionless</td>
<td>Permissioned</td>
<td>Permissioned/permissionless</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
<td>Permissioned</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Speed of Transaction</strong></td>
<td>Slow</td>
<td>Slow</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Fast</td>
<td>Very fast</td>
<td>Moderate</td>
<td>Fast</td>
<td></td>
</tr>
<tr>
<td><strong>Processing Transaction Finality</strong></td>
<td>Probabilistic</td>
<td>Probabilistic</td>
<td>Probabilistic</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Immediate</td>
<td>Probabilistic</td>
<td>Immediate</td>
<td>Probabilistic</td>
<td>Immediate</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Security</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td><strong>Example Blockchain</strong></td>
<td>Bitcoin, Ethereum, Doge Coin, Lite Coin</td>
<td>Steemit, EOS, Bitshares, Ark</td>
<td>Enerchain: Cosmos network</td>
<td>Hyperledger Sawtooth, Hyperledger Fabric, Cosmos network-based</td>
<td>Stellar, Ripple</td>
<td>Quorum Blockchain</td>
<td>POA Network</td>
<td>VeChain thor, POA Network, Ethereum Kovan, Microsoft Azure testnet</td>
<td>Quorum, Corda</td>
<td>Theoretical in nature</td>
<td>Hyperledger Fabric</td>
<td></td>
</tr>
</tbody>
</table>
We established a list of keywords for each response we offered to each RQ in order to identify relevant papers for each specific research question and to categorize these papers for our study. We outlined the proposed keywords in Table 3. Aiming to cover the maximum forms and derivatives of a possible keyword, we removed all the possible affixes (suffixes or prefixes). For example the word stor will cover, in our search, words such store, storing, stored, storage, etc.

Table 3. List of keywords used to detect the different categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Keywords</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy source types (RQ1)</td>
<td></td>
</tr>
<tr>
<td>Fossil energies</td>
<td>fuel, oil, coal, peat, bitumens, tar sands, petrol, gasoline, crude, rock oil, natural gas, fossil energy</td>
</tr>
<tr>
<td>Fissile energies</td>
<td>fissile, nuclear, atomic, uranium, fission</td>
</tr>
<tr>
<td>Renewable energies</td>
<td>renewable energy, green energy, wind, solar, water, sun, tides, waves, geothermal, photovoltaic, biomass, hydropower, marine energy</td>
</tr>
<tr>
<td>Blockchain applications in the energy sector (RQ2)</td>
<td></td>
</tr>
<tr>
<td>Smart grid</td>
<td>smart grid, smart energy, energy internet, smart meter, grid 2.0, Digital grid, virtual power plant, VPP</td>
</tr>
<tr>
<td>Energy storage</td>
<td>stor, distributed energy sources, reserve, cache, save, waste</td>
</tr>
<tr>
<td>Energy management</td>
<td>energy management, energy govern, energy supervision, voltage regulation, energy balancing, energy adjustment, energy consumption, audit, inspect, survey, predict, forecast</td>
</tr>
<tr>
<td>Energy trading</td>
<td>energy trad, purchase, buy, sale, electricity trad, power trad, stackelberg, transaction, peer-to-peer, p2p, commerce, exchange</td>
</tr>
<tr>
<td>Security</td>
<td>secure, safe, cybersecurity, privacy, prevention, surety, danger, attack, threat, trust, spoof, hack</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>UAV, unmanned aerial vehicle, EV, electric vehicle, electrical vehicle, electric car, charging, ecological vehicle, hybrid vehicle</td>
</tr>
<tr>
<td>Carbon emission</td>
<td>green certificate, Renewable Energy Certificate, REC, carbon market, greenhouse gas, CO2, cap and trade, carbon pricing, sustainability</td>
</tr>
<tr>
<td>Types of blockchain used in the energy sector (RQ3)</td>
<td></td>
</tr>
<tr>
<td>Public</td>
<td>public blockchain, permissionless, trustless</td>
</tr>
<tr>
<td>Private</td>
<td>private blockchain, managed, permissioned</td>
</tr>
<tr>
<td>Hybrid</td>
<td>hybrid, hybrid blockchain, consortium, federated, Alliance, AllianceBlockchain</td>
</tr>
<tr>
<td>Blockchain platforms used in the energy sector (RQ4)</td>
<td></td>
</tr>
<tr>
<td>Powerledger</td>
<td>Powerledger, Power Ledger</td>
</tr>
<tr>
<td>Hyperledger</td>
<td>Hyperledger, Fabric, Sawtooth, IBM Blockchain</td>
</tr>
<tr>
<td>Corda</td>
<td>Corda, R3 Corda</td>
</tr>
<tr>
<td>Ethereum</td>
<td>Ethereum, Solid, Remix</td>
</tr>
<tr>
<td>Polkadot</td>
<td>Polkadot</td>
</tr>
<tr>
<td>Binance</td>
<td>Binance</td>
</tr>
<tr>
<td>Emergent technologies combined with blockchain for the energy sector (RQ5)</td>
<td></td>
</tr>
<tr>
<td>Internet of Things</td>
<td>Internet of things, IoT, cloud computing, energy internet, mobile communications, edge computing, smart meter, smart meter</td>
</tr>
<tr>
<td>Artificial intelligence</td>
<td>artificial intelligence, AI, Machine learning, deep learning, bandit learning, big data, Augmented reality, AR, virtual reality, VR, mixed reality, MR, extended reality, XR, data analytics</td>
</tr>
<tr>
<td>Management information systems</td>
<td>management information system, MIS</td>
</tr>
<tr>
<td>Decision support systems</td>
<td>decision support system, DSS, dynamic tariff decision, oracle</td>
</tr>
<tr>
<td>Types of consensus used in blockchain platforms for the energy sector (RQ6)</td>
<td></td>
</tr>
<tr>
<td>Proof of work</td>
<td>proof of work, PoW, PoW, Proof-of-Work</td>
</tr>
<tr>
<td>Raft</td>
<td>raft, kraft, Raft-BFT, BFT-RAFT</td>
</tr>
<tr>
<td>Proof of authority</td>
<td>proof of authority, proof of authority, PoA</td>
</tr>
<tr>
<td>CHB/CHBD</td>
<td>chb, chbd</td>
</tr>
<tr>
<td>Byzantine Fault tolerance</td>
<td>Byzantine fault tolerance, BFT, federated Byzantine fault tolerance, FBFT, practical Byzantine fault tolerance, PBFT, Istanbul Byzantine fault tolerance, IBFT, honey badger, HoneyBadger</td>
</tr>
<tr>
<td>Kafka/Zookeeper</td>
<td>kafka, zookeeper, zookeeper</td>
</tr>
</tbody>
</table>
2.4. Data Collection

Before extracting any data from our reference studies, we pre-processed all our papers so as to improve the accuracy and reliability of our results. For a whole mapping, it was necessary to classify our papers per country. In order to extract all the nations mentioned in these affiliations for each publication, we examined the institutions of the authors’ affiliations for each article. The name of a country could be cited differently from one author to another. For example, some authors would mention “Korea”, and others would call it “South Korea”. For that reason, we made some substitutions in some country names, as mentioned in Table 4.

Table 4. List of countries and their replacements.

<table>
<thead>
<tr>
<th>Country</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popular Republic of China</td>
<td>China</td>
</tr>
<tr>
<td>USA</td>
<td>United States</td>
</tr>
<tr>
<td>England, Scotland and Wales</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>Russia</td>
</tr>
<tr>
<td>Korea</td>
<td>South Korea</td>
</tr>
</tbody>
</table>

The data extraction from our final set of articles was made automatically in a first phase through a Python code. The idea was to go through the body of each paper and count the number of occurrences of all the keywords defined in Table 3 for each potential answer to a particular RQ. If the sum of all the keywords set for one particular answer to a given RQ was superior to 10 occurrences per paper, the answer was automatically validated for that RQ and that particular paper. If this sum was less than 10 but not null, a second phase of processing was applied by the four authors through a manual examination of that specific article to be able to confirm or deny that answer for that particular research question.

2.5. Study Quality Assessment

To guarantee the reliability and accuracy of our results, it was necessary to assess the quality of the primary studies after having applied the inclusion and exclusion criteria. The quality assessment was measured following the quality checklist given by Kitchenham and Charters in [3]. This method is based on answering a set of questions (described in Table 5) with “Yes”, “Partially”, or “No” and giving a score of 1, 0.5, or 0 to each one of these answers, respectively. A specific publication cannot be evaluated for a particular quality question if we cannot apply any of the previous answers in it. We removed any study that did not meet the quality assessment criteria.
Table 5. PS quality assessment questions.

<table>
<thead>
<tr>
<th>Quality Assessment</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td>Are the aims of this SLR clearly described?</td>
</tr>
<tr>
<td></td>
<td>Do the study measures allow the questions to be answered?</td>
</tr>
<tr>
<td></td>
<td>Was the sample size justified?</td>
</tr>
<tr>
<td></td>
<td>Are the evaluation measures fully defined?</td>
</tr>
<tr>
<td><strong>Conduct</strong></td>
<td>Are the data collection methods adequately described?</td>
</tr>
<tr>
<td></td>
<td>Are the results of applying the identification techniques evaluated?</td>
</tr>
<tr>
<td></td>
<td>Are the data sets adequately described (size, programming languages, source)?</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td>Are the study participants or observational units adequately described?</td>
</tr>
<tr>
<td></td>
<td>Are the statistical methods described?</td>
</tr>
<tr>
<td></td>
<td>Are the statistical methods justified?</td>
</tr>
<tr>
<td></td>
<td>Is the purpose of the analysis clear?</td>
</tr>
<tr>
<td></td>
<td>Are the scoring systems (performance evaluation) described?</td>
</tr>
<tr>
<td><strong>Conclusion</strong></td>
<td>Are all study questions answered?</td>
</tr>
<tr>
<td></td>
<td>Are negative findings presented?</td>
</tr>
<tr>
<td></td>
<td>Are the results compared with previous reports?</td>
</tr>
<tr>
<td></td>
<td>Do the results add to the literature?</td>
</tr>
<tr>
<td></td>
<td>Are validity threats discussed?</td>
</tr>
</tbody>
</table>

2.6. Primary Study Database Platform

Having a large number of primary studies (769 articles) pushed us to look for the most appropriate manner to present them to the research community in the field of energy blockchains. For this reason, we implemented a large scale platform [73] that contains all the 769 final articles related to our studies, collected based on the criteria in Section 2 in addition to the results of our research questions (presented in Section 1) presented in tables, charts, histograms, maps, ... in such a way as to be the most effectively exploited. The objective of this platform is to be an efficient, comprehensive, easy-to-use database where researchers and practitioners can discover the latest advancements in the field of energy blockchains, find guidelines and orientations for their future works by quickly identifying relevant existing research papers and tools for their problems based on our proposed taxonomy and classification, and make effective interactions between the different actors in the energy blockchain field to identify relevant problems faced by the community. Our platform includes the following components:

1. A searchable repository of energy blockchain publications based on our proposed taxonomy: The website presents a large table containing our 769 primary studies. The papers can be searched by title, author, country, year of publication or author keywords. A second table in our platform shows the classification of our primary studies per each research question’s answers based on our taxonomy described in Section 2.3.

2. Analysis and visualization of the energy blockchain trends and techniques based on the collected papers. The website dashboard shows the energy blockchain repository. It presents a visual analysis of the obtained results answering the different research questions using charts, histograms and tables. It also includes maps that reflect the spread of energy blockchain research works and applications across the world.

3. Results and Analysis

In this section, we will address all our research questions’ answers that we have obtained after processing our set of 769 primary studies.

Table 6 summarizes these results based on the taxonomy described in Section 2.3 with reference to some articles from our final primary studies. It is worthwhile to note that one
article could present more than one answer for the same RQ. For example, if one research question has 4 potential answers, and one article was dealing with these 4 answers, it will be counted 4 times for that specific RQ (as if it was 4 different articles) and not once, and the percentage of each answer for a particular RQ will be calculated based on the total of all the articles (even duplicate publications) dealing with that RQ and not with reference to our total of 769 articles. The results for each RQ will be presented in graphical formats (histograms, pie-charts, maps, ...) and followed by the observations and insights that can be derived from the classification results.

Before answering the research questions, it was important to identify the entities and the countries that work the most on the implementation of the blockchain technology in the energy sector. Figure 2 displays the global distribution of the currently conducted investigations.

Each paper could have multiple authors, which means that it might correspond to different nations. Our papers are distributed over 74 countries from 5 continents, which are: Asia (573 articles), Europe (319 articles), America (148 articles), Oceania (56 articles), and Africa (23 articles), as presented in Figure 2.

![Figure 2. Distribution of the publications around the world.](image)

The top 10 nations that publish papers on the application of blockchain technology in the energy sector were extracted and displayed in Figure 3. China comes on top of the list, with more than a third of all our final publications (35.7% of all articles), followed by the United States with 14.07% and India with 10.67% of all articles. This list is not at all surprising as these three countries are also the world’s top energy producers in 2021 in exactly the same order (Source: https://www.enerdata.net, accessed on 13 November 2022). What was a bit surprising to us is not finding Russia in the list of our top 10 countries in energy blockchain research, especially given that it is among the world’s top 5 energy producing countries and the world’s top 3 blockchain user countries (although it is mainly for cryptocurrency), in addition to being among the world’s top countries in scientific production in engineering, energy and computer science in 2021 (Source: https://www.scimagojr.com, accessed on 13 November 2022).
Table 6. Paper references for all categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
<th>Papers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source types in energy blockchains (RQ1)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil energies</td>
<td>8.03%</td>
<td>[74–77]</td>
</tr>
<tr>
<td>Fissile energies</td>
<td>0.69%</td>
<td>[66,78–80]</td>
</tr>
<tr>
<td>Renewable energies</td>
<td>91.28%</td>
<td>[81–84]</td>
</tr>
<tr>
<td><strong>Blockchain applications in the energy sector (RQ2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smart grids</td>
<td>7.85%</td>
<td>[85–88]</td>
</tr>
<tr>
<td>Energy storage</td>
<td>14.44%</td>
<td>[89–92]</td>
</tr>
<tr>
<td>Energy management</td>
<td>7.85%</td>
<td>[79,89,93,94]</td>
</tr>
<tr>
<td>Energy trading</td>
<td>25.12%</td>
<td>[84,95–98]</td>
</tr>
<tr>
<td>Security</td>
<td>29.92%</td>
<td>[92,99–101]</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>14.01%</td>
<td>[80,90,102,103]</td>
</tr>
<tr>
<td>Carbon emission</td>
<td>0.82%</td>
<td>[65,104–106]</td>
</tr>
<tr>
<td><strong>Types of consensus used in blockchain platforms for the energy sector (RQ3)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public blockchain</td>
<td>42.19%</td>
<td>[85,99,107,108]</td>
</tr>
<tr>
<td>Private blockchain</td>
<td>37.38%</td>
<td>[78,109–111]</td>
</tr>
<tr>
<td>Hybrid blockchain</td>
<td>20.44%</td>
<td>[112–115]</td>
</tr>
<tr>
<td><strong>Blockchain platforms used in the energy sector (RQ4)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powerledger</td>
<td>6.98%</td>
<td>[80,106–118]</td>
</tr>
<tr>
<td>Hyperledger</td>
<td>2.85%</td>
<td>[98,119–122]</td>
</tr>
<tr>
<td>R3 Corda</td>
<td>0.32%</td>
<td>[93]</td>
</tr>
<tr>
<td>Ethereum</td>
<td>89.2%</td>
<td>[82,123–126]</td>
</tr>
<tr>
<td>Polkadot</td>
<td>0.32%</td>
<td>[123]</td>
</tr>
<tr>
<td>Binance</td>
<td>0.32%</td>
<td>[127]</td>
</tr>
<tr>
<td><strong>Emergent technologies combined with blockchain in the energy sector (RQ5)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internet of Things (IoT)</td>
<td>74.18%</td>
<td>[85,92,128,129]</td>
</tr>
<tr>
<td>Artificial intelligence</td>
<td>15.96%</td>
<td>[130–133]</td>
</tr>
<tr>
<td>Management Information System (MIS)</td>
<td>0.47%</td>
<td>[66,79,94,134]</td>
</tr>
<tr>
<td>Decision-making systems (DMS)</td>
<td>9.39%</td>
<td>[91,134–136]</td>
</tr>
<tr>
<td><strong>Types of consensus used in blockchain platforms for the energy sector (RQ6)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proof of work</td>
<td>21.71%</td>
<td>[116,147–159]</td>
</tr>
<tr>
<td>Proof of stake</td>
<td>29.14%</td>
<td>[68,107,116,140]</td>
</tr>
<tr>
<td>Raft</td>
<td>14.29%</td>
<td>[65,84,141–143]</td>
</tr>
<tr>
<td>Proof of authority</td>
<td>2.29%</td>
<td>[64,79,144,145]</td>
</tr>
<tr>
<td>CHB/CHBD</td>
<td>1.14%</td>
<td>[5]</td>
</tr>
<tr>
<td>Byzantine Fault tolerance</td>
<td>27.99%</td>
<td>[141,146–148]</td>
</tr>
<tr>
<td>Kafka/Zookeeper</td>
<td>3.43%</td>
<td>[149–152]</td>
</tr>
</tbody>
</table>

Figure 3. Number of publications in the top 10 most active countries on energy blockchain research.

Figure 4 shows the yearly evolution of the scientific production in the field of energy blockchains between 2008 and 2021. This curve shows the deep increasing interest of the
scientific community about this thematic. What was interesting to notice in Figure 4 is that it shows the beginnings of saturation in the years 2020 and 2021. Two possible explanations could be given to this shape: it is either because we are reaching the peak of interest and the maturity phase in scientific research for this specific thematic as in any product life-cycle, and we can expect to start to see many energy blockchains over the world, or it is just the effect of the COVID-19 pandemic that obliged the research community in all scientific fields—including engineering—to turn to it. In our point view, the second reason is more likely to be the correct one, especially because blockchain technology itself has not reached yet the level of maturity. Although the first real blockchain application was in 2008 (with the appearance of Bitcoin), the scientific interest in this technology and its applications in the energy sector started only after 2015, which was ignited by the appearance of “smart contracts”. This is very normal, as the smart contracts made a real opportunity for researchers to use the blockchain technology in other sectors and fields rather than cryptocurrency.

![Figure 4. Evolution of research articles from 2008 to 2021.](image)

For the rest of this article, we will present the yearly evolution curves starting from 2015 and not 2008 for the results to be clearer and more exploitable.

3.1. Types of Energy Sources in Energy Blockchain Platforms

When talking about energy blockchains, it is very important to first identify what the energy sources are that can be the most used appropriately with the blockchain technology and what the energy types are that can be future research trends in this subject. Three source types can be considered:

- Fossil energy: which is the most used in the global electricity mix,
- Fissile energy: which has by far the highest capacity factor of any other energy source,
- Renewable energy: which is the most promising energy source nowadays.

Based on existing studies related to blockchain technology in the energy sector, we found that the energy source type most often used with blockchain technology is renewable energies, with a percentage of 91.28% among the studied articles that mentioned a specific source of energy, as shown in Table 6 and in Figure 5. It was very expected for the renewable energy sector to attract the most attention from researchers in this field. In spite of the low current rate of renewable energies in the global electricity mix, which does not exceed 10% [20], it is expected that this rate will reach 90% by 2050 to achieve the strategic plan of “net zero emissions” put forth by the IEA (International Energy Agency) [24]. In addition to that, the annual USD 2 trillion investments in green energy by
2030 (Source: https://www.iea.org/news/world-energy-outlook-2022-shows-the-global-energy-crisis-can-be-a-historic-turning-point-towards-a-cleaner-and-more-secure-future, accessed on 13 November 2022). As expected by the IEA, it seems to be attracting more and more researchers in this field, particularly with the use of blockchain technology. We went deeper in analyzing the research interest in renewable energies. We extracted in Figure 6 the different renewable energy sources that interested the researchers of energy blockchains. Solar energy is by far the most-cited renewable energy source in our primary studies, with a percentage of 82%, followed by wind energy, with a rate of 11.29%. The remaining 6.71% were divided between geothermal power (2.87%), hydroelectricity and biomass (1.92% each). This high focus on wind and solar energies goes synchronously with the “net zero emissions” plan that expects the part of these two renewable energy sources in the global electricity mix to reach 70% by 2050 [24]. The higher interest of researchers in solar energy than wind energy for energy blockchain platforms could be explained by the fact that the decreasing costs of solar panels compared to the wind turbines, in addition to their ease for residential use, has made this technology more appropriate for homeowners and hence more efficient for peer-to-peer trading, which is one of the biggest strength points of using blockchain technology.

We believe that the blockchain is one of the best available tools (if not the best) to popularize the use of renewable energies in the global electricity market by allowing the better and more efficient integration of the renewable energy sources in the grids. This is more obvious in Figure 7, where we present the yearly evolution of the publications per energy source types for energy blockchains. We can see in Figure 7 that the research interest for renewable energies in energy blockchains has been exponentially increasing since 2016. We expect that this axis will keep attracting researchers in this field despite the slight drop of interest between 2020 and 2021 (of 11.19%), which we consider a consequence of the COVID-19 world pandemic that gained a deep research interest in all fields of human knowledge, including engineering.

Figure 5. Histogram illustrating the count of publications in energy blockchain per source type.
The fossil energies obtained 8.03% of research interest among our primary studies. With the world’s awareness about the environmental issues and with the IEA “2050 net zero emissions” plan that forbids any investment in new fossil fuel supply projects [24], and in spite of their current 82% part in the global primary energy use in 2021, the fossil energies are seen as broadly flat in the coming years and not attracting researchers.

The least interest of researchers among our final set of studies on energy blockchains went to the fissile energies, with less than 1%. In spite of their high efficiency, the fissile energies are considered one of the most dangerous types of energy, and the Japanese Fukushima nuclear disaster in 2011 is the latest testament to that. For this reason, they are not a subject of interest for researchers on energy blockchains.
3.2. Blockchain Applications in the Energy Sector

The choice of the possible applications for energy blockchains was made based on the impact of the blockchain technology on that application and how it could provide real solutions as explained in Section 1. We extracted in this study the following seven most promising applications for energy blockchains:

- **Smart grids**: This is about digitalizing the existing grids and improving their infrastructure,
- **Energy management**: This is mainly about ensuring the balance between energy demand and supply, and avoiding potential blackouts,
- **Energy trading**: This is more about adding the peer-to-peer transactions in the energy industry between individuals,
- **Energy storage**: This is especially important given that managing energy storage is one of the best ways to maintain the efficiency of an electrical network,
- **Security**: This is especially important because dealing with energy information could be considered as a matter of national security. This is why ensuring the “security of energy’s transactions” is a mandatory task.
- **Electric vehicles**: This seems to be the future of the automotive industry.
- **Carbon emission**: This is about confirming the energy transition towards green energy.

Figure 8 shows the percentage of publications on the different applications of blockchain technology in the energy sector. At the top of the potential applications for energy blockchains in the articles that are the subject of this study, we find security, with a percentage of 29.92%, and nearly 550 of all our 769 articles have dealt with this subject as it pertains to energy blockchains.

This research interest into security has continued to increase since 2016, as shown in Figure 9. This was expected as secure transactions in energy industry are highly needed whatever the applications is, whether it is a conventional energy system or even a peer-to-peer model using IoT. Blockchain technology is one of the best available tech tools that can ensure a secure platform for energy transactions with privacy preservation. This explains why “security” is the biggest concern of researchers in the field of energy blockchains as per our 769 primary studies.

![Figure 8](image-url)
The energy trading with all its aspects (conventional or peer-to-peer) has obtained the interest of about a quarter of our primary studies’ authors. As shown in Figure 9, the yearly evolution of the research works on energy trading with blockchain was almost the same as security’s until 2019, and the curve started declining starting from 2020. We expect less interest from energy blockchain researchers in energy trading. The existing works have presented almost all possible aspects and scenarios.

With a percentage of 14.44% among and about 270 articles from all our 769 primary studies, energy storage is the third application that has attracted the interest of researchers in this field. This interest in improving the management of energy storage through an intelligent secure platform such as blockchain comes from the fact that it provides an effective method of shifting temporal energy demands and supplies, enabling significant cost reductions under dynamic energy pricing. Although research works on blockchain-enabled energy storage management remained constant for the last three years from 2019 to 2021 (as shown in Figure 9), we expect that it will keep attracting researchers in the field, especially with the appearance of new concepts such as peer-to-peer energy storage sharing [153].

The interest of the energy blockchain researchers in electric vehicles gained about 14% (and a total of 257 articles from our final set of primary studies). As shown in Figure 9, this interest has been increasing in recent years, and we expect this subject to keep attracting more and more researchers for the upcoming years as this sector market size is estimated to be worth USD 1318.22 billion, globally, by 2028 (Source: https://www.globenewswire.com, accessed on 13 November 2022), with a rate of 30% of vehicle electrification by 2030 [154].

Smart grids and energy management both attracted only 7.85% of researchers on energy blockchains. This research interest is even decreasing as shown in Figure 9, which was a bit surprising especially with growing inclinations toward grid digitalisation. An explanation to this could be the fact that the countries who have published the most on energy blockchain among our final set of primary studies have already installed smart grids (China with 18% of overall integrated assets, the United States with 15%, and Europe with 13% [155]).
The energy blockchain application with the lowest interest rate is carbon emissions, with only 0.82%. In spite of the importance of the integration of renewable energies in the electricity mixes around the world, as represented by almost 400 articles among our primary studies (as shown in Figure 5), the use of blockchain technology to generate green certificates does not seem to attract a large number of researchers. We may explain this by the fact that carbon emissions management and delivered green certificates do not really need transparency, immutability, scalability, decentralization, etc., which are the main characteristics of blockchain technology.

3.3. Blockchain Platforms Used in the Energy Sector

The number of existing blockchain platforms is huge and most of them are open source. The choice of one platform or another is not easy. For this reason, we went through all our final set of the 769 primary studies to see what the platforms are that attracted the most researchers on energy blockchains. Our list below of blockchain platforms is not exhaustive. We only kept the platforms that were mentioned at least in one of our final studies. The other platforms were removed from this list:

- Hyperledger, as a platform for exclusively private business blockchains;
- Corda, which is used for private blockchains and builds interoperable blockchain networks that transact in strict privacy;
- Ethereum, which is used for public blockchains, but also for private ones with the Private Ethereum Network;
- Polkadot, which offers communications between different blockchains (even public with private ones);
- Binance, which is a large trading blockchain platform;
- Powerledger, with its specific application on renewable energies.

As shown in Figure 10, about 90% of the papers of this study use the Ethereum platform (either the public or the private one) to build energy blockchains. Although Ethereum is initially a cryptocurrency platform, the way it evolved to introduce Enterprise blockchains in addition to its flexible platform supporting smart contracts with its easy-to-use tools has made it the most attractive platform for researchers on energy blockchains, either public or private or even hybrid.

Figure 10. Histogram illustrating the count of publications per blockchain platform in the energy sector.
The second platform used for energy blockchains is Powerledger, with almost 7% of research interest. It is true that the Powerledger was meant to generate crypto-coins called POWR, but its focus on renewable energies made it appear in 22 papers from our final set of primary studies. Its permissioned and authorized access made it not appropriate for public blockchains (which represent more than 40% of the energy blockchains that are the subject of this study, as will be discussed in Section 3.4. As shown in Figure 11, the research interest on Powerledger has been constant since 2019, and with the updates made on it to incorporate the next generation blockchain technology (Source: https://www.powerledger.io/blockchain-technology, accessed on 13 November 2022), we expect a continuous interest from the energy blockchain research community on this platform offering secure, private and transparent peer-to-peer trading on renewable energies.

The third place goes to Hyperledger with a rate of 2.86%. This percentage was surprising as we were expecting a higher use of Hyperledger on energy blockchains. Used by IBM, Hyperledger was behind so many business’ and enterprises’ successful blockchains around the world, especially given that it supports the use of smart contracts as Ethereum. It is possible that the private nature of the Hyperledger platform was an inconvenience for its utilization on energy blockchains.

The three other platforms in our list, R3 Corda, Polkadot and Binance, appeared each in only one paper from our final set of primary studies with a rate of 0.32%. For R3 Corda, it has been proved that it is less efficient than other platforms such as Hyperledger especially because it does not respect the blockchain requirement of a unique replicated ledger distributed between the different participants of the network. As for Polkadot, it is mainly used to ensure communication between different incompatible blockchains (which could be private and public) more than as a platform to build a blockchain from the start. For Binance, it is essentially linked to cryptocurrency, making it unlikely to be used in Enterprise blockchains and particularly energy blockchains. For these reasons, many researchers refuse even to consider these frameworks, Corda, Polkadot and Binance, as proper blockchain platforms. Taking into consideration their yearly evolution as shown in Figure 11, we believe they will not attract much interest among the energy blockchain research community.

![Figure 11. Yearly evolution of the publications per blockchain platform in the energy sector.](image-url)
3.4. Types of Blockchains Used in the Energy Sector

Based on the way of accessing it, an energy blockchain can be considered:

- Public, with open access for everyone;
- Private, where only permissioned participants can access it;
- Hybrid, which is a combination of both (permissionless and permissioned access).

As shown in Figure 12, the public blockchains have the highest rate among our studies with 42.19%. The private blockchains have a rate of 37.38%. As shown in Figure 13, the evolutions of both public and private blockchains have almost the same momentum. This can be explained by the nature of the energy sector itself. On one hand, big companies in the field would prefer private networks with selective pre-approved access as they are particularly concerned about privacy and trade secrets. On the other hand, since anyone can be concerned directly or indirectly by the energy sector, open access to the large energy community (consumers, private small suppliers, civil society, ...) is required. The public energy blockchain thus seems to offer a more appropriate and valuable solution to true decentralization, democratization and authority-free operation of the energy network. To provide a solution to this dilemma, researchers are becoming more and more interested in hybrid and consortium blockchain networks that provide an interim solution until public blockchains can implement the necessary privacy features businesses demand (as shown in Figure 13 with 20.44% of research interest).

Figure 12. Histogram illustrating the count of publications per blockchain type in the energy sector.
3.5. Emergent Technologies Associated with Blockchain in the Energy Sector

It is natural for researchers on energy blockchains to turn to other new cutting-edge technologies in the search for efficient solutions. We list here below some of the most important emerging tech that can be associated with energy blockchains:

- Internet of Things: This technology would allow different machines (wind turbines, solar panels, energy meters, EV chargers ...) to communicate directly with the blockchain platform.
- Artificial intelligence: This is a large umbrella under which other different technologies are taken into consideration, such as machine learning and big data analysis, and are associated with energy blockchains.
- Management information system: These are needed to make the energy blockchain platform or system better adapt to the actual business needs through appropriate decision making.
- Decision making systems: These could add an intelligent aspect to the blockchain by supporting automated decision making.

As shown in Figure 14, the Internet of Things is at the top of researchers’ interests in the energy blockchain field, with a percentage of 74.18% of our selected papers. In fact, the use of IoT is almost mandatory to build an efficient reliable energy blockchain and a complete digitalization of the electrical grid.
With a rate of almost 16% of our selected papers, artificial intelligence with all its derivatives (machine learning, data science, ...) is the second emergent technology that attracted the interest of researchers on energy blockchains. However, between 2020 and 2021, IoT and AI lost, respectively, about 43% and 50% of researchers’ interest, as shown in Figure 15. This recent decreasing interest in IoT and AI associated with blockchain technology could be explained by the fact that these technologies have reached a certain level of maturity since IoT and AI-enabled solutions are the core to the digitalization of several sectors around the globe, and the number of IoT-connected devices in 2021 reached 35.82 billion (Source: IHS Forbes, ©Statista 2021) worldwide. However, we expect that IoT and AI will continue to attract research interest for energy blockchain solutions.

An increasing interest in decision-making systems can be seen in Figure 15, with about 10% of our selected studies. Currently, existing blockchains are not able to automatically make decisions on specific subjects because the smart contracts used in blockchains today are unable to handle complex transactions. Decision-making systems (DMS) or decision support systems (DSS) have been used as enterprise management tools for a long time and have proven their efficiency. Combining them with blockchain could have positive consequences on improving the energy blockchain platforms where immediate and accurate decisions are very much needed. This is also a sign of the multidisciplinary aspect of blockchains.

The least interest in emergent technologies of energy blockchain researchers went to management information systems (MIS), with a rate of only 0.47%. The MIS is another efficient enterprise management tool that aims to analyze the collected data related to the operational system. We believe that this lack of interest in MIS could be explained by the important interest in AI, including data science and data analysis. By looking to its yearly evolution in Figure 15, we do not expect that it will attract researchers as a tool to be combined with energy blockchains.
3.6. Types of Consensus in Blockchain Platforms for the Energy Sector

Below is the list of the different consensus that we were able to extract from our primary studies on energy blockchains:

- Proof of work, which is the most used consensus but also the most energy intensive;
- Proof of stake, which is the eventual substitution of PoW;
- Byzantine fault tolerance, which includes its different derivatives: PBFT, FBFT, IBFT, and Honey Badger;
- CHB/CHBD, which are only used in permissioned blockchain networks, although they are very similar to the PoW protocol;
- Kafka/Zookeeper, which is one of the most-used consensuses in private business blockchains with Hyperledger Fabric;
- Raft, which has come to remove the dependency on Kafka deployment;
- Proof of Authority, which solves one of the biggest drawbacks of the PoS.

As shown in Figure 16, the proof of stake (PoS) protocol family comes on the top of the consensus algorithms used in our selected papers on energy blockchains with a rate of 29.14%, divided as follows: PoS with 12% and DPoS with 17.14%. The results obtained in Section 3.3 explain these rates. The PoS and DPoS are mainly considered Ethereum projects. Since the Ethereum platform was the most frequently used one in energy blockchains, we expected to see consensuses related to Ethereum at the top of the ones used in energy blockchains. As explained in Table 2, the main advantages of the PoS consensuses compared to the consensus of PoW (the one that is currently used in Ethereum) are that the first ones can be used in both private and public blockchains (and consequently Hybrid ones) and have a faster processing of the transactions. These two qualities are much needed in the energy blockchain applications.

The Byzantine fault tolerance (BFT) family for consensus algorithms comes second, with a rate of 27.99%, where almost 90% of the BFT algorithms are about the PBFT, as shown in Figure 17. With a rate of 24.57% from our selected papers of study, the practical
Byzantine fault tolerance (PBFT) consensus algorithm is the most-used protocol in the energy blockchain papers that were the subject of this SLR, followed by the PoW algorithm, with a percentage of 21.71%. The good performances that PoW consensus have proved mainly in terms of security and scalability during the last years with Bitcoin and the different cryptocurrency platforms made it attract an important number of researchers in the field of energy blockchains. On the other hand, the high computational energy it needs for the transactions’ endorsement in addition to its slow validation process with a large number of nodes is one of its biggest disadvantages, especially given that real-time decisions are very much needed in the energy sector. These PoW flaws are precisely where BFT consensus techniques excel, as explained in Table 2. The BFT algorithms are more efficient in term of work energy. With a delay of only a few seconds, they can reach high performance in the range of tens of thousands of transactions per second (or even less). The drawback of old BFT protocols is that they do not offer open membership or scale to thousands of nodes the way that PoW does, which accounts for the low percentage of traditional BFT consensuses employed in our primary studies (1.14%). In spite of their high scalability and fast transaction processing, the federated BFT protocol and the Honey Badger consensus attracted only 0.57% (the lowest rate) each of researchers on energy blockchains from our selected set of articles. Figure 18 shows the continuously increasing interest of the energy blockchain researchers on the BFT consensuses, and we expect it to keep increasing for the upcoming years, especially for the PBFT.

The Raft consensus was the object of 14.29% of our selected articles. Raft is actually considered to be a good substitution of the Kafka/Zookeeper protocol, which received only 3.43% of research interest in our study, in the Hyperledger Fabric platform v2.x, which was the third most-used platform among our selected papers on energy blockchains (Section 3.3).

Although some researchers consider the proof-of-authority as another variant of proof-of-stake solving one of its major issues, the “nothing-to-stake” problem, and in spite of its interesting characteristics appropriate to the energy sector (low energy consumption, fast transaction processing, high scalability, permissioned and permissionless environments, etc.), it interested only 2.29% of energy blockchain research works from this SLR. However, it is very likely that this consensus protocol will gain more interest and more traction in the future. With only 1.14% of research interest, CHB/CHBD does not seem to be convincing researchers on energy blockchains. With its low scalability and moderate speed of transaction processing properties, in addition to the fact that it can only be used in permissioned blockchain networks, it is very unlikely that it could attract more research interest in the future.

![Figure 16. Histogram illustrating the count of publications per type of consensus for energy blockchain.](image-url)
4. Threats to Validity

In order to ensure the quality of a systematic literature review, we assess in this section on the threats to the validity of our results according to Wohlin et al. [18].

4.1. Construct Validity

The main threats in this category are about how the SLR was conducted from the beginning: the research questions, the search strings and the electronic databases used. To assess the threats related to the research questions, it is important to mention that we have tried to deal with all the aspects of building a blockchain in the energy sector: which platform to choose? which consensus to adopt? which kind of accessibility to guarantee? which energy source type to focus on? what kind of applications would be the most appropriate? which emergent technologies are more likely to be associated with energy blockchains? By answering these questions, we wanted the research community to find

---

**Figure 17.** Pie chart of the BFT consensus algorithms used in energy blockchains.

**Figure 18.** Yearly evolution of the publications per type of consensus for energy blockchains.
useful guidelines and steps on the most convenient way to implement an energy blockchain and what to avoid.

Regarding the databases, we employed the most well-known sources found in the literature, including the most pertinent papers, in our experiment.

There are several risks associated with the search terms that may affect the outcomes and, as a result, the quantity of papers found. For instance, it is possible that some articles do not specifically use the keywords we suggested. We added a manual snowballing phase to the adopted strategy to reduce this issue. Finding no new studies to add was regarded as a positive indicator of the validity of our research strings.

In addition to that, we elaborated well-defined inclusion and exclusion criteria, which we applied carefully to make sure to keep the most relevant primary studies to the subject of energy blockchains.

4.2. Conclusion Validity

Conclusion validity is about the ability to draw the correct conclusions from the extracted data in our study. Our results were obtained from a Python code that was automatically run on our final set of 769 papers to count the number of appearances of our search words in each article. To ensure the correctness of these results, we took some steps in the code, such as changing the text to capital letters and adding spaces before and after the search words (especially the short ones). We also went through a manual verification phase by the different authors. For example, when searching for articles dealing with “Hybrid blockchain”, the search word “hybrid blockchain” itself was not enough. Therefore, we added the word “hybrid”, and we manually removed all the articles where it was referring to “hybrid cars” instead of “hybrid blockchain”. Additionally, a cross-check among the authors was required to ensure that the results reached adequately addressed the research issues. During the extraction and selection of the research, we had numerous discussions and debates in order to reach the most arbitrary findings.

5. Implications and Future Research Directions

The 769 primary studies of the present SLR are an indicator of the big interest of researchers in the energy blockchain research topic and of its high importance. In fact, the evolution of the energy systems today into a more decentralized model accommodating more and more digital platforms using artificial intelligence and data science applications for analysis, forecasting, optimization, control and decision-making presents blockchain as the most promising technology today to provide an efficient and reliable tech-solution for the management of energy systems. However, several aspects of this technology need to undergo more consideration by the researchers in order to fit with the specific nature of the energy sector. We identify in this section the main axes that we consider to be research opportunities for future research directions related to energy blockchains based on the outcomes of our systematic literature review.

5.1. Smart Contract 2.0

The appearance of smart contracts in 2015 made huge progress in blockchain technology and made it more suitable for a large branch of applications in all fields and more particularly in the energy sector. These smart contracts—previously programmed in the blockchain with embedded IF.. THEN statements—can automatically execute the terms of a code (contract) when trigger events occur. However, in the energy sector, where so many external events can occur and have a direct or indirect effect on the network (for example, the price of KWh could be affected by the exchange rate of USD/local currency, the weather forecast, the percentage of energy stored, the prediction of supply and demand, the energy deficit in the electrical mix, the world politics such as the war between Russia and Ukraine in 2022, etc.), there is a big need for more sophisticated and more “intelligent” smart contracts.
5.2. Energy Blockchain Business Model

The energy blockchain is offering a totally new way of energy trading and management. With peer-to-peer energy trading or storage sharing, there will be more and more consumers who do not only consume energy but themselves produce, store, sell and share energy. Under these new circumstances, consumers are gaining a new role as a prosumer, which is totally changing the traditional existing business models for the supply chain. The energy blockchain is hence smartly changing the conventional business model into a convenient and safe new business model: an energy prosumer service model [156].

We went through our final set of 769 primary studies and searched for the words “business model” and “business-model”. They appeared in only 9 papers published between 2018 and 2021 [77,79,157–163]. This number of research works is very low compared to the huge paradigm shift that the energy blockchain could bring to the existing business models. This subject is still under-explored, and it needs more research works in the future.

5.3. New, More Adapted Consensuses

The current literature is still lacking a solution and strategy for the most appropriate choice of consensus to be used while building a blockchain. The decision of which consensus algorithm would be better suited was left as an open issue, and the different researchers on energy blockchains did not clearly justify their choices for the consensus nor discuss how the consensus algorithm would impact their solutions. This is understandable if we take into consideration the specific nature of the energy blockchain: it is neither totally public nor totally private. Each transaction’s validation is very selective, especially if we add the IoT nodes that are not supposed to interfere in the endorsement and the validation of the transactions.

Current blockchain consensus algorithms cannot be simultaneously optimized due to a triangle of paradoxes including decentralization, security, and energy consumption. Deep research works into this subject need to attract the attention of researchers in energy blockchains in order to adapt an algorithm that would be the most suitable for this sector.

6. Conclusions

In this paper, we have conducted a systematic literature review on the use of blockchain technology in the energy sector accompanied by meta-analysis to answer the defined research questions. A total of 769 papers were identified as a result of a thorough search that included a systematic process of steps and an evaluation of the quality of the studies.

Based on the data extracted from these selected papers, we created a thorough synthesis of the state-of-the-art in energy blockchains. We were able to cover six different axes of this research subject: the blockchain types, platforms and applications in the energy sector, the different types of consensus used on energy blockchains, the different types of energy sources where blockchain technology was most appropriate to be used, and the different emergent technologies that can be combined with or associated with the blockchain technology applied in the energy sector. To make it easier for people to understand the information gathered, we examined the primary studies and presented the findings using charts, graphs, and maps. We tried to present a justification for the results we obtained, even when they were not synchronized with what we were expecting.

We were also able to identify three potential research themes related to energy blockchains that we believe were not at all or not sufficiently covered by researchers in the field until the date this review was carried out. These potential research works, which we believe are a mandatory need for the future potential of the energy blockchains, are mainly about (1) the improvement of smart contracts, (2) the creation of new consensus algorithms and (3) the adaptation of the existing business model to take into account the new role of the consumers in the energy blockchains.

The findings of our systematic review will help both academics and industry professionals in comprehending the current state of the field, structuring it, and pinpointing any areas that may need further study.
Author Contributions: Conceptualization, N.K. & N.G.; methodology, N.K.; software, N.K. & N.G.; validation, N.K. & B.N. & N.B.B.; formal analysis, N.K. & B.N. & N.B.B.; investigation, N.K. & N.G.; resources, N.K. & N.G. & B.N.; writing—original draft preparation, N.K. & N.G. & B.N.; writing—review and editing, N.K. & B.N. & N.B.B.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References
5. Debnath, K.B.; Moursesh, M. Corruption significantly increases the capital cost of power plants in developing contexts. Front. Energy Res. 2018, 6, 8. [CrossRef]
6. Poupeau, F.M. Everything must change in order to stay as it is. The impossible decentralization of the electricity sector in France. Renew. Sustain. Energy Rev. 2020, 120, 109597. [CrossRef]
21. Mataloto, B.; Ferreira, J.C.; Cruz, N. LoBEMS—IoT for building and energy management systems. Electronics 2019, 8, 763. [CrossRef]
26. McEnroe, P.; Wang, S.; Liyanage, M. A survey on the convergence of edge computing and AI for UAVs: Opportunities and challenges. IEEE Internet Things J. 2022, 9, 15435–15459. [CrossRef]
34. Buterin, V. A next-generation smart contract and decentralized application platform. White Pap. 2015, 3, 2–1
44. Cao, L. Decentralized AI: Edge Intelligence and Smart Blockchain, Metaverse, Web3, and DeSci. IEEE Intell. Syst. 2022, 37, 6–19. [CrossRef]
97. Okoye, M.O.; Yang, J.; Cui, J.; Lei, Z.; Yuan, J.; Wang, H.; Ji, H.; Feng, J.; Ezeh, C. A Blockchain-Enhanced Transaction Model for Microgrid Energy Trading. IEEE Access 2020, 8, 143777–143786. [CrossRef]
Sustainability 2022, 14, 15826


117. Li, Z.; Bahramirad, S.; Paaso, A.; Yan, M.; Shahidehpour, M. Blockchain for decentralized transactive energy management system in networked microgrids. Electr. J. 2019, 32, 58–72. [CrossRef]


158. Abou Jaoude, J.; Saade, R.G. Blockchain applications—Usage in different domains. *IEEE Access* 2019, 7, 45360–45381. [CrossRef]