energies

Review

Smart Contract Design in Distributed Energy Systems: A Systematic Review

Kimia Honari [1], Sara Rouhani [2], Nida E. Falak [1], Yuan Liu [1], Yunwei Li [1,*], Hao Liang [1], Scott Dick [1,*] and James Miller [1]

[1] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 2R3, Canada; honari@ualberta.ca (K.H.); nidaefal@ualberta.ca (N.E.F.); yuan17@ualberta.ca (Y.L.); hao2@ualberta.ca (H.L.); jimm@ualberta.ca (J.M.)

[2] Department of Computer Science, University of Manitoba, Winnipeg, MB R3T 2N2, Canada; sara.rouhani@umanitoba.ca

* Correspondence: yunwei.li@ualberta.ca (Y.L.); sdick@ualberta.ca (S.D.)

Abstract: Blockchain technology and, in particular, smart contracts based on it, offers a new, decentralized mechanism for entering into and fulfilling contracts in diverse markets. Energy markets are no exception, and indeed, the decentralized nature of the blockchain may be particularly important for them as the penetration of residential prosumers offering microgeneration to the grid grows. At this time, however, the literature on smart contracts in energy markets—and particularly their interaction with the technical infrastructure of the smart grid—is limited and scattered. There is a need to consolidate these studies into a comprehensive understanding of the state-of-the-art in smart contract design for the smart grid. However, no existing reviews focus on smart contracts in energy systems. The scope of our study is the role of smart contracts in energy systems and what limitations they encounter. We conduct a systematic review of this topic, focusing on systems that have been implemented as prototypes. These studies provide key evidence on the scalability of smart contracts for energy systems and their interaction with the technical elements of the smart grid. We selected a pool of 76 papers meeting our criteria, with three others excluded for misinterpreting fundamental aspects of blockchains and smart contracts. After reviewing each paper, we found that this literature falls into four categories: market operations, ancillary services, auditing and monitoring, and cybersecurity. We then identify and examine the cross-cutting concerns of data storage in and interoperability between blockchains. We finally discuss the implications of our findings for future research. In particular, there is likely to be a complex interplay between the data generated and stored via the blockchain versus the data required to meet energy system reliability targets and market obligations for participants.

Keywords: energy systems; distributed; BC; smart contract; smart grid; energy market

Citation: Honari, K.; Rouhani, S.; Falak, N.E.; Liu, Y.; Li, Y.; Liang, H.; Dick, S.; Miller, J. Smart Contract Design in Distributed Energy Systems: A Systematic Review. *Energies* **2023**, *16*, 4797. https://doi.org/10.3390/en16124797

Academic Editor: Mariano Giuseppe Ippolito

Received: 28 April 2023
Revised: 16 May 2023
Accepted: 25 May 2023
Published: 19 June 2023

1. Introduction

Energy systems today are undergoing tremendous change, as the energy demands of a growing population conflict with the need to decarbonize generation and transmission. The Smart Grid, which leverages Information Technology (IT) to improve energy system efficiencies, is a key response to these needs. Blockchain (BC) technologies, and especially Smart Contracts (SCs), are important frontiers in designing the IT infrastructure of the Smart Grid. A number of studies indicate that they may be suitable for decentralization and distributed management of system resources at multiple layers of the Smart Grid.

A BC is a distributed shared ledger replicated across all nodes in a network, which communicate through a peer-to-peer protocol. Data are attached to this ledger as a group of transactions called blocks, with each block cryptographically linked to the previous one. BCs thus offer immutability, tamper resistance, and data provenance. BCs employ decentralized consensus algorithms to validate transactions and add blocks to the chain. Within a BC, SCs are executable code that implements the logic behind each transaction [1,2]. SCs enable the design of distributed applications based on BCs; they specify how data are read from, analyzed, and written to the BC. In particular, SCs for decentralized energy systems can verify and prepare energy data for the ledger and then analyze the stored data.

BC-based management of energy systems may offer several advantages. Data are protected against loss, tampering, and single points of failure. Security and privacy are enhanced through business rules in the SCs and the inherent features of BCs [3,4], while costs are simultaneously reduced [1]. BCs can allow parties with no history of trusting each other to transact safely without needing guarantors [5]. They can also promote social cohesion and a sense of community, preference satisfaction, and uncertainty reduction [6].

Numerous instances exist where smart contracts have been used in distributed energy systems, with various patents and commercial applications being developed. One such example is Power Ledger [7], an Australian startup that developed a blockchain platform for peer-to-peer energy trading using smart contracts to ensure secure and transparent transactions between energy producers and consumers. Other companies, such as SunContract (https://suncontract.org/, accessed on 25 April 2023) and GridPlus (https://gridplus.io/, accessed on 25 April 2023) have also leveraged blockchain-enabled solutions with smart contracts to enable efficient energy markets and grid management. Iberdrola Group (https://www.iberdrola.com/innovation/blockchain-energy, accessed on 25 April 2023) has initiated a blockchain-based project to trace the source of energy in real-time, and WePower (https://www.blockdata.tech/profiles/wepower, accessed on 25 April 2023) promotes green energy consumption by proposing a blockchain-based platform for green energy trading, allowing renewable energy producers to raise capital by issuing energy tokens that represent the energy they pledge to produce and deliver. Through these tokens, energy producers can sell energy upfront to green energy buyers at rates lower than the market value and, in turn, raise capital.

This systematic review focuses on design patterns of SCs in decentralized energy applications. We examined SC responsibilities, development constraints, and platform customizations for different applications in energy systems, finding that this literature falls into four categories: market operations, ancillary services, auditing and monitoring, and cybersecurity. Most of the studies we review use BCs for peer-to-peer energy trading and market settlement. However, other applications have also been investigated, e.g., supply and demand management [8–11], optimization and control of energy resources [12], and auditing and monitoring [9,13–16]. We found that storage of streaming data and interoperability between different BCs are cross-cutting concerns in all of these applications.

The remainder of this paper is organized as follows. In Section 2, we describe the methodology of our systematic review. In Section 3, we provide essential background on BC technology and SCs. In Section 4, we group the selected literature into four main categories and identify the major research themes within each category. In Section 5, we examine data storage within BC applications. In Section 6, we review interoperability between BCs. We close with a summary and discussion of future work in Section 7.

2. Systematic Review

Systematic reviews are a form of meta-study intended to summarize evidence about a particular technology, identify knowledge gaps in the existing literature of a field, or create a framework for positioning a new proposal within a field. As a meta-study, reproducibility is essential, and so the search techniques to locate papers to be reviewed (the *primary reports*) as well as criteria for including or excluding primary reports from the study need to be transparently presented. In this section, we first review existing surveys that address blockchain applications in the energy systems area, discuss why these surveys do not meet the goals we have outlined for this study, and formally define our research questions. We then present our search strategy and inclusion/exclusion criteria.

Existing reviews have focused on BCs in energy systems [17,18], the cybersecurity implications thereof [19], applications in data analysis, etc. [20]. These are summarized in Table 1. However, no existing review focuses on SCs within energy systems, particularly those designs that have been implemented as prototypes. This latter point is essential, as the performance of an SC interacts in complex ways with the BC network. Empirical performance testing is thus essential in evaluating an SC's suitability for its intended role. Our research questions are thus: (Q1) *For what purposes are SCs deployed in energy systems, and how are they implemented?* and (Q2) *What are the limitations of the BC platforms in (Q1), and how might they be addressed?*

Table 1. Summary of recent reviews on smart energy system.

Peper	Research Focus	Smart Contract
Alladi et al. Blockchain in Smart Grids: A Review on Different Use Cases [17]	Five use cases for blockchains in the Smart Grid are identified. For each one, a suggested blockchain architecture and key data items needed for transactions in this use case are discussed. The authors then review existing blockchain solutions for one use case (P2P energy trading) and the subtopic of using virtual currencies for energy payments.	Smart contracts are discussed as enabling technologies for elements of the five use cases, but there is no detailed review of the design or implementation of the SCs.
Zhang et al. Big data analytics in smart grids: a review [20]	Review of big data analytics algorithms and their application in the Smart Grid. Does not review blockchains, but does discuss machine-learning approaches for power quality monitoring, renewables integration, and theft detection that may compete with blockchain technologies.	-
Ali et al. State-of-the-Art Artificial Intelligence Techniques for Distributed Smart Grids: A Review [21]	Review of AI algorithms and their application in the Smart Grid. Does not review blockchains, but does discuss machine-learning approaches for power-flow optimization, renewables and distributed generation integration, energy storage integration, and theft detection that may compete with blockchain technologies.	-
Kushch et al. A review of the applications of the Block-chain technology in smart devices and distributed renewable energy grids [22]	Reviews developments in solar photovoltaic, advanced metering infrastructure, and blockchain technologies in power engineering. The blockchain use cases studied were renewable energy credits and peer-to-peer energy trading.	Smart contracts were only briefly mentioned, not reviewed.
Andoni et al. Blockchain technology in the energy sector: A systematic review of challenges and opportunities [18]	Conducts a systematic review of 140 blockchain research projects and initiatives undertaken by companies and research organizations in the energy sector.	Smart contracts identified in P2P and wholesale energy trading, microgrid management, renewable energy credit trading, virtual currency payments, EV charging, automated billing, and consumer mobility between power providers.
Bao et al. A Survey of Blockchain Applications in the Energy Sector [23]	Reviews blockchain applications in the energy sector. Use cases include P2P energy trading, distributed grid control, EV charging, carbon offset trading, and renewable energy credit trading. Blockchains provide privacy protection for all use cases.	Smart contracts were a key realization of blockchain technology, but they are treated as synonymous to blockchains. The particular characteristics of SCs are not discussed.
Abdella et al. Peer to peer distributed energy trading in smart grids: A survey [24]	Reviews possible P2P energy trading architectures, including the Energy Internet, cooperative models, and game-theoretic models. Blockchains were cited as a possible enabling technology for P2P trading.	Smart contracts were mentioned, but no specific use cases suggested.

Table 1. *Cont.*

Peper	Research Focus	Smart Contract
Mollah et al. Blockchain for future smart grid: A comprehensive survey [25]	Review of blockchain approaches to mitigating security and privacy risks in the Energy Internet. Use cases include EV charging, P2P energy trading, advanced metering infrastructure, cyber–physical systems for energy, and microgrid management.	Smart contracts were only briefly mentioned as enabling “secure script deployment”. Otherwise they are treated as synonymous with blockchains.
Zhuang et al. Blockchain for cybersecurity in smart grid: A comprehensive survey [19]	Reviews blockchains as a solution to the cybersecurity challenges of the existing Smart Grid. Use cases include in-field sensing and control, data aggregation, data management, and system operation.	Focuses on smart contracts as a secure environment for deploying smart grid capabilities as distributed applications.

To address (Q1), we conducted a systematic review [26] of SCs in energy systems. We searched Google Scholar using four sets of keywords: “Energy System Blockchain”, “Energy System Smart Contract”, “Smart Grid Blockchain”, and “Smart Grid Smart Contract”. Our inclusion criterion was that a study must present both the design and implementation of the SCs. Papers that offered incorrect technical details on BC or SC technologies were excluded. From a pool of 79 in-scope primary reports, we excluded three papers due to inaccurate assumptions about BC fundamentals and SCs. Table A1 in online Appendix A further characterizes the selected papers. To address (Q2), we took note of how each study in (Q1) addressed known challenges in SC design. We found that challenges around on-chain data storage and BC interoperability consistently arose; we discuss them and some possible solutions in Sections 5 and 6, respectively.

3. Background

Understanding electrical power systems and their planning and operations is essential to comprehending how blockchain technology and smart contracts can be utilized in energy systems to enhance their efficiency, reliability and security. This section introduces electric power systems and their functioning through planning and operations. We then explore blockchain technology and smart contracts as a potential infrastructure for energy systems.

3.1. Electric Power Systems

Figure 1 is an overview of the electric power system. Bulk generation refers to large electricity generators producing dozens or hundreds of megawatts (MW) from conventional or renewable energy sources. Step-up transformers raise the voltage from 30 kilovolts (kV) at the generator to 230 or 500 kV; this reduces line losses in transmission lines. Power then reaches distribution substations, where step-down transformers bring the voltage down to, e.g., 27.6 or13.8 kV, and power is transmitted to end users via a distribution network. At a residential street, pole-mounted transformers reduce the voltage to 240 V, which is distributed to residences [27].

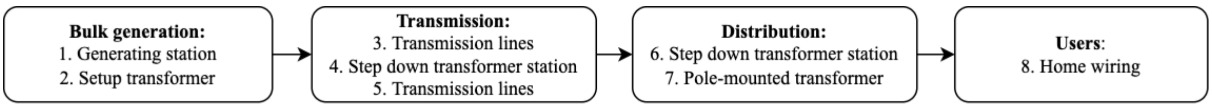

Figure 1. Review of electric power system.

Electric power system planning and operations include: i. system planning, ii. system maintenance, iii. unit commitment, iv. economic dispatch, and v. regulation, control, and protection. These operations are executed at different times [28], as represented in Table 2.

Table 2. Electric power system planning and operation functions.

Function	Time Frame	Smart Contracts
System planning	1–10 years or longer	not applicable
System maintenance	1 week–1 year	The potential can be investigated
Unit commitment	4 h–1 week	Ancillary systems, cyber security, auditing and monitoring
Economic dispatch	10 min–4	Ancillary services
Regulation, control, and protection	10 min or shorter	Ancillary systems, cyber security, auditing and monitoring

3.2. Blockchains

Someone using the pseudonym “Satoshi Nakamoto” introduced Blockchain (BC) and the Bitcoin cryptocurrency in 2008 [29]. A BC is a type of distributed ledger technology, a form of a database stored and maintained by a network of peer nodes. The ledger consists of a linear chain of cryptographically linked "blocks", each containing a collection of transactions (which are thus immutable). Copies of the ledger are kept by each peer. Integrity is ensured through "consensus", by which the peers jointly validate transactions and add them to the ledger. These mechanisms together yield security, immutability, tamper resistance and data provenance for applications in, e.g., energy systems, supply-chain management, and finance.

We first consider the validity of transactions that will be added to a block. The validity of individual transactions or data records in a blockchain are ensured using digital signatures. Technically, a digital signature is an application of asymmetric ("public-key") cryptography. Algorithms in this class use a pair of key values for encryption and decryption; a message encrypted with one key can only be decrypted with the other key. (Explicitly *not* the same one!) Digital signatures work by allowing one of these keys to be publicly known and associated with a person's identity; the other is kept secret. Thus, a message that can be decrypted into a meaningful plaintext by a given person's public key *must* have been encrypted using their private key. Thus, participants who add a transaction to the blockchain generate a digital signature using their unique private key. This signature proves that the transaction is truthful and has been approved by the rightful owner of the private key.

By using their private key, participants mathematically associate their identity with the transaction. Other network participants can verify the transaction's authenticity by employing the corresponding public key, which is accessible to all participants. If the digital signature is valid and matches the transaction data, it assures that the transaction has not been altered.

Figure 2 depicts a generic blockchain along with the contents of a block. The cryptographic hash function $h()$ is the vital element underpinning blockchains. Hash functions, in themselves, are a well-known class of mathematical functions that map a variable-length argument into a fixed-size result. The modulus function is a trivial example; $x \bmod 2$ is 0 or 1 for any integer x. When two different arguments to a hash yield the same result, this is referred to as a collision; practical hashing algorithms are designed to avoid collisions. They are used in, e.g., data storage as a means of performing fast table lookups.

Cryptographic hashes are a subclass of the hash functions with additional properties: it is infeasible (i.e., not possible with any practical amount of computing resources) to determine an input that matches a given hash value, and it is also infeasible to find two inputs that have the same hash value [30]. This obviously implies that, when you produce a hash of some record of information, it is effectively impossible to alter that record without also altering the hash value. This is the reason why cryptographic hashes are important; they prove the integrity of the hashed record.

We can now discuss the basic blockchain depicted in Figure 2. Individual transactions (blocks T1 through T4) are first combined into a "block" that will be added to the blockchain. To do so, the transaction data are hashed, and then the hashes themselves are concatenated and hashed again in a tree pattern until only a single hash remains (technically, this is known as a Merkle tree [31]). This Merkle tree can be efficiently used to prove the integrity of any of the original transaction blocks; it and the transaction blocks form the block data.

The block data are then combined with a block header, which includes the hash of the previous block. This is the complete block to be added to the open end of the blockchain (thus imposing a chronological ordering of transactions recorded in the blockchain). The actual addition of a block is carried out by the consensus mechanism for that blockchain. Once a block B has been added to the chain—and crucially, the *next* block is also added—the hash of B is a part of the header for block B+1. That value is then also part of the hash of block B+1, which is added to block B+2. Continuing on, the hash of B+2 is added to the header of B+3, and so on to the end of the chain. Thus, if an attacker changes the data held in block B, the hash values of *every subsequent block* are also changed. Thus, the attacker's copy of the blockchain will be different from all the other copies of the chain—and will be discarded by the consensus mechanism [1].

Consensus algorithms differ greatly between public and permissioned BCs. Anyone can join the peer network in a public BC (e.g., Bitcoin or Ethereum), and so the consensus must be robust against malicious, colluding insiders without requiring trust amongst peers. Byzantine Fault Tolerance (BFT) algorithms (e.g., Bitcoin's Proof of Work) are usually employed. Conversely, in a permissioned BC (e.g., Hyperledger Fabric (https://hyperledger-fabric.readthedocs.io/, accessed on 25 April 2023) and Corda (https://www.corda.net/, accessed on 25 April 2023)), peers must be authenticated and trusted, so consensus need not employ BFTs.

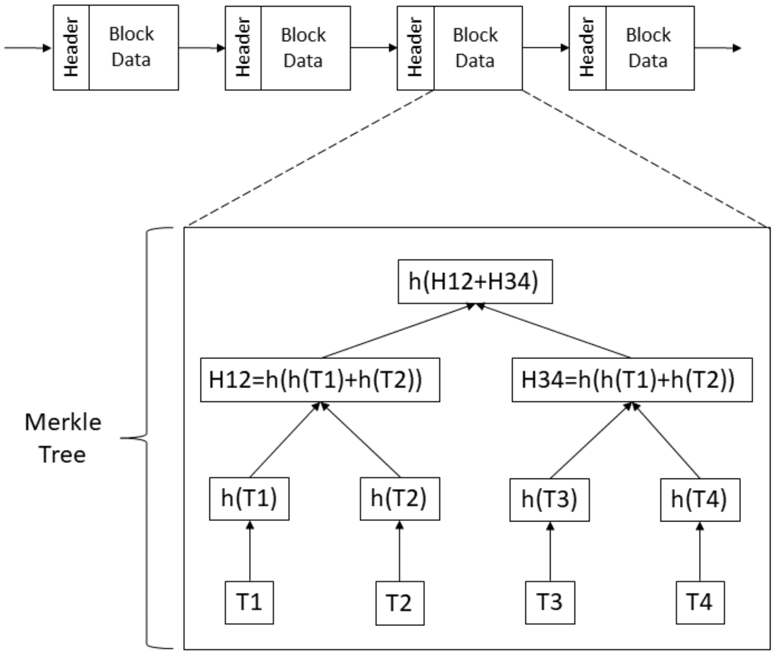

Figure 2. Principal elements of a blockchain.

3.3. Smart Contracts (SCs)

SCs are computer programs that run on the distributed network of a blockchain. They can be written in general-purpose programming languages such as Golang, NodeJs, and Java or specific-purpose programming languages such as Solidity, the first and most popular Turing-complete language for SCs to build Decentralized Applications (DApps). SCs are used to automate various aspects of contract fulfillment and settlement. For instance, in the context of energy systems, SCs are used to facilitate secure and transparent transactions between energy producers and consumers and control the reading, writing, and processing of data on the blockchain ledger.

For example, in a scenario where a homeowner has installed a solar panel system and is willing to sell excess energy back to the grid, an SC could set the agreement terms between the homeowner and the energy provider. The SC's details could be the price and amount of energy, the duration of the agreement, and the conditions for terminating the contract.

Once the involved parties agree upon the terms of the contract, the SC is deployed on the blockchain ledger. When the solar panel system generates excess energy and SC conditions are met, the SC automatically initiates transactions with the energy provider, and consequently, the SC initiates the payment. Since the transaction is recorded on the blockchain ledger, it is secure, transparent, and auditable.

In addition to facilitating transactions, SCs can also be used to dynamically alter the peer network configuration and consensus algorithm of the blockchain. For example, an

SC could be created that adjusts the block size, consensus mechanism, or transaction fees based on the current network dynamics [2].

4. A Review of Smart Contract Design in Energy Systems

This section reviews SC design for energy applications. We found that this literature breaks down into four categories: energy trading markets, ancillary services, auditing and monitoring, and cybersecurity, which shown in Figure 3.

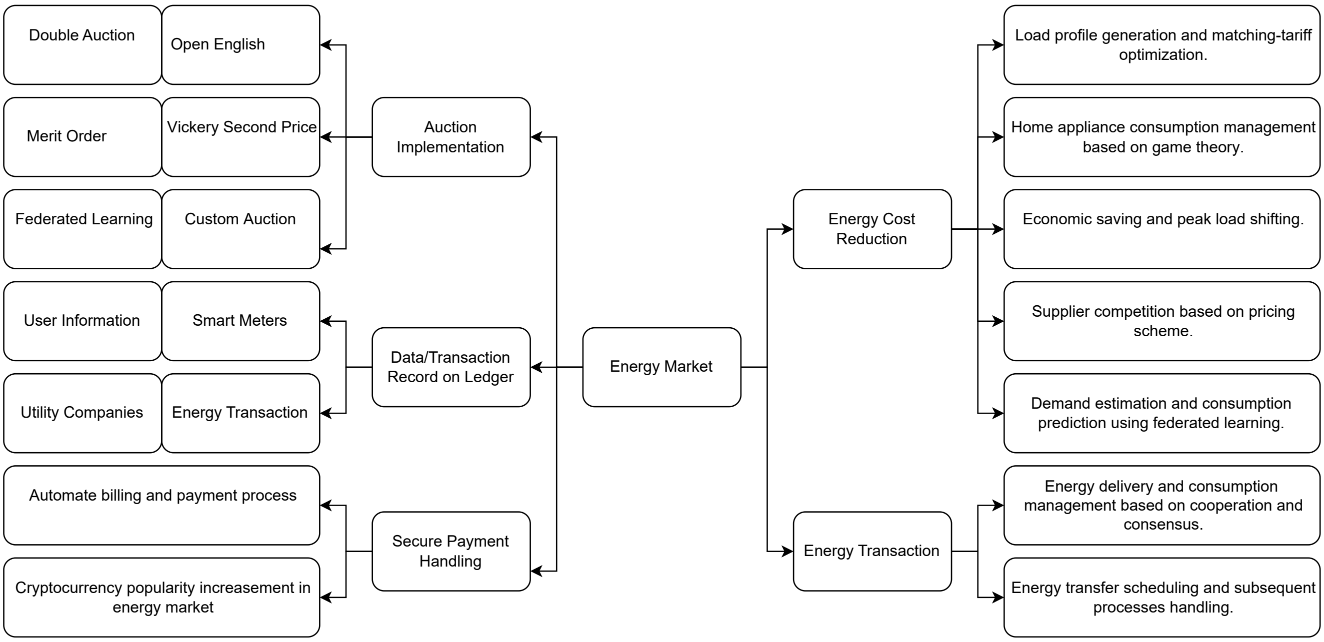

Figure 3. Semantic network for the energy market [1,3–5,11,12,14,29,32–55].

4.1. Energy Trading Markets

Energy trading is the most common application of BCs in energy systems. Multiple studies have investigated BC approaches to energy markets, which eliminate third parties in establishing, regulating, or operating them [5]. Such approaches can make energy system operations more efficient while reducing the peak load [3], increase market efficiency by reducing the threshold of participation for small retailers [1], reduce the cost of energy for residential users [32], and encourage investment in renewable generation plants [33]. A radically decentralized ledger can save and process the necessary trading information, which can improve the efficiency and privacy of energy trading in the smart grid [34]. Based on this theoretical research, energy trading platforms based on BC have been developed [35]. Table A3 in Appendix A summarizes the selected primary reports investigating BC applications in the energy trading market.

4.1.1. User Registration and Data Collection

For permissioned BCs, market participants must be authenticated and authorized to interact with the BC. Kang et al. [13] implemented user registration SCs, which also monitor energy usage and energy remaining in real-time. Prosumers are registered along with their conditions and sell price and are then matched with buyers.

SCs can also collect and record necessary data in the ledger. Such data are commonly generated off-chain and may come from prosumers, utility companies, etc. The data may include selling price and amounts of energy, auction bids, closed bid data [4,5], user energy profiles [9], user satisfaction [36], generation information, demand information [37,38], and smart-meter readings [39,40].

4.1.2. Contract Formation, Fulfillment, and Settlement

Multiple studies use SCs to collect user buy and sell prices for a given time window, which are entered into a selected auction format. These include double auctions [4,41,42], open English auctions [3,43], Vickrey second price auctions [5,44,45], Merit Order [56], and several other formats [11,46–50,57,58]. Auction winners form power purchase contracts. The process then repeats for the next time window (which is potentially as short as five minutes). Table A4 in Appendix A summarizes auction designs that have been implemented as SCs. Comparative studies of SC-based auction models have examined market dynamics (e.g., market efficiency or bidding strategies) [4,44] or BC network performance (e.g transaction latency or throughput) [44]. Both involve simulating the auction on a chosen BC network.

Contract fulfillment can be automated if the BC is integrated with metering infrastructure. The source of energy consumed can be tracked, proving fulfillment and enabling automated billing. Munising et al. [12] presented a decentralized optimal power-flow model for batteries, shapeable loads, and deferrable loads in a distribution network. This can also track the generation source of consumed energy (renewables, fossil fuel, etc.) and its cost [39]. Using this tracked information, it is also possible for the SC to dynamically change the power sources dispatched to fulfill contracts for a given consumer [59]. Individual prosumers in the energy trading market can be dynamically selected as validators of the BC in [51].

Contract settlement via SCs is another frequent topic of research [4,41,46]. Using BCs improves data privacy, identity management, and resilience toward cyber threats. In addition, the atomicity of data transactions in computing results, release, and payment can be assured [7,60]. Some utilities also accept cryptocurrencies for energy and electricity payments. PowerLedger operates a BC-based energy market using the POWER token [61]. Numerous researchers either employ existing cryptocurrencies or create new tokens, e.g., Han et al. [4], El-Syed et al. [62], and Muzumdar et al. [44].

4.1.3. Reducing Energy Cost

SC-based energy markets reduce costs by eliminating third parties [63], providing market access for smaller-scale, low-cost providers, and matching producers and consumers with congruent production and demand patterns. This enables cost reduction, peak load reduction, and enhanced market efficiency [1,32,52–54]. Jiang et al. [55] proposed an SC that can respond to energy demand based on the Stackelberg game, which can reduce the energy loss while maximizing the trading revenue considering the randomness of various energy sources. Gao et al. [64] achieved a 20% reduction in energy transmission cost with a BC based on a fog-computing paradigm. Large-scale energy auctions in this framework can be processed efficiently and with low latency even under conditions of high participation. Knirsch et al. [52] proposed an SC that matches utility generation with forecast consumer loads for optimal tariff selection. Saxena et al. [63] proposed a BC-based energy market for residential communities that reduced peak demand by 46% and energy costs overall by 6%. Bouachir et al. [57] proposed a federated learning method to predict demand and consumption in an auction round, reducing costs by 17.8%. Suther et al. [15] and Kang et al. [13] also proposed an SC-based local energy market. SC-based optimization in a time-of-use tariff model is proposed in [65]. SCs can also react to demand–response pricing signals [66].

4.1.4. Energy Transfer

SCs can schedule energy transfers between consumers and producers. This is distinct from contract fulfillment in that energy transfer requires the physical dispatch of power along a power grid. SCs can define business rules, e.g., scheduled or event-based delivery, or respond to particular situations [67–69]. Each SC can invoke another one, carrying out subsequent delivery processes [62]. Utz et al. [40] connected metering points via SCs, linking each one to a balancing group for settling energy delivery and consumption. In [38], energy trading among multiple regions can be interconnected by soft open points through SCs. This improves flexibility, while the voltage stability and power quality in the system are maintained. Figure 4 showed the semantic network for ancillary services.

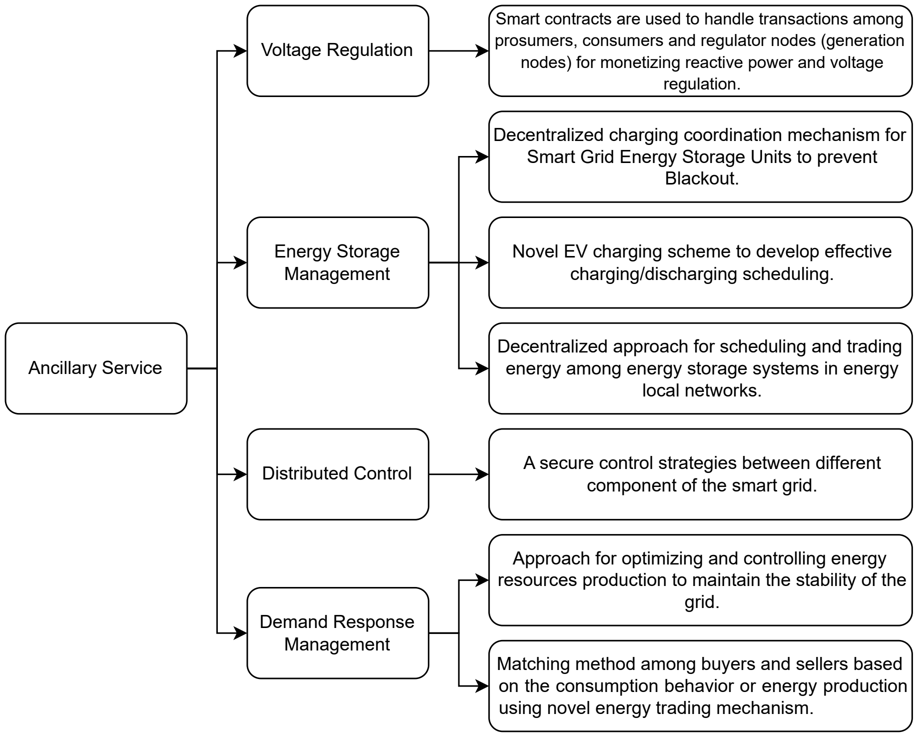

Figure 4. Semantic network for ancillary services [9,12,35,43,53,60–63].

4.2. Ancillary Services

Ancillary services ensure the electric system provides acceptable power quality while ensuring reliability and security. Electric System Operators (ESOs) are responsible for organizing these services to ensure reliability. For example, The Alberta Electric System Operator (AESO) in Alberta, Canada [70], procures ancillary services including Operating Reserve (OR), Transmission Must-Run (TMR), Black Start, and Load Shed Services for imports (LSSi).

1. **Operating Reserve**: These reserves provide additional capacity or frequency support to the system when the energy supply is not adequate for the present demand. Regulating reserves are immediately available whenever a momentary imbalance in supply and demand would cause a voltage sag. Spinning reserve refers to generators that are synchronized to the grid but not yet delivering power; they can quickly inject substantial additional energy into the grid when needed. Supplemental ("standby") reserve refers to generators that are available but not yet synchronized to the grid.
2. **Transmission Must-Run (TMR)**: TMR generation compensates for insufficient local transmission infrastructure relative to local demand.
3. **Black Start Service**: Some generators need start-up power provided to them. Generators that do not are contracted to provide this power in the event of a total system blackout.
4. **Load Shed Services for imports (LSSi)**: LSSi contracts permit AESO to shut down power flow to selected high-demand consumers when necessary to balance energy demand with available supply.

SC implementations of decentralized control systems can be robust, reliable, transparent, traceable, and secure. Energy supply can be optimized by tracking production and consumption and managing and prioritizing energy delivery [9,12,38]. SCs enable secure transactions, can monitor users' behavior and data, define rules, and provide decision support, all of which are particularly important for renewables in microgrids. The intermittency of, e.g., solar or wind power, becomes a larger problem when a grid has a smaller power capacity, covers a smaller physical area, and serves a more homogeneous user base. Danzi et al. [71] proposed an SC-based control scheme using a subset of Distributed Energy Resources (DERs) to act as voltage regulators. Decentralized energy trading allows prosumers to sell excess power [8]. Figure 5 showed the semantic diagram for auditing and monitoring.

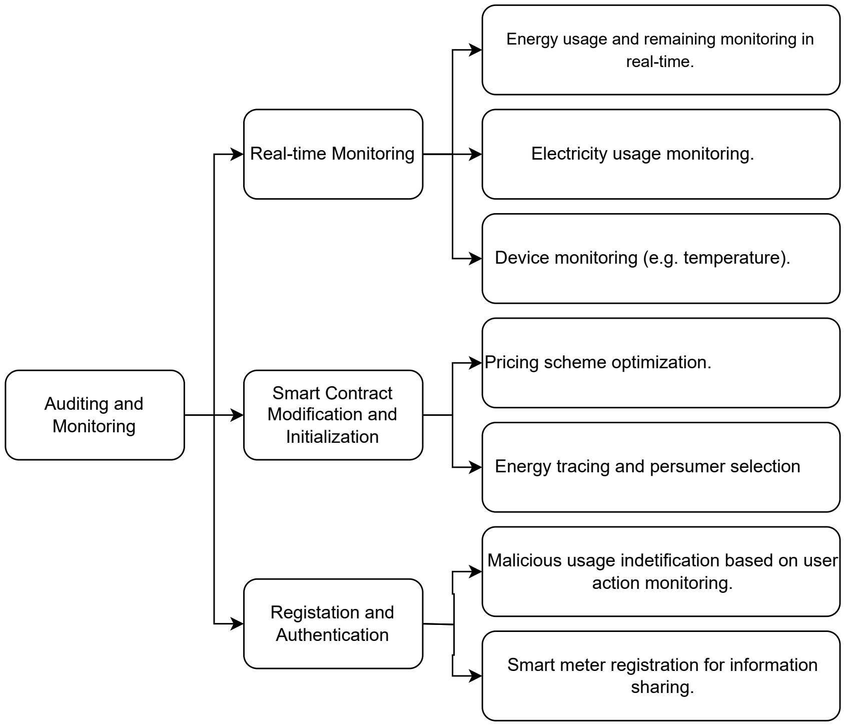

Figure 5. Semantic diagram for auditing and monitoring [8,12–15,54,72].

Energy storage units (ESUs) are essential for integrating renewables into the power grid and need to be integrated into energy markets. Yang et al. [10] introduce an Automated Demand Response framework using SCs for local scheduling and trading of energy among ESUs. It is also essential to coordinate ESU charging/discharging, or else the grid could be destabilized. Baza et al. [73] proposed an SC for scheduling ESU charging. The ESU's power demand, time-to-complete-charging (TCC), and battery state-of-charge (SoC) determine which ESU(s) are charged in the current time window. Liu et al. [74] proposed an SC for electric vehicle (EV) charging to minimize grid fluctuations and charging costs for EV owners. Silvestre et al. [75] present a BC-based management framework for microgrids covering ancillary operations, particularly voltage regulation. [76] developed an SC-based decentralized voltage stability algorithm. They evaluated the performance of SCs in real-time control and investigated sharding mechanisms to improve scalability. Thomas et al. [47] and Mhaisen et al. [72] used SCs to implement security control strategies between different components of the Smart Grid.

4.3. Auditing and Monitoring

SCs can monitor devices, users, and data to detect malicious behavior or prevent threats to the system. Auditing refers to SCs tracking energy usage in real-time, initiating contracts, or auditing user preferences such as price, time, etc. Monitoring applications include Gao et al.'s [14] proposal to identify malicious usage of electrical power and data. Li et al. [77] design a distributed renewable energy system for residential, commercial, and industrial users; SCs are used to maintain stability even under such different load profiles. Yang et al. [16] allow residential consumers to track power usage and interior air temperature and to purchase additional power when needed. Yuhong Li et al. [9] allow consumers to trace the generation of consumed energy and form SCs to select generation sources of their choosing. Monitoring often involves Distributed State Estimation (DSE) using asynchronous data; delays in data transfer can negatively affect DSE. Asefi et al. [78] utilize an SC to improve delayed-delivery tolerance in DSE.

4.4. Cybersecurity

The cybersecurity literature on BCs in the Smart Grid usually focuses on two threats: unauthorized use of personal data or the security of energy transactions (either consumer-to-utility or peer-to-peer). Numerous studies have shown that patterns of energy usage, even just observed on the main feeder, can often be mapped to the identities and activities of persons in a private home [79]. The security of energy transactions, meanwhile, addresses necessary characteristics such as authorization, integrity, non-repudiation, and auditable fulfillment of a contract. The main difference between these two strands of research appears to be the presence or absence of a middleware layer that protects data privacy.

Studies focused on privacy protection rely on ensuring that a data requestor can only access data that the owner explicitly permits them to access, and that, furthermore, the requestor only receives anonymized summarized reports. Access to the raw data itself is not provided, ensuring that the owner's privacy cannot be breached by accident, malicious intent, or external penetration of the requestor's IT systems. Figure 6 is a good example of this approach [7].

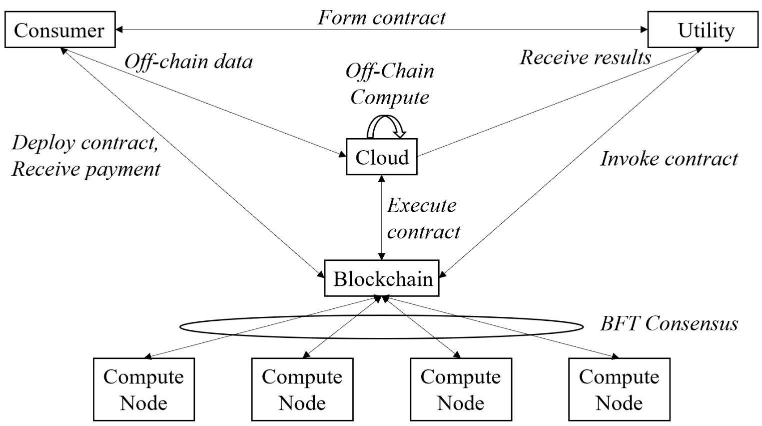

Figure 6. Privacy-preserving data access via Smart Contracts [7].

In Figure 6, a utility wishes to access consumer data. The consumer will securely store his/her data in an off-chain database (assumed to be cloud-based). The utility and consumer will negotiate an SC defining the data to be provided and the compensation to the consumer. The consumer deploys this contract to the BC. The utility can invoke the SC, triggering a (third-party) cloud-based off-chain computation involving the consumer's data. Only the result of this computation is returned to the utility, and the consumer is paid [7]. Another approach to securing raw data is to deliberately add noise to the data, as in Gai et al. [80].

Dorri et al. [60] presented a framework for negotiating an energy price using BCs by using a routing method based on the destination public key. A two-phase commit protocol ensures contract fulfillment and settlement. They evaluate a Proof-of-Concept (PoC) implementation in a second paper [81]. They also investigated removable BC networks to improve scalability, throughput, latency, and privacy [82]. J. Wang et al. [83] proposed an anonymous authentication and key agreement protocol for SCs.

The second research theme, securing energy transactions, is very much a classic application of BCs. The literature on energy trading, in general, is vast, and we direct the reader to those sources for further discussion. In our context, the basic approach of [84] illustrates several key concepts. In Figure 7, consumers and generators negotiate SCs for energy delivery. Each generator creates at least one Authorized Node, which can form contracts and interact with the underlying BC as a peer. In this example, an Ethereum BC is used, using Ethereum's Proof of Stake consensus algorithm. That algorithm requires the Ether coin, and so [84] settlement is also carried out in Ether coins.

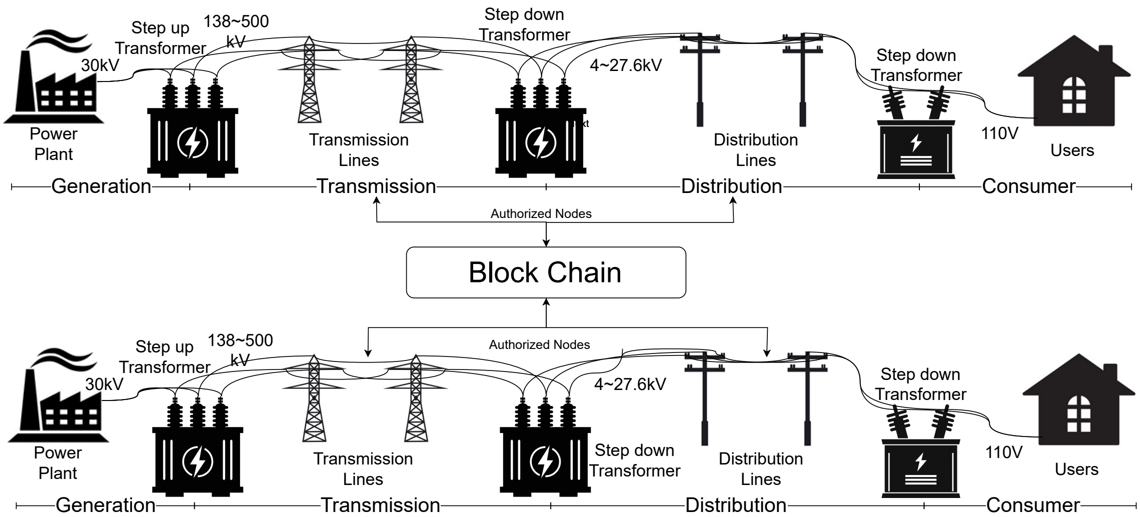

Figure 7. Blockchain-based energy trading [84].

Gai et al. [85] proposed a permissioned BC to counter fraudulent energy usage, communication interference, and data-center attacks. Lombardi et al. [86] implement auctions with SCs, which can also detect and isolate insecure smart meters. Gao et al. [14] used SCs to detect fraudulent power usage. W. Wang et al. [87] suggested a framework for identification and authentication in the smart grid. Hao et al. [88] propose a BC-based anonymous authentication scheme to facilitate fast and privacy-aware roaming and protect private information. SCs are used for user registration, signature verification, and user logout. Aung et al. [89] focus on the privacy of homeowners' data, but they also developed an access control mechanism giving service personnel elevated privileges during emergencies. Guan et al. [90] aim to protect the privacy of both the data owner and receiver. An SC with a novel data obfuscation method based on ring signatures is proposed.

5. Data Storage

Wüst and Gervais [91] investigate when and how BCs are appropriate technologies for a given problem and whether permissioned or public BCs are the best choice. As an immutable and tamper-proof ledger, BCs offer several advantages but also have their disadvantages. The ledger is replicated on all peers, and thus, storing data on-chain is costly. Designers must determine what data are worth keeping on-chain and what should be stored off-chain. In particular, BCs are not appropriate for streaming data, as data that ages out of relevance cannot be discarded. In this context, we note that in many studies discussed in Section 4, SCs gather and record data from smart meters on-chain for further processing. Smart meters, however, have a relatively high data rate, and in a realistic energy market, there would be a very large number of them. This seems to be a poor use of BC network resources. In the following, we discuss three potential solutions to solve the problem of data storage.

5.1. Removable Ledger

In Dorri et al. [82], real-time energy trading data are stored on a temporary BC rather than the main chain. This reduces the size of the ledger and also helps with scalability, throughput, latency, and privacy of users. Two BC network layers are suggested in this study: temporary chain and main chain. Transactions stored in the temporary chain will be removed once they expire; however, the main chain records the hash of all transactions, ensuring traceability.

5.2. Interplanetary File System

InterPlanetary File System (IPFS) (https://ipfs.io/, accessed on 25 April 2023) is a peer-to-peer distributed data storage and file-sharing system [92]. Files are sliced into multiple parts and stored across multiple nodes and tracked via their hash values. IPFS offers low latency and high throughput—desirable characteristics in an off-chain file system [93]. Kumari et al. [3] propose storing smart-meter data, including energy generation, consumption, etc. on IPFS. Then, only the file hash is stored on the ledger. Aung et al. [89] also employ digital signatures coupled with IPFS in their emergency privilege-escalation algorithm.

5.3. Store Synopses and Essential Facts

An off-chain database can store streaming data for a limited period, while synopses of the data are generated. These synopses are then stored on-chain, while the off-chain data can be discarded. Other data that may be stored on the BC include the results of bids and winners, the price of energy, and fulfillment and settlement information.

6. Interoperable Blockchains

The Smart Grid layered architecture includes multiple communicating networks passing large amounts of heterogeneous data between them at various timescales [94]. Using a single BC for such a complex system may not be an effective approach [95]. Alternatively, systems composed of multiple interoperable BCs [96] could automate energy management transactions and secure a complete operations log. Different BC platforms with appropriate properties can be employed for each layer [19]. This can also improve scalability by running multiple chains in parallel and offloading transactions into multiple BC networks. This section, therefore, discusses systems based on multiple interoperable BCs [96].

6.1. Extending the Application Scale

Li et al. [95] propose a framework with four permissioned BCs, responsible for market initialization, energy trading, state estimation, and market settlement, respectively. The market initialization BC includes SCs automating the network and market rule configuration. The energy trading BC runs the energy auctions. The state estimation SCs share data, including operating states at participants' physical boundaries, and estimate the system operating state for energy transfers. The market settlement BC coordinates financial settlement and participants' reputation scores. The framework coordinates the various SCs to allow for a market without third parties or trust between energy market participants. For example, the market settlement BC communicates with the market initialization BC to receive the pseudonym of each transacting microgrid and the power network configuration to settle scheduled and actual energy transfers.

Liu et al. [97] propose an Ethereum-based dual-chain architecture. A local energy trading BC (LETB) focuses on the local electricity market, while the regional renewable energy trading blockchain (RETB) focuses on renewable energy producers. After each participant joins the LETB and RETB, the SC for the LETB matches consumers and producers and updates reputation scores and incentives. If the LETB fails to satisfy the consumers' demand, a renewable energy trading phase is initiated. The RETB SC then matches the renewable energy producers to consumers for the remaining demand.

6.2. Scalability and Performance

Ochôa et al. [98] propose an architecture that uses sidechains to improve scalability and adaptability while ensuring consumer privacy. Sidechains use a Cross-Chain Communication Protocol (CCCP) in which the main BC (mainchain) holds the second BC as an extension of itself. The mainchain keeps a ledger of assets, and it uses CCCP to connect to the sidechain. The proposed framework uses three different BCs, which are integrated with the Open Smart Grid Protocol (OSGP) and SCs. Different BCs are responsible for tracking users' privacy preferences, storing users' data, and contract fulfillment and settlement.

Kong et al. [99] propose a framework for multi-chain networks to enhance the scalability and throughput of BCs. The multi-chain approach is proposed to overcome the scalability problem in the consensus protocol when there is a high arrival rate of new messages. This solution divides the BC authority system into multiple sub-networks called the Blockchain Autonomy System (BAS), where each maintains an independent ledger. BAS is responsible for data collection, broadcasting, and sharing. Block mining and ledger maintenance in separate BASs are independent and parallel. Figure 8 shows the smart meters stream data and store the synopsis on the blockchain.

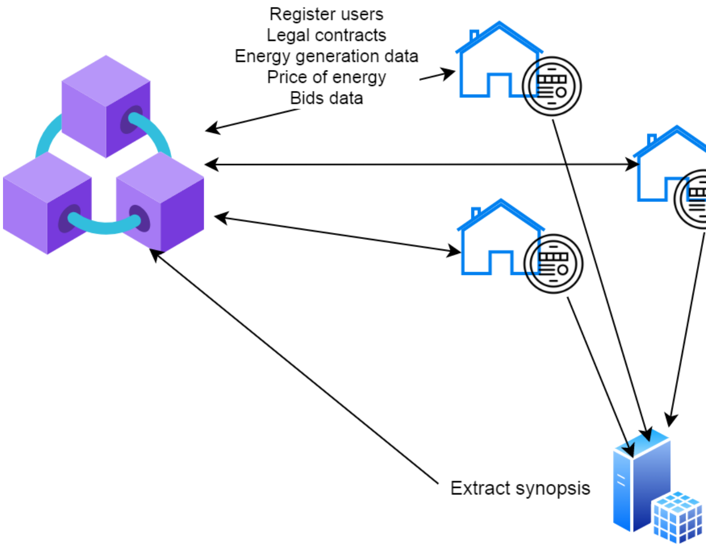

Figure 8. Smart meters stream data and store the synopsis on the blockchain.

7. Future Research Directions

BCs are a possible alternative design for numerous smart grid functions, as summarized in Table 1. However, there remain several challenges that must be addressed before BCs can be credible alternatives in real-world energy systems [100]. These challenges cut across the areas of computer engineering, electric systems, and cyber security. In this section, we highlight a few of the most relevant directions for future research.

Supporting fault and cascading failure analysis: The removable ledgers discussed in Section 5 allow for the temporary storage of streaming data, which is essential for scalability. However, the criteria for discarding a temporary chain do not yet integrate the data needs of incipient fault detection [101] and post-mortem analysis of cascading failures or blackouts [102]. For the former, inferential sensors designed to warn of incipient faults may depend in complex ways on high-granularity data from the temporary chain. Thus, these data must not be discarded until the fault is cleared or the fault analysis is complete. Similarly, post-mortem analysis of cascading failures depends on a detailed and accurate sequence of events, not merely synopses. Both of these are important real-world considerations, and both introduce a tension between the need to retain detailed records of operating conditions and the scalability of BC solutions. Resolving this tension in a manner acceptable to grid operators and regulators will be essential.

Reliability of off-chain storage against false data injection attacks: Several SCs surveyed in this paper rely on off-chain resources, e.g., distributed storage based on IPFS. However, this introduces a whole class of security vulnerabilities concerning the integrity and availability of such off-chain resources. An example is a False Data Injection Attack (FDIA), in which an adversary plants false data items in the off-chain storage. By manipulating the history of voltages, currents, and power transfers at critical points of the system, the adversary can significantly affect grid operation. Furthermore, in the real world, it is essential to assume this adversary is capable of successful FDIAs, and so ensuring security in part requires system resilience in the presence of false data. One potential approach is to embed countermeasures against FDIAs [103] in the SCs. In particular, a two-level approach can be utilized. At the first level, sanity checks on data items can detect alterations to load and generation data that do not accord with basic circuit physics. Some FDIAs, however, are sophisticated enough to generate realistic false data. In those cases, outlier detection based on generation/load statistics can be utilized. Defending against these attacks using SCs raises a number of challenges. Firstly, circuit topology and line impedance are typically regarded as confidential information by utilities, but the SCs that must defend against the FDIAs using them are readable to market participants. Outlier detection in the second phase is also computationally expensive. While the decentralized nature of SCs may be beneficial in spreading the computing load, this also requires some form of a distributed or federated detection algorithm, adding further system complexity.

Joint design of energy and data markets: A distributed market implemented via SCs will necessarily require market participants to share data amongst themselves, rather than just with the system operator, to ensure voltage stability, avoid congestion, etc. Such data could include the real-time load and generation of consumers or prosumers, as well as short-term forecasts of the same data that can map a user's activities alarmingly well (e.g., NILM) [104]. Safeguards for private data were discussed earlier, but some mechanism is needed to compensate users for the risks involved in sharing data. One possibility is a *data market*. For example, in P2P energy trading, the market value of shared data could be based on the energy cost savings thusly achieved; e.g., if line losses in transmission and distribution are reduced by trading with geographically close neighbors, some of those savings should be returned to the peers whose data was used, thus incentivizing that sharing. However, how to design this data market, and its interaction with the energy market, is an open question.

Utility asset upgrades and interoperability: Fundamentally, allowing prosumers more active participation in the smart grid will necessarily imply that they must take on greater obligations. The legal, financial, and technical responsibilities among the SC participants must be clarified [105]; e.g., liabilities need to be clearly defined in case of security breaches leading to financial losses, market anomalies, or electricity disruptions. More immediately, different architectural choices for the SC deployment have different properties and carry different costs. For example, the Authorized Nodes architecture in [84] sees each generator create at least one Authorized Node. This solution might not scale well to widespread solar generation by prosumers. A number of decisions about how system functionality is to be partitioned and what resources a prosumer would be expected *to provide* for system operation will need to be made.

Interoperability between SCs, existing smart grid assets, and future advanced metering infrastructure must also be ensured. For example, the ISO/TC 307 Blockchain and Distributed Ledger Technologies technical committee has published the standard ISO/TR 23455:2019 to clarify SC interactions [105]. Such standards require further integration with future energy system standards, e.g., IEEE 2030, for smart-grid interoperability [106].

8. Conclusions

The increasing penetration of smart meters and residential prosumer sources requires new distributed architectures for managing energy markets. In decentralized energy markets, neighbors could trade their produced and stored electricity locally. BCs and SCs appear to be promising technology to realize this vision. There are some specific areas of distributed energy management applications through BC infrastructure that are already developed and utilized, but the area is largely fragmented. In this study, we presented a literature review on distributed energy management through BC technology, focusing on SC design and development. We categorized the application domains into four main fields, including market operations, ancillary services, auditing and monitoring, and cybersecurity. We determined that data storage and BC interoperability are cross-cutting concerns in all of these areas, and we examined solutions for them.

In summary, SCs can automate the execution of predefined actions, eliminating the need for manual intervention. This can lead to increased efficiency, reduced administrative overhead, and faster transaction settlement. SCs operating on blockchain platforms furthermore provide a transparent and immutable record of all contract-related transactions. This transparency enhances trust among involved parties and reduces the risk of fraud or manipulation. As blockchain networks are decentralized, these SCs also reduce reliance on central authorities or intermediaries. This decentralization can promote a more democratic and inclusive power system, enabling direct peer-to-peer interactions. In particular, SC utilizes cryptographic techniques to ensure the security and integrity of the code and data of the energy system. Once deployed on BC, the code becomes resistant to tampering or unauthorized modifications, enhancing the security of the energy trading process.

However, there still remain some shortcomings of SCs in the energy market. The most urgent challenge is the scalability of existing SCs. When it comes to a large-scale and real-time energy system with millions of prosumers and high-frequency trading, limitations of both computation and communication capacity could hinder the adoption of SCs. Another concern is regulatory and legal challenges. Legal clarity and regulatory adaptation to accommodate and support SCs in the energy trading market are both necessary for widespread adoption of SCs. Additionally, since there have been numerous SCs in the literature and the real energy trading market, the lack of standard protocols and interoperability among different BC platforms will pose challenges for large-scale SC-based energy markets. Ensuring compatibility and seamless integration across different systems and stakeholders is another interesting research topic in the near future.

Funding: This research was supported in part by Alberta Ingenuity under grant No. G2020000136 and in part by funding from the Canada First Research Excellence Fund as part of the University of Alberta's Future Energy Systems research initiative.

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

Appendix A

Table A1. Classification of studies reviewed in the paper.

Scientific Database	Total Number of Papers	Journal	Conference	Workshop	Preprint	Other
IEEE	54	33	20	1	0	0
ACM	0	0	0	0	0	0
Springer	7	4	2	0	0	1
Elsevier	10	10	0	0	0	0
MDPI	2	2	0	0	0	0
Other Journal	2	2	0	0	0	0
Other Conferences	1	0	1	0	0	0
Total	76	35	23	1	0	1

Table A2. Summary of energy system studies based on blockchain.

Application	Summary
Market operations	Auction holdings [3–5,11,15,41–50,56–58,62,63] Payment operations [4,5,7,12,39,41,44,46,60,62] Demand and supply Optimization [11,57] Reduce energy cost and demand management [1,13,15,32,35,52,54,55,57,63–66,68] User registration and collecting energy market data [9,13,34,36–38,51,57,59] Energy transfer [38,40,62,67,69]
Ancillary services	Supply and demand management [8–10,13,38] Charging coordination mechanism for energy storage units [73] Optimization and control of energy resources [12] Voltage regulation [75] Scalable decentralized voltage stability for real-time control [76] Agreements for shared control of energy transfer processes [47] Proportional fairness control strategy to avoid power surplus [71] Electronic vehicle charging/discharging scheduling algorithm [74] Control approach for Battery Energy Storage System [72]
Auditing and monitoring	Monitoring and tracing energy consumption from the smart grid [9,13–15,78] User interaction and behavior evaluation [77] Data monitoring and sharing mechanism [16]
Cybersecurity	Privacy-preserving approach to protect energy trading information [80,88] Edge model for a smart grid network [85] Keeping vulnerable smart meters out of the network [86] Atomicity of data transaction [7,60] Temporarily blockchain network [82] Anonymous authentication and key agreement protocol for the edge-computing-based smart grid [83] Detection of disruptive behavior of electrical power [14] The dynamic join-and-exit mechanism [87] Using cryptography tool [84] Access control [3,89] Data obfuscation based on the ring signatures [90]

Table A3. Energy trading market studies.

Study	Blockchain Platform	Description	Trading Mechanism	Implementation	Perf. Evaluation
You 2019 [66]	-	Proposed demand response model & Reduced energy cost for customers	-	-	-
Hahn 2017 [5]	Private Ethereum	Established a trustworthy market for prosumers	Vickrey second-price auction	Yes	-
Kumari 2020 [3]	Public Ethereum	Proposed a secure energy trading scheme called ET-DeaL	E-auction	Yes	Yes
Wang 2018 [1]	-	Using game theory model for demand-side management and creating an efficient trading system	-	-	-
Han 2020 [4]	Private Ethereum	P2P energy trading system	Double auction	Yes	Yes
Hu 2019 [8]	-	Trading mechanism for energy power supply and demand network (EPSDN)	-	Simulation test	-
Mengelkamp 2018 [41]	Private Ethereum	Presented local energy market (LEM) between 100 residential households	Double auction	Yes	-
Thomas 2019 [47]	Ethereum	Using smart contracts to make agreements for shared control of energy transfer processes.	Highest Combined Offer (HCO) and Ranked Preference Selection (RPS)	Yes	Yes
Afzal 2020 [65]	Ethereum	Distributed demand-side management using game theoretic model	-	-	-
Khattak 2020 [48]	Hyperledger Fabric (Hyperledger composer)	Automate the bidding process based on supply and demand	Custom auction	Yes	-
Munsing 2017 [12]	Ethereum	Proposed a distributed optimization and control approach	-	simulation in SCE 55-bus test network	-
Amanbek 2018 [45]	-	Presented a novel method for a decentralized transactive energy management system	Modified Vickrey Second Price auction	Simulation test	-
Myung 2020 [11]	Ethereum	Using blockchain to reduce the wasted energy	Custom auction	yes	-

Table A3. *Cont.*

Study	Blockchain Platform	Description	Trading Mechanism	Implementation	Perf. Evaluation
Nakayam 2019 [37]	Private Ethereum	Transactive energy market that maximizes the benefit of prosumers by solving an economic dispatch problem of Distributed Energy Resources.	-	Yes	-
Sabounchi 2017 [46]	Ethereum	-	Custom auction	Simulation on the model of SunPower SPR-305E	-
Khalid 2020 [32]	Private Ethereum	A hybrid P2P energy trading market to reduce energy cost	Customized bidding	Yes	-
Mengelkamp 2018 [33]	Tendermint	An energy market to encourage investment in renewable generation plants and locally balancing supply and demand.	-	Yes	-
Dimobi 2020 [58]	Hyperledger Fabric	A peer-to-peer transactive energy operation within a microgrid	Auction-less with normalized sorting metric and a simple auction with penalties	Yes	-
Heck 2020 [56]	Private Ethereum	A local energy market	Merit order	Yes	-
Brousmiche 2018 [42]	Ethermint private	An agent-based simulation framework to implement a distributed energy market	Double auction	Yes	Yes
Monroe 2020 [6]	Power Ledger	An agent-based model of an energy trading market	-	Multiagent Simulation and the Mason Library	-
Kang 2018 [13]	Private Ethereum	Renewable energy trading platform	-	Yes	-
Seven 2020 [43]	Public Ethereum	Virtual power plant trading	Open English	Yes	Yes
El-Syed 2020 [62]	Ethereum	-	Prosumers add offers and consumers select an offer they are interested in	Yes	-
Yang 2020 [10]	-	Proposed a novel Automated Demand Response (ADR) framework	-	Simulation in CPLEX	-
Wen 2020 [68]	Hyperledger Fabric	-	-	Yes	-
Kounelis 2017 [39]	Ethereum	-	-	-	-

Table A3. *Cont.*

Study	Blockchain Platform	Description	Trading Mechanism	Implementation	Perf. Evaluation
Lombardi 2018 [86]	-	Implemented energy trading and auction transactions as well as security enhancement features	-	-	-
Wang 2020 [7]	-	A distributed infrastructure for managing access and sharing the data generated by smart meters and smart appliances in the smart grid	-	-	-
Dorri 2019 [60]	Private Ethereum	An energy trading framework that allows participant to directly negotiate the energy price in a secure way	-	-	-
Dorri 2021 [82]	Hyperledger Fabric	Proposed a blockchain network that records blockchain's transactions temporarily for the purpose of energy trading	-	Yes	Yes
Suther 2020 [15]	Ethereum-React	-	-	Yes	-
Sexana 2019 [63]	Hyperledger Fabric	An energy trading market mechanism for residential communities to reduce overall peak demand and electricity bills	-	Yes	-
Muzumdar 2021 [44]	Ethereum	Proposed a distributed trustworthy and incentivized trading platform	Vickrey auction	Yes	Yes
Zheng 2018 [84]	Ethereum	A smart-grid trading system based on the combination of consortium blockchain, proof-of-stake consensus mechanisms, and cryptography tools	-	-	-
Bouachir 2022 [57]	-	Proposed a Federated Learning model based on blockchain for P2P energy market	-	Yes	Yes

Table A4. The summary of auction implementations based on smart contracts.

Study	Auction Type	Description
Hahn 2017 [5]	Vickrey second-price auction	It guarantees bidders will submit honest bids. The system is outlined for the case when there is one seller and multiple buyers. Further, Vickrey auctions require sealed bids that protect parties from viewing other bidders, and blockchain transactions are public. They implemented two transactions to solve this problem: the CommitBid transaction commits a bid to the contract without revealing the bids; after a specific time, the RevealBid transaction reveals the offers, and the Vickery auction algorithm determines the auction winner and clearing price.
Kumari 2020 [3]	E-auction	They established an energy auction between prosumers and consumers and assigned a time slot for the E-auction to handle the late response from users.
Han 2020 [4]	Double auction	The closed bid function stores the bid amount and bid price provided by producers and consumers in a mapping structure.
Mengelkamp 2018 [41]	Double auction	It is implemented through a closed order book with discrete market closing times.
Thomas 2019 [47]	Using smart contracts to make agreements for shared control of energy transfer processes.	Proposed two algorithms: the HCO algorithm selects the highest combined bid from both network operators; the RPS algorithm selects the bid with the lowest summed rank of the options.
Amanbek 2018 [45]	Modified Vickrey Second Price	They modified the Vickrey second price auction to solve the competition problem in transactive energy systems when multiple participants in the market have excess energy to sell. The energy trading is implemented in this auction based on locational marginal pricing, the contribution metric, and energy availability.
Myung 2020 [11]	-	Auction algorithm includes 5 phases: initialization, bidding, close, withdrawal, and power supply. Initialization: SC invokes auction data from the seller and initializes an auction with parameters such as the amount of power supply, time of supply, minimum bidding, and auction time. Bidding phase: the buyer attempts to bid based on the current auction. The bidder with the highest prices is chosen after the time is up. Withdraw phase: All buyers redeem their remaining bidding amounts. Supply phase: the seller transfers the agreed amount of power.
Sabounchi 2017 [46]	-	In each auction iteration, they receive the currently available resources from the seller coalition and announce them to the buyers, then wait until a specific time or until all of the bids of all buyers are received to compare and announce the winner
Dimobi 2020 [58]	1. Auction-less, 2. auction-less with normalized sorting metric, 3. simple auction with penalties	Proposed three auction mechanisms: i. simple auction-less, ii. auction-less with normalized sorting metric, and iii. simple auction with penalties

Table A4. *Cont.*

Study	Auction Type	Description
Heck 2020 [56]	Merit order	The merit order includes two phases: ask and bid. Ask includes an electricity amount, a price, and the electricity type that the prosumer sells. During each period, the smart contract reads generation and consumption data from participants' smart meters and creates an ask in case of excess. In case of consumption, the smart contract requests the latest smart meter readings and the participants' price preference to create a bid, including the amount and the preference based on the energy type.
Brousmiche 2018 [42]	Double auction	It includes a proposal consisting of energy in Coin, a volume in W, a market turn index, and the address of the proposer. The proposals are recorded in both ask and bid tables using two functions (ProposeBid and ProposeAsk) that enable users to submit their proposals.
Seven 2020 [43]	Open English auction	Four key auction elements defined: Increment: The bid increment value that is set by the auction owner early. Highest Bid Level: the current highest bid, which will be the amount to pay when the auction finishes. Highest Bid: The current highest bid Highest Bidder: The user who made the highest bid. If the consumer's new offer is higher than the previous bid, the new bid is calculated as a summation of the previous bid and increment.
Saxena & Farag 2019 [63]	Double auction	Execute the market clearing price procedure and award service contracts to all winning bids.
Muzumdar 2021 [44]	Vickrey auction	The bidder who has the highest bid wins the auction and, as an incentive, has to pay the amount equal to the second-highest bidder's bid. Then, tokens are assigned to the winner.
Bouachir 2022 [57]	Custom auction using Federated Learning	They designed a Federated learning contract to predict the future demand and production and select the various participants for the coming auction round. They implement two main functions with smart contracts: GetModel, which allows the selected participant to gather the global learning model parameters from the contract; and SetModel, which allows sending or updating the parameters at the end of each round of the auction. The machine learning model enables the prosumers to decide on their participation in the energy-sharing process and their energy-exchanging strategies.
Khattak 2020 [48]	-	Dynamic pricing: calculates dynamic pricing from the extra load available and the load demand of participants in real-time. Bidding Mechanism: uses smart contracts to automate the bidding process for transactions based upon real-time supply and demand. Consumers and prosumers define and set business rules at the time of registration.

References

1. Wang, X.; Yang, W.; Noor, S.; Chen, C.; Guo, M.; van Dam, K.H. Blockchain-based smart contract for energy demand management. *Energy Procedia* **2019**, *158*, 2719–2724. [CrossRef]
2. Rouhani, S.; Deters, R. Security, performance, and applications of smart contracts: A systematic survey. *IEEE Access* **2019**, *7*, 50759–50779. [CrossRef]
3. Kumari, A.; Shukla, A.; Gupta, R.; Tanwar, S.; Tyagi, S.; Kumar, N. ET-DeaL: A P2P Smart Contract-based Secure Energy Trading Scheme for Smart Grid Systems. In Proceedings of the IEEE INFOCOM 2020-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Toronto, ON, Canada, 6–9 July 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1051–1056.
4. Han, D.; Zhang, C.; Ping, J.; Yan, Z. Smart contract architecture for decentralized energy trading and management based on blockchains. *Energy* **2020**, *199*, 117417. [CrossRef]
5. Hahn, A.; Singh, R.; Liu, C.C.; Chen, S. Smart contract-based campus demonstration of decentralized transactive energy auctions. In Proceedings of the 2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 23–26 April 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–5.
6. Monroe, J.G.; Hansen, P.; Sorell, M.; Berglund, E.Z. Agent-Based Model of a Blockchain Enabled Peer-to-Peer Energy Market: Application for a Neighborhood Trial in Perth, Australia. *Smart Cities* **2020**, *3*, 1072–1099. [CrossRef]
7. Wang, Y.; Su, Z.; Zhang, N.; Chen, J.; Sun, X.; Ye, Z.; Zhou, Z. SPDS: A Secure and Auditable Private Data Sharing Scheme for Smart Grid Based on Blockchain and Smart Contract. *IEEE Trans. Ind. Inform.* **2020**, *17*, 7688–7699. [CrossRef]
8. Hu, W.; Hu, Y.; Yao, W.; Lu, W.; Li, H.; Lv, Z. A blockchain-based smart contract trading mechanism for energy power supply and demand network. *Adv. Prod. Eng. Manag.* **2019**, *14*, 284–296. [CrossRef]
9. Li, Y.; Rahmani, R.; Fouassier, N.; Stenlund, P.; Ouyang, K. A blockchain-based architecture for stable and trustworthy smart grid. *Procedia Comput. Sci.* **2019**, *155*, 410–416. [CrossRef]
10. Yang, X.; Wang, G.; He, H.; Lu, J.; Zhang, Y. Automated demand response framework in ELNs: Decentralized scheduling and smart contract. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, *50*, 58–72. [CrossRef]
11. Myung, S.; Lee, J.H. Ethereum smart contract-based automated power trading algorithm in a microgrid environment. *J. Supercomput.* **2020**, *76*, 4904–4914. [CrossRef]
12. Münsing, E.; Mather, J.; Moura, S. Blockchains for decentralized optimization of energy resources in microgrid networks. In Proceedings of the 2017 IEEE Conference on Control Technology and Applications (CCTA), Kohala Coast, HI, USA, 27–30 August 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 2164–2171.
13. Kang, E.S.; Pee, S.J.; Song, J.G.; Jang, J.W. A blockchain-based energy trading platform for smart homes in a microgrid. In Proceedings of the 2018 3rd International Conference on Computer and Communication Systems (ICCCS), Nagoya, Japan, 27–30 April 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 472–476.
14. Gao, J.; Asamoah, K.O.; Sifah, E.B.; Smahi, A.; Xia, Q.; Xia, H.; Zhang, X.; Dong, G. GridMonitoring: Secured sovereign blockchain based monitoring on smart grid. *IEEE Access* **2018**, *6*, 9917–9925. [CrossRef]
15. Suthar, S.; Pindoriya, N.M. Blockchain and smart contract based decentralized energy trading platform. In Proceedings of the 2020 21st National Power Systems Conference (NPSC), Gandhinagar, India, 17–19 December 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5.
16. Yang, Y.; Liu, M.; Zhou, Q.; Zhou, H.; Wang, R. A Blockchain Based Data Monitoring and Sharing Approach for Smart Grids. *IEEE Access* **2019**. [CrossRef]
17. Alladi, T.; Chamola, V.; Rodrigues, J.J.; Kozlov, S.A. Blockchain in smart grids: A review on different use cases. *Sensors* **2019**, *19*, 4862. [CrossRef] [PubMed]
18. Andoni, M.; Robu, V.; Flynn, D.; Abram, S.; Geach, D.; Jenkins, D.; McCallum, P.; Peacock, A. Blockchain technology in the energy sector: A systematic review of challenges and opportunities. *Renew. Sustain. Energy Rev.* **2019**, *100*, 143–174. [CrossRef]
19. Zhuang, P.; Zamir, T.; Liang, H. Blockchain for cybersecurity in smart grid: A comprehensive survey. *IEEE Trans. Ind. Inform.* **2020**, *17*, 3–19. [CrossRef]
20. Zhang, Y.; Huang, T.; Bompard, E.F. Big data analytics in smart grids: A review. *Energy Inform.* **2018**, *1*, 8. [CrossRef]
21. Ali, S.S.; Choi, B.J. State-of-the-art artificial intelligence techniques for distributed smart grids: A review. *Electronics* **2020**, *9*, 1030. [CrossRef]
22. Kushch, S.; Castrillo, F.P. A review of the applications of the Block-chain technology in smart devices and dis-tributed renewable energy grids. *Adv. Distrib. Comput. Artif. Intell. J.* **2017**, *6*, 75. [CrossRef]
23. Bao, J.; He, D.; Luo, M.; Choo, K.K.R. A survey of blockchain applications in the energy sector. *IEEE Syst. J.* **2020**. [CrossRef]
24. Abdella, J.; Shuaib, K. Peer to peer distributed energy trading in smart grids: A survey. *Energies* **2018**, *11*, 1560. [CrossRef]
25. Mollah, M.B.; Zhao, J.; Niyato, D.; Lam, K.Y.; Zhang, X.; Ghias, A.M.; Koh, L.H.; Yang, L. Blockchain for future smart grid: A comprehensive survey. *IEEE Internet Things J.* **2020**, *8*, 18–43. [CrossRef]
26. Kitchenham, B.; Brereton, P. A systematic review of systematic review process research in software engineering. *Inf. Softw. Technol.* **2013**, *55*, 2049–2075. [CrossRef]
27. Liang, H.; Tamang, A.K.; Zhuang, W.; Shen, X.S. Stochastic information management in smart grid. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1746–1770. [CrossRef]
28. Lu, J.; Wu, S.; Cheng, H.; Xiang, Z. Smart contract for distributed energy trading in virtual power plants based on blockchain. *Comput. Intell.* **2021**, *37*, 1445–1455. [CrossRef]

29. Nakamoto, S. Bitcoin: A peer-to-peer electronic cash system. *Decent. Bus. Rev.* **2008**, 21260.
30. Menezes, A.J.; Vanstone, S.A.; Oorschot, P.C.V. *Handbook of Applied Cryptography*, 1st ed.; CRC Press, Inc.: Boca Raton, FL, USA, 1996.
31. Merkle, R.C. A Digital Signature Based on a Conventional Encryption Function. In *Proceedings of the Advances in Cryptology—CRYPTO'87*; Pomerance, C., Ed.; Springer: Berlin/Heidelberg, Germany, 1988; pp. 369–378.
32. Khalid, R.; Javaid, N.; Almogren, A.; Javed, M.U.; Javaid, S.; Zuair, M. A blockchain-based load balancing in decentralized hybrid P2P energy trading market in smart grid. *IEEE Access* **2020**, *8*, 47047–47062. [CrossRef]
33. Mengelkamp, E.; Gärttner, J.; Rock, K.; Kessler, S.; Orsini, L.; Weinhardt, C. Designing microgrid energy markets: A case study: The Brooklyn Microgrid. *Appl. Energy* **2018**, *210*, 870–880. [CrossRef]
34. Zhou, Y.; Manea, A.N.; Hua, W.; Wu, J.; Zhou, W.; Yu, J.; Rahman, S. Application of Distributed Ledger Technology in Distribution Networks. *Proc. IEEE* **2022**, *110*, 1963–1975. [CrossRef]
35. Lin, Y.J.; Chen, Y.C.; Zheng, J.Y.; Chu, D.; Shao, D.W.; Yang, H.T. Blockchain Power Trading and Energy Management Platform. *IEEE Access* **2022**, *10*, 75932–75948. [CrossRef]
36. Patrizi, N.; LaTouf, S.K.; Tsiropoulou, E.E.; Papavassiliou, S. Prosumer-Centric Self-Sustained Smart Grid Systems. *IEEE Syst. J.* **2022**, *16*, 6042–6053. [CrossRef]
37. Nakayama, K.; Moslemi, R.; Sharma, R. Transactive energy management with blockchain smart contracts for P2P multi-settlement markets. In Proceedings of the 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 17–20 February, 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–5.
38. Ji, H.; Jian, J.; Yu, H.; Ji, J.; Wei, M.; Zhang, X.; Li, P.; Yan, J.; Wang, C. Peer-to-Peer Electricity Trading of Interconnected Flexible Distribution Networks Based on Distributed Ledger. *IEEE Trans. Ind. Inform.* **2022**, *18*, 5949–5960. [CrossRef]
39. Kounelis, I.; Steri, G.; Giuliani, R.; Geneiatakis, D.; Neisse, R.; Nai-Fovino, I. Fostering consumers' energy market through smart contracts. In Proceedings of the 2017 International Conference in Energy and Sustainability in Small Developing Economies (ES2DE), Funchal, Portugal, 10–12 July 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–6.
40. Utz, M.; Albrecht, S.; Zoerner, T.; Strüker, J. Blockchain-based management of shared energy assets using a smart contract ecosystem. In Proceedings of the International Conference on Business Information Systems, Berlin, Germany, 18–20 July 2018; Springer: Berlin/Heidelberg, Germany, 2018; pp. 217–222.
41. Mengelkamp, E.; Notheisen, B.; Beer, C.; Dauer, D.; Weinhardt, C. A blockchain-based smart grid: Towards sustainable local energy markets. *Comput.-Sci.-Res. Dev.* **2018**, *33*, 207–214. [CrossRef]
42. Brousmichc, K.L.; Anoaica, A.; Dib, O.; Abdellatif, T.; Deleuze, G. Blockchain energy market place evaluation: An agent-based approach. In Proceedings of the 2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), Vancouver, BC, Canada, 1–3 November 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 321–327.
43. Seven, S.; Yao, G.; Soran, A.; Onen, A.; Muyeen, S. Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts. *IEEE Access* **2020**, *8*, 175713–175726. [CrossRef]
44. Muzumdar, A.; Modi, C.; Madhu, G.; Vyjayanthi, C. A trustworthy and incentivized smart grid energy trading framework using distributed ledger and smart contracts. *J. Netw. Comput. Appl.* **2021**, *183*, 103074. [CrossRef]
45. Amanbek, Y.; Tabarak, Y.; Nunna, H.K.; Doolla, S. Decentralized transactive energy management system for distribution systems with prosumer microgrids. In Proceedings of the 2018 19th International Carpathian Control Conference (ICCC), Szilvasvarad, Hungary, 28–31 May 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 553–558.
46. Sabounchi, M.; Wei, J. Towards resilient networked microgrids: Blockchain-enabled peer-to-peer electricity trading mechanism. In Proceedings of the 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, 26–28 November 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–5.
47. Thomas, L.; Zhou, Y.; Long, C.; Wu, J.; Jenkins, N. A general form of smart contract for decentralized energy systems management. *Nat. Energy* **2019**, *4*, 140–149. [CrossRef]
48. Khattak, H.A.; Tehreem, K.; Almogren, A.; Ameer, Z.; Din, I.U.; Adnan, M. Dynamic pricing in industrial internet of things: Blockchain application for energy management in smart cities. *J. Inf. Secur. Appl.* **2020**, *55*, 102615. [CrossRef]
49. Liu, N.; Tan, L.; Sun, H.; Zhou, Z.; Guo, B. Bilevel Heat–Electricity Energy Sharing for Integrated Energy Systems With Energy Hubs and Prosumers. *IEEE Trans. Ind. Inform.* **2022**, *18*, 3754–3765. [CrossRef]
50. Zhang, M.; Eliassen, F.; Taherkordi, A.; Jacobsen, H.A.; Chung, H.M.; Zhang, Y. Demand–Response Games for Peer-to-Peer Energy Trading With the Hyperledger Blockchain. *IEEE Trans. Syst. Man Cybern. Syst.* **2022**, *52*, 19–31. [CrossRef]
51. Abdelsalam, H.A.; Srivastava, A.K.; Eldosouky, A. Blockchain-Based Privacy Preserving and Energy Saving Mechanism for Electricity Prosumers. *IEEE Trans. Sustain. Energy* **2022**, *13*, 302–314. [CrossRef]
52. Knirsch, F.; Unterweger, A.; Eibl, G.; Engel, D. Privacy-preserving smart grid tariff decisions with blockchain-based smart contracts. In *Sustainable Cloud and Energy Services*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 85–116.
53. Gough, M.; Santos, S.F.; Almeida, A.; Lotfi, M.; Javadi, M.S.; Fitiwi, D.Z.; Osório, G.J.; Castro, R.; Catalão, J.P.S. Blockchain-Based Transactive Energy Framework for Connected Virtual Power Plants. *IEEE Trans. Ind. Appl.* **2022**, *58*, 986–995. [CrossRef]
54. AlSkaif, T.; Crespo-Vazquez, J.L.; Sekuloski, M.; van Leeuwen, G.; Catalão, J.P.S. Blockchain-Based Fully Peer-to-Peer Energy Trading Strategies for Residential Energy Systems. *IEEE Trans. Ind. Inform.* **2022**, *18*, 231–241. [CrossRef]
55. Jiang, T.; Chung, C.Y.; Ju, P.; Gong, Y. A Multi-Timescale Allocation Algorithm of Energy and Power for Demand Response in Smart Grids: A Stackelberg Game Approach. *IEEE Trans. Sustain. Energy* **2022**, *13*, 1580–1593. [CrossRef]

56. Heck, K.; Mengelkamp, E.; Weinhardt, C. Blockchain-based local energy markets: Decentralized trading on single-board computers. *Energy Syst.* **2020**, *12*, 603–618. [CrossRef]
57. Bouachir, O.; Aloqaily, M.; Özkasap, Ö.; Ali, F. FederatedGrids: Federated Learning and Blockchain-assisted P2P Energy Sharing. *IEEE Trans. Green Commun. Netw.* **2022**, *6*, 424–436. [CrossRef]
58. Dimobi, I.; Pipattanasomporn, M.; Rahman, S. A transactive grid with microgrids using blockchain for the energy Internet. In Proceedings of the 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 17–20 February 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5.
59. Mhaisen, N.; Allahham, M.S.; Mohamed, A.; Erbad, A.; Guizani, M. On Designing Smart Agents for Service Provisioning in Blockchain-Powered Systems. *IEEE Trans. Netw. Sci. Eng.* **2022**, *9*, 401–415. [CrossRef]
60. Dorri, A.; Luo, F.; Kanhere, S.S.; Jurdak, R.; Dong, Z.Y. SPB: A secure private blockchain-based solution for distributed energy trading. *IEEE Commun. Mag.* **2019**, *57*, 120–126. [CrossRef]
61. Ledger, P. *Power Ledger White Paper*; Power Ledger Pty Ltd.: Perth, Australia, 2017; Volume 8.
62. El-Sayed, I.; Khan, K.; Dominguez, X.; Arboleya, P. A real pilot-platform implementation for blockchain-based peer-to-peer energy trading. In Proceedings of the 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2–6 August 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5.
63. Saxena, S.; Farag, H.; Brookson, A.; Turesson, H.; Kim, H. Design and field implementation of blockchain based renewable energy trading in residential communities. In Proceedings of the 2019 2nd International Conference on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 19–21 November 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 1–6.
64. Gao, G.; Song, C.; Bandara, T.G.T.A.; Shen, M.; Yang, F.; Posdorfer, W.; Tao, D.; Wen, Y. FogChain: A Blockchain-Based Peer-to-Peer Solar Power Trading System Powered by Fog AI. *IEEE Internet Things J.* **2022**, *9*, 5200–5215. [CrossRef]
65. Afzal, M.; Huang, Q.; Amin, W.; Umer, K.; Raza, A.; Naeem, M. Blockchain enabled distributed demand side management in community energy system with smart homes. *IEEE Access* **2020**, *8*, 37428–37439. [CrossRef]
66. You, H.; Hua, H.; Cao, J. A Smart Contract-based Energy Trading Strategy in Energy Internet. In Proceedings of the 2019 IEEE International Conference on Energy Internet (ICEI), Nanjing, China, 20–24 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 478–483.
67. Zhang, X.; Fan, M. Blockchain-based secure equipment diagnosis mechanism of smart grid. *IEEE Access* **2018**, *6*, 66165–66177. [CrossRef]
68. Wen, Z.; Zheng, Y.; Li, Y. Analysis of Decentralized Energy Transactions Based on Smart Contract. In Proceedings of the 2020 IEEE International Conference on Information Technology, Big Data and Artificial Intelligence (ICIBA), Chongqing, China, 6–8 November 2020; IEEE: Piscataway, NJ, USA, 2020; Volume 1, pp. 819–824.
69. Alao, O.; Cuffe, P. Hedging Volumetric Risks of Solar Power Producers Using Weather Derivative Smart Contracts on a Blockchain Marketplace. *IEEE Trans. Smart Grid* **2022**, *13*, 4730–4746. [CrossRef]
70. The Alberta Electric System Operator. Available online: https://www.aeso.ca/ (accessed on 30 September 2021).
71. Danzi, P.; Angjelichinoski, M.; Stefanović, Č.; Popovski, P. Distributed proportional-fairness control in microgrids via blockchain smart contracts. In Proceedings of the 2017 IEEE International Conference on Smart Grid Communications (SmartGridComm), Dresden, Germany, 23–26 October 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 45–51.
72. Mhaisen, N.; Fetais, N.; Massoud, A. Secure smart contract-enabled control of battery energy storage systems against cyber-attacks. *Alex. Eng. J.* **2019**, *58*, 1291–1300. [CrossRef]
73. Baza, M.; Nabil, M.; Ismail, M.; Mahmoud, M.; Serpedin, E.; Rahman, M.A. Blockchain-based charging coordination mechanism for smart grid energy storage units. In Proceedings of the 2019 IEEE International Conference on Blockchain (Blockchain), Atlanta, GA, USA, 14–17 July 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 504–509.
74. Liu, C.; Chai, K.K.; Zhang, X.; Lau, E.T.; Chen, Y. Adaptive blockchain-based electric vehicle participation scheme in smart grid platform. *IEEE Access* **2018**, *6*, 25657–25665. [CrossRef]
75. Di Silvestre, M.L.; Gallo, P.; Ippolito, M.G.; Musca, R.; Sanseverino, E.R.; Tran, Q.T.T.; Zizzo, G. Ancillary services in the energy blockchain for microgrids. *IEEE Trans. Ind. Appl.* **2019**, *55*, 7310–7319. [CrossRef]
76. Honari, K.; Zhou, X.; Rouhani, S.; Dick, S.; Liang, H.; Li, Y.; Miller, J. A Scalable Blockchain-based Smart Contract Model for Decentralized Voltage Stability Using Sharding Technique. *arXiv* **2022**, arXiv:2206.13776.
77. Li, Y.; Yang, W.; He, P.; Chen, C.; Wang, X. Design and management of a distributed hybrid energy system through smart contract and blockchain. *Appl. Energy* **2019**, *248*, 390–405. [CrossRef]
78. Asefi, S.; Madhwal, Y.; Yanovich, Y.; Gryazina, E. Application of Blockchain for Secure Data Transmission in Distributed State Estimation. *IEEE Trans. Control Netw. Syst.* **2022**, *9*, 1611–1621. [CrossRef]
79. Wang, H.; Zhang, J.; Lu, C.; Wu, C. Privacy Preserving in Non-Intrusive Load Monitoring: A Differential Privacy Perspective. *IEEE Trans. Smart Grid* **2020**, *12*, 2529–2543. [CrossRef]
80. Gai, K.; Wu, Y.; Zhu, L.; Qiu, M.; Shen, M. Privacy-preserving energy trading using consortium blockchain in smart grid. *IEEE Trans. Ind. Inform.* **2019**, *15*, 3548–3558. [CrossRef]
81. Dorri, A.; Hill, A.; Kanhere, S.; Jurdak, R.; Luo, F.; Dong, Z.Y. Peer-to-peer energytrade: A distributed private energy trading platform. In Proceedings of the 2019 IEEE International Conference on Blockchain and Cryptocurrency (ICBC), Seoul, Republic of Korea, 14–17 May 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 61–64.

82. Dorri, A.; Luo, F.; Karumba, S.; Kanhere, S.; Jurdak, R.; Dong, Z.Y. Temporary immutability: A removable blockchain solution for prosumer-side energy trading. *J. Netw. Comput. Appl.* **2021**, *180*, 103018. [CrossRef]
83. Wang, J.; Wu, L.; Choo, K.K.R.; He, D. Blockchain-based anonymous authentication with key management for smart grid edge computing infrastructure. *IEEE Trans. Ind. Inform.* **2019**, *16*, 1984–1992. [CrossRef]
84. Zheng, D.; Deng, K.; Zhang, Y.; Zhao, J.; Zheng, X.; Ma, X. Smart grid power trading based on consortium blockchain in Internet of Things. In Proceedings of the International Conference on Algorithms and Architectures for Parallel Processing, Guangzhou, China, 15–17 November 2018; Springer: Berlin/Heidelberg, Germany, 2018; pp. 453–459.
85. Gai, K.; Wu, Y.; Zhu, L.; Xu, L.; Zhang, Y. Permissioned blockchain and edge computing empowered privacy-preserving smart grid networks. *IEEE Internet Things J.* **2019**, *6*, 7992–8004. [CrossRef]
86. Lombardi, F.; Aniello, L.; De Angelis, S.; Margheri, A.; Sassone, V. A blockchain-based infrastructure for reliable and cost-effective IoT-aided smart grids. In Proceedings of the Living in the Internet of Things: Cybersecurity of the IoT—2018, London, UK, 28–29 March 2018; pp. 1–6. [CrossRef]
87. Wang, W.; Huang, H.; Zhang, L.; Su, C. Secure and efficient mutual authentication protocol for smart grid under blockchain. *Peer-Peer Netw. Appl.* **2021**, *14*, 2681–2693. [CrossRef]
88. Hao, X.; Ren, W.; Choo, K.K.R.; Xiong, N.N. A Self-Trading and Authenticated Roaming Scheme Based on Blockchain for Smart Grids. *IEEE Trans. Ind. Inform.* **2022**, *18*, 4097–4106. [CrossRef]
89. Aung, Y.N.; Tantidham, T. Ethereum-based Emergency Service for Smart Home System: Smart Contract Implementation. In Proceedings of the 2019 21st International Conference on Advanced Communication Technology (ICACT), Pyeong Chang, Republic of Korea, 17–20 February 2019; IEEE: Piscataway, NJ, USA, 2019; pp. 147–152.
90. Guan, Z.; Zhou, X.; Liu, P.; Wu, L.; Yang, W. A Blockchain-Based Dual-Side Privacy-Preserving Multiparty Computation Scheme for Edge-Enabled Smart Grid. *IEEE Internet Things J.* **2022**, *9*, 14287–14299. [CrossRef]
91. Wüst, K.; Gervais, A. Do you need a blockchain? In Proceedings of the 2018 Crypto Valley Conference on Blockchain Technology (CVCBT), Zug, Switzerland, 20–22 June 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 45–54.
92. Benet, J. IPFS-content addressed, versioned, P2P file system (DRAFT 3). *arXiv* **2014**, arXiv:1407.3561.
93. Huang, H.; Lin, J.; Zheng, B.; Zheng, Z.; Bian, J. When blockchain meets distributed file systems: An overview, challenges, and open issues. *IEEE Access* **2020**, *8*, 50574–50586. [CrossRef]
94. Kuzlu, M.; Pipattanasomporn, M.; Rahman, S. Communication network requirements for major smart grid applications in HAN, NAN and WAN. *Comput. Netw.* **2014**, *67*, 74–88. [CrossRef]
95. Li, Z.; Bahramirad, S.; Paaso, A.; Yan, M.; Shahidehpour, M. Blockchain for decentralized transactive energy management system in networked microgrids. *Electr. J.* **2019**, *32*, 58–72. [CrossRef]
96. Belchior, R.; Vasconcelos, A.; Guerreiro, S.; Correia, M. A survey on blockchain interoperability: Past, present, and future trends. *ACM Comput. Surv.* **2021**, *54*, 168. [CrossRef]
97. Liu, Z.; Wang, D.; Wang, J.; Wang, X.; Li, H. A blockchain-enabled secure power trading mechanism for smart grid employing wireless networks. *IEEE Access* **2020**, *8*, 177745–177756. [CrossRef]
98. Sestrem Ochôa, I.; Augusto Silva, L.; De Mello, G.; Garcia, N.M.; de Paz Santana, J.F.; Quietinho Leithardt, V.R. A cost analysis of implementing a blockchain architecture in a smart grid scenario using sidechains. *Sensors* **2020**, *20*, 843. [CrossRef]
99. Kong, X.; Zhang, J.; Wang, H.; Shu, J. Framework of decentralized multi-chain data management for power systems. *CSEE J. Power Energy Syst.* **2019**, *6*, 458–468.
100. Khan, S.N.; Loukil, F.; Ghedira-Guegan, C.; Benkhelifa, E.; Bani-Hani, A. Blockchain smart contracts: Applications, challenges, and future trends. *Peer-Peer Netw. Appl.* **2021**, *14*, 2901–2925. [CrossRef] [PubMed]
101. Sidhu, T.S.; Xu, Z. Detection of Incipient Faults in Distribution Underground Cables. *IEEE Trans. Power Deliv.* **2010**, *25*, 2901–2925. [CrossRef]
102. Dagle, J.E. Post-mortem analysis of power grid blackouts - The role of measurement systems. *IEEE Power Energy Mag.* **2006**, *4*, 30–35. [CrossRef]
103. Deng, R.; Xiao, G.; Lu, R.; Liang, H.; Vasilakos, A.V. False Data Injection on State Estimation in Power Systems—Attacks, Impacts, and Defense: A Survey. *IEEE Trans. Ind. Inform.* **2017**, *13*, 411–423. [CrossRef]
104. Ruano, A.; Hernandez, A.; Ureña, J.; Ruano, M.; Garcia, J. NILM techniques for intelligent home energy management and ambient assisted living: A review. *Energies* **2019**, *12*, 2203. [CrossRef]
105. Fulli, G.; Kotzakis, E.; Fovino, I.N. *Policy and Regulatory Challenges for the Deployment of Blockchains in the Energy Field*; JRC Technical Report; Publications Office of the European Union: Luxembourg, 2021.
106. *IEEE Std 2030-2011*; IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads. IEEE: Piscataway, NJ, USA, 2011; pp. 1–126. [CrossRef]