








Review

Integrating Blockchain in Smart Grids for Enhanced Demand Response: Challenges, Strategies, and Future Directions

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Abstract: This research, conducted throughout the years 2022 and 2023, examines the role of blockchain technology in optimizing Demand Response (DR) within Smart Grids (SGs). It critically assesses a range of blockchain architectures, evaluating their impact on enhancing DR's efficiency, security, and consumer engagement. Concurrently, it addresses challenges like scalability, interoperability, and regulatory complexities inherent in merging blockchain with existing energy systems. By integrating theoretical and practical viewpoints, it reveals the potential of blockchain technology to revolutionize Demand Response (DR). Findings affirm that integrating blockchain technology into SGs effectively enhances the efficiency and security of DR, and empirical data illustrate substantial improvements in both cases. Furthermore, key challenges include scalability and interoperability, and also identifying opportunities to enhance consumer engagement and foster system transparency in the adoption of blockchain within DR and SGs. Finally, this work emphasizes the necessity for further investigation to address development hurdles and enhance the effectiveness of blockchain technology in sustainable energy management in SGs.



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1. Introduction

The 21st century has ushered in significant transformations in the electrical sector, impacting both the generation and consumption of electricity. Population expansion, economic progress, technological innovations, urbanization, and the shift towards eco-friendly modes of transportation—especially in developing nations—are all contributing factors to the escalating global demand for electricity [1–3]. This increase in demand is coupled with a global shift towards Renewable Energy Sources (RES), which underscores the need for innovative energy management strategies. Evidence indicates that the electricity generation industry is transitioning from reliance on fossil fuels to a focus on low-carbon RES, such as wind and solar power, in response to growing concerns over climate change [4]. However, the integration of these intermittent and variable energy sources presents significant challenges to the stability and efficiency of power grids [5–7].

One key strategy to address these challenges is the implementation of Smart Grids (SGs), which are advanced electrical grids enhanced with digital technology for monitoring, analysis, control, and communication [8]. SGs enable the effective integration of RES, improve reliability and efficiency, and facilitate DR programs. DR involves adjusting or shifting electricity usage in response to grid demands, particularly during peak periods and

is critical for balancing the intermittent nature of renewable energy. In this rapidly evolving energy landscape, blockchain technology presents itself as a transformative solution. It not only offers the potential for Peer-to-Peer (P2P) energy trading, allowing consumers to trade surplus energy from renewable sources, but it also provides a robust platform for the real-time implementation and management of DR programs.

This paper aims to conduct an in-depth examination of the integration of blockchain technology in DR programs within SGs, ensuring a comprehensive understanding of current trends, challenges, and advancements.

To address these emerging trends and challenges in the integration of blockchain technology in SGs, we address the following research questions:

1. How/Can blockchain technology be effectively integrated into SGs to enhance the efficiency and security of DR systems?
2. What are the key challenges and opportunities associated with the adoption of blockchain in DR within SGs?

Despite the growing interest in blockchain technology for energy systems, there remains a significant research gap in understanding how blockchain can specifically enhance DR in SGs. This gap pertains to the absence of comprehensive research on the actual implementation of blockchain architectures in DR systems. This means that there is a shortage of empirical evidence supporting their efficacy and efficiency, unlike the case of blockchain applications in other domains, for example, agriculture [9].

1.1. The Emergence of Demand Response

DR has significantly evolved from being a tool for emergency response to a strategic element in modern energy systems. Initially, Demand Response (DR) focused on large-scale industrial adjustments for managing peak loads during critical times, primarily for emergency grid stabilization [10]. With advancements in SG technologies and the adoption of smart meters, the scope of DR expanded to include residential and commercial sectors, marking a significant shift in energy management strategies [11].

The integration of RES has elevated the importance of DR in current energy systems. It is now vital for balancing the intermittency of renewables, ensuring grid stability and efficiency [12,13]. Technological advancements in data analytics, the Internet of Things (IoT), and smart devices have enhanced DR's capability for real-time energy usage control, making it an essential facet of daily energy management [14]. Another key aspect of DR involves supervised learning data mining procedures like one [15] or multi-step [16] load or generation [17] forecasting when sometimes modeling information as complex information networks [18].

Policy evolution and incentive programs have also played a significant role in promoting DR, underscoring its importance in sustainable energy practices [19]. Additionally, modern DR initiatives are increasingly focusing on consumer empowerment. By offering tools and incentives, these programs encourage active consumer participation in energy management, thereby contributing to overall energy efficiency and grid stability [20,21].

1.2. The Rising Potential of Blockchain

In recent years, there has been escalating interest in employing blockchain technology for DR, primarily due to its capacity to enable P2P energy trading and enhance the efficiency and security of DR programs. Blockchain technology heralds a new era in energy system management, characterized by decentralized transparent operations [22]. The incorporation of Smart Contracts (SCs) is poised to revolutionize DR challenges such as load control and real-time management. SCs, autonomous in nature with predefined terms, facilitate instantaneous DR actions, streamlining energy consumption adjustments in line with grid demands [23]. This feature, combined with blockchain's cryptographic methods and consensus algorithms, effectively tackles the limitations faced by traditional DR programs, which typically rely on day-ahead planning, thus enhancing real-time load control [24].

The literature emphasizes the potential of blockchain in transforming the energy sector into a more efficient, secure, and sustainable market. Researchers have developed various solutions for supporting DR using different blockchain technologies, addressing the challenges and exploring the prospects of these applications. Researchers have investigated the potential and contributions of energy blockchain development in distributed power and energy markets, providing a comprehensive perspective on the integration of blockchain in electricity systems [25,26]. On the other hand, other evaluations provided an in-depth look at blockchain's technical aspects and their practical applications in various scenarios, elucidating both the advantages and challenges of this emerging technology [27].

1.3. Main Goals of the Research

This research is dedicated to a thorough assessment of blockchain technology's integration into SGs, with a dual focus on enhancing DR systems and exploring the broader implications and applications of DR itself. Specifically, the main goals of this paper are:

1. To undertake a detailed examination of DR, focusing on its current challenges, opportunities, and role in modern energy systems. This will provide a foundational understanding of how blockchain technology can be applied to optimize and revolutionize DR.
2. To analyze the existing applications of blockchain in SGs, identifying gaps in knowledge and implementation. This will help in pinpointing areas where blockchain can be most effectively utilized in DR.
3. To analyze the principles of blockchain technology, including its architecture, distributed consensus mechanisms, and the use of SCs. Comprehending these key elements is crucial for assessing blockchain's applicability in DR and SGs.
4. To evaluate various blockchain models such as public, private, and consortium blockchains, investigating their respective strengths and weaknesses. This assessment will guide the selection of the appropriate blockchain type for different DR scenarios.
5. To present practical use cases of blockchain in the energy sector, particularly concerning DR. This includes exploring the challenges that must be navigated for successful blockchain implementation, such as technological, regulatory, and infrastructural issues.
6. To assess how blockchain can be seamlessly integrated with existing DR systems to enhance their efficiency, transparency, and security. The study will also examine the potential of SCs in automating DR processes and blockchain's role in creating fair and transparent energy markets.

By accomplishing these objectives, this paper seeks to provide a holistic and detailed understanding of blockchain's impact on DR and SGs. The findings are intended to guide stakeholders in making informed decisions about integrating blockchain into DR systems and broader energy management strategies.

The rest of the manuscript is structured as follows. Section 2 analyzes the methodological tools utilized for this research. Section 3 discusses the concept of DR, detailing its critical aspects and implications. Section 4 examines the fundamentals of blockchain technology, including its core principles and network types, the distributed consensus mechanisms, and the SCs. Section 5 explores various Blockchain-based solutions and their potential to enhance DR adoption, focusing on both public and private blockchain network types. Section 6 dives into the challenges and broader implications of integrating blockchain technology in DR, encompassing technological hurdles, economic factors, regulatory considerations, and the impact on consumer engagement and security. Section 7 discusses challenges and various issues, spanning from technical complexities and scalability concerns to regulatory and market barriers. Finally, the paper concludes with Section 8, summarizing key findings and proposes directions for future research in Section 8.1 like technological advancements, economic and market analysis, regulatory policies, societal impacts, environmental sustainability, also addressing issues about security, privacy, and trust in blockchain systems.

2. Materials and Methods

2.1. Data Collection and Sources

In this study, primary data were sourced from a series of case studies focusing on the application of blockchain technology in DR within SGs. Selected for their relevance and representation of diverse blockchain architectures, these case studies provide practical insights into the deployment of blockchain in energy systems. To complement this, secondary data were gathered from an extensive literature review, involving peer-reviewed journals, industry reports, and whitepapers. This article offers a foundational understanding of blockchain technology, its current applications in energy systems, and its potential to enhance DR's efficiency and security.

2.2. Methodological Approach

Our methodological approach was primarily qualitative, focusing on the in-depth analysis of the selected case studies. This analysis involved a thematic evaluation to extract insights into the practical applications, challenges, and opportunities of implementing blockchain in DR systems. The emphasis was on identifying common trends, strengths, and limitations across various blockchain architectures and their implications in SGs. The process depicted in Figure 1, involved reviewing the available literature and selecting almost one hundred papers that were related to the sources, strings, and keywords as specified in Table 1. The criteria for choosing these papers are stated in Table 2.

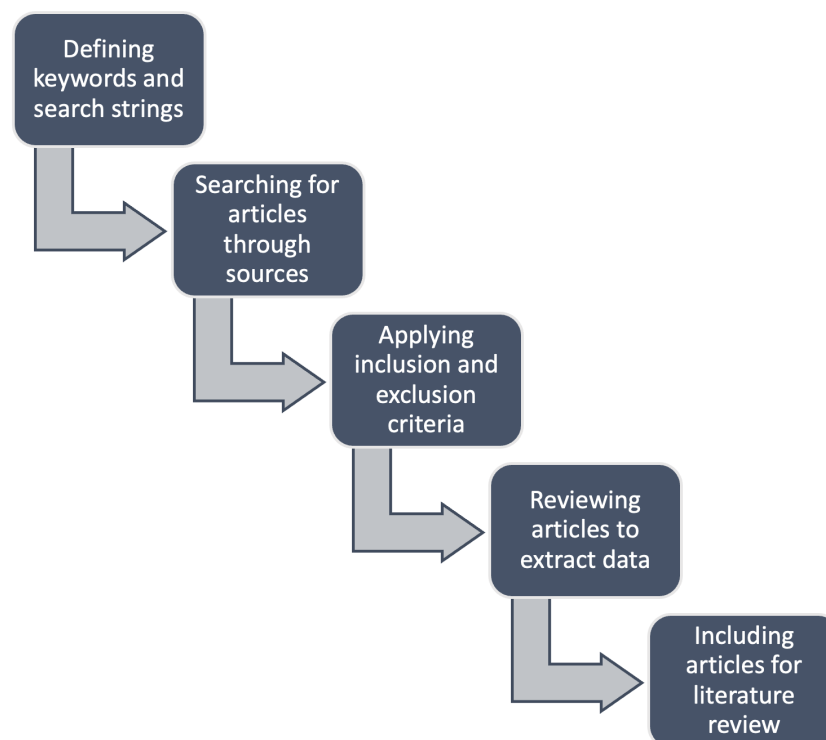


Figure 1. Process of forming the literature review.

2.3. Phased Structure of Research

The research unfolded in distinct yet interconnected phases:

1. **Establishing Theoretical Groundwork:** the initial phase involved analyzing secondary data to build a theoretical foundation and identify gaps in the existing body of knowledge.
2. **Primary Data Examination:** this stage comprised a detailed exploration of case studies, focusing on blockchain applications in DR within SGs.
3. **Qualitative Analysis and Synthesis:** following the primary data collection, a comprehensive qualitative analysis was conducted. This phase aimed to draw practical insights and assess the role and impact of blockchain technology in DR.

4. Formulating Conclusions: the final phase involved synthesizing the theoretical and practical findings to arrive at comprehensive conclusions and strategic recommendations for future research and applications in the field.

Table 1. Reconstructed methodology for literature collection.

Criteria	Details
Sources	IEEE Xplore, Elsevier, Springer, MDPI, O'Reilly Media, Google Scholar
Keywords	'Blockchain', 'Demand Response', 'Smart Grid', 'Energy Management', 'Renewable Energy', 'Distributed Ledger Technology', 'Energy Trading', 'Smart Contracts', 'Cybersecurity', 'Energy Market', 'Sustainable Energy', 'Energy Policy'
Search Strings	'Blockchain and Demand Response', 'Blockchain in Smart Grid', 'Renewable Energy and Blockchain', 'Distributed Ledger Technology in Energy', 'Smart Contracts for Energy Management', 'Blockchain Technology in Sustainable Energy'

Table 2. Literature inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Articles published in peer-reviewed journals, conference proceedings, and articles published in reputed journals	Editorial pieces, prefaces, summaries, book reviews, and other non-peer-reviewed materials
Studies focusing on blockchain technology application in SGs and demand response and whitepapers	Studies without empirical evidence or that do not provide a clear blockchain application in SGs or DR
Publications in the English language	Articles not relevant to the targeted area of blockchain in SGs and DR
Articles published between 2004 and 2023	Non-English articles

3. Demand Response Analysis

DR, facilitated by Demand-Side Management (DSM), strategically reduces electric energy consumption in response to electricity price hikes or incentive-based programs aimed at lowering usage during peak periods [28]. Its primary goal is to modulate peak load and align consumption patterns with the dynamics of power generation. Price-based programs, such as Time-of-Use (TOU) rates and Real-Time Pricing (RTP), employ dynamic power pricing rates, reflecting the real-time cost and availability of electricity [29]. DR encompasses consumer modifications to consumption patterns, influencing the timing, level of instantaneous demand, or total electricity consumption.

The integration of RES, notably wind and solar power, into grid-connected Micro-Grids (MGs) has raised concerns regarding flexibility, stability, and reliability. Given the intermittent availability of RES, MGs and their Energy Management Systems (EMS) must be capable of responding to fluctuations in energy generation and demand in real time. DSM, particularly DR, is a viable option for balancing supply and demand amidst increased RES penetration. DR within MGs can be achieved through various sources, including elastic loads and Electric Vehicles (EVs), aiding in balancing supplied power against real-time demand.

Climate change, the expanding use of RES, the need for more flexibility in system operations, the desire to increase energy efficiency, and the need to postpone expensive

investments are just a few of the factors driving DR's growing significance. It represents a shift in electricity usage by consumers from their typical consumption patterns in response to variations in electricity prices or to incentive payments designed to encourage reduced electricity usage, especially during periods of high wholesale market prices or when system reliability is at risk [28].

As a crucial mechanism for future energy systems, DR enables consumers to dynamically modify their electricity consumption in response to time-of-use electricity pricing signals or real-time dispatching instructions. This effectively reduces critical-peak demand and shifts power consumption across different periods. The advantages of DR are substantial: it reduces the peak load of the power system, prevents investments in new generation units and transmission lines, increases the consumption of renewable energy, and decreases the adjustment and start-up/shutdown costs of thermal power units during off-peak hours [20]. This, in turn, increases the operational safety of the power system. DR can be classified as either price-based or incentive-based, with price-based DR further divided into time-of-use price, real-time price, critical-peak price, and multi-step price, among others. Incentive-based DR includes direct load control, non-dispatchable load, demand-side bidding, and emergency DR [30].

Electric power systems characterized by high peak loads often face inefficiencies and escalated costs due to increased losses under heavy loading, which follow a non-linear quadratic relationship with current flow. These systems are engineered to accommodate the highest anticipated demand, primarily driven by end-user consumption patterns. Maintaining equilibrium between load and generation necessitates the operation of large central generation plants, which not only meet demand but also maintain a reserve margin for reliability, often leading to surplus generation capacity that remains unused. DR allows consumers to play a pivotal role in grid operations, aiding in the reduction or shifting of electricity consumption during peak periods in response to time-based rates or other financial incentives [10].

DR programs extend several benefits to SGs, such as aiding power markets in establishing optimal energy prices, mitigating market power, enhancing economic efficiency, and improving security. The benefits of DR can be categorized based on client classification (commercial, industrial, domestic, individual), employed technologies, and the overall structure of the SG (Table 3):

Table 3. Benefits of DR.

Type of Benefit	Description
Financial Benefits	Clients can achieve cost savings by consuming less energy during high-priced hours or shifting their electricity usage to cheaper hours [11]
Reliability Benefits	DR contributes to a reduction in the likelihood of involuntary supply interruptions, such as blackouts [12]
Market Performance	DR participation inhibits electric power companies from exercising market dominance, promoting a balanced energy market [21]
System Security	DR provides System Operators (SOs) with adaptable tools to manage unforeseen circumstances, enhancing energy system resilience [20]

The Adoption of Blockchain in Demand Response

Figure 2 illustrates the interrelated themes identified within the current body of literature on blockchain applications in DR systems. The size of the nodes reflects the frequency of keyword occurrence, while the thickness of the lines indicates the strength

of the connection between themes. The coloring adds information regarding the year that each specific theme was observed. Keywords like 'blockchain' and 'demand response' form central nodes, highlighting their prominence. Surrounding nodes such as 'smart grids' and 'energy management systems' suggest areas where blockchain technology is actively being researched in the context of smart energy solutions.

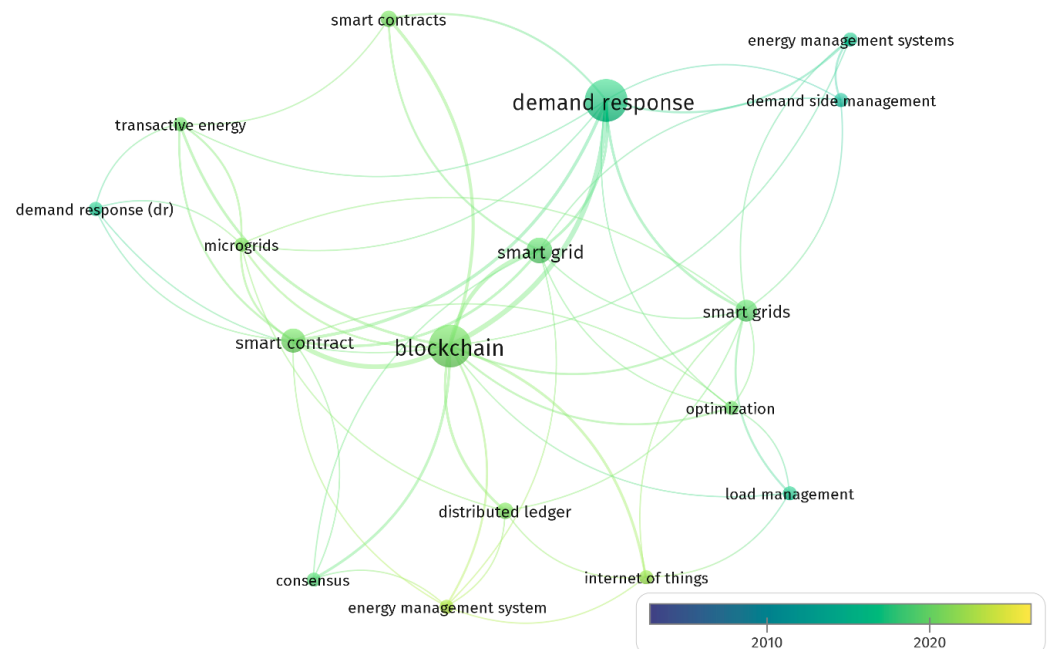


Figure 2. Visualization of keyword co-occurrences in blockchain-enhanced SG DR selected literature for years 2004–2023.

In addition, Table 4 offers details regarding the way that Figure 2 was produced. The column 'Keywords' contains 17 distinct terms, selected based on the greatest values of occurrence and co-occurrence. Therefore, the column 'Occurrences' counts how many times each specific keyword was found in the investigated literature, while the column 'Co-occurrence' counts how many times a keyword is found together with other keywords. A minimum threshold of three 'Occurrences' was set to make sure that the information in this figure remains concise. Finally, it is important to mention that certain themes are presented in similar keywords or their singular and plural variants, i.e., 'demand response (dr)' and 'demand response', 'energy management system' and 'energy management systems', 'smart grid' and 'smart grids', and 'smart contract' and 'smart contracts'. These were not merged into a single theme/term to make sure that the most common ways of their appearance persisted.

Bibliometric analyses by Ante et al., and holistic assessments by Choobineh et al., have identified distinct blockchain application patterns in energy systems [31,32]. These studies dissect the degree to which blockchain applications are dependent on the technology itself versus broader systemic improvements, offering insights into its intrinsic properties and future integration prospects.

Furthermore, studies explored the practical applications of blockchain in P2P energy trading, demonstrating its potential to disrupt traditional energy markets by enabling decentralized energy transactions [33]. This shift towards a more democratized energy market challenges existing regulatory frameworks and requires a rethinking of market structures and participant roles. Recent studies, also, delve into how blockchain can facilitate the integration of RES into the grid. This poses a critical element for advancing sustainable energy goals but also presents challenges in terms of grid stability and energy storage [27].

Table 4. Keyword analysis of occurrence and co-occurrence in the investigated literature.

Keyword	Occurrences	Co-Occurrence
blockchain	28	50
demand response	28	27
smart contract	9	23
smart grid	10	19
smart grids	7	14
microgrids	3	10
transactive energy	3	10
smart contracts	4	9
distributed ledger	4	7
energy management system	3	7
internet of things	3	7
optimization	3	7
consensus	3	6
energy management systems	3	6
demand side management	3	5
load management	3	5
demand response (dr)	3	4

Additionally, blockchain technology opens up new avenues for consumer engagement in energy systems, empowering consumers to take an active role in energy trading, DR, and overall energy management [34]. This consumer-centric approach not only enhances energy efficiency but also promotes a deeper understanding and responsibility toward energy consumption patterns. An extensive review of DR-related technologies and their impact while scrutinizing the factors driving the adoption of DR programs and the barriers that might hinder their expansion was presented by Paterakis et al. [29]. Despite the informative nature of these studies, they often fall short in demonstrating the practicality of blockchain in DR, failing to move beyond theoretical advantages to present concrete, real-world applications, and pilot project insights [33]. This gap in the literature underscores the need for more empirical research and pilot studies to fully grasp the implications of blockchain in DR and energy systems.

In summary, the integration of blockchain in energy systems, particularly in DR and P2P energy trading, presents a paradigm shift in how energy is managed, distributed, and consumed. It offers a path toward more sustainable, efficient, and consumer-centric energy systems. It also necessitates careful consideration of its technical, regulatory, and social implications. Previous literature reviews on P2P and community-based markets often focused on specific aspects, such as blockchain technology alone. The present study, however, offers a more exhaustive review of the application and implementation of blockchain technology in DR, including a classification of the literature based on permissionless and permissioned blockchain types, considering their distinct benefits, drawbacks, and ideal uses.

4. Blockchain Technology Analysis

This section delves into the intricate world of blockchain technology, offering a detailed examination of how it operates and its essential components. Understanding these elements is crucial as they fundamentally define the technical characteristics of blockchain systems. A particular focus is given to the architecture types and the mechanisms of distributed consensus that underpin these systems.

4.1. Fundamental Principles, Distributed Consensus and Smart Contracts

Blockchain technology facilitates data transfer analogous to the duplication of data across different locations. In contexts like cryptocurrencies, this involves transferring virtual assets from one digital wallet to another. A primary challenge in these systems is ensuring that each digital asset is spent only once, thereby solving the double-spending problem. Traditionally, central authorities like banks have acted as intermediaries, maintaining ledger integrity and managing updates, but this centralization introduces higher costs, dependency on third-party trust, and risks associated with a single point of failure [35].

Blockchain reduces this dependency on intermediaries through a network of digital users who collectively validate transactions and maintain the ledger's integrity. Participants in the blockchain network either keep a personal copy of the ledger or access it via cloud services, ensuring transparency and authenticity. The challenge lies in effectively synchronizing these multiple ledger copies, usually through a consensus mechanism similar to distributed voting, where members agree on a consistent ledger state [36].

The security and efficiency of blockchain are heavily reliant on distributed consensus algorithms. These algorithms, supported by game theory-based incentives, foster collaboration and trust among network nodes [37]. The difficulty of altering the blockchain without substantial network consensus underpins its security. Cryptographic hash functions in blockchain convert input data into a fixed-length hash output, providing collision resistance. Public-key cryptography is also employed, where each user has a private key for personal use and a public key for sharing, allowing secure transaction authentication and authorization [38,39].

The potential of blockchain technologies is enhanced when combined with SCs [40]. These executable programs on the blockchain can trigger changes to the ledger automatically under certain conditions, like respecting transaction agreements. SCs encode legal constraints and agreement terms in computer language, and are self-enforcing and tamper-proof, offering at the same time advantages such as intermediary elimination and reduced transaction costs. They make low-value transactions cost-effective and ensure interoperability among transaction systems.

4.1.1. Distributed Consensus Algorithms

Distributed consensus algorithms are fundamental to blockchain technology, playing a critical role in validating the authenticity of transactions within the network. These algorithms are pivotal, not only in defining the blockchain's scalability, transaction speed, security, and energy efficiency but also in determining its applicability and effectiveness in various use cases, including DR. By examining these algorithms, we gain insight into how blockchain can be tailored and optimized for DR applications, where rapid and secure transaction processing is essential. The process begins with a node proposing a new block containing transactions in the network. The consensus algorithm, a procedure that ensures dependability and trustworthiness in decentralized environments, must validate and accept this block for integration into the blockchain [24]. This validation step is crucial in maintaining the integrity of the blockchain, making it a reliable tool for managing the dynamic and complex requirements of DR systems.

Consensus in a distributed network faces technical failures, cyber-attacks, and manipulative node behaviours. Ensuring resilience against such issues is crucial for maintaining blockchain integrity and security [24]. Key aspects involve reliable message transmission among nodes, protection against corrupt or malicious nodes, and maintaining consensus even with some nodes being unresponsive or dishonest.

Blockchain consensus mechanisms are broadly categorized into lottery and election-based approaches. In lottery-based systems, such as Proof of Work (PoW), nodes vie to solve cryptographic puzzles, with the winner adding a new block to the chain. PoW, known for its security, requires significant computational power. Election-based methods like Proof of Stake (PoS) select validators based on criteria such as the amount of cryptocurrency held, promoting honest conduct [41].

Among voting-based consensus methods, Byzantine Fault Tolerance (BFT) algorithms, particularly Practical Byzantine Fault Tolerance (PBFT), play a pivotal role. BFT algorithms operate under the premise that consensus is achievable even amidst nodes that might fail or act maliciously. These algorithms necessitate multiple voting rounds from nodes to authenticate a block, thereby ensuring the blockchain's resilience against any single node's corrupt activities [42].

4.1.2. Key Characteristics of Blockchain

Through the aforementioned section, we could summarize the fundamental attributes that define the functionality and advantages of blockchain technology, in general, as in Table 5:

Table 5. Key attributes of blockchain technology.

Attribute	Description
Decentralization	The absence of a centralized owner or operator minimize human error and manipulation. It also helps avoid extra intermediate transaction fees [43]
Transparency	Blocks are distributed to all participants for consensus approval, enhancing data transparency, corruption prevention, and system credibility [39]
Immutability and Traceability	The chained data structure of the blockchain allows for easy access to historical data. Modifying a block requires consensus from all participants, bolstering the trust between participants and service providers [44]
Automation	SCs automate blockchain operations, increasing productivity, and reducing errors and manipulation caused by human intervention [27]

4.2. Blockchain Network Types

The blockchain landscape has recently expanded with various distributed ledger platforms, each distinguished by the access level granted to users. Permissionless or public blockchains permit open participation in the network's functions, including transaction proposal and auditing to any joining entity. On the other hand, permissioned or private blockchains require entities to undergo authentication and authorization for network participation and specific activities like accessing or auditing blockchain data. Understanding this differentiation is essential for comprehending the various solutions that researchers have created utilizing private and public frameworks, emphasizing their distinct characteristics, benefits, and drawbacks [36].

Despite their differences, both public and private blockchains share a decentralized nature, distributing ledger management among users and enabling peer-to-peer transactions without a central trusted authority [45]. This decentralized approach states loudly the core philosophy of blockchain technology, allowing for a more transparent and secure method of transaction recording.

Private blockchains are characterized by their high transaction processing speeds, thanks to a limited number of authorized users. This limited access results in quicker consensus achievement, allowing more transactions to be processed per second. Conversely, public blockchains often experience slower transaction processing rates. In systems like Bitcoin's Proof-of-Work (PoW), the entire network must reach a consensus on transaction states, leading to longer processing times [46,47]. The requirement for widespread consen-

sus in public blockchains means that modifying a single block, which must be reflected in all succeeding blocks, is a more time-consuming process [48,49].

The distinction between public and private blockchains significantly influences their functionality and security. Public blockchains, characterized by their extensive decentralization and a larger number of nodes, utilize cryptography for secure communication. This allows anonymous nodes to interact securely without mutual trust [50]. The transparency of public blockchains is notable, as each transaction is publicly verifiable. However, this transparency comes with data privacy concerns; the append-only data structure of public blockchains, while ensuring immutable data storage and enhancing data integrity, poses risks to data privacy. Once sensitive data are uploaded to a public blockchain, retraction is impossible [46,47].

Contrarily, private blockchains are distinguishable by their limited access, which limits transaction validation and verification to a network of authorized participants. This controlled environment offers greater data privacy and allows for quicker consensus processes, leading to swift alterations upon unanimous node agreement [51]. However, the limited number of nodes in private blockchains raises concerns about network security. Fewer nodes could possibly imply a higher risk of malicious actors seizing network control, making the blockchain more vulnerable to hacking and data manipulation. As a result, few studies consider public blockchains more secure against such specific threats [52]. Despite that fact, private blockchains are considered more safe and secure than public ones.

Lastly, while public blockchains typically do not incur infrastructure costs, their private counterparts necessitate significant investment for setup and ongoing operational expenses. This difference highlights the varying resource requirements and security dynamics between the two types of blockchain networks.

4.2.1. Advantages of Public Blockchains

Public blockchains, known for their open and decentralized nature, offer several distinct advantages that contribute to their robust and inclusive network. Table 6 summarizes these key benefits.

Table 6. Advantages of public blockchains.

Advantage	Description
Open Architecture	Any user can participate in network maintenance and transaction verification, fostering decentralization without central authority reliance
Transparency	All transactions are visible to every node, ensuring auditable and verifiable transactions, with considerations for privacy [53]
Pseudo-Anonymity	While transactions are transparent, the direct linkage between transaction IDs and real-world identities is obscured [54]
Radical Decentralization	Peer-to-peer methodology allows rapid network expansion and scalability without centralized oversight [55]
Network Resilience	Highly resistant to attacks, with control over a majority of nodes being practically unfeasible in large networks [52]

4.2.2. Advantages of Private Blockchains

At the heart of a permissioned blockchain lies a network controlled by a central authority, responsible for regulating user access, data encryption, and data access. This typically involves making the blockchain private. Unlike permissionless systems that offer extensive network resilience but expose all data, permissioned blockchains opt for increased privacy protections, trading off radical decentralization. This shift makes it feasible to implement permission systems for storing personal information, login details, and identity credentials securely on the blockchain [56,57]. The main advantages of permissioned blockchains are summed up in Table 7.

Table 7. Advantages of private blockchains.

Advantage	Description
Enhanced Security	Geared towards protecting sensitive data, offering secure storage for confidential information [57]
Customization	Provides greater control over ledger operations, allowing tailored solutions for specific needs [56]
Increased Transaction Speed	Designed for scalability with faster transaction processing compared to permissionless systems [56,57]
Decentralization	Offers a level of decentralization, reducing risks associated with centralized database systems

Overall, permissioned blockchains present a more secure, scalable, and adaptable alternative to their permissionless counterparts. They are particularly well-suited for organizational and enterprise environments where privacy, customization, and speed are paramount, despite their lower levels of public accessibility and decentralization.

4.2.3. Main Blockchain Platforms

The landscape of blockchain technology, particularly relevant for DR applications, is dominated by three primary platforms: Ethereum, Hyperledger Fabric, and R3's Corda. Each offers unique features and functionalities suited to different industrial requirements.

Ethereum: Ethereum represents a significant advancement in blockchain technology, introducing SCs in 2015 and progressing beyond the scope of cryptocurrency. Its transition from PoW to Proof-of-Stake (PoS) signifies a shift towards more energy-efficient operations. Ethereum supports diverse account types and SC development with its scripting language, Solidity. This versatility makes Ethereum suitable for a wide range of applications, including DR scenarios requiring decentralized solutions [53,54,58].

Hyperledger Fabric: Launched under the Linux Foundation, Hyperledger Fabric is a collaborative effort involving major corporations. It stands out as a private, permissioned blockchain platform, offering a modular architecture that's ideal for enterprise applications. Fabric supports SCs in various programming languages and features an innovative execute-order-validate transaction flow, enhancing data privacy and operational efficiency. The architecture of the platform, which lets nodes play different roles like clients, peers, and ordering service nodes, makes it ideal for DR systems that need strong data privacy and access control [56,59–62].

Corda R3: R3 specifically created Corda for the financial industry, focusing on legally binding SCs and transaction validation that prioritizes privacy. It diverges from traditional blockchains by offering a unique validation mechanism that ensures privacy and complies with financial sector confidentiality requirements. Corda's SCs are both programmable and legally enforceable, bridging the gap between digital agreements and legal enforceability. Additionally, Corda's architecture accommodates regulatory observer nodes, ensuring compliance with financial regulations, and seamlessly integrates with existing financial communication standards [37,57,63].

Each platform, with its distinct attributes, contributes uniquely to the blockchain ecosystem. Ethereum's general-purpose, decentralized approach, Hyperledger Fabric's private and customizable nature, and Corda's focus on the financial sector's legal and privacy requirements, together provide a comprehensive insight into the potential of blockchain technology. Understanding these platforms is crucial for effectively integrating blockchain into various domains, including EMS and DR, where security, scalability, and regulatory compliance are key.

5. Blockchain-Based Solutions to Accelerate DR Adoption

The adoption of DR programs is poised for transformation through blockchain technology. Blockchain's inherent transparency, decentralization, and openness align well with the needs of DR, particularly in enhancing prosumer engagement and addressing privacy concerns. This section explores various blockchain-based approaches that have been proposed to optimize DR programs. Detailed summaries of these approaches are provided in Tables 8 and 9.

5.1. Public Blockchain Networks

Public blockchain technologies can integrate into DR systems to address and provide various solutions optimizing economic, environmental and societal aspects (Figure 3).

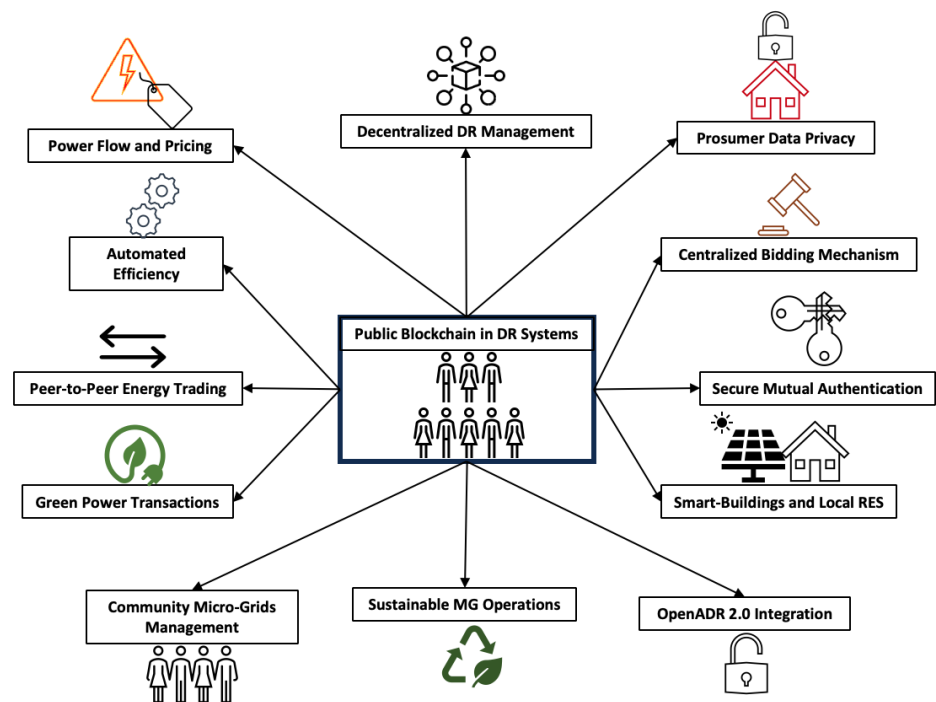


Figure 3. Public blockchain applications in DR systems.

Pop et al. devised an innovative decentralized solution for managing DR programs within SGs, integrating blockchain technology with SCs [64]. This approach is essential for programmatically setting expected levels of energy flexibility, validating DR agreements, and balancing energy demand and supply. Their blockchain-based system was tested using energy data from UK buildings, creating a prototype on the Ethereum platform. The outcomes indicate the grid's ability to adjust energy demand in near real-time, implement predefined energy flexibility levels, and validate DR agreements effectively. This method not only improves grid efficiency and responsiveness but also paves the way for a peer-to-peer decentralized energy trading mechanism, eliminating intermediaries like Distribution System Operators (DSOs), hence reducing costs associated with energy transactions. Future enhancements aim to accommodate multi-stakeholder markets, including DSOs, Transmission System Operators (TSOs), and retailers, either as competitors or cooperators in a shared energy flexibility market. This forward-looking vision is a significant stride towards more efficient, flexible, and cost-effective energy markets, leveraged by sophisticated blockchain applications. The results validate that a blockchain-based distributed demand-side management system can precisely match energy demand and production in SGs, adhering to the DR signal while minimizing the need for energy flexibility during the convergence process.

Further addressing privacy concerns, Pop et al. proposed a method that combines SCs with zero-knowledge proofs to protect prosumer energy data within decentralized DR

programs [65]. This innovative solution maintains the confidentiality of prosumer data while allowing aggregators to validate compliance, representing a significant advancement in balancing data transparency and privacy in public blockchain networks. The results of this approach demonstrate its effectiveness in protecting prosumer privacy while enabling the necessary validations by aggregators. This method represents a significant step forward in addressing the dual needs of data transparency and privacy preservation in the realm of public blockchain networks applied to DR programs.

Mao et al. approached DR from a different angle, proposing a centralized bidding mechanism built on the Ethereum blockchain [66]. This method utilizes a repeated verification process within SCs to manage bidding transactions and subsidy settlements. It aims to enhance the efficiency and transparency of standard DR transactions, showcasing how centralized blockchain applications can offer novel solutions in energy management.

These studies illustrate the versatility of blockchain technology in DR programs, ranging from decentralized systems enhancing grid efficiency and privacy to centralized mechanisms improving transaction processes. The collective insights from these approaches underscore blockchain's potential in revolutionizing DR, catering to various aspects such as energy flexibility, privacy protection, and operational efficiency.

To enhance security in SG environments, Park et al. proposed the Blockchain-Enabled Privacy-Preserving Scheme (BPPS) for DR Management [67]. BPPS is designed to withstand a variety of attacks and ensures secure mutual authentication and key agreement, leveraging blockchain to uphold the integrity of DR data. The scheme underwent rigorous informal and formal security analyses, demonstrating robustness against various attacks and the ability to maintain session key security. Simulations on NS3 and the Ethereum testnet indicated BPPS's high-level security, affirming its suitability for real-world SG networks.

Afzal et al. introduced a distributed demand-side management system for community Micro-Grids (MGs), integrating smart meters and RES [38]. Central to this system is an innovative energy consumption game that incentivizes smart home users to optimize their energy usage, aiming to reduce both individual and community-level power costs. The system's participants engage in self-renewable generation and shared MG management, employing cost-effective strategies while preserving the privacy of their energy usage data. Blockchain technology plays a crucial role in this setup, providing secure communication channels and enabling autonomous device monitoring and electricity payment facilitation through SCs written in Solidity. This decentralized approach not only enhances the system's security and reliability but also effectively minimizes energy consumption and costs for individual users and the community as a whole.

Wu et al. [68] explored the use of blockchain technology in managing power flow calculations and electricity pricing within an MG. They established a power flow calculation model for a 34-node MG optimized for generator workloads to enhance operational efficiency. Their study also delved into customized electricity pricing, creating a priced DR mechanism that adjusts prices based on demand and supply dynamics. The core of their system is a blockchain-integrated power management setup, which records all power flow and pricing data securely and transparently. SCs, generated automatically based on power calculations and pricing data, streamline the process of asset transfer within the MG. This method not only reduces manual intervention but also ensures transaction accuracy and reliability.

Van Cutsem et al. introduced a decentralized framework for optimizing electrical consumption in Smart-Buildings and utilizing local RES [69]. The framework uses SCs to facilitate collaborative planning among buildings and energy producers to minimize energy consumption costs. This collaborative planning approach aids grid operators in day-ahead dispatch planning, enhancing energy distribution efficiency. Simulation results showed that the algorithm effectively encourages local energy usage optimization, with potential reductions in peak grid demand. The framework, scalable to communities with numerous Smart-Buildings and RES usage, promotes intelligent and autonomous energy consumption without relying on a central supervisory entity.

Table 8. Summary of public blockchain-based approaches for DR programs.

Citation	Author(s)	Approach	Platform	Focus Area	Key Benefits
[64]	Pop et al.	Decentralized DR management	Ethereum	Energy Flexibility, DR Agreements	Grid Efficiency, P2P Energy Trading, Cost Reduction
[65]	Pop et al.	SCs with Zero-Knowledge Proofs	Ethereum	Prosumer Data Privacy	Data Transparency and Privacy Balance
[66]	Mao et al.	Centralized Bidding Mechanism	Ethereum	Transaction Management	Enhanced Efficiency and Transparency
[67]	Park et al.	BPPS for DR Management	Ethereum (Testnet)	Security in SGs	Robust Security, Secure Mutual Authentication
[38]	Afzal et al.	Decentralized community MGs	Ethereum	self-renewable generation and shared MG management	Security, P2P Energy Trading, Cost Reduction
[68]	Wu et al.	Power Flow Management	MultiChain	Power Flow Calculations, Electricity Pricing	Reduced Manual Intervention, Accurate Transactions
[69]	Van Cutsem et al.	Decentralized Framework for Smart Buildings	Ethereum	Consumption Optimization	Local Energy Usage Optimization, Reduced Peak Demand
[70]	Tsao et al.	Real-Time Price-Based DR	Ethereum	Sustainability Goals	Operational Profitability, Customer Satisfaction
[71,72]	Tsolakis et al.	OpenADR 2.0 Integration	Ethereum, Hyperledger, IOTA, Tendermint	DR Transaction Management	Streamlined Energy Management, Transaction Integrity

Table 9. Summary of private blockchain-based approaches for DR programs.

Citation	Author(s)	Approach	Platform	Focus Area	Key Benefits
[73]	Zhou et al.	AI and contract theoretical modeling, EVs-based DR	Consortium blockchain	Energy Trading	Lowers computation costs, maximizes social benefits
[74]	Samadi et al.	DR Stackelberg game model, conserving DERs	Blockchain-based system for DR, novel Proof of Energy Saving (PoES) consensus algorithm	Cooperative Distributed Storage	Encourages energy use reduction, engages in block mining for rewards
[75]	Guo et al.	Dual-incentive DR scheme	Consortium blockchain	Energy Management Efficiency	Reduces electricity costs, addresses system imbalances
[76]	Bracciale et al.	Hyperledger Fabric for distributed EMS in DR	Hyperledger Fabric	Privacy in Energy Management	Enhances privacy, Secure Multiparty Computation protocol
[77]	Lucas et al.	DLTs for DR provision and validation	Hyperledger Fabric	Data Integrity and Origin	Ensures data integrity, permissioned ecosystem
[78]	Danzi et al.	SC for DR Programs	Private Ethereum	Energy Procurement and Imbalances	Automation, New Business Models for BRPs
[79]	Lin et al.	Blockchain Power Trading	Private Ethereum	EV Charging, Energy Management	Facilitates Power Transactions, Optimises Green Power Usage
[80]	Yang et al.	Transactive EMS for Smart Homes	Private blockchain-based energy management platform	Energy Trading, User Privacy	Peer-to-Peer Energy Trading, Enhanced System Efficiency
[81]	Deshpande et al.	Permissioned blockchain framework for DR marketplace	Any private permissioned blockchain	Transparency and Decentralization	Enhanced transparency, efficient DR allocation model
[82]	Di Silvestre et al.	Distributed DR mechanism using blockchain and SCs	Hyperledger Fabric	Interaction with DSO	Ensures fairness and privacy, load adjustment requests
[83]	Wang et al.	Energy management model for renewable energy MGs	Hyperledger Fabric	Renewable Energy MGs	Ensures privacy and security, reduced communication delays
[84]	Merrad et al.	Decentralized architecture for DR management using SCs	Compatibility with Ethereum or similar platforms	Decentralized Energy Generation Management	Nash game approach for fairness, Optimal Power Flow (OPF)-based demand response management system
[85]	Li et al.	Blockchain-based trans-active EMS	Ethereum and Hyperledger Fabric or similar	Networked MGs and Local Distribution Grid	Transparency and trustworthiness, automates energy trades
[86]	Augello et al.	Hyperledger Fabric with SCADA systems	Hyperledger Fabric	Aggregating DR Energy Resources	Robust and efficient solution for DR management
[87]	Sciume et al.	Blockchain-based distributed DR service	Hyperledger Fabric	Tracking and Certification	Transparency and fairness in customer participation
[88]	Di Silvestre et al.	Blockchain technology and SCs for DR compensation	Hyperledger Fabric	DR Compensation System	Trustworthiness and transparency, direct interaction

Tsao et al. utilized public blockchain technology to pioneer real-time price-based DR programs aligned with comprehensive sustainability goals [70]. They adopted a multi-objective Mixed Integer Linear Programming (MILP) approach to formulate these objectives, addressing the dynamic nature of energy demand and supply and factors influencing the economy, environment, and society. Their novel method, a robust fuzzy multi-objective optimization technique, aimed to optimize the allocation and capacity of renewable distributed generation units. This method also facilitated informed decision-making on supply equilibrium and dynamic pricing. A practical case study in Vietnam evaluated the effectiveness of their model. The results were promising, showing that a blockchain-managed sustainable MG could significantly boost operational profitability (by 1.68%) and customer satisfaction (by 2.61%), while reducing environmental impact by 0.97%. This study demonstrates blockchain's potential to optimize MG operations holistically, addressing economic, environmental, and societal aspects of sustainability.

Tsolakis et al. introduced an innovative DR architecture by integrating the OpenADR 2.0 standard with blockchain technology [71,72]. The architecture revolves around deploying fog-enabled intelligent devices at each energy node, capable of performing tasks like measurement aggregation, flexibility calculation, and forecasting. These devices also serve as blockchain nodes (either full or light nodes), enhancing the security and reliability of DR transactions. The integration of these functionalities streamlines energy management processes and strengthens transaction integrity within the energy network. Initially designed on the open Ethereum framework, the solution exhibits a commitment to established blockchain technologies, with Tsolakis et al. expressing openness to exploring other platforms like Hyperledger, IOTA, and Tendermint. This flexible approach seeks to develop a comprehensive energy DR-related blockchain network, balancing security and efficiency. The study highlights the potential of blockchain to transform energy transaction management, improving operational effectiveness and security in modern energy networks.

5.2. Private Blockchain Networks

Private blockchain technology can integrate into DR systems to address various challenges and provide solutions (Figure 4).

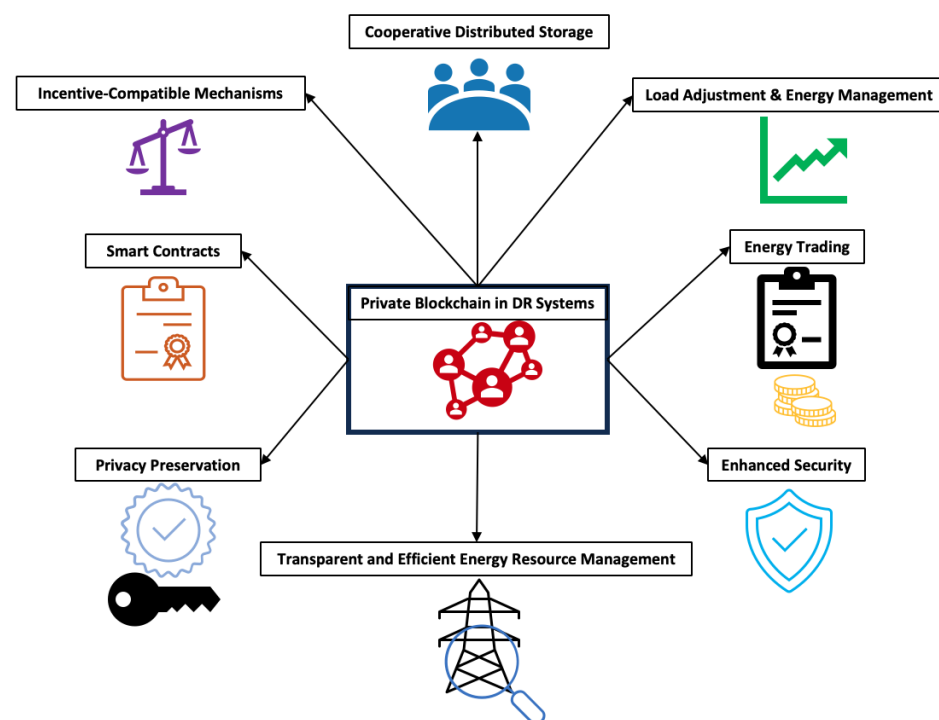


Figure 4. Private blockchain applications in DR systems.

Using AI and contract theoretical modeling in conjunction with a consortium blockchain, Zhou et al. developed an advanced energy trading framework optimized for the Internet of EVs-based DR [73]. This mechanism takes advantage of blockchain's security, decentralization, and trust to significantly lower computation costs. They crafted an incentive-compatible DR mechanism that maximizes social benefits, especially useful in scenarios where information is asymmetric. This approach represents a significant advancement in blockchain-based energy trading, demonstrating the potential for optimizing economic and social outcomes in energy markets.

Incorporating an innovative mechanism for conserving Distributed Energy Resources (DERs), Samadi et al. created a DR Stackelberg game model that employed blockchain technology [74]. This model promotes cooperative distributed storage and interactive demand reduction in residential areas. The aim is to encourage consumers to reduce energy use during peak times, engage in block mining for rewards, and effectively utilize excess DERs. The approach also provides incentives for strategic EV charging and discharging. Their results showed a 35% reduction in consumer energy consumption during peak times and demonstrated the security and resilience of the proposed consensus mechanism against malicious activities. This study highlights the effectiveness of blockchain in managing DER resources and incentivizing consumer participation in energy conservation.

In their research, Guo et al. proposed a blockchain-enabled DR scheme with a unique dual-incentive system, combining profit-based and contribution-based strategies [75]. This scheme, utilizing consortium blockchain technology, aims to secure the DR process and enhance energy management efficiency. The profit-based strategy involves individualized incentive pricing, optimized using the Differential Evolution method, to align customer responses with the objectives of electricity retailers, thereby balancing demand and supply and reducing costs. The results from their study show that this blockchain-enabled DR scheme could considerably reduce electricity costs and address system imbalances.

Bracciale et al. developed an architecture using Hyperledger Fabric to enhance privacy in blockchain-based distributed EMS for DR [76]. This architecture strategically utilizes multiple private channels for confidentiality in individual user data while managing network-level energy distribution. A significant innovation is the implementation of a Secure Multiparty Computation protocol to calculate aggregated baseline consumption without compromising individual privacy. The integration with Hyperledger Fabric's privacy features and advanced computation protocol addresses critical privacy concerns in energy management, ensuring both individual data confidentiality and effective network management.

Lucas et al. employed Distributed Ledger Technologies (DLTs) via blockchain to securely track DR provision and validation processes [77]. Their approach focuses on ensuring data integrity and origin, with a permissioned ecosystem encompassing TSOs, DSOs, Balance Responsible Parties (BRPs), aggregators, and prosumers. They developed a DR registry framework on Hyperledger Fabric and tested it in a lab setting with real assets, demonstrating the practicality and potential of blockchain in managing and validating DR activities securely.

Danzi et al. tackled the challenges faced by BRPs in the power system, particularly concerning energy procurement and imbalances [78]. They developed a blockchain-based SC to facilitate DR programs, reducing the need for extensive infrastructure investment by BRPs. Their solution, evaluated on a private Ethereum platform, demonstrated increased automation and efficiency in the balancing market, enabling new business models for BRPs and enhancing the cost-effectiveness of energy imbalance management.

Lin et al. [79] developed a vehicle-to-everything blockchain power trading and energy management platform, integrating AI, IoT, and blockchain. This platform aims to facilitate power transactions in EV charging stations in commercial buildings. It handles DR bids, bidirectional power flows, and green power transactions. The platform uses distributed ledgers and SCs for bidding, matching, and settlement in power trading while maintaining real-time records of transaction information and power data. The AI-enabled EMS in the

platform schedules charging and discharging operations, optimizing green power usage and enhancing operational efficiency in MGs.

Yang et al. created a blockchain-based transactive EMS for IoT-enabled smart homes, allowing for vertical and horizontal energy transactions [80]. Smart homes can feed surplus energy into the grid or trade energy with other homes, managing these operations while ensuring user privacy. The system uses a distributed algorithm within the blockchain to safeguard privacy and enable efficient energy control. This setup allows peer-to-peer energy trading among smart homes, improving the overall efficiency of the system. Blockchain compatibility with IoT devices and the integration of SCs support comprehensive transactive energy management.

Deshpande et al. presented a permissioned blockchain-based framework for a DR marketplace. The framework emphasizes enhanced transparency, trustlessness, and decentralization, addressing common blockchain challenges such as scalability and SC overhead. They proposed an effective DR allocation model using MILP optimization, showing high efficiency even in complex scenarios with substantial computational demands [81].

Di Silvestre et al. illustrated a distributed DR mechanism utilizing blockchain and SCs, allowing network members to interact with the DSO and offer flexibility [82]. The DSO uses Hyperledger Fabric channels for load adjustment requests, and SCs calculate each user's contribution, ensuring fairness and privacy. The study indicated the effectiveness of blockchain technology in addressing privacy concerns in a DR context.

Wang et al. proposed an energy management model for renewable energy MGs using a permissioned blockchain [83]. This model assigns distinct identities to participants and maintains transaction indices while ensuring privacy and security. The permissioned blockchain's distributed nature offers advantages like reduced communication delays and plug-and-play capabilities, enhancing the operational efficiency of the MG.

Merrad et al. designed a DR management system based on Optimal Power Flow (OPF) with a decentralized architecture using SCs [84]. This system eliminates centralized control over energy sources and hardware, instead employing a decentralized consortium for compliance enforcement. The system employs a Nash game approach for proposal verification and rewarding optimal solutions, deterring collusion and encouraging fairness and efficiency in energy generation management.

Li et al. introduced a blockchain-based trans-active EMS for networked MGs and local distribution grids [85]. Their system is structured into three layers: the physical layer (power distribution infrastructure), the cyber layer (communication and computing devices), and the trans-active energy system layer (interaction between the physical and market layers). The system enhances the transparency and trustworthiness of decentralized energy transactions by automating and enforcing energy trades determined by the market layer.

Augello et al. evaluated the integration of Hyperledger Fabric blockchain with Supervisory Control and Data Acquisition systems (SCADA) for aggregating DR energy resources [86]. They contrasted centralized data gathering in trusted environments using OpenADR and SCADA systems with a distributed and secure approach using blockchain. Their proposed architecture combines SCADA and blockchain to offer a robust and efficient solution for DR energy resource management, addressing challenges in integrating novel technologies into DR programs.

Sciume et al. developed a blockchain-based distributed DR service with a focus on tracking and certification [87]. The system utilizes a SC to execute DR events, determine users' baseline energy consumption, and compensate users with utility tokens. Their experimental setup, involving power electronic converters and Smart Meters, demonstrated the practical viability of DLTs in managing SGs, highlighting the enhanced transparency and fairness in customer participation.

Di Silvestre et al. employed blockchain technology and SCs within the Hyperledger Fabric framework to create a DR compensation system characterized by trustworthiness and transparency [88]. Their system enables direct interaction between prosumers and

the grid operator, with a SC calculating each customer's contribution to load adjustment. The introduction of a representative ID and a market operator node enhances user privacy within the network.

6. Discussion

The literature suggests that the impacts of blockchain in DR programs are transformative. Blockchain technology can revolutionise the management and execution of energy systems, enhancing decentralized control, security, transparency, and operational efficiency in the energy sector. Blockchain emerges not only as a technological tool but as a catalyst for a more sustainable, efficient, and consumer-centric energy future.

The integration of blockchain technology in the energy sector, particularly in DR, has led to several innovative approaches and unique solutions (Figure 5). These advancements are not only enhancing the efficiency and effectiveness of EMS but also introducing novel concepts like the integration of AI and the enhancement of data security and privacy.

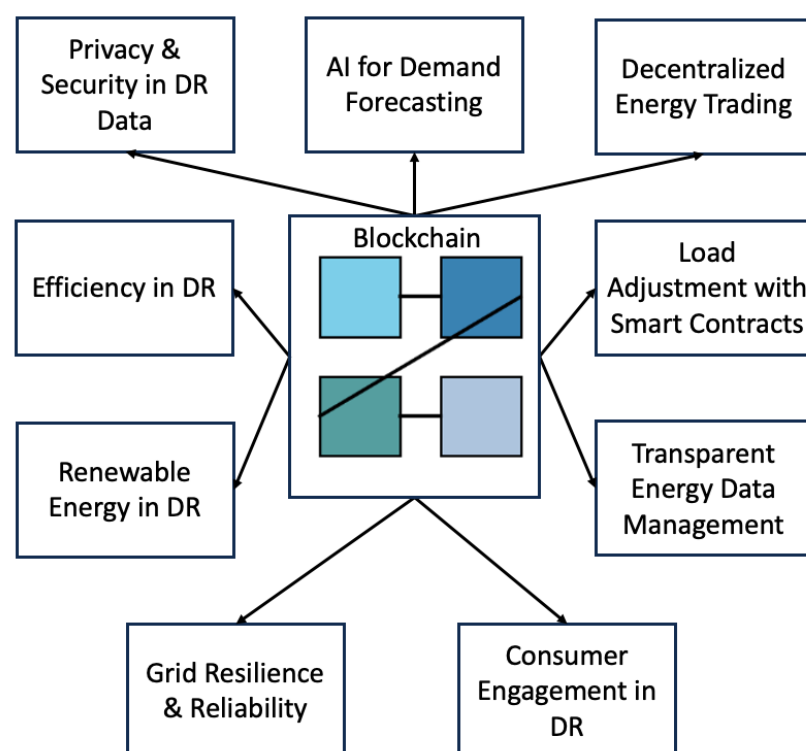


Figure 5. Conceptual diagram of blockchain applications in DR.

6.1. Impact of Blockchain and AI-Driven DR Optimization and Forecasting

The combination of AI and blockchain technology presents a formidable tool for energy management in DR. AI algorithms can analyze vast amounts of data to optimize energy distribution and forecast demand, while blockchain ensures the integrity and transparency of these transactions. Tsao et al. explored a sustainable MG powered by blockchain technology while being enhanced by AI for profitability and customer satisfaction improvements [70]. AI's role in automated decision-making has been pivotal in evolving blockchain-based P2P energy trading platforms. By employing AI algorithms, blockchain platforms can efficiently match energy demands with supply, dynamically adjust pricing, and ensure optimal energy distribution [79].

The development of decentralized, blockchain-based P2P energy trading platforms has been a groundbreaking innovation. These platforms empower consumers to trade energy directly with one another, bypassing traditional centralized utilities. These platforms can

revolutionize energy markets, offering consumers more control and potentially lower costs [33].

One of the standout innovations in blockchain for DR is the use of SCs. SCs can automate load adjustments in response to grid demands in real-time, reducing manual intervention and enhancing efficiency and stability [78,82]. Furthermore, by distributing the control and management of the grid across multiple nodes, blockchain can enhance grid resilience and reduce the risk of single points of failure [77].

Blockchain's ability to create transparent and efficient energy marketplaces is a notable innovation. By providing a platform where energy production, consumption, and pricing are transparently recorded, blockchain can foster fairer and more competitive energy markets [75].

Blockchain's autonomous execution of DR events, coupled with its ability to calculate user contributions and manage utility tokens, can significantly simplify operational processes. This automation not only eases the burden on BRPs but also introduces a level of precision and efficiency previously unattainable in traditional EMS [78,87]. Additionally, the technology is capability of managing real-time data and establishing transparent DR compensation systems through the use of SCs. Such advancements are not merely technical but are pivotal in building consumer confidence and ensuring equitable energy distribution.

Advanced DR distributed mechanisms using blockchain and SCs, can allow network members to interact with DSOs and offer flexibility. This approach not only ensures data privacy but also maintains transparent and equitable energy transactions, marking a significant advancement in the way energy systems operate. The critical role of SCs in automating DR actions and transaction verifications not only facilitates the detailed management of energy systems but also ensures the equitable distribution of rewards and responsibilities. This functionality is transformative, as it allows for a level of management detail and fairness previously unattainable in traditional DR programs [78].

In terms of securing energy transactions and enhancing system transparency, Bracciale et al. and DiSilvestre et al. explored the use of blockchain to secure energy transactions and enhance transparency in EMS [76,88]. The first proposes a privacy-preserving architecture on Hyperledger Fabric, and showcases how blockchain can provide a secure platform for energy transactions without compromising user privacy. Di Silvestre et al., on the other hand, demonstrate the efficacy of a trustworthy DR compensation system established using smart contracts. These findings suggest a future where energy transactions are not only secure and transparent but also respectful of individual privacy concerns.

6.2. Blockchain's Role in Energy Sustainability and Consumer Empowerment

The role of blockchain in decentralized and automated energy management is further exemplified by Danzi et al. [78]. Their work focuses on the utilization of blockchain-based SCs to minimize the involvement of BRPs in DR. This decentralized approach significantly enhances the automation in energy management, fostering the development of new and more efficient business models for BRPs, leading to a more dynamic and responsive energy market

Wang et al. and Merrad et al. contribute valuable insights into the innovative application of blockchain in reducing system imbalances and fostering consumer engagement in DR programs [83,84]. They specifically focus on a permissioned blockchain model for MGs and an OPF-based management system with a decentralized architecture. These studies demonstrate the potential of blockchain to not only enhance operational efficiency but also to engage consumers more actively in the management of their energy consumption, thereby contributing to more sustainable energy systems.

Blockchain technology has also been instrumental in facilitating the integration of RES into the grid. Through P2P energy trading platforms, consumers can trade renewable energy, promoting its adoption and use. Sciume et al. demonstrate how blockchain can support renewable energy trading in SGs, making it more accessible and cost-effective [87].

Blockchain platforms can also provide mechanisms for incentivizing renewable energy usage. By tokenizing energy production and consumption, blockchain platforms can reward consumers for using RES, contributing in addition to the transition towards a more sustainable and low-carbon energy system [83,85]. This reduction is critical in combating climate change and achieving global sustainability goals [76]. The adoption of blockchain in energy management opens up new economic opportunities and the potential for job creation. The development, implementation, and maintenance of blockchain-based energy systems require a skilled workforce, fostering economic growth and innovation [13].

Blockchain technology can contribute to energy equity by enabling more equitable access to energy resources. P2P energy trading platforms allow communities to trade energy independently, reducing reliance on large utilities and promoting energy access in underserved areas [33].

6.3. Comparing Different Blockchain Applications in DR Scenarios

The application of blockchain technology in DR via the different blockchain platforms we showcased presents various advantages and challenges. Ethereum and Hyperledger Fabric platforms have seen significant use in various DR scenarios.

As already discussed, Ethereum is a permissionless blockchain, known for its decentralized approach. This feature is particularly advantageous in DR scenarios that require broad participation and transparency. Ethereum's SC capability allows for the creation of Decentralized Applications (DApps) that can automate DR processes and transactions. For instance, Ethereum's SCs have been used to automate the settlement of energy trades in P2P energy markets [33]. However, Ethereum's permissionless nature often leads to scalability issues. The platform can experience slower transaction speeds and higher operational costs, especially when the network is congested. This aspect is critical in DR scenarios where real-time data processing and responses are essential [27].

In contrast to Ethereum, Hyperledger Fabric is a permissioned blockchain, often chosen for enterprise solutions due to its efficiency and scalability. As a permissioned blockchain, it offers faster transaction speeds and greater control over the network. This is particularly beneficial in DR scenarios involving large utilities or energy consortiums that require efficient and secure transaction processing. Mackhdoom et al. discuss the application of Hyperledger Fabric in enterprise-level energy systems, emphasizing its suitability for managing complex energy transactions with greater speed and privacy [89]. Another significant advantage of Hyperledger Fabric is its interoperability and modular architecture [90]. This feature allows for greater flexibility in integrating various EMS and applications, making it an attractive option for DR scenarios that require integration with existing grid infrastructure and diverse energy assets.

When choosing between permissioned and permissionless blockchains, the decision often balances transparency and control. Ethereum, a permissionless blockchain, is preferred in decentralized P2P energy trading due to its transparent nature that allows unrestricted participation. Conversely, in scenarios demanding heightened privacy and operational efficiency, permissioned blockchains like Hyperledger Fabric or Corda are preferred, as they offer a controlled environment; participants are known and verified entities and legal compliance is crucial [54,60].

In everyday contexts, the selection between these blockchain types hinges on the specific demands of the DR scenario. For example, public utility companies might lean towards Hyperledger Fabric to benefit from its internal efficiencies and privacy controls. In contrast, community-led renewable energy projects might find Ethereum more appealing for its decentralized and open features. Corda on the other hand, distinguishes itself in the DR context with its focus on privacy and legal compliance. As a permissioned blockchain, it excels in scenarios requiring the confidential handling of energy data and legally enforceable SCs. While it lacks the broader decentralization of Ethereum, Corda's controlled data sharing is ideal for regulated DR environments, setting it apart from both Ethereum's open transparency and Hyperledger Fabric's enterprise efficiency [57].

The optimal choice of blockchain in DR scenarios is thus contingent on the project's goals, whether they center on transparency and extensive participation or prioritize efficiency and confidentiality [91].

7. Challenges and Implications of Blockchain in DR

While blockchain technology offers a plethora of advantages in enhancing DR programs, its integration into the energy sector is not without challenges. These hurdles span a range of issues, from technical complexities and scalability concerns to regulatory and market barriers (Figure 6). The intricate balance between leveraging the innovative potential of blockchain and navigating its limitations is crucial for the successful adoption of this technology in DR systems. This section aims to provide a comprehensive exploration of these challenges, drawing from the literature and practical scenarios.

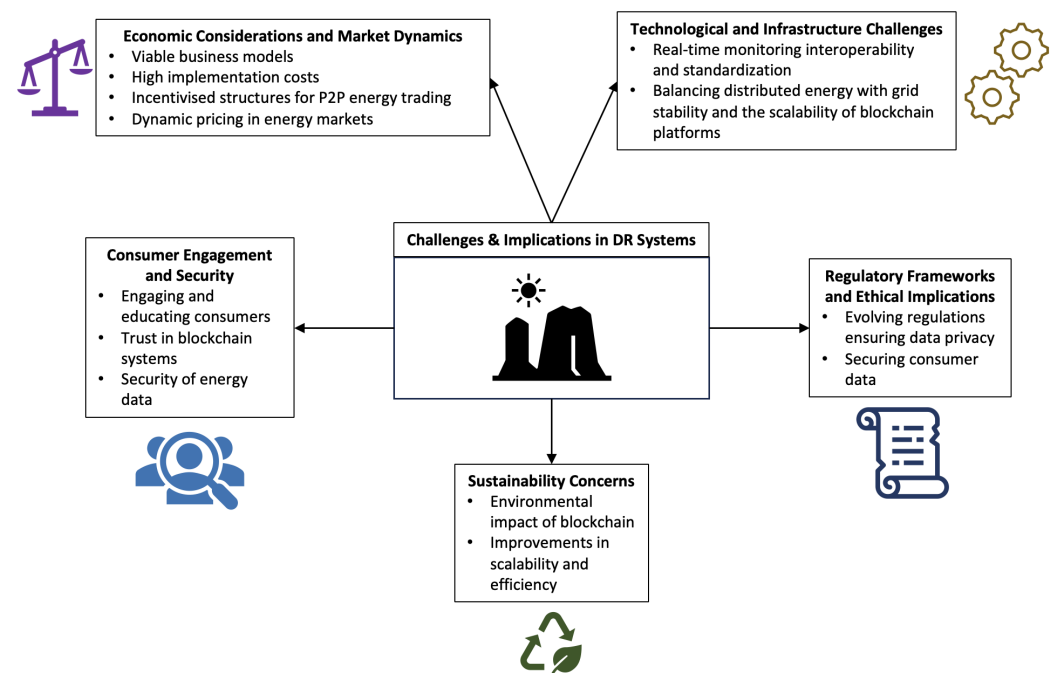


Figure 6. Challenges of blockchain in DR.

7.1. Technological and Infrastructure Challenges

The evolution of DR systems is closely tied to the development of advanced metering and communication technologies. These technologies are essential for the real-time monitoring and management of energy consumption, necessitating significant investment and technological advancement [64]. However, the deployment of such infrastructures faces several challenges.

A key obstacle is achieving interoperability and standardization across different regions and countries, each with its own technologies and standards. This complexity, emphasized by Park et al., complicates the creation of a unified DR system [67]. Furthermore, integrating P2P energy trading systems into existing grid infrastructures presents technical challenges, particularly in balancing distributed energy generation with grid stability. This aspect is explored in depth by Mao et al., who stress the importance of sophisticated control systems [66].

The scalability of blockchain platforms, crucial for handling the high volume of real-time energy trades in DR and P2P systems, is another significant challenge. Platforms like Ethereum, commonly employed for these transactions, face limitations in scalability and real-time processing, as discussed by Andoni et al. and Maihaylov et al. [27,92]. These issues highlight the need for blockchain networks that can efficiently manage the demands of real-time operational needs in energy trading and DR systems.

Moreover, the inherent technical complexity of blockchain technology poses barriers to its widespread adoption, requiring specialized technical knowledge that may not be readily available. This complexity is noted by Aitzan et al., who point out the necessity for entities to have or acquire the technical expertise needed for implementing blockchain solutions effectively [22].

In addition to these challenges, the issue of standardization and compatibility across different blockchain platforms exacerbates the problem of interoperability, as different platforms often have varied protocols and standards. Mihaylov et al. stressed this lack of uniformity, which poses a significant obstacle to the development of a cohesive and unified energy trading system [92].

In conclusion, the successful integration of blockchain into DR systems hinges on overcoming a range of technological and infrastructural challenges. These include establishing advanced metering infrastructures, resolving interoperability issues, addressing the scalability and real-time processing limitations of blockchain platforms, and overcoming the barriers posed by technical complexity. Tackling these challenges is crucial for fully realizing the potential of blockchain for enhancing DR systems.

7.2. Economic Considerations and Market Dynamics

The economic landscape of DR systems and blockchain-based energy trading is marked by several challenges and evolving dynamics. A critical aspect is the development of viable business models that can adapt to changing financial incentives and market structures. Creating such models for DR systems involves complexities in ensuring economic feasibility and the equitable distribution of benefits [85].

Another significant challenge is the high implementation costs associated with DR systems, which pose substantial barriers, particularly for smaller entities and consumers. The financial burden of deploying advanced metering and communication technologies is a key concern [76]. This issue extends to the development and maintenance of blockchain-based energy trading systems, where economic feasibility becomes a crucial consideration, especially for smaller players [89].

Furthermore, the establishment of economically viable and incentivized structures for P2P energy trading remains a daunting task. Samadi et al. suggest that developing attractive financial models is essential for the success of P2P trading systems [74]. Alongside this, the risk of non-payment in P2P energy transactions is a major concern for suppliers, highlighting the need for secure and reliable transaction mechanisms [75].

Navigating the complex regulatory landscape also poses challenges in deploying DR programs. The intricate nature of energy policies and regulations across different jurisdictions complicates the implementation of standardized DR solutions [73].

Additionally, the integration of blockchain in energy marketplaces facilitates dynamic pricing and real-time settlement of energy trades. This approach not only makes energy markets more responsive but also provides consumers with more control over their energy costs [76]. It represents a significant shift towards more efficient and consumer-centric energy markets.

In summary, the economic considerations in DR systems and blockchain-based energy trading involve balancing the development of viable business models, managing high implementation costs, ensuring financial viability and incentive structures, mitigating transaction risks, navigating regulatory challenges, and leveraging blockchain for dynamic pricing and real-time settlement. These factors collectively shape the economic and market dynamics of modern energy systems.

7.3. Regulatory Frameworks and Ethical Implications

The regulatory landscape of P2P energy trading and blockchain in energy systems is a domain marked by continuous evolution and complexity. Navigating these evolving regulations poses significant challenges. Yang et al. emphasize the necessity for adaptive policies that can accommodate the innovative nature of P2P energy systems [80]. This need

for adaptability is also echoed in the broader context of blockchain in energy trading, where governments and regulatory bodies are grappling with understanding and legislating the use of blockchain. This state of flux creates a landscape of uncertainty for all stakeholders involved [93].

Moreover, deploying DR programs often encounters regulatory hurdles. The intricate nature of energy policies and regulations across different jurisdictions complicates the implementation of standardized DR solutions [73]. This complexity in regulatory frameworks necessitates a careful approach to ensure compliance and effectiveness in implementing DR systems.

An additional concern within this regulatory context is the privacy and security of data in P2P energy transactions. Ensuring data privacy is crucial, especially considering the increasing digitization of energy systems. Another study explores the challenges of securing consumer data, highlighting the ethical implications and importance of robust data protection measures in digital energy systems [38].

In essence, the regulatory frameworks governing P2P energy trading and blockchain applications in energy systems are characterized by their dynamic nature and the need for constant adaptation. Balancing regulatory compliance with innovation, ensuring data privacy and security, and navigating the complexities of diverse energy policies are pivotal aspects that shape the ethical and regulatory landscape of modern energy trading systems.

7.4. Consumer Engagement and Security

One of the significant challenges in the implementation of DR programs is actively engaging consumers. The difficulties in educating and incentivizing consumers about the benefits of DR programs are well-documented [33]. This challenge extends to engaging consumers in P2P energy trading systems, where building trust is a crucial aspect. As Pop et al. point out, incentivizing consumers plays a vital role in encouraging their participation in these new models of energy trading [65].

However, despite blockchain's inherent security and trustless nature, gaining user trust in blockchain-based systems remains a challenge. Users may be hesitant to engage with a technology that operates on principles fundamentally different from traditional centralized systems [94]. This hesitancy highlights the importance of building trust in what is perceived as a trustless system.

Furthermore, with the increasing use of digital technologies in energy management, the security of energy data has become a critical concern. The need to protect data related to energy consumption and production is imperative, as it forms the foundation of consumer trust and system integrity [69].

In addition to these challenges, the risk of non-payment in P2P energy transactions is a major concern, particularly for suppliers. This risk needs to be addressed to ensure the financial security and viability of P2P energy trading systems [75].

7.5. Sustainability Concerns

The implementation of blockchain in energy systems also brings forth sustainability concerns. The high energy consumption required to run some blockchain networks, especially those based on proof-of-work, can conflict with the goals of sustainable energy systems. This stands as a paradox of blockchain's environmental impact [95]. Alongside environmental concerns, there is also an inherent need for continuous improvements in the scalability, efficiency, and interoperability of blockchain networks. These improvements are necessary to fully harness the potential of this new technology in energy management [27].

8. Conclusions

This research aimed to explore the potential of integrating blockchain technology in DR programs. The focus is on how blockchain can facilitate P2P energy exchanges and enhance DR programs in the energy sector. The investigation included a thorough examination of the operational efficiencies and technological innovations offered by blockchain, as well

as the challenges and obstacles involved in its implementation. This work delved into various aspects of blockchain applications in DR such as scalability, security, and regulatory considerations. Also, it provides a comprehensive understanding of how blockchain can revolutionize energy management and distribution. The research has also emphasized the importance of consumer engagement and the evolving economic and regulatory frameworks influencing the successful adoption of blockchain-based DR systems. In conclusion, a summary of the key insights derived from this research offers a cohesive overview of the potential impacts, prospects, and strategic directions necessary for leveraging blockchain technology in the realm of DR and energy trading.

This study initially stated specific Research Questions (Section 1) aimed at exploring the role and impact of blockchain technology in DR within SGs. Our findings provide clear answers to these queries:

1. Research Question 1: How/Can blockchain technology be effectively integrated into SGs to enhance the efficiency and security of DR systems? Our research indicates a positive affirmation, with empirical evidence suggesting significant improvements in both efficiency and security.
2. Research Question 2: What are the key challenges and opportunities associated with the adoption of blockchain in DR within SGs? We identified critical challenges, such as scalability and interoperability, alongside opportunities for enhancing consumer engagement and system transparency.

The integration of blockchain technology in SGs demonstrates a substantial enhancement in DR efficiency. Key findings include a notable reduction in response time and improved reliability in load adjustments. Security aspects have also been positively impacted, with blockchain solutions significantly reducing the instances of data breaches and unauthorized access in SG networks. Blockchain technology's application in SGs marks also a significant step forward in sustainable energy management. It not only optimizes DR operations but also paves the way for more resilient and user-centric energy systems.

8.1. Future Directions

This work can be expanded by addressing several domains of study that are crucial for advancing our understanding and implementation of blockchain in the energy sector. Figure 7 summarizes these domains while the subsequent subsections elaborate on them.

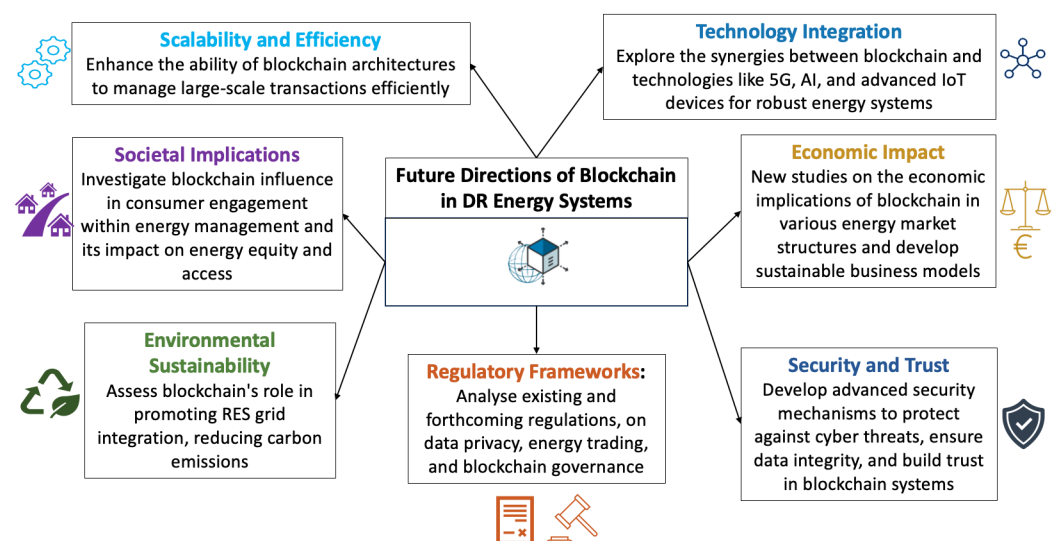


Figure 7. Future research directions for blockchain technology in DR energy systems.

8.1.1. Detailed Technological Improvements and Innovations

Future research in blockchain technology for energy management should prioritize enhancing scalability and efficiency. Addressing these challenges is crucial, especially in the context of blockchain architectures capable of handling large-scale transactions [27]. Furthermore, the integration of blockchain with emerging technologies such as 5G, AI, and advanced IoT devices could offer significant advancements. For instance, the work by Yang et al. provides insights into how these integrations could lead to more robust and efficient energy systems [80].

8.1.2. Economic and Market Analysis

In-depth economic impact studies of blockchain in the energy sector are vital. These studies should focus on the cost-benefit aspects of blockchain implementations in different energy market structures, drawing upon findings from [83]. Additionally, developing sustainable business models for blockchain applications in energy management is another critical area of research. Guo et al. have highlighted the potential of blockchain in supporting novel pricing strategies and financial incentives, which could be explored further [75].

8.1.3. Regulatory and Policy Frameworks

The advancement of blockchain in the energy sector demands a comprehensive analysis of current and emerging regulatory frameworks. This exploration should encompass data privacy laws, cross-border energy trading regulations, and governance models specific to blockchain [93]. Additionally, it is imperative to develop policy recommendations that support the adoption of blockchain in energy management. These guidelines should be based on in-depth stakeholder analysis and work to ensure ethical and long-lasting blockchain implementation [73].

8.1.4. Societal Implications and Consumer Engagement

Investigating consumer behavior and engagement in response to blockchain-based energy systems is a crucial area for future research. It is important to understand how blockchain technology affects consumer participation in energy conservation and management [13]. Additionally, assessing the impact of blockchain on energy equity and access, particularly in underserved communities, is vital. This aspect involves exploring how blockchain can facilitate equitable energy distribution and improve access to energy resources [33].

8.1.5. Environmental Sustainability and Renewable Energy Integration

Exploring the environmental impact of blockchain technology in energy management, especially its role in promoting RES and reducing carbon emissions is a vital area for future research. Studies have already begun to address these issues [85]. Furthermore, how blockchain can aid in the integration of RES into the grid, considering aspects like energy storage and grid stability, is a critical area to investigate [76].

8.1.6. Security, Privacy, and Trust in Blockchain Systems

The development of advanced security mechanisms for blockchain in energy management is essential. Research should focus on protecting against cyber-threats and ensuring data integrity [80,96]. Additionally, building trust among users in blockchain systems is crucial, especially in the context of transparent and secure energy transactions [76].

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BFT	Byzantine Fault Tolerance
BRP	Balance Responsible Party
DApps	Decentralized Applications
DCS	Distributed Control System
DER	Distributed Energy Resources
DLT	Distributed Ledger Technology
DR	Demand Response
DSM	Demand-Side Management
DSOs	Distribution System Operators
EMS	Energy Management System
EV	Electric Vehicle
IoT	Internet of Things
ISO	Independent System Operator
MG	Micro-Grid
MILP	Mixed Integer Linear Programming
OPF	Optimal Power Flow
P2P	Peer-to-Peer
PBFT	Practical Byzantine Fault Tolerance
PoS	Proof of Stake
PoW	Proof of Work
RES	Renewable Energy Sources
RTP	Real-Time Pricing
SC	Smart Contracts
SCADA	Supervisory Control and Data Acquisition
SG	Smart Grid
SO	System Operator
TOU	Time-of-Use
TSOs	Transmission System Operators

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