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The Potential of Blockchain Technology and Smart Contracts in the Energy Sector: A Review

Panagiotis Vionis and Theodore Kotsilieris *

Department of Business and Organizations Administration, University of Peloponnese, 24100 Kalamata, Greece; p.vionis@office365.uop.gr
* Correspondence: t.kotsilieris@uop.gr; Tel.: +30-2721045255

Abstract: The energy sector is undergoing a period of technological transformation, driven by the emergence of blockchain and smart contracts. These technologies have the potential to revolutionize energy markets and significantly reduce transaction costs, improve efficiency, and increase transparency. The rising energy prices in recent years have been a cause for global concern. As the EU recorded historically high energy prices in 2022, according to the EU Council, this price rise is linked to increased energy demand following the COVID-19 pandemic, the war in Ukraine, and the acceleration of climate change. This paper aims to critically examine the current state of blockchain and smart contracts technology in the energy sector, focusing on use cases, key challenges, and potential solutions. It further explores the impact of these technologies on energy markets and their potential to contribute to a sustainable, low-carbon energy future. Finally, it examines the prospects of blockchain and smart contract technologies to transform the energy industry and the policy implications for governments and regulators.

Keywords: blockchain; smart contracts; energy sector; SWOT analysis

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1. Introduction

Rising energy prices in recent years have been a cause for global concern. In 2022, the EU recorded historically high energy prices, according to the EU Council. This price surge is attributed to an increased demand for energy following the COVID-19 pandemic, the war in Ukraine, and the acceleration of climate change. In 2022, Russia's decision to suspend gas supplies to most EU member states increased gas and electricity prices in the EU. As an example, between January 2021 and January 2023, domestic industrial energy producer prices increased by 127% while consumer prices increased by 63.5%. Considering the high volatility of energy prices, as well as the fact that the energy sector is undergoing a period of digital transformation, blockchain technology and smart contracts potentially offer the ability to revolutionize the energy sector by providing a secure, transparent, and efficient platform for energy transactions. Blockchain is a distributed ledger technology that enables peer-to-peer (P2P) transactions with no central authority or intermediary oversight body [1].

This technology can be used both to support complex energy transactions between consumers and energy producers and to develop new business models such as peer-to-peer energy transactions [2].

The use of blockchain in the energy sector has been gaining momentum in recent years due to its ability to provide secure, transparent, and efficient transactions. Energy companies can reduce costs associated with traditional energy trading processes, such as transaction fees and administrative costs [3]. Furthermore, blockchain technology can help to improve the accuracy and reliability of energy data, which can lead to better decision-making and improved customer service [4].

Blockchain technology can also provide increased security for energy transactions. By using cryptographic algorithms, blockchain technology can ensure that only authorized users have access to energy data and transactions [5]. Consequently, it helps protect against cyber-attacks and other malicious activities by providing an unalterable record of energy transactions, which contributes to fraud and manipulation prevention [6].

Beyond the technological benefits, on a business level, blockchain technology can also enable the development of new business models in the energy sector. For example, it can enable P2P energy trading, that is, the ability for consumers to buy and sell energy directly from and to each other without the need for an intermediary. This could potentially lead to lower energy prices and more efficient energy markets [7].

The purpose of this paper is to review and assess the application of blockchain technology and smart contracts in the rapidly evolving energy market. To this end, we identify their characteristics, the challenges, and their potential under the prism of a detailed literature review. Also, we will attempt to identify and qualitatively evaluate the most recent, and mature research efforts in the field. More specifically, this work:

- presents the characteristics and advantages of blockchain technology to justify its adoption trend in the energy sector. Furthermore, an analysis of the concept, the properties, and the use cases of smart contracts is performed. Consequently, their relation to the different forms of energy trade (P2P, P2G, EVs, EAAS, etc.) is thoroughly described. At the same time, the limitations and challenges that have been recently encountered by the scientific community are mentioned.
- carries out a comprehensive and scientifically based literature review, including the progress made in recent years in the field. The scientific articles included are classified into three categories (Energy Market and Regulations (EMnR), Energy Management and Operations (EMnO), and Business Models and Applications (BMnA)). In addition, the independent smart contract technology (SCT) class that focuses on the technological aspects of developing smart contracts is identified. Finally, after having listed the advantages, limitations, challenges, and risks of adopting blockchain technology in the energy sector, a SWOT analysis is carried out, to provide the reader with a comprehensive view of the field's potential in the near future.

The rest of the paper is organized as follows: Section 2 provides the necessary background information and captures the roots and principles of blockchain technology and smart contracts. Section 3 depicts the overall approach to the research process, attempts a thorough literature review, and classifies research efforts into three dominant dimensions and an independent class. Section 4 performs a SWOT analysis towards an assessment of the potentials, weaknesses, opportunities, and threats that underlie the application of blockchain and smart contracts in the energy sector. In Section 5, the discussion focuses on the role of smart contracts in enhancing efficiency and reducing operational costs in the energy sector. It is explored how their automation capabilities and inherent security features address key challenges, fostering broader adoption and trust in this technology. Finally, Section 6 concludes the paper, providing a brief review of the main findings and results of the study.

2. Background Information

2.1. Blockchain Technology

Blockchain technology refers to the sum of emerging techniques, processes, and methods that have revolutionized digital transactions, and are radically transforming not only existing business models but also the way that data, goods, and services are exchanged. It is a distributed ledger technology that captures and stores data in a decentralized and immutable format, secured using cryptographic algorithms [8].

The birth of blockchain technology can be traced back to Satoshi Nakamoto's 2008 white paper [9] which proposed a decentralized digital currency system using a peer-to-peer network to record and verify transactions. Valid or verified transactions are stored as blocks or lists of transactions linked to the previous transaction. When a new block is created, the hash value of the previous block is inserted into it (Figure 1). In this way, any changes to a previous block result in a different hash code in the immediately following block and are therefore immediately visible to all participants in the chain.

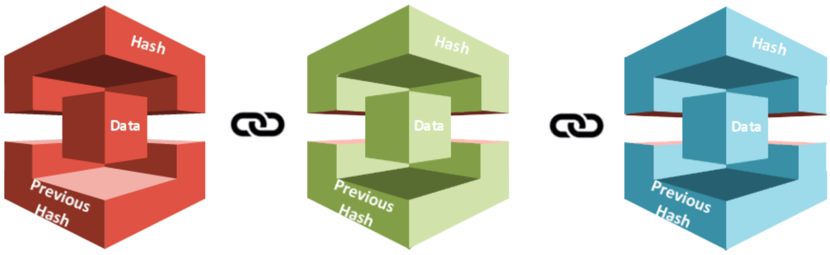

Figure 1. Blockchain with random numbers of blocks.

This property is referred to in the literature as data file immutability, where the recorded data cannot be modified after being accepted by the blockchain network [10]. Due to these characteristics, blockchain technology has become the underlying technology for many digital transactions, including cryptocurrencies and smart contracts [11].

2.2. Smart Contracts

A smart contract is a digital protocol intended to make it easier to verify or enforce the negotiation or execution of a contract. Smart contracts enable reliable transactions to be executed without the involvement of third parties. These transactions are traceable and irreversible. According to Szabo [12], "a smart contract is a set of promises specified in digital form, including the protocols within which the parties execute those promises".

It is usually encoded in a language based on Blockchain technology, such as Solidity https://soliditylang.org/ (accessed on 23 November 2023), Vyper https://docs.vyperlang.org/en/stable/ (accessed on 23 November 2023), Cairo https://www.cairo-lang.org/ (accessed on 23 November 2023), Rust https://www.rust-lang.org/ (accessed on 23 November 2023), etc., and stored and replicated in a distributed ledger system. The basic structure of a smart contract consists of an initiation event and a set of rules or terms of the contract. The initiating event is the action or event that triggers the smart contract, such as the arrival of a specific date or an incoming payment. Conditions are the requirements that must be met for the smart contract to be executed [13]. The set of rules or terms of the contract are the instructions to be followed, such as transferring of assets or the provision of services.

Several blockchain platforms leverage smart contracts to facilitate decentralized and automated processes. Ethereum, a pioneering platform, introduced smart contracts, enabling trustless and transparent execution of code for various applications, from decentralized finance (DeFi) to non-fungible tokens (NFTs). Binance Smart Chain (BSC), an Ethereum-compatible alternative, emphasizes fast and cost-effective transactions, making it popular for DeFi projects. Polkadot, a multi-chain network, employs smart contracts through its parachain structure, fostering interoperability and scalability. Tezos stands out for its self-amending blockchain and on-chain governance, providing a platform for smart contract deployment. Cardano incorporates smart contracts for secure and scalable decentralized applications. Solana focuses on high-performance blockchain, utilizing smart contracts for decentralized applications with low transaction costs. These platforms showcase the diverse landscape of technologies utilizing smart contracts, each contributing unique features to the broader blockchain ecosystem. Some use cases of smart contracts are automated insurance claims [14], supply chain management [15], real estate transactions [16], voting and election system [17], crowdfunding [18], cloud storage [19], healthcare records [20], copyright protection [21], online purchases [22], loan management [23], and energy trading [24], where smart contracts can be used to automate the energy trading process and ensure that all parties adhere to the terms of the agreement.

2.3. A Use Case of Smart Contract for Energy Trade

A sample smart contract is described below (i.e., Figure 2) to highlight the energy sector use case. The detailed steps of the smart contract are as follows:

1. The contract is named "Energy Trade".
2. The smart contract begins by reading essential parameters, such as the Owner Address (OA), Energy Balance of Owner (EBoO), Requested Value per Unit (RVpU), and SmartMeterReadings. SmartMeterReadings are included for dynamic energy balancing.
3. A check is introduced to evaluate if the SmartMeterReadings fall below a defined Minimum Threshold. If the energy production is below this threshold, the contract cannot be fulfilled, preventing transactions during periods of insufficient energy generation.
4. The contract proceeds to evaluate whether the Quantity of Energy Requested (QoER) is less than or equal to the Energy Balance of the Owner (EBoO). This condition ensures that the owner has sufficient energy to fulfill the requested amount.
5. A credit-based transaction condition checks if the Requested Value (RV) is within the Total Funds Available (TFA) and if the Buyer's Credit Score meets the Minimum Credit Score requirement.
6. If all conditions are met, the Build_Contract is set to "True", indicating that the contract can be executed. The necessary adjustments are made to the energy balances of both the owner and the buyer. SmartMeterReadings are updated to reflect dynamic energy balancing.
7. If any of the conditions fail, the Build_Contract is set to "False", and a corresponding error message (Msg) is generated. Failure conditions include insufficient funds, low credit scores, or inadequate energy from the owner.

```
// Energy_Trade //

// Initialization
Read OA, EBoO, RVpU, SmartMeterReadings
Read BA, EBoB, QoER, TFA, BuyerCreditScore

// Calculate Requested Value (RV)
RV = QoER * RVpU

if SmartMeterReadings < MinimumThreshold {
    Build_Contract = "False"
    Msg = "Energy production below threshold, contract cannot be fulfilled"
} else {

    // Trade Execution Conditions
    if QoER <= EBoO {
        // Include credit-based transaction condition
        if (RV <= TFA && BuyerCreditScore >= MinimumCreditScore) {
            Build_Contract = "True"
            EBoO = EBoO − QoER
            EBoB = EBoB + QoER

            // Include dynamic energy balancing
            SmartMeterReadings = SmartMeterReadings - QoER
        } else {
            Build_Contract = "False"
            Msg = "Transaction failed due to insufficient funds or low
credit score"
        }
    } else {
        Build_Contract = "False"
        Msg = "The owner doesn't have the required amount of energy"
    }
}
```

Pseudocode Variables

OA: Owner Address
BA: Buyer Address
EBoO: Energy Balance of Owner
EBoB: Energy Balance of Buyer
RVpU: Requested Value per Unit
RV: Requested Value
QoER: Quantity of Energy Requested
TFA: Total Funds Available
SmartMeterReadings: Readings from smart meters
BuyerCreditScore: Credit score of the buyer
MinimumThreshold: Minimum energy production threshold
MinimumCreditScore: Minimum credit score required for the transaction

Figure 2. The pseudocode of a sample smart contract.

3. Research Methodology and Literature Classification

3.1. Review Search Strategy

The search strategy and the implementation of the systematic review followed the PRISMA 2009 [25] flow diagram (Figure 3) as it is a well-established, widely recognized, and extensively used framework for conducting systematic reviews. It provides a comprehensive and structured approach, which was particularly valuable for the authors' review of blockchain and smart contracts in the energy domain. The authors conducted the initial survey for the collection of the articles using over Google Scholar as it is a search engine that encompasses most available academic knowledge, comprising journals and conference proceedings. Thus, we avoided querying each popular scientific database. To obtain the intended literature, the query phrase we used was "Blockchain" AND "smart contracts" AND "energy sector". Subsequently, we filtered the resulting literature and excluded the articles that did not include the search terms in their title, abstract, or keywords. In the next step, we applied a time criterion. We carefully selected the time criterion, limiting our consideration to publications from 2020 to March 2023, considering the observed trend in the literature over smart contract applications in the energy sector as depicted in the Figure 4. Furthermore, it is not an arbitrary assumption that most recent publications (i.e., those published from 2020 onwards) have a higher impact and maturity. Finally, non-English-language articles were excluded from our literature search as the publication language of the most popular journals and conferences is English.

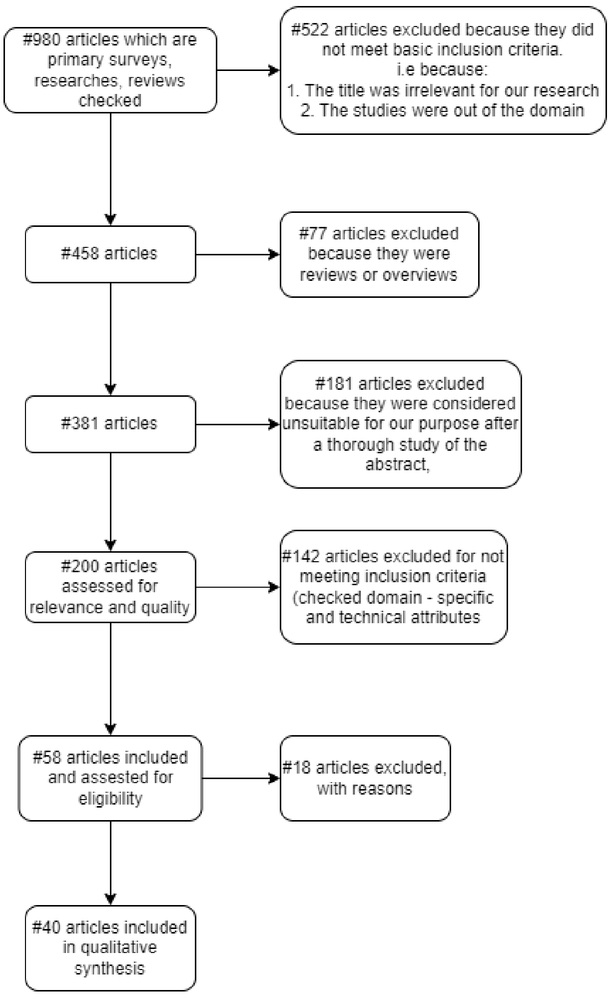

Figure 3. Flow chart of the study selection process.

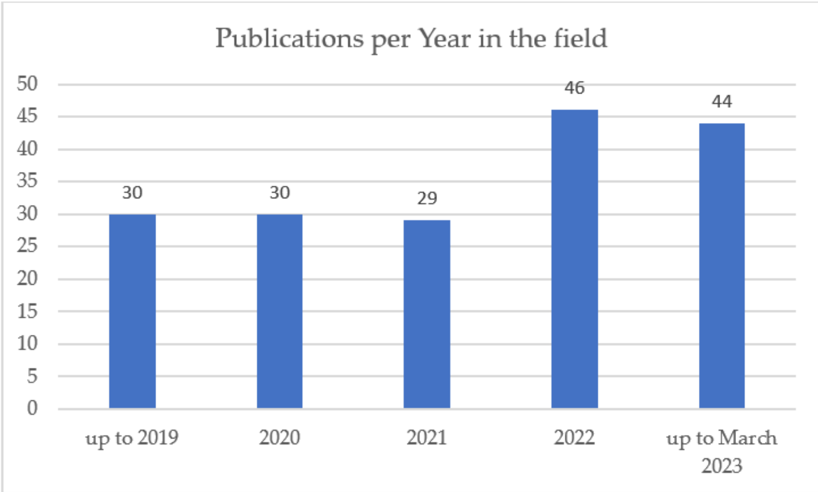

Figure 4. The trend of publications per year according to the search criteria (obtained through the Scopus database).

3.2. Literature Classification

Our research, as already stated, focuses on blockchain technology applications and specifically on smart contracts in the energy sector. The classification of the studies that stemmed from the review search strategy was considered important for the following reasons:

1. It focuses on issues of interest regarding the application of smart contracts in the energy sector.
2. It facilitates an in-depth understanding of this paper.
3. It presents the up-to-date and global view of the research and literature progress advancements.

The chosen categories for articles classification were meticulously selected based on several methodological criteria. The categories were derived from a careful consideration of key domains within the energy sector, ensuring comprehensive coverage of critical aspects such as energy policy, governance, management, and innovative business models.

The inclusion of the SCT class reflects an emerging research issue that emphasizes the technological aspects of smart contract development and the diverse blockchain platforms utilized in the energy sector, such as Ethereum, and the decentralized applications (DApps) that operate using smart contracts. The literature review identified papers in which the technological framework of their implementation was considered worthy of reference, regardless of the category in which they were included.

This systematic classification aims to provide readers with a holistic understanding of the practical significance of blockchain technology and smart contracts across various dimensions of the energy landscape, showcasing their potential to address real-world challenges and foster sustainable energy practices. The categories identified are as follows:

1. Energy Market and Regulations (EMnR): Refers to the energy market and the regulations governing it. It includes issues such as energy trading and market mechanisms, energy policy and governance, market design, and pricing mechanisms.
2. Energy Management and Operations (EMnO): This category refers to the management and operation of the energy system. It includes issues such as demand response and energy flexibility, grid management and balancing, and asset management and maintenance.
3. Business Models and Applications (BMnA): Refers to business models and applications related to smart contracts technology in the energy sector. This category includes topics such as peer-to-peer energy trading applications, the creation of virtual power plants (VPPs), energy as a service (EaaS), and the use of carbon credits exchange to promote sustainability.

The summary table and the relevant Venn diagram presented in Table 1 and Figure 5 depict the classification of the papers included in this review, in a clear and easy to follow manner.

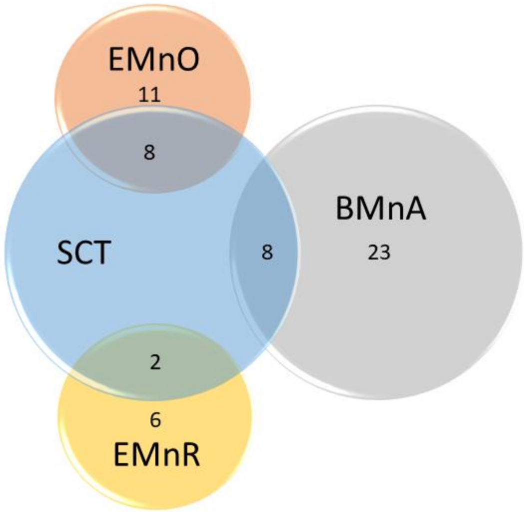

Figure 5. Venn diagram of studies by category.

Table 1. Literature classification categories.

No	Papers—Studies Titles	Year	Smart Contract Technology	Energy Market and Regulations	Energy Management and Operations	Business Models and Applications
1.	Reconfigurable Smart Contracts for Renewable Energy Exchange with Re-Use of Verification Rules [26]	2022	X		X	
2.	Peer-to-peer energy trading in a microgrid leveraged by smart contracts [27]	2021				X
3.	Blockchain and smart contract based decentralized energy trading platform [28]	2020				X
4.	Peer-to-peer electricity trading system: smart contracts-based proof-of-benefit consensus protocol [29]	2021				X
5.	Standardization of smart contracts for energy markets and operation [30]	2022	X		X	
6.	Decentralized energy to power rural homes through smart contracts and carbon credit [31]	2021				X
7.	Poverty mitigation via solar panel adoption: Smart contracts and targeted subsidy design [32]	2021				X
8.	A survey of blockchain applications in the energy sector [33]	2020	X	X		
9.	Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts [34]	2020				X
10.	Vulnerabilities and excess gas consumption analysis within Ethereum-based smart contracts for electricity market [35]	2020	X		X	
11.	A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract [36]	2021				X
12.	ET-DeaL: A P2P smart contract-based secure energy trading scheme for smart grid systems [37]	2020				X
13.	Towards Blockchain-Based Energy Trading: A Smart Contract Implementation of Energy Double Auction and Spinning Reserve Trading [38]	2022		X		

Table 1. *Cont.*

No	Papers—Studies Titles	Year	Smart Contract Technology	Energy Market and Regulations	Energy Management and Operations	Business Models and Applications
14.	Energy Trading Web Platform Based on the Ethereum Smart Contracts and Blockchain [39]	2020	X			X
15.	Study of blockchain based smart grid for energy optimization [40]	2021			X	
16	Energy trading in microgrids using blockchain technology [41]	2020	X			X
17.	A secure and decentralized blockchain based EV energy trading model using smart contract in V2G network [42]	2021	X			X
18.	Challenges and opportunities of Blockchain technology in the energy sector [43]	2020	X	X		
19.	Securing smart grid communication using Ethereum smart contracts [44]	2020	X		X	
20.	Demystifying distributed ledger technologies: Limits, challenges, and potentials in the energy sector [45]	2020		X		
21.	Blockchain based trading platform for electric vehicle charging in smart cities [46]	2020				X
22.	Smart contract formation enabling energy-as-a-service in a virtual power plant [47]	2022				X
23.	Smart contract for distributed energy trading in virtual power plants based on blockchain [48]	2021	X			X
24.	Distributed framework via block-chain smart contracts for smart grid systems against cyber-attacks [49]	2020	X		X	
25.	Integrating blockchain technology into the energy sector—from theory of blockchain to research and application of energy blockchain [50]	2020		X		
26.	Design of integrated energy market cloud service platform based on blockchain smart contract [51]	2022				X
27.	Hedging Volumetric Risks of Solar Power Producers Using Weather Derivative Smart Contracts on a Blockchain Marketplace [52]	2022		X		
28.	A Taxonomy of the Risks and Challenges of Embracing Blockchain Smart Contracts in Facilitating Renewable Electricity Transactions [53]	2022	X			X
29.	Application possibilities of blockchain technology in the energy sector [54]	2020	X			X
30.	IoT and blockchain based peer to peer energy trading pilot platform [55]	2020				X
31.	Automated scheduling approach under smart contract for remote wind farms with power-to-gas systems in multiple energy markets [56]	2021	X		X	
32.	Smart Contract Development for Peer-to-Peer Energy Trading [57]	2022				X
33.	Joulin: Blockchain-based p2p energy trading using smart contracts [58]	2020				X
34.	A survey on blockchain-enabled smart grids: Advances, applications and challenges [59]	2021			X	
35.	Smart contract for electricity transactions and charge settlements using blockchain [60]	2021	X			X
36.	FederatedGrids: Federated learning and blockchain-assisted p2p energy sharing [61]	2022	X		X	
37.	Smart Contracts for Households Managed by Smart Meter Equipped with Blockchain and Chain [62]	2022			X	
38.	Application of blockchain and smart contract to ensure temper-proof data availability for energy supply chain [63]	2020	X		X	
39.	Setup of a local P2P electric energy market based on a smart contract blockchain technology [64]	2020				X
40.	Modeling of smart contracts in blockchain solution for renewable energy grid [65]	2020	X			X
	Total:		**18**	**6**	**11**	**23**

During the review process we identified comparable technical challenges, research focuses, and contributions. A compiled version of these similarities is depicted in Tables 2 and 3, along with an outline of the technical environment applied.

Table 2. Main focus and contribution along with technical environment characteristics.

Paper Title	Main Focus and Contributions	Technical Environment
Reconfigurable Smart Contracts for Renewable Energy Exchange with Re-Use of Verification Rules [26]	- Introduction of Smart Contract Design Pattern (SCDP) - New UML profile for smart contracts - Rigid nature of smart contract verification rules - Energy exchange difficulties	- Platform independent - Java
Blockchain and smart contract based decentralized energy trading platform [28]	- Implementation of an interactive web-based user interface - Secure financial and energy deviation settlement mechanisms - Distributed control and management in the energy trading sector - Uncertainties in energy trades	- Ethereum (EVM) - Solidity - React JavaScript
Energy Trading Web Platform Based on the Ethereum Smart Contracts and Blockchain [39]	- Creation of a web-based electricity trading platform utilizing Ethereum Blockchain - Administrative intervention and potential record manipulation in energy exchanges	- Ethereum (EVM) - Solidity
Challenges and opportunities of Blockchain technology in the energy sector [43]	- Proposal for using blockchain in energy exchanges and flexibility management in microgrids - Traceability and transparency in energy transactions - Development of new business models	- Distributed Ledger Technologies (DLT) - Distribution System Operator (DSO)
A survey of blockchain applications in the energy sector [33]	- Comprehensive review of blockchain deployments in energy management, P2P trading, EV applications - Security and/or privacy concerns	- No information provided
Application possibilities of blockchain technology in the energy sector [54]	- Exploration of blockchain architecture and applications in electricity trading and EV charging - Hardware efficiency and platform uniformity in blockchain implementation	- No information provided
Study of blockchain based smart grid for energy optimization [40]	- Emphasis on blockchain in enhancing smart grid security, efficiency, and decentralized control - Distributed control and management in the energy trading sector - Security and/or privacy concerns	- No information provided
Smart Contract Development for Peer-to-Peer Energy Trading [57]	- Software architecture and algorithm analysis for smart contracts in P2P energy exchanges - Distributed control and management in the energy trading sector - Integration issues of renewable energy sources	- Ethereum (EVM) - Solidity - OpenZeppelin Library
Decentralized energy to power rural homes through smart contracts and carbon credit [31]	- Development of a DApp for solar energy trading and carbon credit incentives in rural areas - Energy distribution challenges in rural settings - Incentivization through carbon credits	- IOTA Tangle Blockchain - Python - Raspberry pi
Securing smart grid communication using Ethereum smart contracts [44]	- Proposal for a communication infrastructure using Ethereum smart contracts - Security and/or privacy concerns	- Ethereum - Solidity
Energy trading in microgrids using blockchain technology [41]	- Blockchain application for P2P transactions in microgrids - Distributed control and management in the energy trading sector	- Ethereum - Solidity

Table 2. *Cont.*

Paper Title	Main Focus and Contributions	Technical Environment
Joulin: Blockchain-based p2p energy trading using smart contracts [58]	- Joulin platform for energy trading using Ethereum blockchain - Development of new business models	- Ethereum - Solidity - MythX - GoLang
Peer-to-peer electricity trading system: smart contracts-based proof-of-benefit consensus protocol [29]	- P2PEBT system with proof-of-Benefit consensus on Ethereum - Grid stability incentives	- Ethereum
Design of integrated energy market cloud service platform based on blockchain smart contract [51]	- Decentralized cloud service platform for energy trading - Transaction types and dispatch subsidies in energy markets	- Antchain
Peer-to-peer energy trading in a microgrid leveraged by smart contracts [27]	- Frameworks for blockchain-supported P2P energy transactions - Reliability and cost-effectiveness in P2P transactions	- Ethereum - Ganache-cli - Mocha - Solidity - React.js - Web3.js
Standardization of smart contracts for energy markets and operation [30]	- Reference model for DLT in energy industry standardization - Security and/or privacy concerns	- Distributed Ledger Technologies (DLT)
Smart contract for electricity transactions and charge settlements using blockchain [60]	- Streamlining transactions between grid enterprises and market members - Efficiency and reliability in bilateral trading and trust costs in the electricity market	- Ethereum
Distributed framework via block-chain smart contracts for smart grid systems against cyber-attacks [49]	- Framework incorporating blockchain for secure data handling in smart grids - Security and/or privacy concerns	- Ethereum - Solidity - Ganache
Poverty mitigation via solar panel adoption: Smart contracts and targeted subsidy design [32]	- Analysis of government subsidy policies linked to household energy behaviour - Economic hurdles and managing uncertainties in solar energy generation	- No information provided
Blockchain based trading platform for electric vehicle charging in smart cities [46]	- Leveraging utility infrastructure for peer-to-peer energy trading in smart cities - Integration with existing utility billing; scalability of a private Ethereum network	- Ethereum - JavaScript - GoLang
ET-DeaL: A P2P smart contract-based secure energy trading scheme for smart grid systems [37]	- ET-DeaL system utilizing Ethereum smart contracts and IPFS - Security and/or privacy concerns	- Ethereum - Solidity - Truffle - Inter Planetary File System (IPFS)
Setup of a local P2P electric energy market based on a smart contract blockchain technology [64]	- Model for local P2P energy trading emphasizing distributed generation - Distributed control and management in the energy trading sector	- Distributed Ledger Technologies (DLT)
Peer-to-peer energy trading in virtual power plant based on blockchain smart contracts [34]	- Efficient, transparent P2P energy trading system in VPPs - Distributed control and management in the energy trading sector	- Ethereum (EVM) - Remix - Metamask - Web3.js - Infura.io - Ropsten
A survey on blockchain-enabled smart grids: Advances, applications and challenges [59]	- Detailed review of technological advances in blockchain for smart grids - Security and/or privacy concerns	- Ethereum (EVM) - Web3.js - Solidity
Smart contract for distributed energy trading in virtual power plants based on blockchain [48]	- Blockchain-based transaction model reflecting real-time supply and demand - Distributed control and management in the energy trading sector	- Ethereum - Solidity

Table 2. *Cont.*

Paper Title	Main Focus and Contributions	Technical Environment
IoT and blockchain based peer to peer energy trading pilot platform [55]	- Integration of a user-friendly web interface for connectivity - Distributed control and management in the energy trading sector	- Node Red - Ethereum - Ganache - Metamask - Arduino
Application of blockchain and smart contract to ensure temper-proof data availability for energy supply chain [63]	- Decentralized application for connecting energy supply industries - Security and/or privacy concerns	- Ethereum (EVM) - Solidity - Metamask - Truffle - Ganache - Solidity - Web3.js - React.js - Node.js
A Taxonomy of the Risks and Challenges of Embracing Blockchain Smart Contracts in Facilitating Renewable Electricity Transactions [53]	- Taxonomy categorizing challenges in technical and social dimensions - Scalability and volatility in blockchain networks - Security and/or privacy concerns	- Ethereum (EVM)
A secure and decentralized blockchain based EV energy trading model using smart contract in V2G network [42]	- Dynamic pricing, mutual authentication, and private blockchain in V2G networks - Distributed control and management in the energy trading sector	- No information provided
FederatedGrids: Federated learning and blockchain-assisted p2p energy sharing [61]	- Federated learning for predicting future energy production and demand - Balancing energy consumers and prosumers - Security and/or privacy concerns	- Ethereum (EVM) - Remix - Ganache - Geth
Demystifying distributed ledger technologies: Limits, challenges, and potentials in the energy sector [45]	- Guidelines for DLT implementation in energy sector use cases - Understanding technical aspects, benefits, and limitations of DLT	- Ethereum
Smart contract formation enabling energy-as-a-service in a virtual power plant [47]	- Evolutionary computing strategy for smart contract formation - Optimizing energy transactions in VPPs	- Distributed Ledger Technologies (DLT)
Towards Blockchain-Based Energy Trading: A Smart Contract Implementation of Energy Double Auction and Spinning Reserve Trading [38]+	- Development of Ethereum-based smart contracts for energy sector - Smart contracts for energy auctions management	- Ethereum (EVM) - Remix - Solidity
A comprehensive hierarchical blockchain system for carbon emission trading utilizing blockchain of things and smart contract [36]	- Innovative approach for controlling carbon emissions using blockchain - Transparency and integrity in carbon trading	- Ethereum - Hyperledger - Polkadot - Interledger
Integrating blockchain technology into the energy sector—from theory of blockchain to research and application of energy blockchain [50]	- Insights into the growth of blockchain-related energy research - Developments in renewable energy sector	- No information provided
Hedging Volumetric Risks of Solar Power Producers Using Weather Derivative Smart Contracts on a Blockchain Marketplace [52]	- Decentralized finance instruments for managing uncertainties in solar production - Managing risks associated with solar power generation	- No information provided
Smart Contracts for Households Managed by Smart Meter Equipped with Blockchain and Chain 2 [62]	- Real-time billing, energy savings through enhanced smart meters - Security and/or privacy concerns - Bidirectional data flow for energy management	- No information provided
Automated scheduling approach under smart contract for remote wind farms with power-to-gas systems in multiple energy markets [56]	- Non-linear model for P2G system - Automated scheduling framework - Coordination and information stability challenges	- Open Vote Network (OVN)

Table 2. *Cont.*

Paper Title	Main Focus and Contributions	Technical Environment
Vulnerabilities and excess gas consumption analysis within Ethereum-based smart contracts for electricity market [35]	- Empirical analysis and tool evaluations for smart contract security - Vulnerabilities and gas expenditure optimization	- Ethereum (EVM) - Solidity - SmartCheck
Modeling of smart contracts in blockchain solution for renewable energy grid [65]	- PoC implementation - Flexible design pattern for smart contracts - Developments in renewable energy sector	- Corda - Java

Table 3. Common technical challenges identified.

Common Technical Challenges	Papers—Studies
Security and/or Privacy Issues in Smart Energy Networks	[33,40,44,49,59,62,63]
Management and Integration in Energy Systems and Blockchain	[28,39,42,43,45,47,48,53–55,57]
Technical Issues in Energy Transactions and Markets	[26,27,29,38,51,56,58,60,61]
Implementation of Blockchain Technology and Smart Contracts	[26,30,31,34,35,64,65]
Renewable Sources and Efficiency in Energy Production	[32,36–38,41,46,50,52]

The Venn diagram in Figure 5 represents the number of articles assigned in each category and the relationship between the EMnR, EMnO, and BMnA categories and the independent class SCT. The purpose of the analysis is to explore the common and non-common components of these sets and to provide a complete picture of the dimensions of each category and the correlations between them.

First, the multitude of articles in each category is determined. The EMnR category includes 6 articles, while 11 articles were assigned to the EMnO category. In addition, the BMnA category includes 23 articles, while the independent class SCT shares 8 articles with the EMnO class, 2 articles with the EMnR, and 8 articles with the BMnA class,

The following sections present the categories identified along with the main characteristics of the studies included in each of them, such as their objectives, the challenges faced by the researchers, the proposed solutions, and the results achieved.

3.2.1. Energy Market and Regulations (EMnR)

The category "Energy market and regulations" focuses on the policies, regulations, and specific market mechanisms governing the energy sector. The subcategories identified in this category are as follows:

- Energy transactions and market mechanisms: This subcategory deals with the various mechanisms involved in energy trading, such as spot, futures, and derivatives markets. It also encompasses the different types of market participants, such as producers, suppliers, and consumers.
- Energy policy and governance: Deals with the various policies and governance structures that affect the energy sector. It includes government policies related to energy security, energy efficiency, and renewable energy issues.
- Market design and pricing mechanisms: This subcategory focuses on the design of energy markets and the pricing mechanisms used to set energy prices. It tackles issues such as capacity markets, price caps, and auctions.

The study of Bao [33] reviews how blockchain technology has been, and can be, deployed in energy applications. It also studies the existing architectures and solutions, and existing and emerging security and privacy challenges. This paper tackles the challenges posed by the transition to renewable energy sources, the need for decentralized energy systems, and the promotion of carbon emission reduction through trading mechanisms. One of the main findings of the paper is that blockchain technology has been, and can be, deployed in a variety of energy applications, such as energy management, peer-to-peer trading, electric vehicle-related applications, and carbon emissions trading.

Damisa et al. in [38] discuss Ethereum-based smart contracts that facilitate dual energy auctioning and negotiation of spinning reserves. The efficiency of the contracts in executing the auction process and making payments is validated using an energy/reserve market scenario. The paper addresses the need for a transition to renewable energy sources, the inefficiencies and high transaction costs associated with centralized energy trading systems, and concerns related to data privacy, scalability, and security. The main findings of this paper are that a blockchain-based smart contract is well suited to transparently facilitate transactions between consumers and energy producers without the services of intermediaries. Ethereum-based smart contracts are also being developed to facilitate dual auctioning of energy and trading of spinning reserves. Finally, the proposed system encourages further adoption of distributed energy resources and participation in local P2P energy transactions.

According to Botticelli in [43], blockchain technology has the potential to revolutionize the energy sector by providing a secure, transparent, and efficient platform for energy transactions, and start-up initiatives have developed energy solutions based on blockchain and distributed ledger technology. The paper focuses on issues related to energy traceability, transparency in energy tariffs, and the security of energy transactions. It addresses the need for a tamper-proof platform for energy networks and the regulatory framework required for renewable energy consumers and communities. Finally, the paper presents a concept of a possible application of blockchain technology, through a smart contract defining an energy token, to manage the flexibility applied to a microgrid from the Distribution System Operator (DSO) point of view. The energy token is valued with a dynamic price, taking into account the state of the network, the availability of energy, and production forecasts.

Hrga et al. in [45] provide an overview of Distributed Ledger Technologies (DLT) and their potential applications in the energy sector. It discusses the benefits and limitations of DLT and identifies technical challenges that need to be solved to enable widespread usage of DLT in energy systems. Furthermore, this work aims to provide solutions for scalability issues, which are a complex and rapidly evolving area in DLT. Balancing technical depth with accessibility for a diverse readership poses another challenge. It also categorizes energy applications and platforms, and presents several solutions for each category. According to the paper, blockchains can enable complex mechanisms through smart contract capabilities, and on the other side, DAGs (Directed Acyclic Graphs) offer processing speed and scalability of financial transactions.

According to Q. Wang and Su in [50], developed countries dominate the basic research of energy blockchain because they have mastered more advanced blockchain technology, while developing countries are playing an increasingly important role in the global energy blockchain research system. Also, an important challenge for developing countries to develop energy blockchains in the future is how quickly they can build a complete distributed power system. Furthermore, ongoing research in the field focuses on renewable energy trying to solve the problems in its development process and providing better solutions for the replacement of fossil energy.

Alao and Cuffe in [52] address the cash flow volatility risks faced by solar power producers (SPPs) due to fluctuating electricity prices and unpredictable weather-dependent energy generation. The challenges include the need to mitigate these risks to secure favorable financing terms, the limited attention given to long-term volumetric risks, and the scarcity of weather derivative mechanisms tailored to SPPs. Additionally, the emerging field of Decentralized Finance (DeFi) introduces new risks that require assessment, and the blockchain-based approach suggested in the paper is still in its early stages, necessitating a better understanding of its risks and potential. They propose a solar radiation-based weather derivative smart contract arrangements on a blockchain marketplace to address some of the main limitations of traditional instruments. These smart contracts are analytically evaluated, and a suite of novel smart contract autonomous mechanisms is presented. Results emanating from notional simulations indicate that the proposed approach could be more suitable for hedging the volumetric risks of solar power producers than traditional instruments.

3.2.2. Energy Management and Operations (EMnO)

The category "Energy management and operation" encompasses the technical aspects of energy systems management and optimization. The following subcategories were identified in this category:

- Demand response and energy flexibility: This subcategory deals with the ability of energy systems to adjust their power output in response to changes in the grid load. Demand response strategies contribute to the reduction of peak loads on the grid and the supply and demand balancing.
- Network management and balancing: Mainly concerned with managing electricity flow on the grid to ensure that supply meets demand. This may include real-time monitoring of the grid, balancing power flows, and managing the integration of renewable energy sources.
- Asset management and maintenance: Focuses on the maintenance and optimization of energy assets such as power plants, transmission lines, and distribution networks. This may include monitoring of equipment performance and optimizing scheduled maintenance of assets so as to minimize downtime.

The study of Cali et al. [30] delves into the challenges of standardization, cybersecurity establishment, legal aspects, and inter-operability enhancement of smart contracts, aiming to assist decision-makers. It also presents a first attempt towards the standardization of smart contracts (SCs) within the field of power and energy as a work in progress activity under the IEEE Standards Association (IEEE SA) P2418.5 Working Group. A template that can be applied to various energy use cases is suggested to assist in creating a DLT agnostic reference model. This model aims to promote the adoption of DLT technology by industry players in a consistent way. The ultimate goal is to speed up the adoption of this technology, while at the same time it discusses additional aspects of smart contracts regarding standardization, cybersecurity, legality, and inter-operability to help users and policymakers in the decision-making process.

According to Patil et al. [40] the challenges faced in integrating green and renewable energy technologies through the smart grid concept include the effective management of the growing interconnections within the energy grid as it evolves from a centralized to a decentralized structure. In addition, the paper addresses issues related to security, data protection, and privacy in the use and exchange of electricity data within the smart grid. It is estimated that blockchain technology has the potential to enhance the smart grid concept by facilitating energy trading, providing record aggregation systems, managing power flow in specific regions, improving energy trading processes through credit-based payment systems, and addressing the confidentiality and safety concerns of the grid. They also report the limitation that blockchain-based energy technology is at an early phase globally and lacks a uniform structure that will permit the technology to display its full potential. The transition from conventional means of payment for energy to an economy with new transaction structures will take some reasonable time for effective use by the young to the elderly.

The study of Ji et al. [56] address issues related to the efficient coordination of wind farms equipped with power-to-gas (P2G) systems across multiple energy markets. The challenges posed include handling the remote locations of wind farms, ensuring secure and reliable coordination, and managing complex smart contracts with limited logic complexity. Additionally, it deals with the need to optimize scheduling results while considering revenues from energy trades and potential penalties for contract violations. It also proposes an automated scheduling approach for wind farms with power-to-gas systems. It uses a smart contract to coordinate between the wind farms and multiple energy markets. It also reports that by deploying P2G (Peer to Grid), wind farms can not only benefit from participating in multiple energy markets, but also contribute more for carbon reduction.

The main objective of a work by Liu et al. [29] is to gain profound comprehension of the consensus mechanism within the energy industry along with enhancing the progress of intelligent grid management systems. There is also skepticism about the usefulness of the current consensus mechanism in terms of its ability to meet the requirements in the domain. At the same time, the authors provide guidelines for the development of security standards, the normalization of the smart contract code, the improvement of data encryption at the network layer, and the authentication mechanisms for user authentication.

FederatedGrids is introduced by Bouachir et al. [61] as a platform that combines federated learning and blockchain technology to enable P2P energy trading and sharing. The platform establishes a collaborative setting that ensures all participants in different microgrids are satisfied with their involvement. This paper highlights the issues of consumers lacking funds to buy energy and the costly energy storage management by prosumers, which can discourage participation. Additionally, the authors discuss the need for robust security and privacy features in P2P energy trading systems, emphasizing that prosumers and consumers are reluctant to adopt technologies that do not guarantee these aspects. Future work on the project involves elaborating on the mechanism for incentivizing energy sharing and conducting a comprehensive evaluation of the entire energy trading and sharing system, with a specific emphasis on safeguarding the privacy of all participants.

Lazaroiu et al. [62] tackle critical challenges, including the necessity for accurate and automated billing and payment processes, the bidirectional exchange of data, the enhancement of energy awareness, and the seamless interoperability of blockchain technology within existing smart metering infrastructure. According to the authors, digital technologies, along with smart meters, have the potential to enhance energy efficiency and facilitate new services like real-time pricing, energy usage awareness, and boost smart contracts task automation. However, along with the implementation of smart meters and related digital technologies, privacy concerns arise as well. It is also reported that blockchain and smart contracts can be used to improve the security and privacy of residential energy customers.

Górski, in [26], describes the challenges associated with designing and implementing smart contracts on blockchain platforms, focusing on permissioned blockchains like Hyperledger Fabric, R3 Corda, and Quorum. These blockchains have limitations in terms of hardcoded verification rules within smart contracts, which hinder flexibility, reconfigurability, and the ability to reuse rules across contracts. To overcome these challenges, he introduces a new design pattern for creating smart contracts that are resilient and robust. This pattern is platform-independent and implemented in Java programming language. It enables greater source code reusability and facilitates testing. By reusing verification rules, the pattern simplifies the process of updating smart contracts. The author demonstrated that the pattern is suitable for extending smart contracts and adapting them to evolving business requirements. The pattern can also simplify the process of creating smart contracts for distributed applications that facilitate collaboration among communities of renewable energy producers and consumers.

According to Danielius et al. [35], the use of smart contracts can enable the creation of decentralized electricity markets that are highly independent. Additionally, smart contracts can facilitate seamless and dependable transaction settlement. However, there may be vulnerabilities and excessive gas consumption within Ethereum-based smart contracts used for electricity markets, but they can be detected and resolved with appropriate measures such as improving the design and implementation of smart contracts, optimizing gas usage, and conducting comprehensive security testing.

A study conducted by Akhras et al. [44] suggests that a blockchain-based communication infrastructure, using Ethereum as the underlying network, can be employed to safeguard the communication between different entities within a smart grid. To achieve this, smart contracts can be utilized to validate the authenticity of each smart meter and ensure secure and private reporting of the readings. However, challenges in terms of scalability and cost need to be addressed. It is experimentally proven that the cost is not determined by the size of the network, but rather by the complexity of the transaction. The transaction fees are associated with the operations involved in each transaction. As the operations become more complex, the transaction costs increase.

According to Alkaeed et al. [49], the challenges in securing smart grids have become crucial components of modern electrical networks. The integration of smart grid technology, while promising greater reliability and efficiency, also introduces vulnerabilities in terms of cybersecurity. The primary issues revolve around weaknesses in cybersecurity, potential power outages, theft of electricity, and privacy breaches for energy consumers. Furthermore, smart grids are a popular solution for integrating distributed energy sources and ensuring the safety and security of power supply networks. One technology that can enhance the security of smart grids is blockchain. Blockchain technology provides secure, decentralized, and democratized system for information storage and dissemination across various industry sectors. The authors introduce a new distributed framework that enhances the self-defense capabilities of smart grids by adopting blockchain technology to protect energy systems against cyber-attacks.

An approach that involves utilizing the Ethereum blockchain platform in conjunction with the current conventional infrastructure to monitor and examine energy supply chain operations is suggested by [63]. However, several issues need to be addressed. The first one involves integrating blockchain into government organizations and ensuring the secure and efficient transfer of data. Additionally, the need to maintain a balance between centralized and decentralized processes for cybersecurity and data safety is a significant challenge. Finally, concerns about data security and the development of tools for transferring database services to the blockchain are key obstacles. They also report that smart contracts can be utilized to document activities securely and make them accessible to stakeholders in accordance with established protocols and best practices. According to the authors, through a DApp, it is possible to rapidly connect the existing energy supply industry at multiple geographical locations to monitor and trace related data in the energy market. Some benefits are the monitoring of supply chains by regulators and the improvement of fair competition between companies. Also, the application of blockchain technology can help government agencies to monitor and track invoices transparently.

3.2.3. Business Models and Applications (BMnA)

The category “Business models and applications” explores new ways of doing business in the energy sector using emerging technologies and innovative ideas. The most important subcategories identified in this category are:

- P2P energy trading: Explores the idea of allowing energy consumers to trade electricity with each other without the intervention of a traditional utility company.
- Virtual Power Plants (VPP): Refers to a system where multiple small-scale energy sources, such as solar panels or wind turbines, are aggregated and managed as a single entity to provide grid services and sell energy in wholesale markets.
- Energy as a Service (EaaS): Explores the concept of energy as a service, whereby customers enjoy increased flexibility and are charged on a pay-as-you-go basis, rather than owning the energy production infrastructure.

The challenges addressed in [27] involve transitioning from an aging centralized power grid to a more distributed and complex network that includes prosumers actively contributing to energy production. The authors explore the need to adapt to real-time energy supply and demand, considering intermittent renewable energy sources. It also discusses the formation of microgrids as local energy markets and their role in achieving sustainability and resilience, both in terms of grid management and cybersecurity. More specifically, the authors examine how blockchain technologies and auction mechanisms can be utilized to enable autonomous P2P energy trading in microgrids. Two frameworks are devised and contrasted by utilizing a dataset from the real world. The outcomes indicate that a P2P trading platform that merges blockchain technologies and agent-based systems has the potential to supplement the existing centralized energy grid. As arises from the article, both the independent microgrid and the centralized national grid should work in conjunction with each other to promote a more eco-friendly and cost-effective energy market.

Blockchain technology and smart contracts have the potential to establish a distributed energy trading platform, which allows prosumers to exchange their surplus energy without mediators. In [28], the authors introduce a blockchain and smart contract-based trading platform that addresses various challenges in the energy sector. This platform offers transparency, affordability, and self-sufficiency to both prosumers and consumers situated at the grid's edge. By leveraging distributed renewable energy-based generators, the platform promotes sustainability and emphasizes the significance of long-term energy security. The paper aims to tackle these challenges and presents a decentralized energy trading platform that not only benefits energy users but also contributes to a more reliable and efficient energy ecosystem.

In response to the challenges in the energy sector, Liu et al. [29], introduce a Peer-to-Peer Electricity Blockchain Trading (P2PEBT) system that leverages existing charging and discharging protocols for electric vehicles (EVs) within the smart grid. To address issues of grid stability and incentivize demand response, the authors integrate Proof-of-Benefit (PoB) consensus mechanisms into this blockchain system. Their work aims to achieve a reduction in power fluctuation and eliminate the reliance on third-party intermediaries while promoting transparent and stable electricity trading.

In the demanding context of India's energy sector, which faces significant challenges such as limited grid connectivity in remote areas, blockchain-based solutions like a DApp offer promising prospects, as suggested by Lakshmi and Thiyagarajan in [31]. The proposed solution securely documents the ownership and usage of solar energy through IoT devices. These solutions have the potential to incentivize utility providers and investors through mechanisms like carbon credits and renewable energy certificates, thus addressing the issue of attracting investments for green initiatives. Moreover, the capacity of the DApp to enable energy trading in off-grid rural areas provides a decentralized alternative to meet the surging demand for rural electrification. However, the intricate technical and economic aspects of implementing such solutions effectively must be addressed, particularly in resource-constrained environments.

The accommodation of heterogeneity and uncertainty of quantity competition is in the spotlight of Guo et al. [32], who suggest smart contracts as a solution which can benefit households residing in both energy-poor and energy-rich regions, as well as the government. To mitigate solar uncertainty, subsidy design schemes led by the government can help to decrease overall subsidy expenditures. However, mechanism design schemes may be more effective than market competition in terms of cost-effectiveness, but only when the latter is confined to a single region.

Developing a P2P energy trading system within VPPs using public blockchain technology presents several significant challenges. These include ensuring true decentralization and scalability without relying on costly intermediary authorities. Furthermore, seamlessly integrating complex power systems with blockchain ecosystems adds a layer of technical complexity. Designing modular smart contracts that can adapt to various use cases within the VPPs framework requires careful consideration. Real-world testing and validation of the proposed P2P energy trading system, including cryptographic testing, is essential to bridge the gap between theoretical concepts and practical implementation. Additionally, addressing potential challenges related to user adoption and interface design is crucial when transitioning to DApps. The work by [34] serves as a relevant example, as they validated a similar approach for P2P energy trading within VPPs using smart contracts on the Ethereum Blockchain Platform. Their use of realistic data in the Ethereum Virtual Machine (EVM) environment underscores the importance of practical validation in the context of blockchain-based energy trading.

Al Sadawi et al. in [36] propose a hierarchical blockchain framework designed to monitor and decrease carbon emissions. Their framework includes three levels: an upper-level public blockchain for applications, a lower measurement level functioning as a blockchain consortium for measurements with restricted access, and a cross-transfer level facilitating data and information exchange between these tiers. Smart contracts within the

Blockchain of Things (BoT) are implemented to maintain system integrity and achieve fair trade status. Emphasizing transparency as a top priority in their design, this framework aligns with the paper's overarching goals, which address challenges related to carbon emission trading and blockchain integration. The challenges highlighted include the necessity to improve transparency, eliminate non-transparency and corruption in existing carbon trading systems, establish robust legislation and tracking systems, and address the complexity of carbon allowance allocation and its impact on participant distribution. Furthermore, the paper identifies the lack of integration in carbon markets as a concern that needs resolution. The authors' ultimate objective is to propose a comprehensive blockchain-based framework to enhance the effectiveness of carbon emission trading while promoting sustainability and equity.

Kumari et al. [37] introduce ET-DeaL, a secure energy trading scheme designed to enhance energy transfer (ET) systems, particularly within the context of Smart Grids. The evolving energy landscape, driven by increasing energy demand and digitalization, underscores the need for more efficient electricity distribution. Existing centralized Smart Grid systems grapple with performance and reliability issues, necessitating innovative solutions. While researchers have explored blockchain's potential in ET systems, persistent challenges, including data storage limitations, high data storage costs, and data redundancy, require attention. In response, ET-DeaL is a system that leverages blockchain technology, particularly Ethereum, to optimize security and privacy in P2P energy transactions within Smart Grids. ET-DeaL distinguishes itself by storing its ET data on a distributed off-chain IPFS database, thereby improving data access efficiency. Additionally, it employs smart contracts to manage permissions and roles for different entities within the energy transfer process. Ensuring interoperability between entities in remotely located Smart Grids is facilitated by utilizing a public Ethereum blockchain.

According to Karthik and Anand [41], the utilization of blockchain technology has the potential to enable direct exchange of energy among peers within microgrids, bypassing the need for intermediaries. With the assistance of Solidity, smart contracts can be established for facilitating P2P energy trading. The adoption of blockchain technology in the energy industry can aid in resolving challenges associated with energy trading in microgrids. Within the context of this paper, the challenges addressed include transitioning from a centralized to a decentralized power system, managing the volatility of renewable energy sources, reducing losses in microgrid power generation, and ensuring efficient utilization of renewables. Additionally, the paper emphasizes the importance of secure and efficient energy trading and highlights the technical, regulatory, and operational hurdles that must be overcome during this transition.

A structure for energy trading of electric vehicles within the context of smart cities that relies on blockchain technology is suggested by Lasla et al. in [46]. Specifically, the architecture involves a trading platform that uses smart contracts and operates on a private Ethereum network. The authors' trials have demonstrated that the implementation of Ethereum is capable of accommodating charging demands from electric vehicles, even during periods of high demand in densely populated urban areas. The major issues addressed in this paper revolve around enabling efficient P2P energy trading for Electric Vehicle (EV) charging using blockchain technology. These challenges include maintaining security and trust in a decentralized environment, despite the associated high storage footprint, computational overhead, and communication requirements.

The work of Mishra et al. [47] focuses on addressing challenges related to the coordination of transactions and assets within VPPs, particularly in the context of a transition from a small number of large assets to a large number of small assets within VPPs. The primary challenge is enabling P2P transactions among asset owners and stakeholders within VPPs using EaaS business models. The paper specifically tackles the scenario where multiple picogrids participate as asset owners in a VPP. Notably, there is limited prior research available on the topic of EaaS within VPPs, making this a novel area of exploration. The authors claim that the use of smart contracts has the potential to enable EaaS in VPPs. In order to develop a simulation environment for contract formation, the authors introduce a new strategy based on evolutionary computing. The strategy was compared to other methods such as random order, random selection, and profit-based ranking, and was found to be effective for coordinating the formation of contracts. In conclusion, the article recommends exploring demand side flexibility, enhancing the transparency of energy flows, and utilizing various heuristic techniques.

Lu et al. [48] introduced a blockchain-based transaction model for VPPs that anticipates the future energy internet's reliance on real-time electricity prices. This innovative model leverages smart contracts to enable distributed energy trading within VPPs, providing real-time visibility into supply and demand dynamics, thereby facilitating two-way selection under conditions of information symmetry as distributed energy resources integrate seamlessly into the energy grid. This research underlines the transformative potential of blockchain technology in enhancing energy market efficiency, transparency, and adaptability to evolving energy landscapes, offering insights into the challenges of integrating blockchain into China's ongoing electricity marketization reform.

The study of Wang et al. [51] addresses several challenges in the existing integrated energy market and its application of blockchain technology. These challenges include the need to establish a credible and independent cloud service platform to replace intermediary functions and support expanding carbon trading markets. It also highlights concerns related to quantifying and accurately categorizing different types of energy loads, as well as issues with existing integrated energy markets' ability to meet evolving demands. The paper further underscores the practical problems and limitations of previous blockchain-based energy trading systems, such as high costs, centralized bidding, and conceptual-level analysis. To overcome these challenges, a cloud service platform for an integrated energy market is proposed by the authors. The platform employs blockchain smart contracts to ensure the security and convenience of energy trading. It is designed by Antchain (https://www.antchain.net, accessed on 30 November 2023) and can simulate the energy trading and dispatch process of the cloud service platform. The simulation results demonstrate that the platform, based on the blockchain smart contract, can achieve efficient and intelligent energy dispatch, in addition to providing a secure and convenient energy trading environment.

Another energy trading platform is proposed in the study of [55]. It is a P2P platform that includes essential features such as energy transfer, metering, and money transfer to facilitate energy trading. The proposed system is developed entirely using open-source software and is designed to cater to the needs of prosumers and offers economic benefits to all participants involved in the trading process. The challenges addressed in this paper revolve around the development of an IoT-based energy trading platform integrated with blockchain technology. They concern the creation of a decentralized and secure system that enables P2P energy trading while utilizing cryptocurrency incentives. The platform seeks to overcome challenges related to reducing reliance on intermediaries in energy trading and establishing a transparent and flexible pricing mechanism through negotiations between peers.

According to Budak et al. [57], the utilization of smart contracts ensures secure transactions between two parties in a P2P network, which are validated by the contract's self-operating logic structure without introducing any weaknesses in the system. The paper confronts several challenges associated with the integration of blockchain technology into the evolving model of P2P energy trading. These challenges encompass the optimization of blockchain-based P2P trading systems to reconcile the blockchain trilemma, encompassing security, decentralization, and scalability, while considering transaction fees and public network conditions. Another notable challenge pertains to ensuring the energy efficiency of blockchain transactions. The paper underscores the necessity to address issues associated with managing sudden changes in energy markets and grid operations, especially in the context of renewable resources. The research presents a software platform with a user interface that includes an instrument panel and offers prices based on the supply-demand relationship. The objective of the study is to advance decentralization by integrating renewable energy sources within a P2P trading framework enabled by blockchain technology.

In a study conducted by Perk et al. [58], blockchain technology is also proposed as a fitting option for P2P energy trading. The primary challenges include ensuring the efficiency and transparency of direct energy transfers between users without relying on third-party intermediaries. Additionally, the paper emphasizes the need for an effective buyer and seller matching service within the system. For this reason, the authors present a marketplace for energy trading that operates based on smart contracts on the blockchain named Joulin. The prototype of Joulin was created using the Ethereum blockchain and demonstrated its usability. The main findings suggest that it is possible to develop an easily expandable and dependable system with low transaction costs while maintaining usability, flexibility, and resilience. The Ethereum gas costs are minimal, and the response times are rapid, confirming the platform's usability. Additionally, the smart contracts according to the authors have undergone security testing to prevent potential external manipulations, ensuring their reliability.

A double-chain blockchain model that offers a secure and automated system for electric energy trading within the local electricity market, without any need for intermediaries, is proposed by Perekalskiy et al. [64]. This model is designed to provide an adequate level of security for all parties involved. The paper's primary challenges revolve around establishing a reliable and cyber-stable system for local P2P energy markets using blockchain technology. The challenges include ensuring the fairness of all transactions while maintaining the overall stability of the energy system. The paper aims to address security concerns, such as potential hacker attacks, by leveraging blockchain's decentralized and secure data management capabilities. According to the authors, distributed network blockchain technology can be employed to manage and meter electricity effectively in a distributed generation system. The implementation of such an electrical network is expected to enhance the system's dependability.

Tonev in [39] highlights the necessity of ensuring the integrity and immutability of electricity trading records in market environments. He also emphasizes that current web technologies used in energy exchanges may not guarantee the permanent immutability of transaction data, as these systems can be vulnerable to administrative intervention and data manipulation. In this paper, a web-based platform is implemented that uses Ethereum smart contracts and blockchain technology to enable energy trading among multiple entities in a decentralized manner. The platform utilizes smart contracts to automate and execute energy transactions securely and transparently, without the need for intermediaries. It also allows users to track and monitor their energy consumption, as well as the energy they produce and sell back to the grid. Overall, the paper focuses on the business model and practical application of blockchain technology and smart contracts in the energy industry.

A study conducted by Iqbal et al. [42] focuses on the development of a new business model that uses blockchain technology and smart contracts to enable secure and decentralized energy trading among electric vehicles in a Vehicle to Grid (V2G) network. The challenges in this area include the need for a secure and tamper-proof transaction recording mechanism to facilitate trust in the trading process and protect against fraudulent activities. The paper proposes a novel approach that utilizes smart contracts to automate and execute energy transactions between electric vehicles and the grid, ensuring security and transparency without the need for intermediaries. It also demonstrates the feasibility and effectiveness of the proposed model through simulations and analyses.

According to Alao and Cuffe [53], the use of blockchain smart contracts is becoming increasingly popular in the renewable energy sector due to their ability to address issues with traditional electricity hedging methods. To explore the potential risks and challenges associated with implementing these contracts, a new taxonomy has been developed (i.e., technological risks and challenges at the blockchain and smart contract ledger, and risks and challenges that result from society's perception and use of the technology). The authors mention the importance of collaboration and partnerships between technology developers and researchers to facilitate the adoption of blockchain smart contracts in the renewable energy industry.

The potential applications of blockchain technology in the energy sector are explored by Zielińska in [54]. The authors mainly focus on the deployment of smart contracts by enabling decentralized energy trading and tracking of renewable energy credits. They also discuss the potential benefits (increased transaction security, elimination of legal uncertainty, reduction in transaction costs, and support for pro-ecological activities) and challenges (lack of sufficiently efficient hardware base, lack of uniformity of individual platforms, lack of operational coherence) of using blockchain technology in the energy sector.

Lu et al. in [60], propose the use of smart contracts on a blockchain to facilitate P2P transactions for buying and selling electricity among 4000 nodes. The success rate of the suggested method is 99.38% and the average time for each transaction is 16 s. By using smart contracts, the trust cost of electricity market transactions can be reduced, settlement efficiency can be improved, and the electricity retail market can be made more intelligent. Ethereum was chosen by the authors as the smart contract platform due to its ease of use, high speed, low cost, good safety, and scalability, but it has limitations. These limitations include the centralization of consensus, the requirement of tokens to run smart contracts, and vulnerability to certain attacks. Finally, the authors recommend that future research should prioritize improving consensus algorithms' efficiency and developing smart contracts with strict logic and customizable rules that can adjust to the intricate business rules of the grid and different types of settlement contracts.

Górski and Bednarski [65] grapple with several critical challenges in the realm of smart contracts. These challenges encompass the imperative need to enhance smart contract flexibility, ensure seamless interoperability among IT systems for energy exchange, establish platform independence for smart contract design, and devise effective methods for verifying rules. To address these challenges, the authors elucidate their modeling approach using an illustrative system that generates renewable energy. In pursuit of this goal, their article introduces an extension of the Unified Modeling Language (UML) known as the UML Profile for Smart Contracts, designed to facilitate smart contract design, and outlines a method for implementing smart contracts in Java programming language.

4. SWOT Analysis

In an attempt to clarify the multifaceted issue of the adoption of smart contracts in the energy sector and to describe the various issues involved, a SWOT analysis was conducted to evaluate all the affecting factors (Figure 6).

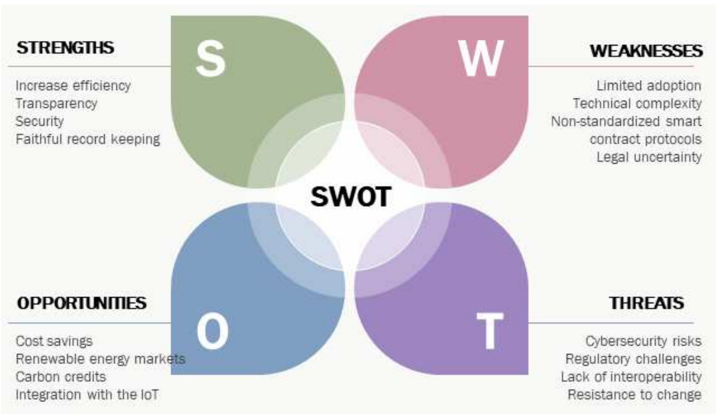

Figure 6. SWOT analysis for the adoption of smart contracts in the energy sector.

A thorough SWOT analysis will assist the entry strategy planning for this innovative technology into the energy trading sector. Subsequently, the detailed study of the Strengths, Weaknesses, Threads, and the emerging Opportunities mentioned by the research community is necessary in order to develop innovative energy trading services as a next research step and enact new and evolving business models.

4.1. Strengths

One notable advantage lies in the potential to enhance efficiency within the energy sector through the implementation of smart contracts [66]. By automating various processes, smart contracts significantly minimize the need for manual handling, resulting in reduced time and resource requirements. As a result, organizations can achieve increased operational efficiency and realize substantial cost savings.

The aspect of security is also a prominent feature of smart contracts, as they are stored on a decentralized ledger. This decentralized nature provides an added layer of security compared to traditional contracts. By utilizing distributed ledger technology, smart contracts become inherently resilient to single points of failure and are less vulnerable to hacking attempts [67]. The robustness of the system makes it exceedingly challenging for hackers to compromise the integrity and confidentiality of the smart contract ecosystem.

Additionally, smart contracts excel in the realm of faithful record-keeping by leveraging the capabilities of blockchain technology. Through the inherent design of smart contracts, every transaction is automatically and immutably recorded within the blockchain. This meticulous and unalterable record of activities serves as a perpetual ledger, preserving a comprehensive and tamper-proof account of all interactions. By ensuring the integrity and transparency of recorded data, smart contracts establish a trusted and unambiguous trail of information, fostering accountability and enhancing the overall reliability of the system.

Moreover, transparency stands as a key attribute of smart contracts, enabling all parties involved to have clear visibility into the contract's terms and its execution process. Through the utilization of smart contracts, the entire lifecycle of a contract becomes traceable and accessible to authorized participants. This heightened transparency cultivates a sense of trust and openness among the involved parties, as they have a comprehensive understanding of the agreement's provisions and the actions taken within its framework [23]. By mitigating information asymmetry and fostering a shared understanding, smart contracts contribute to the prevention of disputes and promote more harmonious and collaborative business relationships.

4.2. Weaknesses

One notable weakness that deserves attention is the relatively low adoption rate of smart contracts in the energy sector. Currently, the implementation of this technology is in its early stages, with only a limited number of companies actively embracing it [30]. The cautious adoption can be attributed to various factors, including the complex nature of transitioning to a new technological framework, concerns about interoperability and standardization, and the need for regulatory clarity and support [68]. As a result, the widespread adoption of smart contracts in the energy sector is still a work in progress, necessitating further exploration, experimentation, and collaboration among stakeholders.

Moreover, the technical complexity associated with the application of smart contracts in the energy market presents a significant hurdle. The development and implementation of smart contracts demand a substantial level of technical expertise, making it a potential entry barrier for smaller companies or those with limited technical resources [69]. The intricate nature of smart contract programming languages, blockchain integration, and secure execution necessitates a comprehensive understanding of decentralized technologies and cryptographic protocols. This expertise requirement poses challenges for organizations lacking the necessary technical skills or resources to navigate the intricacies of smart contract deployment. Consequently, smaller companies and those with limited technical capabilities may face difficulties in harnessing the benefits offered by smart contracts, hindering their ability to fully participate in the evolving landscape of the energy market. Addressing this barrier requires educational initiatives, accessible tools, and collaborative efforts to bridge the knowledge gap and foster a more inclusive adoption of smart contract technology in the energy sector.

Another significant weakness hindering the widespread interoperability of smart contract platforms is the lack of standardization in their protocols. The absence of standardized protocols prevents seamless communication and integration among different platforms operating within the same ecosystem [70]. This lack of interoperability is exacerbated by the prevalence of proprietary software and closed-source platforms, which restrict the ability of these systems to effectively interact with their environment. These proprietary software solutions create silos, limiting the exchange of data and functionality between platforms and impeding the potential for collaborative innovation and integration. As a result, the energy sector faces obstacles in achieving a unified and interconnected network of smart contract applications. To address this challenge, the industry needs to foster open standards, encourage collaboration among developers, and promote the adoption of interoperable smart contract protocols that can facilitate seamless interaction and enable the creation of a robust and scalable ecosystem [71].

In addition, the industry faces a significant challenge regarding the legal uncertainty surrounding smart contracts. The evolving nature of smart contract technology has resulted in an unclear legal status in many jurisdictions, raising concerns about potential legal challenges in the event of disputes [72]. The lack of well-established legal frameworks and precedents for smart contracts creates ambiguity and unpredictability in terms of their enforceability and validity. This uncertainty can undermine confidence and trust among parties involved in smart contract transactions, as they may face difficulties in determining their legal rights and obligations. As a result, the industry needs to navigate this complex legal landscape by collaborating with legal experts and regulatory bodies to establish clear and comprehensive guidelines and regulations that recognize the unique characteristics and potential of smart contracts [73]. By providing a robust legal framework, jurisdictions can promote the adoption and utilization of smart contracts while ensuring adequate protection and recourse in case of legal disputes.

4.3. Opportunities

One notable opportunity that smart contracts bring to the table is the potential for significant cost savings within the energy sector. By streamlining processes and eliminating intermediaries, smart contracts effectively reduce transaction costs associated with traditional methods [74]. Additionally, the automation and efficiency enhancements provided by smart contracts lead to optimized resource allocation and improved operational effectiveness [75]. As a result, companies operating in the energy sector can achieve tangible cost savings, allowing for better financial sustainability and prospective reinvestment in other areas of their business.

Moreover, the implementation of smart contracts holds the ability to revolutionize renewable energy markets by facilitating the emergence of innovative trading platforms. With the advent of smart contracts, new avenues for decentralized and P2P trading of renewable energy can be explored [76]. The direct engagement of household renewable energy prosumers in energy transactions with one another, bypassing traditional intermediaries, is a notable paradigm. By leveraging the transparency, automation, and security features of smart contracts, a dynamic ecosystem can be established where surplus energy generated by solar panels can be efficiently exchanged between neighboring households, fostering a localized and sustainable energy economy [77]. This paradigm shift not only empowers individuals to actively participate in renewable energy markets but also fosters greater energy independence, community collaboration, and the adoption of cleaner energy sources.

In addition, the utilization of smart contracts holds significant potential in facilitating the trading of carbon credits, thus playing a crucial role in assisting companies to achieve their carbon reduction targets. With the application of smart contracts, a transparent and automated platform can be established to streamline the exchange of carbon credits between entities [78]. These contracts would enable seamless tracking, verification, and transfer of carbon credits, ensuring accurate accounting and adherence to regulatory requirements.

By leveraging the inherent features of smart contracts, such as immutability and traceability, the carbon credit trading process becomes more efficient, reliable, and secure [79]. This transformative approach not only supports the transition to a low-carbon economy but also encourages collaboration and accountability among companies in their collective efforts to combat climate change. Through the adoption of smart contracts, the trading of carbon credits can be optimized, facilitating the advancement of sustainable practices and helping organizations fulfil their environmental commitments.

Another compelling prospect lies in the integration of smart contracts with the Internet of Things (IoT), allowing for the seamless automation of energy management and pricing. By merging smart contracts with IoT devices, a comprehensive network can be established, enabling real-time monitoring, control, and optimization of energy consumption [80]. This integration empowers devices and sensors within the IoT ecosystem to autonomously interact with smart contracts, facilitating intelligent decision-making based on predefined conditions and criteria. As a result, energy management processes can be efficiently automated, leading to optimized energy usage, demand response, and load balancing.

Moreover, the integration of smart contracts with the IoT enables dynamic pricing models, where energy prices can be adjusted in real-time based on supply and demand fluctuations [81]. This synergy between smart contracts and IoT technology revolutionizes energy systems, enabling efficient and responsive energy management while promoting sustainability and cost-effectiveness.

4.4. Threats

The realm of cybersecurity presents a significant concern when it comes to smart contracts. These contracts are susceptible to various hacking and cyber threats, exposing them to potential risks such as unauthorized access, data breaches, and financial losses. The complex nature of smart contract programming and the underlying blockchain infrastructure introduces potential vulnerabilities that malicious actors can exploit [82]. The repercussions of successful attacks on smart contracts can be severe, ranging from the loss of funds tied to the contract's execution to the compromise of sensitive information stored within the contract's code. This highlights the critical need for robust cybersecurity measures, including rigorous code auditing, continuous monitoring, and prompt response mechanisms to detect and mitigate threats [83]. Proactive efforts to enhance the security of smart contracts and their underlying infrastructure are essential to maintain trust, protect investments, and safeguard the integrity of the entire ecosystem.

Additionally, the utilization of smart contracts in the energy sector presents regulatory challenges that cannot be overlooked. The application of smart contracts may encounter hurdles in jurisdictions where the legal status of this technology remains uncertain. The evolving nature of smart contracts and their intersection with existing legal frameworks may pose complexities in terms of compliance, contractual obligations, and regulatory oversight [73].

The lack of well-defined regulations specific to smart contracts in the energy sector can lead to ambiguity and potential conflicts. As a result, companies and stakeholders in the energy industry must navigate these regulatory challenges to ensure compliance with existing laws and regulations while advocating for the development of clear and comprehensive frameworks that address the unique characteristics and implications of smart contracts. Collaboration between industry participants, policymakers, and regulatory bodies is crucial to establish a favorable regulatory environment that supports the adoption of smart contracts, fosters innovation, and ensures consumer protection.

Another significant threat that arises from the lack of standardization in smart contract protocols is the potential for interoperability problems among different platforms. The absence of widely accepted standards for smart contracts restricts their seamless integration and communication across diverse platforms and systems. This lack of interoperability hampers the realization of the full potential benefits offered by smart contract technology [84]. Without standardized protocols, platforms may struggle to effectively interact and exchange data, functionality, and assets, hindering the scalability, efficiency, and collaborative potential of smart contracts [85]. To address this challenge, industry-wide collaboration, standardization efforts, and the establishment of open protocols are necessary to enable seamless interoperability between platforms, maximize the benefits of smart contracts, and foster a more interconnected and vibrant ecosystem.

Finally, resistance to change poses a significant barrier to the widespread adoption of smart contracts in the energy sector, particularly among companies deeply entrenched in traditional processes. The established practices and routines in the industry may engender resistance, skepticism, and hesitancy towards embracing the transformative potential of smart contract technology. This resistance can stem from concerns about the unfamiliarity of the technology, potential disruptions to existing workflows, and perceived risks associated with implementing a new and relatively untested approach. Overcoming this resistance requires comprehensive change management strategies, targeted education, and awareness campaigns to emphasize the value proposition and long-term benefits of smart contracts. Engaging stakeholders, fostering a culture of innovation, and showcasing successful case studies can help alleviate resistance, foster organizational buy-in, and drive the transition towards a more efficient and digitally empowered energy sector.

5. Discussion

The automation and reduction of manual processing through smart contracts can increase efficiency and address the weaknesses of limited adoption and technical complexity. By streamlining processes and reducing the need for manual intervention, smart contracts can make it easier for companies, including smaller ones with limited technical resources, to adopt the technology and benefit from its efficiency gains [86].

The enhanced security provided by smart contracts stored on a distributed ledger can help alleviate concerns about cybersecurity risks. The transparency and immutability of blockchain technology make it more challenging for hackers to compromise the system, thereby mitigating potential threats and protecting funds and sensitive information [87].

The automatic recording of transactions in the blockchain ensures accurate and permanent record-keeping. This can help address legal uncertainty by providing a transparent and tamper-proof audit trail of all activities, reducing the risk of disputes and ensuring compliance with regulations [88].

The reduction in transaction costs and increased efficiency offered by smart contracts can address concerns about the high costs associated with implementation. By automating processes and eliminating intermediaries, companies in the energy sector can achieve significant cost savings, making the adoption of smart contracts more financially viable [89].

The transparency of smart contracts enables all parties involved to see the terms and execution of the contract. This increased transparency can enhance trust among stakeholders and help prevent disputes, ultimately addressing concerns related to legal uncertainty and regulatory challenges [90].

By leveraging these strengths, the energy sector can overcome the identified weaknesses and barriers associated with smart contract adoption, paving the way for broader implementation and reaping the benefits of increased efficiency, security, cost savings, transparency, and reliable record-keeping.

6. Conclusions

In conclusion, this paper provides a comprehensive review of the extensive applications of smart contracts and blockchain technology within the energy sector. Through the categorization into three main areas—EMnR, EMnO, and BMnA—we have unveiled the vast array of possibilities these innovative technologies offer to enhance energy efficiency, security, and transparency.

A balanced perspective emerges from our analysis, as the SWOT assessment underscores both the advantages and challenges associated with the adoption of smart contracts and blockchain in the energy sector. The benefits of increased transparency and automation promise more efficient management of energy resources, yet they are accompanied by potential challenges, including the substantial initial costs and technical complexities, necessitating thoughtful strategic planning.

Moreover, the surging acceptance of blockchain technology opens doors to exciting opportunities, but at the same time, the potential reactions from traditional industry players and evolving legal requirements present formidable hurdles to overcome.

In summary, the prospects of incorporating smart contracts and blockchain technology into the energy sector are indeed promising. However, successful implementation hinges on the ability of stakeholders to effectively address and navigate the challenges that arise. Achieving this requires meticulous planning, collaboration with key stakeholders, and the development of pragmatic solutions to harness the opportunities at hand. It is imperative that flexible frameworks are developed and legislative guidelines are established that are attuned to the evolving needs of the energy industry. By doing so, a future can be ushered in where these transformative technologies play a pivotal role in shaping the energy landscape, fostering efficiency, security, and transparency throughout the sector.

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