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Blockchain-Based Applications for Smart Grids: An Umbrella Review

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Review

Blockchain-Based Applications for Smart Grids: An Umbrella Review

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Abstract: This article presents an umbrella review of blockchain-based smart grid applications. By umbrella review, we mean that our review is based on systematic reviews of this topic. We aim to synthesize the findings from these systematic reviews and gain deeper insights into this discipline. After studying the systematic reviews, we find it imperative to provide a concise and authoritative description of blockchain technology because many technical inaccuracies permeate many of these papers. This umbrella review is guided by five research questions. The first research question concerns the types of blockchain-based smart grid applications. Existing systematic reviews rarely used a systematic method to classify these applications. To address this issue, we propose a taxonomy of these applications, first by differentiating them based on whether the application is focusing on functional or non-functional aspects of smart grid operations, and then by the specific functions or perspectives that the application aims to implement or enhance. The second research question concerns the roles that blockchain technology plays in smart grid applications. We synthesize the findings by identifying the most prominent benefits that blockchain technology could bring to these applications. We also take the opportunity to point out several common technical mistakes that pervade the blockchain literature, such as equating all forms of blockchains to data immutability. The third research question concerns the guidelines for deciding whether a blockchain-based solution would be useful to address the needs of smart grids. We synthesize the findings by proposing benefit-based guidelines. The fourth research question concerns the maturity levels of blockchain-based smart grid applications. We differentiate between academic-led and industry-led projects. We propose a five-level scale to evaluate the maturity levels. The ranking of the industry-led projects is performed through our own investigation. Our investigation shows that more than half of the industry-led projects mentioned in the systematic reviews are no longer active. Furthermore, although there are numerous news reports and a large number of academic papers published on blockchain-based smart grid applications, very few have been successfully embraced by the industry. The fifth research question concerns the open research issues in the development of blockchain-based smart grid applications. We synthesize the findings and provide our own analysis.

Keywords: smart grid; blockchain; renewable energy; green certificate; energy trading; smart meter; demand-side response; demand–supply balance; smart contract; decentralized consensus; data immutability; security; privacy; trust

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1. Introduction

Smart grids have been widely referenced in news stories, online posts, and academic publications, along with many "smart-x" phrases, such as smartphones, smartwatches, smart health, smart contracts, smart meters, smart buildings, and smart cities. The term "smart" in these phases generally implies the integration of digital technologies with the subject at hand. Indeed, in the context of smart grids, digital technologies have been playing ever more important roles in modernizing electric power grids [1]. According to [2], a particular characteristic of smart grids is two-way communication between electric utilities and their customers, which is facilitated through digital technologies.

The term "grid" in "smart grid" refers to the electric power grid, on which every one of us depends in our daily lives. The grid consists of a network of components that are essential to deliver electricity from power plants to every household and business [1]. These components include transmission lines, substations, and various types of transformers. Digital technologies have proven to drastically improve the efficiency, safety, security, stability, and robustness of electric power grids. A smart grid would imply that it exhibits one or more of these benefits. For example, the transmission of electricity is more efficient, the electricity can be restored more quickly after a power disturbance, the peak demand can be reduced by implementing more efficient energy trading for better demand-supply matching, and consumers may also become energy suppliers (such as by installing rooftop solar panels) by selling excess energy to the grid (hence, they become prosumers).

On the other hand, blockchain technology has been hyped as the next big technical innovation that could transform our society [3]. Indeed, the possibility of replacing a trusted third party with a decentralized platform consisting of thousands of computing nodes, where rules are enforced by computer algorithms, is extremely attractive. In fact, Bitcoin [4], the first cryptocurrency powered by blockchain technology, was created during the 2008 great recession, which was caused by too-big-to-fail financial institutions. With the introduction of smart contracts that comes with the second major cryptocurrency, Ethereum, it is possible to develop decentralized applications (DApps) and decentralized autonomous organizations (DAOs) that could execute Turing-Complete programming code.

Due to the many unique and highly desirable properties of blockchain technology, there has been great research interest in using blockchain technology in smart grid applications. Research on smart grids and blockchains has been well-reviewed in recent years. Even limiting the scope of blockchain-related smart grids, the number of reviews is relatively large. Considering the maturity of blockchain technology [5] and smart grids, it would be valuable to conduct an umbrella review [6] of these reviews to synthesize the findings and gain deeper insights into how blockchain technology has been and can be employed to address the challenges in developing the next generation of smart grids. We are not aware of any umbrella reviews of this topic. This umbrella review is guided by the following research questions:

RQ1: What smart grid applications have been proposed?
RQ2: What specific roles does blockchain technology play in smart grid applications?
RQ3: What guidelines have been proposed to help decide whether a blockchain-based solution is a good fit for smart grids?
RQ4: What are the maturity levels of the proposed blockchain-based solutions for smart grids?
RQ5: What are the open research issues in developing blockchain-based smart grid applications?

While conducting the literature view, we noticed some technically inaccurate descriptions of various aspects of blockchain technology in many systematic reviews [7]. Such issues are identified in a related section within our umbrella review. To help readers who are unfamiliar with blockchain technology, a background section on blockchains is intentionally included in this review, with the goal of providing a concise and authoritative description of blockchain technology. This is important so that managers in the electric power grid industry can have an accurate understanding of blockchain technology. Otherwise, they might not be able to make the right decisions on blockchain-based smart grid applications.

This umbrella review makes the following research contributions:

- We propose a novel taxonomy for blockchain-based smart grid applications.
- We identify a set of the most prominent roles that blockchain technology plays in smart grid applications.

- We propose benefit-driven guidelines for deciding whether a blockchain-based approach is a good fit for smart grid applications.
- We propose a five-level maturity scale for existing blockchain-based smart grid projects. Furthermore, we investigate numerous industry-led projects with two purposes: (1) to identify which ones are still active, and (2) to determine their maturity levels.
- We synthesize the open research issues that have been identified in existing reviews and provide our own analysis.
- We identify common technical inaccuracies regarding blockchain technology and explain why they are incorrect, which could be essential for developing next-generation blockchain-based smart grid applications.

The remainder of this umbrella review is organized as follows. Section 2 describes our method for literature collection. Section 3 presents a concise and authoritative description of blockchain technology. Section 4 reports our findings for the first research question regarding the classification of blockchain-based smart grid applications. Section 5 elaborates on our findings for the second research question regarding the roles played by blockchain technology in smart grid applications. Section 6 summarizes our findings for the third research question regarding the guidelines proposed to decide whether a blockchain-based solution is appropriate. Section 7 documents our findings for the fourth research question regarding the maturity levels of academic- and industry-led blockchain-based solutions for smart grids. Section 8 presents our findings for our fifth research question regarding the open research issues identified in the reviews. Section 9 summarizes our research findings, identifies the limitations of our research, and provides some future prospects. Section 10 concludes this paper.

2. Method of Literature Collection

We followed the PRISMA guidelines for systematic reviews [8]. We chose to use the Web of Science core collection as the literature repository to find relevant review publications because it is the most authoritative and comprehensive source for high-quality academic publications. We used the search term "blockchain smart grid" and limited the results to the review type. The search returned a total of 85 publications. The selection process is illustrated in Figure 1. Then, we screened these publications by inspecting the title and abstract of each record, which eliminated 34 records that we deemed irrelevant. The full texts of the remaining 51 records were then retrieved for further evaluation. We removed 18 records based on the following criteria: (1) published in English; (2) focused on smart grid applications; (3) the blockchain played a major role in the smart grid applications; and (4) provided substantial technical details. This umbrella review is based on 33 publications.

The included publications were divided into three categories. The first category consisted of comprehensive reviews ($n = 16$) that examined blockchain-based solutions for smart grids in general. The second category consisted of single-topic reviews ($n = 10$) that focused on blockchain-based solutions in a specific application for smart grids. The third category consisted of reviews ($n = 7$) that considered blockchains as only one of the enabling technologies for smart grids. Reviews that belonged to the third category were required to have a sufficient discussion on blockchains to be included.

To give an idea of the number of studies that are covered in this umbrella review, we report the total number of publications in each of the 33 comprehensive reviews in Table 1. As can be seen, these reviews included up to 4471 studies. We do not identify duplicated studies due to the short revision window. The actual unique studies and studies that are focused on blockchains could be a fraction of the total. Nevertheless, the number of studies is large.

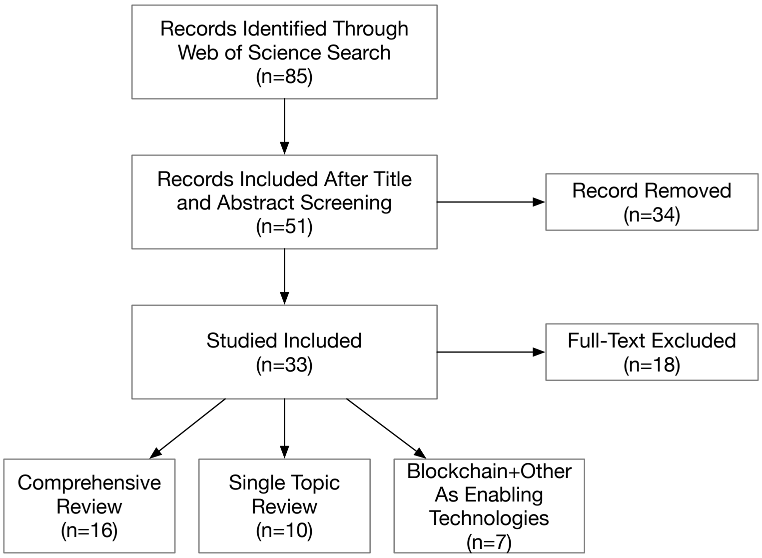

Figure 1. Literature selection process.

Table 1. Number of studies included in each comprehensive review.

Review	Studies
Al-Abri et al. [9]	121
Allladi et al. [10]	91
Appasani et al. [11]	131
Baidya et al. [12]	220
Gawusu et al. [13]	292
Hasankhani et al. [14]	225
Henninger et al. [15]	94
Junaidi et al. [16]	11
Khan et al. [17]	117
Malla et al. [18]	132
Miglani et al. [19]	179
Musleh et al. [20]	103
Nour et al. [21]	185
O’Donovan et al. [22]	20
Wang et al. [23]	81
Yapa et al. [24]	192
Asif et al. [25]	201
Bandeiras et al. [26]	130
Bielecki et al. [27]	110
Chiarini et al. [28]	116
Kapassa et al. [29]	20
Karumba et al. [30]	119
Kirli et al. [31]	269

Table 1. *Cont.*

Review	Studies
Thukral et al. [32]	95
Wu et al. [33]	119
Yan et al. [34]	28
Casquico et al. [35]	95
Ding et al. [36]	164
Hua et al. [37]	124
Mololoth et al. [38]	123
Singh et al. [39]	180
Thasnimol et al. [40]	237
Ye et al. [41]	147
Total	**4471**

3. Blockchain Technology

The primary goal of the original blockchain technology, as exhibited by Bitcoin, was to ensure that it was very difficult to modify the data recorded on the blockchain. This property is often referred to as data immutability. Unfortunately, this has led to a common misconception that any system that takes the form of a blockchain guarantees data immutability. This is, in fact, far from the truth. How to achieve data immutability is the most fundamental concern in blockchain design.

The purpose of this section is to provide a concise and authoritative introduction to blockchain technology as it was intended in several parts: (1) the nuts and bolts of blockchain technology; (2) data immutability; (3) decentralized consensus; and (4) benefits of permissionless (i.e., public) vs. permissioned (i.e., private and consortium) blockchains. More in-depth and comprehensive discussions can be found in our previous publications [7,42,43].

3.1. Nuts and Bolts of Blockchains

Here, we only consider the traditional blockchain design, as seen in Bitcoin [4] and Ethereum [44]. Newer distributed ledger designs such as IOTA, although innovative, have not reached the same level of maturity as traditional blockchains. Despite the claims of a decentralized design, the actual implementation usually depends on some form of centralized control (e.g., the coordinator in IOTA). There are five technical foundations for blockchains [45]: (1) an open peer-to-peer network; (2) cryptography; (3) the blockchain data structure; (4) decentralized consensus; and (5) smart contracts.

Open peer-to-peer network. The blockchain system consists of a network of computing nodes that are set up and owned by different individuals or organizations. The system is open to anyone who wishes to join. The independence of the computing nodes in the blockchain network is the basis for decentralized computing. Here, we emphasize the "open" aspect of the network. If a node must seek permission from any individual or organization before it can join, then the entire network is controlled by this particular individual or organization. Hence, it is self-conflicting to claim decentralized computing with a permissioned network.

Cryptography. In blockchains, cryptographic primitives are used for (1) account holder or stakeholder identification and verification (i.e., via a digital signature); (2) transaction identification (i.e., via a cryptographic hash); (3) block identification (i.e., via a cryptographic hash); and (4) consensus (i.e., via a cryptographic hash). The cryptographic primitives are assumed to be strong, so (1) no one can impersonate another by faking the digital signature, i.e., only the holder of the private key may generate a correct digital signature;

and (2) given a hash value, it is practically impossible to find a conflict, which ensures that a transaction or blockchain can be uniquely identified by the hash, and any modification to the transaction or blockchain would render the corresponding hash different from the original hash, and a miner would have to honestly search for a solution that leads to a hash meeting the proof-of-work target value. There is no doubt that cryptography is the foundation of the security of any blockchain system. That being said, it is a mistake to claim that data immutability is guaranteed by cryptography alone. Further explanations are provided later.

Blockchain data structure. The term "blockchain" comes from the way the transactions are logged in a blockchain system. First, a set of transactions are grouped into a block. Then, one block is chained with a parent block by including the hash of the parent block in the current block's header. Hence, the blocks form a chain, starting with a special block referred to as the genesis block. Miners compete to gain the right to build the next block. In a proof-of-work system, each block naturally incorporates some amount of computation resulting from searching for the solution to the proof-of-work puzzle. Due to the chaining of the block, if one attempts to modify the content of a block, e.g., by removing or replacing a transaction, the adversary must reperform the proof-of-work computation not only for the current block but also for all descendant blocks. This implies that the deeper a block is in the chain, the more difficult it is to change its contents.

Decentralized consensus. The use of cryptographic primitives has been a best practice in building secure systems long before the creation of the first blockchain system. The idea of chaining data while performing symmetric key encryption has also been a best practice for a long time. The most significant innovation in blockchain technology is a new and first-ever way of reaching consensus among a potentially very large set of nodes that geographically span the Earth. This method is known as the proof-of-work consensus algorithm, which essentially transformed the consensus-building process from collective decision making via voting to a competitive lottery task [5]. The consensus is achieved probabilistically, and there is no particular point in time when all nodes would be sure that a consensus has been reached. The proof-of-work algorithm is the first algorithm that can achieve decentralized consensus, where no membership is assumed and no explicit voting is involved [5].

Smart contract. Bitcoin supports some limited forms of scripting functionality, which can be regarded as a primitive smart contact. In Bitcoin, the smart contract is intentionally designed to be Turing Incomplete to avoid the hang problem [5]. Ethereum created a practical solution for supporting Turing-Complete smart contracts by using a virtual machine and associating each instruction with some cost measured by "gas", similar to incurring gasoline consumption when we drive a car. Every smart contract transaction must include some amount of gas. When the gas has been used up before the smart contract is fully executed, the transaction is aborted, effectively solving the potential hang problem during Turing-Complete code execution.

3.2. Data Immutability

In traditional currency, all transactions are settled by central banks. The role of the central bank is to ensure that transactions are valid and that all transactions are recorded so that there is no ambiguity about whether or not a transaction has taken place once settled. Bitcoin aimed to replace the trusted central bank by (1) recording all transactions in a blockchain; (2) ensuring that all nodes in the system see the same copy of the blockchain; and (3) making it very difficult to modify, replace, or remove a transaction once it has been recorded in the blockchain. In Bitcoin, these requirements are satisfied by the proof-of-work algorithm, the blockchain data structure, and the use of secure cryptographic primitives. In particular, these mechanisms together create a self-imposed barrier to changing the blockchain. Ideally, this barrier is so high that it becomes insurmountable, leading to data immutability. Assuming that all nodes have similar computing power, the more nodes the system has, the higher the barrier is for changing the data in the blockchain.

Due to the mechanisms incorporated by Bitcoin (and its derivatives), the only way to modify the blockchain is to create a fork so that an alternative blockchain is regarded as the main chain. To successfully create an alternative chain to be accepted as the main chain, it requires the adversary to control more than half of the computation power (i.e., more specifically, the total hashing power). Although it is possible for an adversary to break into existing mining nodes and control them, it is much easier to simply set up additional nodes as part of the blockchain network to overtake the system. According to https://bitnodes.io, accessed on 18 June 2023, there were 16,774 reachable nodes. To overtake the existing Bitcoin and introduce changes to the blockchain at will, the adversary would need to set up 16,775 nodes. Assuming that each node costs USD 10,000, this would require the adversary to invest USD 167.775 million. Although a middle-class family certainly cannot attack Bitcoin in this way, wealthy individuals and large corporations can easily break the data immutability guarantee of Bitcoin. Therefore, the claim of data immutability for blockchain-based systems is not absolute, even for the largest known blockchain systems. It is questionable to make such a claim if public blockchain systems with much fewer nodes are used, let alone permissioned blockchains.

3.3. Decentralized Consensus

Traditional distributed consensus algorithms are not a good fit for an open peer-to-peer system because there is no way to track the membership of the current system, which is a prerequisite for reaching consensus in traditional distributed consensus algorithms [5,46,47]. The proof-of-work algorithm is the first algorithm that can be used to reach consensus probabilistically in a decentralized system. As demonstrated by the proof-of-work algorithm, decentralized algorithms have major differences from traditional distributed consensus algorithms. The two approaches can be compared according to seven metrics: (1) decision level, (2) knowledge of membership, (3) coordination for consensus, (4) complexity level, (5) guarantee of timely decision, (6) guarantee of universal agreement, and (7) adaptivity on decision interval. We intentionally omit the more detailed technical discussions.

3.4. Benefits of Blockchains

The set of benefits of a large public blockchain, as shown in Figure 2a, is enabled by the fundamental building blocks of blockchain technology, i.e., blockchain, smart contract, cryptography, and decentralized consensus. We separate consensus and decentralization so that we can compare the benefits offered by the original permissionless (i.e., public) blockchain versus the permissioned (i.e., private and consortium) blockchain. For the permissionless blockchain, we identify the following set of benefits: privacy, security, transparency, data immutability, fault tolerance, censorship resistance, data provenance, atomic contract execution, and trust.

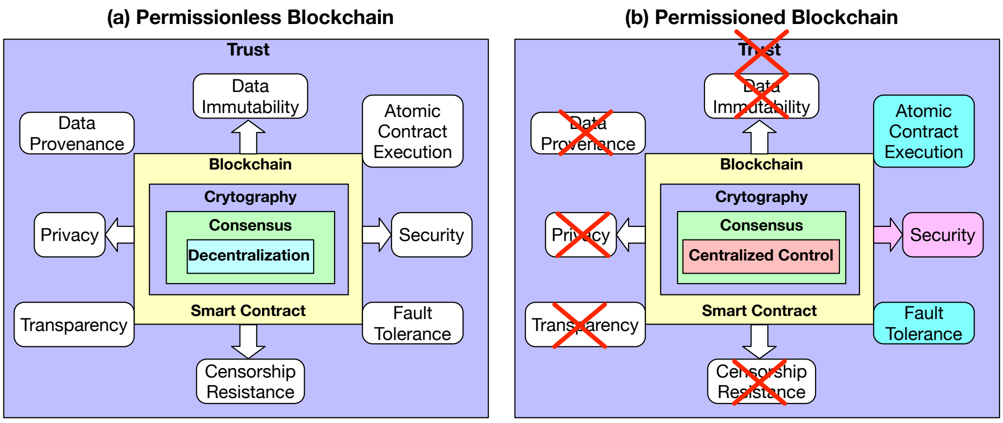

Figure 2. Benefits of blockchain technology.

Privacy. In a blockchain system, the user is identified by a pair of self-generated public–private keys. To prove ownership, the user must demonstrate the correct digital signature corresponding to an address. This design offers some degree of privacy to users (usually referred to as pseudo-anonymity), although it is subject to analysis-based tracking.

Security. Although many publications have claimed that blockchains enable better security than traditional systems, how this occurs is rarely explained clearly. For cryptocurrency, security means that only the owner may spend their funds and no one may double-spend their funds. When a blockchain is used to enable other types of applications, security usually refers to the basic security mechanisms offered by blockchain technology and the integrity of the data placed on the blockchain.

Transparency. This property refers to the fact that all transactions are logged on the blockchain and they are open to the public to inspect. Essentially, the blockchain system manages a public ledger of all transactions.

Data immutability. Strictly speaking, data immutability should be a prerequisite for the integrity of a system. However, traditional centrally controlled systems (distributed or not) lack an effective means to protect the data from modifications. As we explained in Section 3.2, blockchain technology introduced an effective mechanism to mitigate the attack on data by enacting a self-imposed barrier. Because of this innovation, it is worthwhile to single out this particular property of blockchain technology.

Censorship resistance. Censorship refers to actions that prevent free speech. Censorship can come in the form of prohibiting some people from expressing their opinion, but can also come in the form of removing published material from the media (such as books, journals, etc.). Censorship implies that there is no admission control over who may write data to the blockchain, and it also requires data immutability. Obviously, only large public blockchain systems can offer censorship resistance.

Data provenance. Data provenance refers to establishing the full contextual records of a data item, such as its owners, custody, or location [48]. A blockchain could be used for implementing data provenance because all transactions and blocks in the blockchain are timestamped, and all data have some degree of data immutability.

Atomic contract execution. Thanks to Ethereum smart contracts, a user can define a piece of code as a smart contract, and the code is automatically executed when invoked. Furthermore, due to the massive degree of redundancy in a large blockchain system, the execution of the contract is guaranteed to be fault tolerant. It is worth noting that fault-tolerant code execution in a blockchain (via a smart contract) is a much more scalable and robust method compared to that of traditional approaches [5,49]

Fault tolerance. Fault tolerance is implied in atomic contract execution. Even without code execution, the data stored in the blockchain become fault-tolerant due to the massive degree of redundancy in a blockchain system (i.e., every full node has a complete copy of the blockchain). Unlike traditional fault tolerance, in a blockchain, only a single node updates the system state (i.e., the blockchain) and executes the smart contract, which avoids the need for highly complex coordination of multiple nodes that all update the system state or execute the code.

Trust. Similar to the term "security", trust is often used pervasively without a clear definition. Here, we refer to trust as a high level of assurance of a system to its users [50]. A trustworthy system should exhibit properties such as dependability, security, and privacy. In a blockchain, trust is guaranteed collectively by other properties.

Largely facilitated by HyperLedger, many publications have proposed solutions based on private or consortium blockchains. At least some of these publications explicitly or implicitly claim that their solutions ensure data immutability. As we demonstrated in Section 3.2, there are two issues with using a permissioned blockchain with respect to data immutability: (1) a permissioned blockchain is controlled by a single individual or an organization, and as such, the owner could suspend or remove any node at any time; hence, the consensus process is not decentralized; and (2) a permissioned blockchain typically has a very small set of nodes, which lacks the scalability needed to enact a sufficient barrier for the modification of the existing blockchain, even if we could ignore the first issue. Hence, data immutability and all properties (i.e., data provenance, censorship resistance, and trust) that depend on data immutability cannot be assumed to exist in a permissioned blockchain, as shown in Figure 2b.

Furthermore, a permissioned blockchain cannot ensure privacy due to its design, i.e., all users need permission to join the system. While a permissioned blockchain may claim to have transparency because the blockchain can be made publicly visible, transparency is not guaranteed because a permissioned blockchain could easily restrict access to the blockchain.

A permissioned blockchain may ensure security at the same level as a centralized controlled system, but not at the level of a large public blockchain due to the lack of a data immutability guarantee.

Quite interestingly, the mechanisms for fault tolerance and atomic contract execution in a blockchain do not depend on decentralization. These mechanisms offer a new and more robust way of achieving fault tolerance and atomic contract execution.

4. RQ1: Proposed Smart Grid Applications

In this section, we report our findings in relation to our first research question. We first elaborate on the types of blockchain-based smart grid applications based on our taxonomy. Then, we discuss individual studies.

4.1. Taxonomy of Blockchain-Based Smart Grid Applications

Existing systematic reviews classify blockchain applications in smart grids in several different ways. We synthesize these reviews and propose a taxonomy of blockchain applications, first based on whether or not the application is targeting the functional or non-functional requirements, then based on the specific objectives of each type of requirement, as shown in Figure 3.

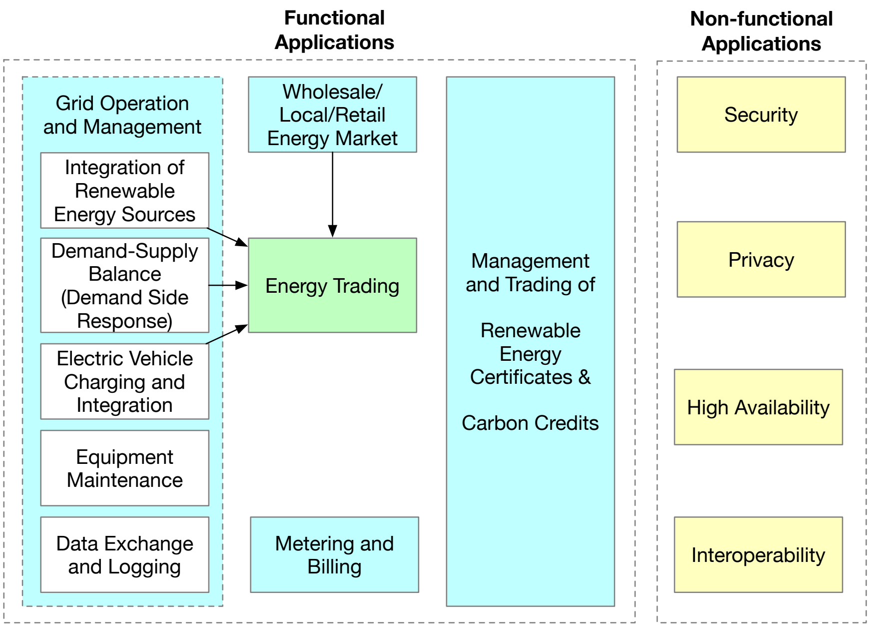

Figure 3. Taxonomy of blockchain-based smart grid applications.

Previous studies have found that blockchains could play an important role in almost all smart grid operations and help satisfy both functional and non-functional requirements. We divide functional blockchain applications in smart grids into four types: (1) grid operation and management; (2) energy market at the retail, local, and wholesale levels; (3) metering and billing; and (4) management and trading of renewable energy certificates and carbon credits. Blockchain technology is also a natural fit for improving the non-functional properties of the grid operation, including security, privacy, high availability, and interoperability.

The four types of functional applications encompass the entire spectrum of smart grid functions. Grid operation and management is the core function of both traditional electric power grids and smart grids. In smart grids, there are two additional challenges: (1) the integration of renewable energy sources into the power grid; and (2) electric vehicle charging and integration. Furthermore, data exchange and logging become more urgent in smart grids compared to traditional grids. By integrating with information and computer technologies, the demand–supply balance could be more effectively accomplished, and the efficiency and reliability of equipment maintenance could also be improved.

The energy market is another key function of power grids, which pertains to the economic aspect of power grids. Typically, there are three levels of the energy market: (1) retail; (2) local; and (3) wholesale. Metering and billing are related to the measurement of consumption and charging of the customers, respectively, which are essential functions of both traditional power grids and smart grids. Renewable certificates and carbon credits mostly pertain to smart grids. The management and trading of these certificates and credits could lead to wider adoption of renewable energy sources in electric power generation and consumption.

4.1.1. Applications for Grid Operation and Management (GO)

Most blockchain-based applications are related to electric grid operation and management. One particular characteristic of a smart grid is the presence of numerous renewable energy sources (also referred to as resources) such as electricity generation based on wind and solar energy. These sources typically generate a small amount of electricity sporadically, and some of them are operated by individuals who are mostly consumers of the electric power grid (often referred to as prosumers). Hence, it is a big challenge to integrate these sources into a traditional electric power grid. A blockchain offers a practical way of integrating these renewable energy sources into a traditional electric power grid via energy trading.

Closely related to the integration of renewable energy sources, as well as the prevalence of electric vehicles, how to dynamically balance the demand and supply is another huge challenge. One type of effort is referred to as demand-side management, which aims to regulate electricity demand by altering consumer electricity usage patterns. Demand response is usually considered an energy flexibility program under demand-side management. However, demand-side management and demand response are often used interchangeably. More specifically, demand response may use pricing regulations and incentives to induce changes in the electricity usage patterns of consumers so that the peak demand is lowered. Again, this issue could be effectively addressed by blockchain-mediated energy trading. To encourage consumers to participate in demand response, non-fungible tokens could be used as a reward [29].

Electric power grids are mission-critical systems; hence, any issues with grid equipment (such as substations and smart meters) must be quickly detected, diagnosed, and resolved. Traditionally, maintenance logistics are complex and labor-intensive and are often limited by regional restrictions [10]. Blockchains can be used to streamline the maintenance process.

The utility sector is typically heavily regulated by the government. To satisfy various regulations, it may be necessary to keep all important operating data available for auditing and reporting purposes. Blockchains are a natural fit for logging important data regarding grid operations [24].

4.1.2. Applications for Energy Markets (EM)

Traditional wholesale, local, and retail electricity markets consist of many intermediaries, such as regulators, banks, brokers, and trading agents, due to the complexity of the market processes. Hence, it is very difficult for distributed renewable energy sources to join the market [21]. A blockchain offers a low-cost and more efficient platform for conducting energy trading in energy markets without intermediaries.

4.1.3. Applications for Metering and Billing (MB)

Traditional metering and billing processes contain manual steps and also have low transparency [21]. Blockchain technology could streamline processes, lower costs, and increase transparency levels. In [27], a blockchain-based framework was proposed, as illustrated in Figure 4. The metering operator is in charge of measuring electricity usage (using smart meters, for example). The metering operator works closely with the distribution system operator, which is in charge of billing and issuing payments to electricity generators and prosumers. A generator injects electricity into the grid. A consumer consumes electricity from the grid. A prosumer consumes electricity from the grid and also may inject electricity into the grid. Typically, the proposed solutions for blockchain-based metering and billing introduce custom tokens as the virtual currency for payment. A token-fiat currency exchange would need to be made available for consumers, prosumers, and generators to make exchanges.

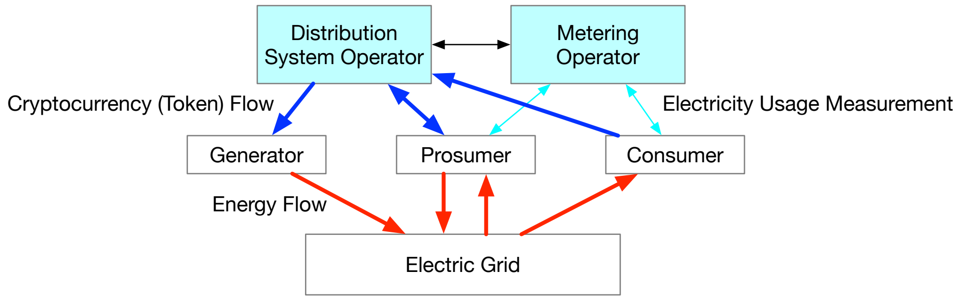

Figure 4. Cryptocurrency-based electricity usage settlement.

4.1.4. Applications for Management and Trading of Renewable Energy Certificates and Carbon Credits (RECCC)

A blockchain offers a platform for trading carbon credits and also for connecting renewable energy sources with consumers who prefer to consume green energy. Smart meters could be used to generate green (or renewable energy) certificates as proof that the energy was generated from renewable sources.

4.1.5. Applications for Enhancing Non-Functional Properties of Grid Operations (NF)

Non-functional properties are desirable for all systems. Because a smart grid incorporates information and data communication technologies, it is more vulnerable to cyberattacks. By using a blockchain, the data exchanged and logged can be made more secure. Another need for smart grids is standardization and interoperability among the numerous components. By using a major blockchain platform, such as Ethereum, it effectively imposes a single standard for interaction, which is conducive to interoperability. Many reviews mentioned the benefit of enhancing privacy using a blockchain. However, we have strong reservations regarding the need for privacy in smart grids. Due to the financial stakes, particularly for prosumers (i.e., those who invest in and operate renewable energy sources), they must be vetted, and their reputation should be known to other partners.

Although high availability was rarely mentioned in the systematic reviews, we believe this would be a highly desirable property that can be achieved by using a blockchain-based solution. The way a blockchain achieves high availability (via decentralized consensus) is drastically different from traditional fault tolerance, which makes the system much more robust and elegant [5,49].

4.2. Systematic Reviews of Blockchain Applications for Smart Grids

We first discuss the group of articles that span all applications in smart grids. Then, we outline those that focus on a single aspect of smart grid operations (such as energy trading) or a single aspect of blockchain applications (such as the use of smart contracts). Finally, we discuss the articles that consider blockchains as one of the building blocks in smart grid applications.

4.2.1. Comprehensive Reviews

The comprehensive reviews of blockchain applications for smart grids are summarized in Table 2. These reviews grouped blockchain applications in different ways. Some studies took a systematic approach, such as [23], in which the authors examined the applications according to several different dimensions. However, most did not. Nevertheless, we were able to match the applications with categories according to our taxonomy. The terminologies used were sometimes also different. For example, renewable energy sources were also referred to as renewable energy resources, and renewable energy was also referred to as green energy.

Table 2. Comprehensive reviews of blockchain-based smart grid applications. GO refers to grid operation and management; EM refers to energy markets; MB refers to metering and billing; RECCC refers to the management and trading of renewable energy certificates and carbon credits; and NF refers to non-functional properties.

Review	GO	EM	MB	RECCC	NF
Al-Abri et al. [9]	✓	✓		✓	✓
Allladi et al. [10]	✓	✓			✓
Appasani et al. [11]	✓		✓		
Baidya et al. [12]	✓		✓		
Gawusu et al. [13]	✓	✓			
Hasankhani et al. [14]	✓	✓		✓	✓
Henninger et al. [15]	✓	✓	✓	✓	✓
Junaidi et al. [16]	✓	✓		✓	✓
Khan et al. [17]	✓	✓		✓	✓
Malla et al. [18]	✓	✓			✓
Miglani et al. [19]	✓	✓	✓	✓	✓
Musleh et al. [20]	✓	✓			✓
Nour et al. [21]	✓	✓	✓	✓	✓
O'Donovan et al. [22]	✓	✓	✓	✓	
Wang et al. [23]	✓	✓	✓	✓	✓
Yapa et al. [24]	✓	✓	✓		✓

In [9], blockchain applications were divided based on the target components: (1) microgrids and smart grids, which include blockchain-based applications for the energy market, peer-to-peer trading, energy management, and carbon emission trading; (2) electric vehicles, which concerns how to integrate electric vehicles into the grid with energy trading; and (3) privacy protection of the users.

In [10], the blockchain applications included peer-to-peer energy trading, energy trading in electric vehicles, secure equipment maintenance for smart grids, and security and privacy in power generation and distribution.

In [11], blockchain-based applications were divided into energy management systems via energy trading; applications for microgrids, which refers to distributed renewable energy sources; applications for electric vehicles; and applications for advanced metering infrastructure. Although this review also covered home automation, we do not consider it an essential part of smart grids.

In [12], smart contract-based energy trading was used for secure energy management and the integration of distributed renewable energy sources into the grid, where energy trading is used to help balance supply and demand. Furthermore, this paper also mentioned secure micropayments for grid usage, grid data exchange, and provenance, as well as secure equipment maintenance.

In [13], the reviewed blockchain applications were centered around integrating renewable energy sources into the grid with energy trading. This spans wholesale and local energy markets, grid operation, incentivizing renewable energy sources, and balancing the demand and supply.

In [14], blockchain applications were divided into those used for balancing demand and supply, those used for integrating electric vehicles into the grid, those used for integrating distributed renewable energy sources, those used for energy trading, those used for carbon credit trading, and non-functional issues such as security, privacy, and interoperability.

In [15], a blockchain-based architecture was proposed as the foundation to integrate distributed renewable energy. Quite interestingly, the authors proposed to introduce decentralized identity and verifiable credentials, both exploiting the data immutability feature of blockchain technology to establish the trustworthiness of the participants while protecting their privacy. The architecture covers peer-to-peer energy trading; energy markets; the registration of grid assets, carbon credits, and green certificates; and billing, grid management, and non-functional issues such as privacy and interoperability.

In [16], blockchain applications were grouped into eight categories. Some of these categories are based on grid components, such as micrograms, smart grids, and electrical vehicles, and others are based on the primary purpose of the application, such as demand response (demand-side management), energy trading, energy management, integration with distributed renewable energy, and energy trading.

In [17], four types of blockchain applications for smart grids were reviewed: (1) transactive energy, which is another term for blockchain-based energy trading; (2) integration of electric vehicles into the grid, which is also achieved via energy trading; (3) demand response, which is about balancing demand and supply in response to renewable energy sources; and (4) non-functional issues such as privacy and security.

In [18], blockchain-based applications for smart grids were divided into six domains: (1) energy trading; (2) power flow, which is about integrating distributed renewable energy resources into the grid; (3) the integration of electric vehicles; (4) demand-side management, which is about balancing demand and supply; (5) grid automation, which encompasses various operations such as grid control and automation in the presence of renewable energy sources, energy trading, and the management of green certifications; and (6) non-functional issues such as security.

In [19], the reviewed blockchains applications included energy trading, demand-response management (i.e., balancing demand and supply, which is part of grid operation), billing and secure payments, the management of green certificates, and security.

In [20], blockchain applications were categorized as follows: (1) energy trading; (2) microgram operations (mostly about balancing demand and supply in the presence of renewable energy sources); and (3) security.

In [21], blockchain applications were divided into the following categories: (1) peer-to-peer energy trading; (2) wholesale markets; (3) metering, billing, and retail markets; (4) trading of renewable (i.e., green) energy certificates and carbon credits; (5) electric vehicle charging; (6) grid operation and management; (7) investment in renewable energy sources; and (8) security.

In [22], several types of blockchain applications for smart grids were mentioned without any details, which included energy trading, electric e-mobility (i.e., electric vehicles), metering and billing, grid management, green certification, and carbon trading. The authors also mentioned investment, asset management, and home automation, which we do not believe are essential components of smart grids.

In [23], the role blockchain technology could play was examined in multiple dimensions: (1) technical (using blockchain technology to reduce costs and improve efficiency), economic (using blockchain technology for fair and secure energy trading), engineering (using blockchain technology for safe and reliable grid data management), the environment (using blockchain technology to manage environmental pollution), and social (using blockchain technology to implement a unified energy market). Although the classifications are different, the discussed applications span all the categories that we proposed.

In [24], blockchain applications were divided into peer-to-peer energy trading, integration of distributed renewable energy resources, demand-side integration, grid automation, distribution network management (mostly concerning equipment health monitoring, fault detection and isolation, and periodic maintenance), and energy data management.

As can be seen in Table 2, all 16 reviews considered blockchain applications in grid operation and management. Out of the 16 reviews, 14 reported blockchain applications in some forms of energy markets; 8 reported blockchain applications in metering and billing; 9 considered blockchain applications in the management and trading of green certificates and carbon credits; and 12 reported blockchain applications in enhancing the non-functional properties of smart grids.

4.2.2. Single-Subject Reviews

The single-subject reviews are summarized in Table 3 regarding the types of applications that have been covered. One advantage of single-subject reviews is that the reviews may be more in-depth compared to comprehensive reviews of a particular issue.

Table 3. Single-subject reviews of blockchain-based smart grid applications. GO refers to grid operation and management; EM refers to energy markets; MB refers to metering and billing; RECCC refers to the management and trading of renewable energy certificates and carbon credits; and NF refers to non-functional properties.

Review	GO	EM	MB	RECCC	NF
Asif et al. [25]					✓
Bandeiras et al. [26]		✓			
Bielecki et al. [27]		✓	✓		
Chiarini et al. [28]	✓	✓			
Kapassa et al. [29]	✓				
Karumba et al. [30]	✓	✓			
Kirli et al. [31]	✓	✓			
Thukral et al. [32]	✓	✓			
Wu et al. [33]	✓	✓			
Yan et al. [34]	✓				

In [25], blockchains, in conjunction with physical unclonable functions (PUFs), were proposed to enhance the security of smart grids (referred to as the Internet of Energy), where all devices are protected by a PUF.

In [26], energy trading at the local, retain, and wholesale levels was discussed. Blockchain-based decentralized energy trading, as well as other approaches (centralized and distributed trading), were reviewed.

In [27], studies on using cryptocurrency as a settlement method for energy trading and electricity usage were reviewed. A common approach in these studies was to issue a custom token as a form of payment. This review identified a number of benefits of using cryptocurrency for settlement. Some benefits, such as enforcing self-balancing and promoting pro-efficiency behaviors, can also be accomplished using traditional fiat currency. Other benefits are clearly unique to the blockchain-based solution, such as faster settlement and lower transaction costs.

In [28], blockchain-based energy trading was thoroughly examined. Decentralized energy trading is instrumental in facilitating the integration of renewable energy sources, the balance of demand and supply, and the transformation of the energy market, as illustrated in Figure 3. The authors pointed out that decentralized energy trading is conducive to the decentralization of energy production and energy distribution. However, the authors also recognized that at the current stage, decentralized trading still depends on a centralized energy infrastructure because of the volatility of renewable energy sources.

In [29], studies on demand response in the context of electric vehicles were reviewed. There are two strategies in demand response: (1) time-based, and (2) incentive-based. In time-based demand response, the demand is regulated via changing prices of electricity. In incentive-based demand response, desirable consumer behavior is accomplished via varying payments. A blockchain is used to help schedule electric vehicle charging and facilitate energy trading between electric vehicles and network operators.

In [30], the barriers to adopting blockchain-based decentralized energy trading were reviewed. The authors provided a concise summary of the activities of demand-side management, which include improving the transparency and security of energy-efficient markets and using electric vehicles as spinning energy reserves, in addition to demand-response activities. The authors also outlined and envisaged a decentralized energy trading system, where energy trading is used to enable renewable energy integration throughout the entire grid operation (generation, transmission, distribution, and prosumption) and improve various aspects of the grid operation.

In [31], the review focused on smart contract-based applications in smart grids. The authors grouped the applications into two categories: (1) energy and flexibility trading; and (2) distributed control. Energy and flexibility trading spans application areas including peer-to-peer trading, peer-to-grid, automatic demand-side management, the electricity market, and market design. Distributed control spans application areas including electric vehicle management, battery management, grid management, energy management systems, smart homes, auditing and certification of the supply chain, virtual power plants, and integration with the Internet of Things. These applications roughly correspond to grid operation and management and energy markets according to our taxonomy.

In [32], blockchain-based energy trading was reviewed. Energy trading has been used in microgrids, for demand response, for implementing optimal power flow, and for integrating electric vehicles into the power distribution network.

In [33], the review of blockchain-based energy trading was approached from a unique angle. The authors recognized blockchain technology as the enabling technology for the development of both a peer-to-peer energy society and interoperative marketplaces. At the technical level, a blockchain can be used for transaction control and for achieving energy flexibility with multi-scale services. Furthermore, this review examined blockchain-based energy trading from the perspective of the players that engage in energy trading and the trading mechanisms, as shown in Figure 5. Four types of trading were identified based on the players who participate in energy trading, which include energy trading between prosumers, energy trading between community operators, energy trading between a prosumer and multi-class energy players, and energy trading between federated prosumers (forming a power plant) for trading with the traditional grid. Furthermore, decentralized energy trading requires a pricing mechanism, a digital transaction loop, and an energy delivery loop.

In [34], a blockchain-based demand-response framework was proposed. In the proposed framework, demand response is implemented using an auction-based energy trading scheme. A blockchain is used to address the concerns in centralized demand response by (1) improving the trustworthiness of the data; (2) increasing the privacy protection of the bids submitted; (3) simplifying the demand-response settlement; (4) reducing demand-response management costs; and (5) improving the supervision of demand-response programs. Essential to the project's goal is data immutability and trust. Unfortunately, a consortium blockchain was proposed, which does not ensure data immutability and trust.

As can be seen in Table 3, out of the ten studies in this category, seven discussed the adoption of blockchain technology to facilitate grid operation and management, seven reported the application of blockchain technology in facilitating energy markets, one reported on a blockchain application for metering and billing, and one reported on the enhancement of the non-functional properties of smart grids.

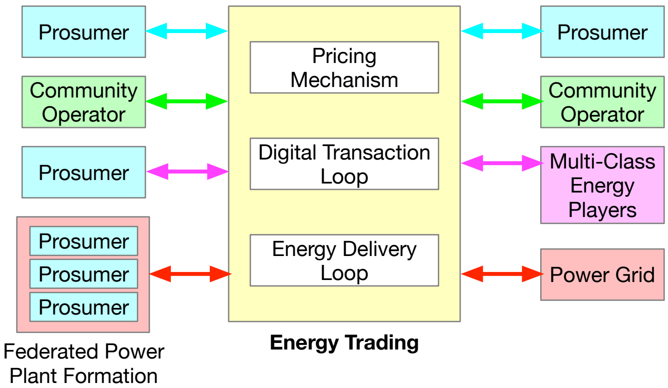

Figure 5. Four types of energy trading are identified based on the players who participate in energy trading. Furthermore, decentralized energy trading requires a pricing mechanism, a digital transaction loop, and an energy delivery loop.

4.2.3. Reviews of Blockchains and Other Technologies

In [35], the Internet of Things (IoT) and blockchain technology were identified as two key pillars for the decentralization of smart grids. IoT technology is needed, as it enables the components in a smart grid to collect the status of energy consumption, distribution, and production and make immediate decisions when necessary. Blockchain technology was proposed as the enabling technology for decentralized energy trading.

In [36], the security issues in smart grids were reviewed. Blockchain technology was identified as a way to mitigate cyberattacks on smart grids, together with machine learning and deep learning (and other techniques). A blockchain was proposed to enhance identification and authentication (to prevent identity-based attacks), improve privacy protection, and incentivize honest behavior.

In [37], blockchain and artificial intelligence were identified as two important technologies to facilitate the integration of prosumers into smart grids. A blockchain was proposed as the enabling technology for decentralized energy trading, whereas artificial intelligence was proposed to support power system operations. Within the field of artificial intelligence, game theory and machine learning play important roles in smart grid applications.

In [38], blockchains and machine learning were regarded as two fundamental technologies for smart grids. A blockchain was used to provide a decentralized, trusted platform for energy trading and providing various services. Machine learning was used to enable intelligent smart grid operations. The authors mentioned several industry-led blockchain projects, which we examine regarding their maturity levels in Section 7.

In [39], blockchain technology was identified as the technology of choice to enable energy trading for next-generation energy systems (termed Energy System 4.0). Besides blockchains, the Internet of Things, edge computing, big data, and artificial intelligence were identified as the other pillars of smart grids.

In [40], blockchain technology was listed in conjunction with a long list of other technologies (such as fog computing, edge computing, cloud computing, and database management platforms for large data) as the enabling technology for smart distribution networks. The authors used blockchain technology to facilitate energy trading for various purposes.

In [41], blockchains and machine learning were used as the enabling technologies for securing solar energy generation systems (i.e., photovoltaic systems). Machine learning was used for data-driven cyberattack detection and mitigation. The authors provided a concise but insightful summary of how blockchains can be used to secure solar energy generation systems in different layers. More details are provided in Section 5.4.

To summarize, in addition to blockchain technology, the IoT, machine learning, artificial intelligence, edge computing, and big data have been identified as instrumental technologies in advanced smart grids.

5. RQ2: Specific Roles that Blockchain Technology Plays in Smart Grid Applications

The reviews identified a variety of benefits that blockchain technology brings to smart grid applications. We outline the most common and important ones in this section.

5.1. Data Immutability

Data immutability is the most prominent feature of blockchain technology. Hence, it is the most often-cited benefit of using blockchain technology. Data immutability is the foundation for the registration, management, and trading of green certificates [21]. A green certificate, by definition, is proof that the electricity is generated from renewable sources, which requires both data provenance (i.e., a stronger form of data immutability) and transparency.

Smart grid physical equipment security is also achieved via the data immutability feature of blockchain technology. In [25], a blockchain was used to store information related to the PUFs of the equipment and devices for authentication.

All applications based on smart contracts also depend on the immutability of the smart contracts. If a smart contract can be altered, then no one would trust the smart contract anymore.

Although it might not be obvious at first, all forms of energy trading depend on the immutability of transaction records placed on the blockchain or stored via smart contracts. Similarly, records regarding equipment maintenance, all forms of data exchange, and logging depend on the immutability feature of the blockchain. Metering and billing also involve the recording of important data that should be made immutable and the transaction records cannot be tampered with either.

5.2. Transparency

Transparency means that all the logged data can be inspected by the public. One could argue that transparency is the only way for the public to verify that the data placed on the blockchain are immutable. Hence, without transparency, the data immutability claim cannot be verified. Data immutability and transparency are the foundations for achieving a degree of trust that is not achievable in traditional centralized systems. The applications that depend on the data immutability feature, in fact, also depend on the transparency feature.

5.3. Smart Contracts

Smart contracts have been pervasively used in blockchain-based smart grid applications. Energy trading, which is the most often-cited blockchain-based smart grid application, depends on smart contracts. Smart contracts depend on the data immutability property of blockchain technology because if the smart contract can be modified, then the trust in the contract will be severely compromised.

According to [21], smart contracts have been used for all the main steps in energy trading, including (1) user and smart grid asset registration and authentication; (2) management of bids and offers; (3) smart grid status monitoring (such as smart meter readings); (4) matching of bids and offers (i.e., market clearing); (5) payment transactions; (6) generating new contracts; (7) data logging; and (8) synchronization and coordination of activities. It is worth noting that although a smart contract may execute arbitrary computations, it is common to include only a minimum amount of simple calculations in a smart contract due to financial costs and security concerns [21,51].

In [31], a six-layer architecture for smart contracts in smart grids was proposed. However, the bottom three layers are blockchain internal operations. Hence, we only outline the top three layers, which we believe offer the greatest insight into the smart contract structure. The lowest layer consists of the native contracting functions, including financial transactions and user registrations. The middle layer consists of the implementation of energy management algorithms such as matching and control decisions. The highest layer consists of bids, offers, device status, and grid signals. These two methods are roughly consistent with each other. As illustrated in Figure 6, the eight steps in energy trading outlined in [21] can fit into the three-layer architecture for smart contracts in the energy domain.

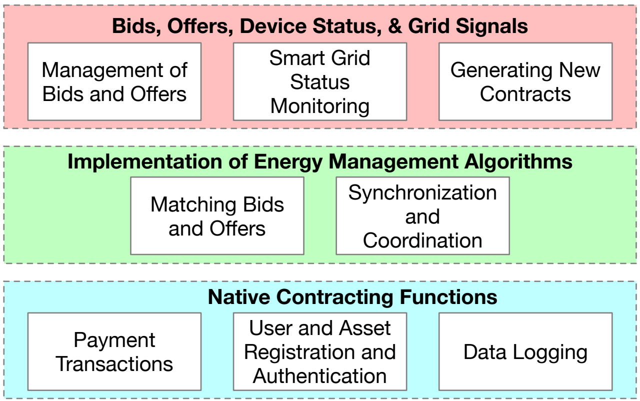

Figure 6. Main steps in energy trading can be roughly organized according to a 3-layer architecture.

5.4. Security

Traditional secure communication solutions inevitably require public key certificates for server-side authentication. This is necessary because the clients want to verify that the public key indeed belongs to the particular service provider, which requires a trusted third party to verify the authenticity of the certificate. This, in turn, requires the existence of a public key infrastructure. On the contrary, blockchain technology adopted a drastically different design philosophy, where a user is identified by an address derived from the user's public key, and as long as the user can prove that it has the corresponding private key, then the user is authenticated. It is worth noting that the user itself generates the public–private key pairs, and the blockchain does not store any secret that belongs to any user. This design is essential to achieving truly decentralized peer-to-peer computing without relying on any trusted entity.

In a typical use case, a blockchain expects a user to generate a digital signature corresponding to an address for authentication. Because the only one who possesses the right private key can generate a valid digital signature corresponding to a given address, this is a simple yet elegant way of performing authentication. The downside of this design is that the users are burdened with keeping the private key secure in two respects: (1) the user must prevent others from accessing the private key, and (2) the user must have a copy of the private key to generate a digital signature when required. The theft of the private key by anyone else would be equivalent to having lost all the funds associated with that address. The loss of the private key would also mean that the user can no longer access the funds (i.e., actually no one can).

Some reviews, such as [25], proposed to enhance blockchain security by incorporating the physical unclonable functions (PUFs) of physical devices. The proposals for integrating blockchains with PUFs require the use of a trusted node to keep a safe copy of the set of inputs and expected outputs. We would like to point out that this goes directly against the design principle of blockchain technology. If a particular node is so trustworthy that it can be used to store the secrets of the users, then why not use that node to coordinate consensus and other essential tasks? This is clearly unacceptable for decentralized computing.

In [41], the authors elaborated on how blockchains can be used to secure solar energy generation systems in different layers, as shown in Figure 7. At the hardware level, the data immutability property of the blockchain can be used to ensure that only authorized hardware components are used in the system, where the information regarding the authorized hardware components and all related supply chains are stored in a blockchain. At the onboard interface level, a lightweight blockchain can be used to secure the onboard network, according to [41]. However, we are concerned with their approach, even if a lightweight blockchain is developed because such a system can hardly ensure data immutability, which is the foundation for ensuring security. Data storage security can be ensured by placing important data in the blockchain due to the data immutability of the blockchain. Firmware security can be facilitated by storing the hash of the correct version of the firmware in the blockchain. Then, the actual firmware can be validated using the stored hash. Network security can be achieved by blockchain-style device identification and smart contract-based access control. In our prior work on securing sensing data processing and logging, we implemented both methods [51,52].

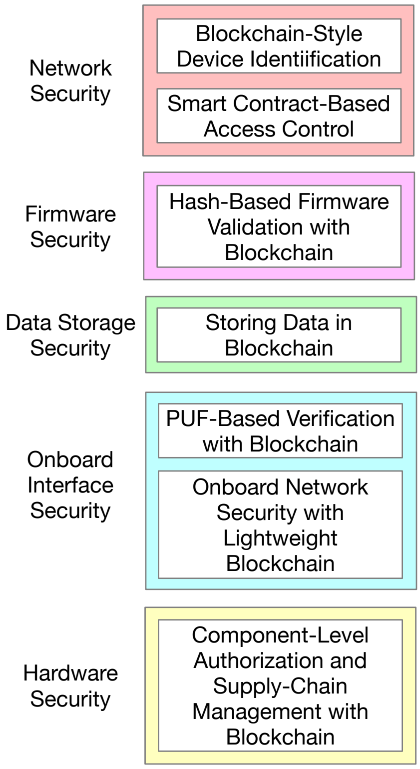

Figure 7. Blockchains could help improve all levels of security in smart grids.

5.5. Technical Inaccuracies in the Literature

Although some reviews presented blockchain technology accurately, many contained various technical inaccuracies regarding blockchain technology. Virtually all the technical inaccuracies are due to the pervasive use of permissioned blockchains in blockchain-based smart grid applications.

A common mistake was equating blockchains to data immutability or considering them tamper-proof. As we argued in Section 3.2, this is far from the case. Only large public blockchains can ensure data immutability to a certain degree. A permissioned blockchain, such as a private or consortium blockchain, cannot offer data immutability any better than a traditional centralized system because the owner of such a blockchain may arbitrarily exclude nodes and include new nodes during the consensus process, and as such, the blockchain can be easily forked from one chain to another chain, thereby changing the records on the ledger.

Furthermore, a permissioned blockchain cannot be regarded as a decentralized system, again, because such a system is controlled by the owner who can decide who may join the system. Unfortunately, many papers claimed to provide decentralized platforms for energy-related operations using a permissioned blockchain.

Privacy is often a cited reason for using a permissioned blockchain for smart grid applications. While this approach may prevent the public from knowing the data stored in the permissioned blockchain, the identities of the participants are known to the owner of the permissioned blockchain, unlike a public blockchain, which offers pseudo-anonymity to its users. If the owner is compromised, the privacy violation could be much worse than when using a public blockchain because all public blockchains allow users to store encrypted data in their transactions.

Another significant technical issue is the use of traditional distributed consensus algorithms, particularly the practical fault-tolerance protocol (PBFT), for blockchain consensus. As we discussed in Section 3.3, this is a big mistake.

6. RQ3: Guidelines to Help Decide Whether to Adopt a Blockchain-Based Solution

In this section, we first report the guidelines proposed in the literature and analyze the issues in these guidelines. Then, we propose our own benefit-based guidelines.

6.1. Existing Guidelines

Two of the reviews [18,21] provided guidelines to help decide whether a blockchain-based solution is appropriate for smart grid applications. While there are merits in both guidelines, we identify several issues, which are discussed below.

In [18], four criteria were used to determine whether blockchain technology is a good fit:

1. If multiple parties submit data, blockchain technology might be useful.
2. If a centralized trusted entity is required, blockchain technology is not a good fit.
3. If transparency is required, blockchain technology would be useful.
4. If the data should be made immutable (i.e., tamper-proof), blockchain technology would be useful.

It is unclear to us why the first criterion exists because a traditional database-based system can certainly support multiple users that inject data into the system. The second criterion is also unnecessary. The blockchain system could still be useful in some cases, even if the application depends on a centralized trusted entity. The third criterion is relevant. Transparency is typically considered a benefit of using blockchain technology because the data on the blockchain are visible to the public (because anyone could join the system and receive a copy of the blockchain in a public blockchain system). Although transparency may be considered a criterion, it is not the most important one. The last criterion listed, i.e., data immutability, is the most prominent feature of (public) blockchain technology, and, therefore, should be used as the number one criterion for deciding whether a blockchain is a good fit.

Several other factors were identified to help decide the type of blockchain (i.e., blockchain bridge, layer-2 blockchain, permissioned or permissionless blockchain) to be used. We list these factors and comment on them below:

- If interoperability is required, then a blockchain bridge should be used. We suppose that interoperability means the use of multiple different blockchain systems. Although it is indeed desirable to not be tied to a specific blockchain platform, we caution against the use of a third-party bridge because the bridge implementation must be decentralized on its own. Otherwise, the bridge could become a single point of failure, and it may also become the most vulnerable component of the system. Furthermore, despite the fact that there are thousands of cryptocurrency systems, only Bitcoin and Ethereum are large enough to offer strong data immutability protection. If Turing-Complete smart contracts are needed, then the only choice is Ethereum. Hence, the choices are very limited.

- If high scalability is required, then a layer-2 blockchain solution such as Polygon should be considered. Polygon runs an internal consensus based on the PBFT protocol and relies on Ethereum for data immutability. Essentially, Polygon integrates a private blockchain and a public blockchain. Most data are stored in the private blockchain. This approach is sound. However, we do have concerns about the reliability and robustness of the PBFT implementation because traditional distributed consensus has its intrinsic issues due to its reliance on membership and multiple-round voting [43].
- If the data placed on the blockchain should be kept confidential, then a permissioned blockchain should be used. In our opinion, this recommendation is not sound. First, if one needs data immutability, then a permissioned blockchain alone is not appropriate because the permissioned blockchain cannot offer data immutability protection. Second, data confidentiality can be easily satisfied by encrypting data using a permissionless blockchain system. A hybrid layer-2 blockchain solution may also be appropriate.

The guidelines provided by [21] also offer a set of criteria to decide whether blockchain technology would be a good fit, as well as some other factors related to the type of blockchain to be used. We list the criteria and comment on them below:

- If using a central operator would create a problem, blockchain technology could be a good fit. Using a central operator has inherent problems because the operator could constitute a single point of failure (hardware faults, software bugs, and operator errors). Hence, decentralization is desirable. That being said, one should not use decentralization for the sake of decentralization. One must consider whether other benefits of the blockchain are desirable for the application.
- If the transparency of the data is required, blockchain technology would be a good fit. That being said, the factors outlined for determining the type of blockchain to be used conflict with this criterion because a permissioned blockchain may not be available for the public to inspect.
- The last criterion concerns whether transactions are validated by many players. Although this is a very interesting viewpoint related to whether blockchain technology would be a good fit, we strongly disagree with using this criterion. The benefits offered by blockchain technology are not simply due to the existence of many players validating the transactions. The benefits result from several innovative mechanisms combined. The most important of all is the decentralized consensus algorithm—proof of work. These innovative mechanisms together create a barrier to changing the data placed on the blockchain, which is the foundation for achieving data immutability.

The first additional factor to consider when deciding the type of blockchain to be used is whether all players (that validate transactions) are known. We suppose that this criterion means that all miners (or validators) are pseudo-anonymous, like those in Bitcoin and Ethereum. If not all players are known, then it is recommended to use a permissionless blockchain.

The second additional factor is whether all players (that validate transactions) are trusted. If so, blockchain technology is not recommended. In our opinion, the question should have been whether any of the players are trusted. The design principle of blockchain technology is decentralization, that is, it does not use any trusted entity.

The third additional factor is a follow-up question about whether or not public verifiability is required (only if the answer to the second question is no). If public verifiability is required, then a public permissioned blockchain is recommended; otherwise, a private permissioned blockchain is recommended. We have a serious issue with the differentiation of permissioned blockchains into public or private. By definition, a permissioned blockchain is controlled by an individual or by an institution, or a group of them. As such, the owner(s) would decide what information to disclose, if at all. To achieve truly public verifiability, a permissionless blockchain must be used.

As we argued previously, although the idea of looking at who is validating the transactions sounds interesting, it completely misses the main goal of blockchain technology.

Other than the issues we have pointed out, in both guidelines, the identified criteria are chained together, and a blockchain is recommended if all the criteria are satisfied. In fact, blockchain technology could be useful even if any of the criteria are met.

6.2. Proposed Guidelines

In this section, we propose guidelines for deciding whether blockchain technology should be adopted. Instead of criteria-based guidelines, our guidelines are based on the desirable blockchain features we outlined in Section 3.4. We intentionally omit two composite blockchain features, namely security and trust, because they are based on other specific features. The guidelines are illustrated in Figure 8.

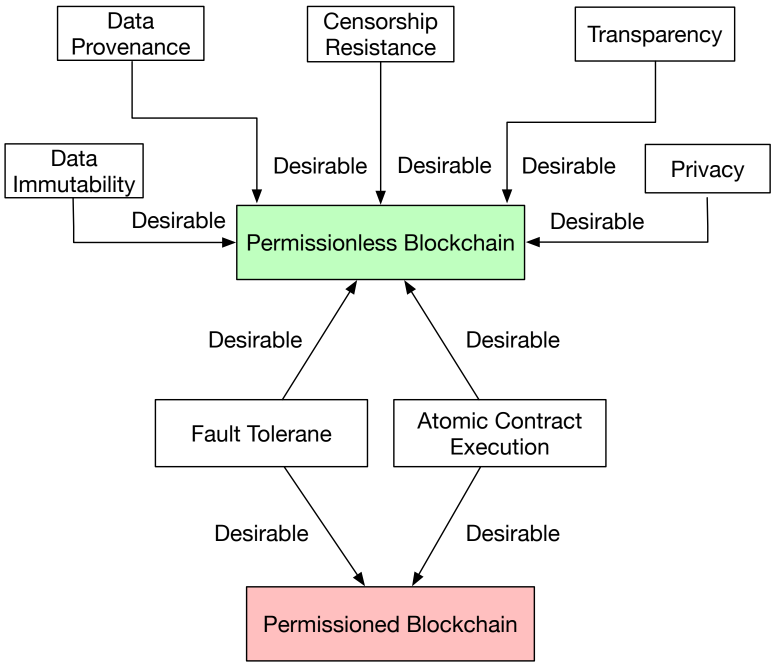

Figure 8. Feature-based guidelines for blockchain adoption.

If any of the following features are desirable, a permissionless blockchain may be used: (1) data immutability; (2) data provenance; (3) censorship resistance; (4) transparency; and (5) privacy. Regardless of whether one finds the above list of features desirable (or essential), if one is looking for a robust solution for fault tolerance (i.e., high availability) and atomic contract execution, either a permissionless or permissioned blockchain may be used.

7. RQ4: Maturity Levels of the Proposed Blockchain-Based Solutions

We propose a scale for evaluating the maturity levels of blockchain applications using the following five stages: (1) conceptual (L1); (2) testing with simulation (L2); (3) testing with experiments in a lab setting (L3); (4) pilot testing in the field (L4); and (5) practical usage (L5), as shown in Figure 9. For the conceptual stage, the requirements of the application and the potential benefits have been analyzed without any validation. For the simulation stage, the feasibility and benefits of the proposed application have been validated using simulation. Because there could be a large gap between the simulation and the actual environment, the simulation results should be taken with caution. For the lab experiment stage, the proposed solution has been validated using a private node or a small set of nodes to emulate an actual blockchain and grid environment. For the pilot testing stage, actual users and/or the components of the electrical grid (such as a microgrid) have been involved. For the practical use stage, the proposed solution has been used in some regions in an actual grid.

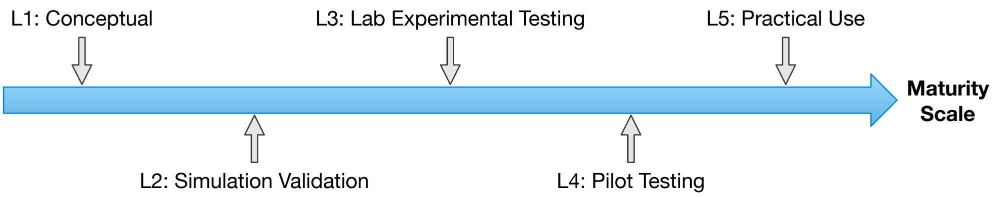

Figure 9. The proposed five-level maturity scale.

7.1. Maturity Levels Reported in the Literature

The systematic reviews rarely indicated the maturity levels of the included studies. We use the maturity levels indicated in [16] as a reference to gauge the overall maturity levels of the research on using blockchains to develop smart grid solutions. The authors' classification of the maturity levels is slightly different from ours. We regard conceptual, case study, and theoretical as L1; simulation as L2; experimental as L3; and real-world case studies as L4. No practical use cases were reported. For some studies, no maturity level was determined, which was excluded from our calculation. Table 4 shows the maturity levels of the projects in each application category.

Table 4. Maturity levels of blockchain applications.

Application Category	LI	L2	L3	L4	L5
Demand Response (12)	3	9	0	0	0
Energy Trading (49)	4	40	4	1	0
Electric Vehicles (22)	0	22	0	0	0
Microgrid (18)	3	14	1	0	0
Smart Grid (11)	2	9	0	0	0
Renewable Energy (3)	0	1	2	0	0
Energy Management (3)	0	3	0	0	0
Total (118)	12 (10.2%)	98 (83.1%)	7 (5.9%)	1 (0.8%)	0

To provide a visual of the current maturity levels of academic-led projects, we show the distribution of the maturity levels of these projects in Figure 10. As can be seen, most of the projects are in the early development stages.

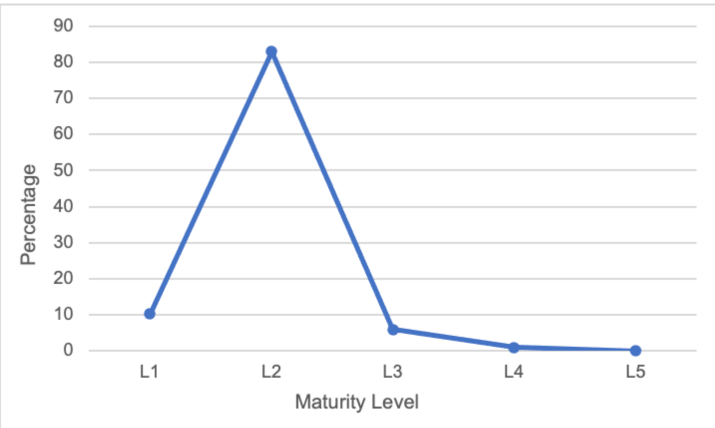

Figure 10. The distribution of maturity levels of academic-led blockchain projects for smart grids.

7.2. Maturity Levels of Industry-Led Projects

Several systematic reviews [13,21,31,38] included a list of industry-led projects. We investigated the current status of these projects and report the findings here. We separate the projects into two categories: (1) active as of the writing of this paper; and (2) inactive as of the writing of this paper. We identified 10 active projects and 12 inactive projects. Although there were several more inactive projects mentioned in the literature, we chose to omit them due to a lack of specific technical information and supporting websites in English for the projects.

As can be seen in this section, only a single project was ranked at the highest maturity level, L5. This project takes a very different approach from most other projects by encouraging businesses to invest in more energy-efficient operations and offering them Ethereum-based custom tokens as a form of incentive. In this project, a blockchain is not used to directly help solve problems in smart grid operations, and it uses the biggest blockchain system that supports smart contracts. This is the main reason why it is successful and sustainable.

7.2.1. Active Projects

The active projects are summarized in Table 5. The determination of the activeness and maturity level of each project was mostly based on the projects' websites.

Table 5. Maturity levels of active industry-led blockchain projects.

Project	Purpose	Website	Maturity Level
EFFORCE	Incentivize energy efficiency	https://efforce.io, accessed on 1 August 2023	L5
Greeneum	Green certificate trading	https://www.greeneum.net/, accessed on 1 August 2023	L4
Powerledger	Energy trading	https://www.powerledger.io, accessed on 1 August 2023	L3+
Energy Web	Blockchain-based smart grid	https://www.energyweb.org, accessed on 1 August 2023	L3
Block-Z	Renewable energy matching	https://www.blok-z.com, accessed on 1 August 2023	L3
GridSingularity	Energy exchange	https://gridsingularity.com, accessed on 1 August 2023	L3
SolarCoin	Incentivize solar energy	https://solarcoin.org/, accessed on 1 August 2023	L3
NRGcoin	Incentivize green energy	https://nrgcoin.org, accessed on 1 August 2023	L3
Presume	Energy data management	https://prosume.io, accessed on 1 August 2023	L1

The EFFORCE project has a dedicated website [53]. The goal of the project is to create a blockchain-based platform for improving energy efficiency. The project's white paper [54] claims that the company was co-founded by Steve Wozniak, and in its 8 years of operation, it has saved 2000 clients over USD 700 million. The project awards its clients tokens if they improve energy efficiency in their operations (enforced by a smart contract). The EFFORCE tokens are ERC-20-compliant tokens running on an Ethereum blockchain. Based on the reputation of Ethereum and the savings stated in the white paper, we rank this project at L5. The approach taken by the project is sound both from a technical and business perspective. Unlike many other projects, this project avoids recreating the wheel and uses the largest public blockchain that supports smart contracts.

The Greeneum project has a dedicated website [55]. The goal of the project is to enable carbon credits and green certificate trading using blockchain technology. Unfortunately, no technical details are disclosed. One would have to complete a form to request a white paper. From the blogs posted on the website, the project is clearly active. Also, according to the website, it has conducted a successful pilot program in Israel. Hence, we rank this project at maturity level L4.

The Powerledger project aims to create a blockchain-based peer-to-peer energy trading platform in Vietnam. The project has a dedicated website [56] and offers a white paper (last updated in 2019) to explain the project's goal and technical design [57]. No GitHub repository could be found for the source code of the project. Hence, the technical content of the project cannot be examined directly. According to the white paper, this project uses a hybrid approach, where both Ethereum and a consortium blockchain are used together. Ethereum is used to support the management of the project's custom tokens, and the consortium blockchain is used to support the smart contract and transaction operations via state channels. In theory, this combination offers extremely high throughput while preserving trust at the Ethereum level. The project goal, as stated in the white paper, is to transition to a public proof-of-state blockchain. Due to the lack of access to the project's source code, it is difficult to assess its maturity level. It is safe to speculate that the maturity level would be at least at L3, but it could be at a higher maturity level.

The Energy Web Project has an active website [58] and a GitHub repository [59]. The goal of the Energy Web project is to accelerate energy transition using blockchain technology. Example applications include managing user assets; facilitating data exchange; and registering, tracking, and trading low-carbon products. The project started in early 2017 and the application-side development appears to be active. The design is reasonably well-documented in a white paper [60]. Instead of using a large public blockchain such as Bitcoin or Ethereum, the project plans to develop a permissioned chain using a validator-based consensus algorithm for faster consensus. Unfortunately, this design has two serious issues: (1) it is a centralized control system rather than a decentralized system; and (2) the claim about the immutability of its smart contracts is unfounded because the proposed design does not have any mechanism to prevent the owner of the project from making changes to the smart contract and the blockchain. According to the project's Telegram channel announcement, the development of the proposed energy web chain is still in the alpha testing phase. Nevertheless, it is an active project at the L3 level.

Block-Z is a startup company specializing in renewable energy matching based on blockchain technology. The company's website [61] does not disclose any technical details regarding the underlying blockchain technology. One of the advertised products is a managed blockchain, which is concerning because a managed blockchain is, by definition, a permissioned blockchain. The usefulness of a permissioned blockchain is very limited because it does not offer data immutability or a higher level of trust compared to traditional centralized control systems. From the company's GitHub repository [62], it appears that it is associated with the Energy Web project. The project appears to be active. Although the website does not contain sufficient information regarding its maturity level, we speculate that it is at L3 due to its association with the Energy Web project.

The GridSingularity project [63] uses Energy Web's chain as the underlying blockchain layer for energy exchange. The technical details are provided on a separate website [64]. The GridSingularity project announced that it has recently received a new European Union research and development fund to further its mission. Hence, this is an active project and we rank it at the L3 level.

The SolarCoin project aims to incentivize the use of solar energy, where solar users can register and claim tokens offered by a custom-made blockchain called SolarCoin. The project has a dedicated website [65] and SolarCoin's legacy source code is available on GitHub (https://github.com/solarcoin, accessed on 1 August 2023). In 2021, the project decided to switch to Energy Web's chain according to an online article [66] and SolarCoin ceased operation. Hence, we would rank the maturity level of the SolarCoin project the same as that of the Energy Web Foundation project at L3.

The NRGcoin is a project that aims to promote the consumption of green energy (the user would be awarded 1 NRGcoin per kWh consumed) and reward prosumers for generating green energy. The project has a dedicated website [67]. According to the documents posted on the website, NRGcoin uses custom tokens based on Ethereum smart contracts. The project grew out of the AI lab of the Vrije Universities, Brussels [68]. Although the idea is compelling, it does not appear that the project has been embraced by the energy industry. Hence, we rank the project at the L3 level.

The Prosume project aims to offer a blockchain-based energy data management platform. The project has a dedicated website [69], which provides a presentation deck [70]. According to the deck, the project will provide decentralized governance and ensure data immutability. Unfortunately, no further technical details are provided, let alone the project source code. Hence, we can only speculate that the project is still in the conceptual stage (i.e., L1).

To show the overall distribution of the maturity levels of active industry-led blockchain projects for smart grids, we plot the distribution of their maturity levels in Figure 11. As can be seen, industry-led blockchain projects have attained higher levels of maturity compared to academic-led projects. That being said, there are still very few projects (in fact, only one) that have been deployed for practical use.

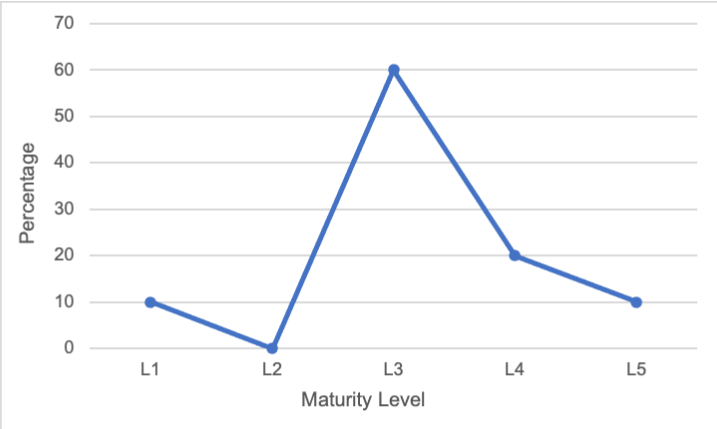

Figure 11. The distribution of maturity levels in industry-led blockchain projects for smart grids.

7.2.2. Inactive Projects

The inactive projects are summarized in Table 6. The websites for some of these projects are still available. However, the websites for other inactive projects are no longer accessible. As a result, we could find little information regarding the latter projects. Hence, the maturity levels of some inactive projects cannot be determined due to a lack of information.

Table 6. Maturity levels of inactive industry-led blockchain projects.

Project	Purpose	Website	Maturity Level
Brooklyn microgrid	Solar energy marketplace	https://www.brooklyn.energy, accessed on 1 August 2023	L4
Electron	Digital energy marketplace	https://electron.net, accessed on 1 August 2023	L4
Electrify	Energy trading	https://electrify.asia/, accessed on 1 August 2023	L4
PylonCoin	Blockchain for the energy industry	https://pylon.network/, accessed on 1 August 2023	L3

Table 6. *Cont.*

Project	Purpose	Website	Maturity Level
Enerchain	Energy trading	https://enerchain.ponton.de/index.php, accessed on 1 August 2023	L3
WePower	Energy trading	https://wepower.network/, accessed on 1 August 2023	L1
Nimray	Incentivize solar energy	https://nimray.com/index.html, accessed on 1 August 2023	L1
Innogy	Energy market	http://www.innogy.com/, accessed on 1 August 2023	n.a.
GridPlus	Energy trading	n.a.	n.a.
Share and Charge	Electric vehicle charging	n.a.	n.a.
Bankymoon	Electric vehicle charging	n.a.	n.a.
Energy Labs	Decentralized autonomous energy communities	n.a.	n.a.

The aim of the Brooklyn Microgrid project was to create a locally-generated solar energy marketplace. The project has a dedicated website [71]. The website discloses less information compared to the Powerledger project. Based on the fact that neither the provided link for the parent company who sponsored this project, LO3 Energy [72], nor the website that is supposed to contain more technical information are accessible or active, we can conclude that the project is no longer active. According to [73], which reported the Brooklyn Microgrid and TransActive Grid projects as case studies (the Brooklyn Microgrid project was running on top of the TransActive Grid platform), we rank the project at L4 when it was active.

The goal of the Electron project was to create a digital energy marketplace. The project has a dedicated website [74]. The current website does not reveal any technical details. According to [13], Electron used Ethereum and had been used to support energy trading for a demand-side response to manage energy data assets and improve smart meter data privacy. According to the timeline provided in [74], the Electron project started in 2015 and concluded in 2020. It appears that the project is no longer active. Nevertheless, the website listed several pilot projects that have been completed. Therefore, we rank the maturity level of this project at L4.

The Electrify project has a dedicated website [75]. The website claims that peer-to-peer energy trading is powered by blockchain technology. According to the website, the company conducted a successful initial coin offering in 2018. Furthermore, the website reports that a pilot for peer-to-peer energy trading with 15 participants was successfully conducted in the first quarter of 2019. Unfortunately, no technical details about blockchain technology are disclosed. The most recent news posted on the website was on 18 May 2021. There is no indication that the blockchain-based project is active as of 2023. Nevertheless, we rank the maturity level of the project at L4 (when it was active).

The Pylon Network Blockchain (i.e., PylonCoin) was positioned to be the first open-source blockchain designed for the energy sector. The project has a dedicated website [76], and its source code is available on GitHub [77]. The project has a white paper [78] that elaborates on the project's goal and its high-level design specification. From the block explorer of PylonCoin [79], it is clear that the blockchain has ceased operation because the latest block was created on 13 December 2021, and the last few blocks each contain a single transaction. Hence, we conclude that this project is at the L3 level, and it is no longer in operation.

The Enerchain project has a dedicated website [80]. The project's goal was to enable and promote decentralized energy trading. The website claims that Enerchain 1.0 went live in May 2019. The website contains strong evidence that the project was once very active, with a proof-of-concept demonstration and sponsorship of hackathons. However, few technical details have been disclosed. The project claimed to use the WRMHL blockchain framework, which appears to be a permissioned blockchain. There is no strong evidence that the project is still active. We rank this project at L3.

The WePower Network project intended to create a blockchain platform for decentralized energy trading. However, the project's website is no longer active [81]. The GitHub source-code repository [82] only contains a collection of smart contracts. The CoinMarketCap website is still tracking WePower, but its total market cap is less than USD 170,000, far less than what the project received in its initial coin offerings, as reported in [83]. Hence, it is clear that this project is no longer active, and we rank this project at the conceptual level (L1).

The Nimray project aimed to promote solar energy with a blockchain-based platform. It has a dedicated website [84]. According to the website, the company conducted an initial coin offering during the last two months of 2019. It is unclear if the initial coin offering was successful. From the posts on the website, it appears that all activities occurred before the initial coin offering. There is no evidence that the project conducted any pilots. Hence, we suspect that the project is no longer active, and the maturity level is most likely at the L1 stage.

According to [13], Innogy once announced plans to develop a blockchain-based energy market. A search for "Innogy blockchain" returned several news reports published in 2018. Innogy was acquired by another German company, E.ON, in 2018–2019. The company website for Innogy [85] is automatically directed to E.ON. Since the latter is in German, no relevant information can be extracted. Due to the lack of concrete evidence for any real outcomes, we conclude that the project is no longer active.

The GridPlus project was mentioned in [38] as a platform for decentralized energy trading. Unfortunately, our check of the referred website [86] showed that the project is no longer active. The website is now about hardware wallets for cryptocurrencies, and it has nothing to do with energy trading. We do not have any information about whether this project was once active.

The Share and Charge project was mentioned in [31,38]. The project was supposed to develop a platform for electric vehicle charging. The referenced website is no longer available. Apparently, the project is no longer active. It is unclear whether the project was once active.

The goal of the Bankymoon project was to allow electricity consumers to pay for electricity using Bitcoin. Unfortunately, the project's website [87] is not accessible. Apparently, the project is no longer active.

The Energy Labs project was listed in [13] as one of the many projects that would incorporate blockchain technology. The stated goal of the project was to create decentralized, autonomous energy communities. Unfortunately, the project's website [88] is no longer available. Hence, we conclude that the project is no longer active.

8. RQ5: Open Research Issues

Most reviews included a section on open research issues or the limitations of blockchain-based solutions for smart grids. While the open research issues were identified from different perspectives, they were more or less consistent with each other. The limited throughput of large public blockchains (such as Bitcoin) and the delay in confirming a transaction were the most well-identified issues. Some studies also singled out privacy and security issues, whereas others pointed out the financial costs of running smart contracts. One of the studies [30] was dedicated to discussing the potential issues of adopting blockchain-based solutions in smart grids, and the authors essentially provided a superset of the open research issues. Hence, in this section, we focus on analyzing the issues identified in [30]. In [30], the issues were referred to as the barriers to adopting blockchain-based decentralized energy trading. The barriers (i.e., open research issues) were divided into technical, administrative, standardization, and economic barriers.

Four technical barriers were identified, including scalability, privacy, security, and interoperability. It is well known that the throughput in terms of transactions settled per second is very limited in blockchain systems compared to traditional centralized systems. The limited throughput is typically referred to as the scalability problem of blockchain technology. Many so-called lightweight blockchain systems have been proposed. Unfortunately, the limited throughput is intrinsic to blockchain design because a decentralized system must incorporate self-enacted protection mechanisms. The security and trust of blockchains primarily rely on two closely related innovations: (1) decentralized consensus, where all nodes maintain an identical copy of the transaction history (referred to as the ledger); and (2) a self-enacted barrier to prevent changing the data on the ledger. Achieving these goals would require the participation of a large number of independent nodes and sufficient time for reaching a consensus. It turns out that the cost of reaching a consensus constitutes a barrier to modifying the data on the ledger, which is the foundation of the security of a blockchain system. If a consensus can be reached very easily with very little effort and time (which means high throughput of the system), then what would prevent some adversary from changing the data on the ledger? Without security and trust, the proposed lightweight system would be useless because the strongest incentive to use a blockchain-based solution is to render the data placed on the ledger immutable (i.e., tamper-proof).

Nevertheless, the limited system throughput indeed imposes a barrier to adopting blockchain technology if one wishes to store all data on the blockchain. Fortunately, many effective solutions have been proposed to work around the issue of limited throughput. A common theme in these solutions is to store the raw data generated and exchanged in the smart grid outside the blockchain, for example, in the Inter-Planetary File System (IPFS), which is a decentralized replicated file system, and to only record the fingerprint of a batch of data on the blockchain [51]. This way, the throughput demand on the blockchain is significantly reduced, as shown in Figure 12. Another solution is to use what is referred to as a layer-2 blockchain, such as Polygon.

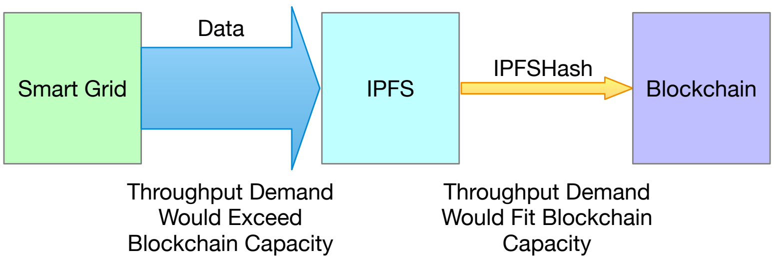

Figure 12. The throughput demand can be drastically reduced by storing the fingerprint of each batch of raw data (such as the IPFS hash) on the blockchain while saving the original raw data off-chain, such as in an IPFS.

We do not think privacy would constitute a barrier to adopting blockchain technology in smart grids because compared to the traditional (centralized) approach, blockchain technology is equipped to provide much better privacy protection for its users. It is unclear why it is desirable to offer a privacy level beyond the pseudo-anonymity provided by blockchain technology.

It is always a challenge to develop a secure system, regardless of whether a blockchain is used. However, a blockchain (actually, only a large public blockchain system) offers a unique property—data immutability (i.e., the data are tamper-proof)—that is not possible in traditional centralized approaches. This property can be used to store critical information about the security of a system, such as authentication data. Previously, we demonstrated that by using a blockchain-based sensor identification and authentication scheme for fossil fuel power plants, a large array of identity-based cyberattacks can be mitigated [52]. Hence, we do not regard security as a technical barrier to adopting a blockchain. In fact, a blockchain would offer developers a suite of primitives to build a more secure application compared to traditional approaches.

Interoperability could be an issue if one does not wish to be tied to a particular blockchain platform. That being said, if smart contracts must be used, then Ethereum is the only large public blockchain that offers this feature. As a side note, we have strong concerns about the use of private or consortium blockchains (such as Hyperledger) if data immutability is desired by the application.

The administrative barrier refers to the uncertainties of governmental regulations, particularly in different countries. There is also a lack of standards regarding blockchain applications in smart grids. However, many efforts are currently taking place toward standardization. For example, the IEEE standards association has formed an IEEE blockchain conformity assessment program that aims to develop blockchain and distributed ledger standards. That being said, we caution against developing standards prematurely without first gaining sufficient experience, considering that the maturity levels of blockchain-based solutions for smart grids are rather low.

The economic barrier mentioned in [30] is related to concerns about the block reward model in Bitcoin. In our opinion, this concern is misplaced because large public blockchains such as Bitcoin and Ethereum have proven to grow in terms of the number of mining nodes (i.e., the built-in incentive mechanism is working), and as such, smart grid applications do not need to worry about not being able to attract miners. That being said, the increase in the value of ETH makes the transaction fee in Ethereum more costly, which could constitute an economic barrier to the adoption of blockchain technology due to the high cost.

9. Discussion

In this section, we summarize our findings, acknowledge the limitations of the current study, and provide some future prospects.

9.1. Findings

This umbrella review was guided by five research questions. The first research question concerned the types of blockchain-based smart grid applications. The existing systematic reviews rarely used a systematic method to classify these applications. To address this issue, we proposed a taxonomy for these applications, first, by differentiating them based on whether the application's focus was on functional or non-functional aspects, and then by the specific functions or perspectives that the application aimed to implement or enhance. Blockchain-based applications have been developed to address functional needs in all aspects of smart grid operations, including grid operation and management, energy markets (wholesale, local, and retail), metering and billing, and the management and trading of green certificates and carbon credits. Blockchain-enabled decentralized peer-to-peer energy trading has been pervasively used to support energy markets and grid operations. In particular, energy trading has been found to be a practical method for integrating renewable energy sources into the traditional grid, and it has also been found to be essential for demand-side response management to help balance demand and supply. Additionally, energy trading has been found to be critical for addressing the issues in electric vehicle charging and the integration of electric vehicles as an energy source.

The second research question concerned the roles that the blockchain plays in smart grid applications. We synthesized the findings by identifying the most prominent benefits that blockchain technology could bring to these applications, namely data immutability, transparency, smart contracts, and security. We also took the opportunity to highlight several common technical inaccuracies that were pervasive in the blockchain literature. The most common inaccuracy was equating blockchains to data immutability. It is important to understand data immutability is not solely achieved via the use of cryptography.

Although a transaction protected by a digital signature cannot be changed without being detected, an adversary could create a new fork off the main chain and exclude one or more particular transactions in the new fork. A public blockchain has a built-in mechanism to enact a barrier to prevent such an attack (typically referred to as the 51% attack or the double-spending attack). The larger the number of nodes that participate in the mining competition, the higher the barrier. The proof-of-work decentralized consensus algorithm, in conjunction with a network consisting of a large number of independent mining nodes, is what it takes to ensure data immutability. Hence, the use of any permissioned blockchain would mean that data immutability cannot be guaranteed because the owner could arbitrarily include or exclude nodes from the system.

The third research question concerned the guidelines used to decide whether a blockchain-based solution could be used to address the needs of smart grids. Two systematic reviews included a section on guidelines. While each set of guidelines had merits, we noticed some technical inaccuracies in these guidelines. For example, one of the criteria was data immutability; if data immutability is desirable, then a blockchain is recommended. Unfortunately, subsequent criteria were provided to help decide whether a permissioned or permissioned blockchain should be used. As we pointed out several times in this article, data immutability cannot be guaranteed by a permissioned blockchain. Hence, we proposed a set of benefit-based guidelines to address the issues found in the existing guidelines.

The fourth research question concerned the maturity levels of blockchain-based applications. Our findings revealed that most blockchain-based projects were in the preliminary stages. Despite the large number of blockchain-based projects reported in the literature, they did not prove to be practical or sustainable. To classify the blockchain-based projects for smart grids, we introduced a five-stage maturity-level scale: conceptual (L1); simulation (L2); experiments in a lab setting (L3); pilot testing in the field (L4); and practical usage (L5). We were able to identify only a single project at an L5 maturity level. Furthermore, more than half of the industry-led projects reported in the literature are no longer active. This demonstrated that the proposed projects were not adequately self-sustainable, i.e., once the grant had been spent, the project ended.

The fifth research question concerned the open research issues in developing blockchain-based smart grid applications. Several common issues with blockchain technology have been identified, including the limited throughput, the energy cost of reaching a decentralized consensus, and the financial cost of running smart contracts. One of the systematic reviews we included in our study was dedicated to identifying barriers to adopting blockchain technology in smart grid applications. The barriers were essentially another way of expressing open research issues. We analyzed the barriers identified in the aforementioned paper and provided our opinions.

9.2. Limitations of Our Study

The depth of each topic covered in this umbrella review could have been deeper. For each research question, the review could have been strengthened by conducting a separate comprehensive literature search and identifying recent studies that had not yet been included or adequately discussed in the comprehensive reviews we considered. Furthermore, this review could have been enhanced by conducting a thorough search of industry-led blockchain projects for smart grids. Although we included some industry-led projects, it is likely that we omitted some recent efforts. Yet another task that could have been carried out was a compilation and analysis of smart contracts used for blockchain applications in smart grids, as smart contracts play a predominant role in blockchain-based smart grid applications. Such a task could be instrumental in the future development of blockchain applications in smart grids.

9.3. Future Prospects

Layer-2 blockchains, such as Polygon and Energy Web, are becoming an industry trend. These blockchains rely on Ethereum smart contracts as the foundation for a higher-layer blockchain operation, such as determining the set of validators and a particular application-specific blockchain. In layer-2 blockchains, transactions can be performed faster and with fewer costs compared to Ethereum or Bitcoin, which addresses a major concern of blockchain technology, i.e., its low efficiency as reflected by the small number of transactions per section. That being said, the security, trustworthiness, and reliability of layer-2 blockchains should be further analyzed.

Furthermore, the integration of other digital technologies, such as the Internet of Things and machine learning, could also lead to more practical and sustainable smart grid applications.

10. Conclusions

In this article, we presented an umbrella review of blockchain-based smart grid applications. Although umbrella reviews are reasonably popular in the field of medicine and healthcare, they are rarely seen in other fields. In this article, we demonstrated that performing an umbrella review could help us gain deeper insights into how to develop successful blockchain-based smart grid applications, considering that there are already numerous systematic reviews on this topic. These systematic reviews were performed from the authors' own perspectives. By synthesizing the findings of these reviews, we were able to present a more comprehensive and deeper understanding of this field.

Prior to reporting our findings, we provided a concise and authoritative description of blockchain technology in a separate section because many technical inaccuracies permeated much of the literature. The most problematic mistake was the claim that data immutability can be achieved by all forms of blockchains, i.e., public, private, and consortium blockchains. In fact, this is far from the truth. Even a small public blockchain could easily be compromised by a double-spending attack, let alone private or consortium blockchains. We hope this umbrella review will guide future research in blockchain-based applications.

One particular finding in this study was that layer-2 blockchains, such as Polygon and Energy Web, appear to address the limited throughput problem of traditional blockchains while preserving the highly desirable properties of data immutability. Layer-2 blockchains are becoming the platform of choice for decentralized application development.

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Abbreviations

The following abbreviations are used in this manuscript:

DApps	Decentralized Applications
DAO	Decentralized Autonomous Organization
IPFS	Inter-Planetary File System
PBFT	Practical Fault-Tolerance Protocol
PUF	Physical Unclonable Function

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