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Blockchain Technology for Renewable Energy: Principles, Applications and Prospects

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Abstract: Blockchain, or distributed ledger, is an innovative technology that is emerging in various sectors and industries across the globe. It has attracted the attention of different interest groups such as energy companies, SMEs and start-ups, information technology developers, financial institutions, national authorities, and the university community. Through, for example, the decentralization of authority in transactions, Internet of Things (IoT) implementation, and smart contracting, the improvement of the daily business operations is firmly forecasted. In the energy sector, digitalization is already present in solutions such as smart grids, smart meters, electric vehicles, etc. Moreover, a new concept of the Internet of Energy (IoE) has been introduced in the academic literature. In this article, the level of trust and maturity of Blockchain technology implementation is investigated through the Blockchain Maturity Questionnaire, developed by the authors. The database consists of responses from upper management professionals from the renewable energy industry. The analysis reveals the state of know-how about Blockchain, the main benefits and bottlenecks associated with its implementation as well as willingness to integrate this technology in the case companies' future operations. The insight from the industry experts helped to provide a "Roadmap for Blockchain Adoption" in future energy systems. This curiosity study yields numerous applications not only for the renewable energy industry experts but also for the interest groups coming from different industries, as well as public authorities and researchers scrutinizing the fields taken into its scope.

Keywords: blockchain; technology adoption; business models; peer-to-peer (P2P); distributed energy; smart contract; energy digitalization; renewable energy; circular economy; Finland

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1. Introduction

The current energy systems are incorporating increasing shares of renewable energy sources (RES). This transformation, driven by a sustainable triple-bottom-line concept of generating value through economic, environmental, and societal performances of the energy companies, has been further boosted by privatization, as well as financial and energy policy incentives [1,2]. In 2020, the share of renewable energy sources in Finland has raised to nearly 40%, which has exceeded the share of fossil fuels and peat combined for the first time in the country's history [3]. However, RES are inconstant, hard to forecast and weather-depending, which causes difficulties in operations management of electricity systems [4]. The emergence of distributed energy markets requires novel technology solutions to support energy and information sharing. Hence, due to distributed and irregular nature of renewable energy sources, innovative technologies are essential to bringing their expansion to the next level [5,6]. Therefore, some flexibility measures are required to enhance grid stability, such as timely supply and demand response mechanisms or energy storage solutions [7]. Based on a rapidly growing number of incorporated smart meters across the globe, it is claimed that energy systems are on the verge of performing a digital revolution [8]. It is evident that this revolution cannot be achieved with the centralized energy markets of today [9] as there is a need for better information-sharing solutions such as ICT [10]. These novel, often local energy markets, which provide improvements in, for example, energy efficiency, environmental and socioeconomic sustainability performance, etc. require decentralization and digitalization solutions to become more proactive (by including more actors) and effective in peer-to-peer energy trading management [11].

The solution to these issues can be blockchain technology, which was primarily designed to enhance decentralized transactions by removing the central authorities from transactional processes. It can be also defined as a distributed ledger technology (DLT) or Internet of Value [12] that securely stores and shares digital transactions without the centralization of management. This structure allows for the automated execution of smart contracts in peer-to-peer trading platforms [13]. Blockchains can be also perceived as a global database that allows multiple users to modify the ledger, and automatically updates those modifications by making multiple copies of the new records in the chain. Contrary to centralized, single-authority management systems, changes must be approved by the users through consensus mechanisms, which makes this network transparent, secure, and "trustless". To ensure even more resilience to human-specific misconducts and errors, the anonymity of users is covered by implementing cryptographics while connecting new transactions to the existing ones in a block. The literature suggests that such radical technological changes in the existing structures would generate a need for new business models and reconsideration of the current technology paradigms [14–17]. For instance, in supply chain management, the current schemes would be revolutionized by removing the intermediaries through decentralized, blockchain-based supply chains [18,19]. Importantly, blockchain seems to perfectly fit into the context of '*Energy 3Ds*', which stands for decarbonization, decentralization, and digitalization, by offering solutions to obtain these energy capabilities in the near future, and to foster energy transition and dynamic innovation in the field of renewable energy technologies (RET) [20,21]. However, as there is a limited number of use cases, it should be noted that blockchain adoption in the renewable energy industry is not definite and there are other digital solutions that may enhance the performance of the companies in this sector. Blockchain is still an emerging technology, and its widespread diffusion requires multi-dimensional contribution from various sectors of society, as suggested further in this study.

However, while not being universally implemented yet, blockchain usage is associated with numerous regulatory, societal, and technological barriers, such as scalability issues, lack of regulations, integration challenges, etc. Nevertheless, it is claimed that the potential benefits coming from blockchain integration far outweigh these bottlenecks [22].

Most current studies provide reviews of the literature and use cases of blockchain utilization. However, the mainstream of research refers to the overall energy sector, and thus, there are limited studies that are focused solely on renewable energy technologies. Furthermore, authors tend to specialize in specific features or applications of blockchains, such as smart contracts, peer-to-peer platforms, energy efficiency improvement, IoT enabling, etc., whereas in our article, we provide a multidimensional and holistic approach towards DLT application in the RET industry. This curiosity study can contribute to the existing literature on energy digitalization, by providing the prospective viewpoints of the executives of the Finnish renewable energy companies. Because Finland is a member state of the European Union, this research can provide implications for the European energy policy and energy transition analyses, as well as suggest new directions towards achieving the energy decarbonization, digitalization, and decarbonization within the EU. In this article, we present empirical evidence from the Finnish renewable energy industry through the 'Blockchain Maturity Questionnaire' developed by the Authors, revealing the level of knowledge and trust in DLT, followed by an indication of the major potential benefits and challenges in implementing blockchain in Finland, its impact on business models as well as the willingness of the industry experts to utilize blockchains in future. Such a novel insight will shed new light on the principles of blockchain, its applications in the renewable energy sector, and prospects for the future. The remainder of this article is structured as follows. Section 2 analyses the academic literature on blockchain and its usefulness for the renewable energy industry. The methodology implemented in this study is presented in Section 3, where case companies are introduced as well. Section 4 reveals the results of our empirical analysis and its multidimensional implications. Section 5 provides limitations of the study as well as future research directions. Lastly, the main outcomes of this article are summarized in Section 6.

2. Literature Review

In this section, we will provide theoretical background for our study. First, we will explain the basic architecture and principles of blockchain. Then, we are going to present the favorable features of this technology, which will be supported by successful examples of use cases. Finally, we will focus on our core area of renewable energy by reviewing the possible pros and cons of blockchain implementation within the RET sector.

2.1. Basic Principles of Blockchain

Blockchain (or distributed ledger technology—DLT) is a technology that ensures digital information distribution in a shared database that contains a continuously expanding log of transactions and their chronological order. In other words, it is a ledger that may contain digital transactions, data records, and executables that are shared among blockchain partaking agents [13,23]. Blockchain technology is distinct from other previously known information systems by its four main features: non-localization (decentralization), safeness, verifiability, and smart execution [24]. It is a highly innovative technology that is the outcome of a decade's efforts from "*an elite group of computer scientists, cryptographers, and mathematicians*" [25].

The basic procedure within blockchains is structured as follows. Initially, the agent creates a new transaction to be included in the blockchain. This recently created transaction is distributed with the network for authentication and audit. As soon as the transaction is authorized by most of the nodes based on pre-determined and multilaterally established rules, this activity can be transferred to the chain as a new block. A record of that transaction is stored in separate dispersed nodes to ensure the safety of the whole system. In the meantime, the smart contract, as a key component of blockchain, facilitates trustworthy transactions to be performed without third party contribution [18,26]. Figure 1 illustrates this process.

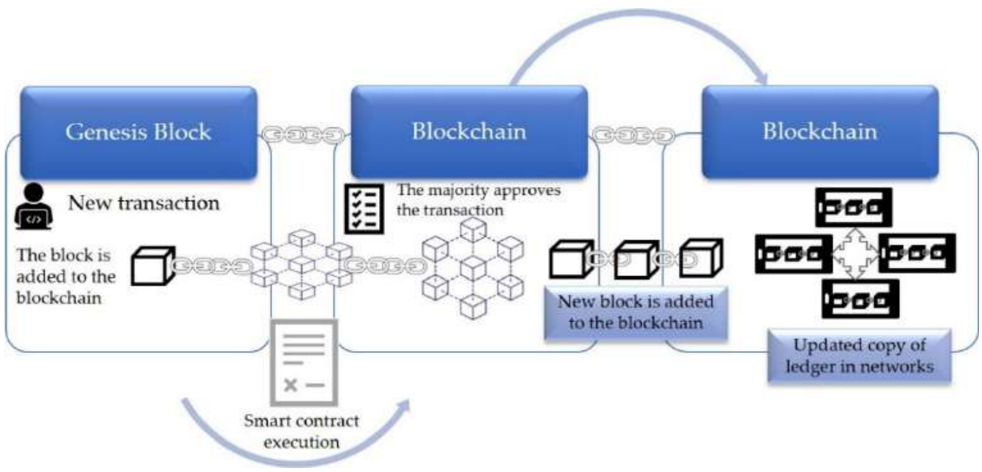

Figure 1. Basic steps in blockchains.

To illustrate the substantial change in current information systems, a comparison with the Internet could facilitate the realization of the possible effect of blockchain technology on current structures. Principally, the Internet (as opposed to blockchain), was designed to transfer information (not value) as well as to process and relocate copies of things (not original information). Therefore, in blockchains, value is generated through transactions logged in a distributed ledger, which is secured by arranging a certifiable, time-stamped record of transactions that results in protected and verifiable information [27]. These digital transactions go through auditing and verification processes that are agreed upon by the system consensus guidelines. When the new record passes this whole process, it is verified and included in the blockchain, and then multiple copies are generated in a decentralized way to establish a trustworthy chain [18].

2.2. Features and Applications of Blockchain Technology

One of the most significant features of blockchain is decentralization, which meaningfully improves information legitimacy. Accumulation, updating, or deleting information in centralized information systems is not only inefficient and expensive, but such structures are more vulnerable to hacking, fraud, or critical errors [28]. Blockchain, by arranging decentralized information sharing systems, significantly increases the trust level of the performed transactions, as per there is no longer a requirement to appraise the reliability of the middle-men (who are removed) or of any other network participants, and this data is effortlessly available and verifiable. This decentralization creates an additional substantial advantage attributed to blockchain implementation, which is the transparency of information whereas safeguarding the anonymity of participants, for example, through cryptographic systems [29]. Additionally, this design enhances minimizing any human, social or behavioral misconduct such as fraudulence or sluggishness, guaranteeing the security and integrity of the network.

Depending on a specific technology application, blockchain architecture can be divergent while establishing public ("permissionless") or private ("permissioned") data systems and ledgers. Both public and private blockchain systems are decentralized and distributed between their users to track all peer-to-peer deals without the involvement of habitually trusted middlemen to approve them [30,31]. However, in private or closed blockchains, the partners can identify each other so there is no anonymity, which creates a necessity to introduce certifiers who are accountable for verifying network members as well as maintaining these private systems. In contrast, in public or open blockchains, cryptographic solutions are utilized to guarantee trust among numerous anonymous participants to permit them to access the network and perform operations inside of it.

To linger on this comparison, let us deliberate on the main distinguishing aspects. First, private blockchains have higher transaction processing rates with fewer authorized members. Hence, a shorter time is needed to achieve the network consensus and a bigger number of transactions can be managed within a given time. By contrast, public blockchains are characterized by limited transaction processing rates. The consensus mechanisms, like Bitcoin's Proof-of-Work (PoW) inside public blockchains, require the entire network to reach an agreement on the current status of transactions. Moreover, data privacy for public blockchains is more prone to risk due to their distinctive nature. On the other hand, private blockchains have more solid data security foundations where any modification can be made only when all nodes approve that the information can be altered through a consensus mechanism [31].

Concurrently, the innovative transactional applications that augment trust, transparency, and auditability are possible through blockchain, and these applications are run by smart contracts. Smart contracts are software solutions for storing principles and regulations throughout the negotiation of terms, conditions, and activities between participants. They serve to automatically verify if pre-established rules and conditions have been fulfilled and then, (if so) to execute transactions. Smart contracts could alleviate informational asymmetry and develop welfare and customer surplus by providing enhanced access and competition, although distributing information throughout consensus creation might cause larger complicity [26].

Blockchain technology was first introduced in 2008 as a trading platform supporting the Bitcoin cryptocurrency [23], but since then, its applications are numerous across different sectors, such as fintech, healthcare, luxury goods, etc. These successful use cases are presented in Table 1 and show the universal applicability of blockchain. However, it should be noted there are only few examples of blockchain utilization at the advanced stage of development, as many applications are still at their infancy level and most of them are at the testing or pilot phases [13,15]. Even though it is no longer an unknown technology, its rapidly developing applications are innovative and thus have a disruptive nature due to its transparency, interoperability, and decentralization, which helps markets to provide more secure, resilient, and both cost- and time-efficient solutions [6].

Table 1. The application of blockchain in various industrial segments.

Industrial Segment	Application of Blockchain	Authors
Government/Public sector	• Voting • Taxes • Tender processes	[32–38]
Industrial sector	• Manufacturing processes • Internet of Things (IoT) device management • Service industry	[39–44]
Financial services	• Foreign exchange • Corporate debt/bonds • Trading platforms • Payment remittance	[45–48]
Insurance policy	• Claims processing • P2P insurance • Ownership titles • Sales and underwriting	[49–51]
Retail business	• Loyalty points • Identity management • Trust industry • Capital asset management • Letters of credit	[52,53]
Luxury business	• Luxury items	[54–56]
Sustainable and circular supply chains	• Sustainable Supply Chain Management (SSCM)	[18,57–59]
Supply chain and logistics	• Food supply chain • Drug supply chain • Textile and clothing supply chain • Agricultural supply chain • Automotive supply chain • Freight logistics • Construction supply chain	[19,60–64]

2.3. Blockchain for Renewable Energy

Blockchain technology has also gathered considerable attention in the energy market, where blockchain has already contributed to the emerging concept called the Internet of Energy (IoE) [65] which enables transparent, decentralized energy prosumer networks, including energy trading platforms [66]. There have been several successful applications of blockchain in the energy industry, where improvements provided by this technology fostered the energy transition and circular economy initiatives through for example, novel solutions for electric e-mobility, energy democratization, P2P energy trading platforms, demand-response mechanisms, smart metering, smart grid management, automation of green certificates issuance and carbon trading, etc. [13,24]. In substance, as Wang and Su highlighted, blockchain can provide three major benefits for the energy sector, which are (1) decentralized energy trading and energy supply, (2) effective, automated control of energy and storage flows through smart contracts, and (3) secure records of all the business activities in the energy industry [67].

In this part, we will discuss the applications of DLT in RET and circular economy in more detail, which will help us to categorize major possible benefits and barriers to use in the research results presentation. The list of identified categories of main advantages of blockchain in the (renewable) energy sector is presented in Figure 2.

Figure 2. Applications of blockchain technology in the renewable energy industry.

Next, we will discuss the highlighted benefits coming from possible blockchain adoption within the renewable energy industry in a detailed way, one by one.

2.3.1. Distributed Energy Trading—P2P Platforms and Energy Democratization

As previously mentioned, decentralization is one of the key features of blockchain technology. The concept of removing the intermediaries from the transactional processes emerged from the introduction of smart contracts, that serve to automatically verify and execute the contract rules. Therefore, security and trust, previously granted by third parties, now can be ensured by blockchains [24]. Blockchain, by being a distributed ledger technology (DLT) enhances the integrity and reliability of the stored data, by limiting the need to authorize new transactions and updates by certified third parties. Such processes are automated through consensus mechanisms, which improves time- and cost-efficiency as well as provides transparency and interoperability of the blockchain-based systems. Moreover, asymmetric cryptographic systems serve to ensure the trustworthiness and anonymity of the transaction parties.

This decentralization can act favorably, particularly in the Solar PV generation, trading, and storage activities, where energy prosumers (producers and consumers all at once) can have a more active role in the market, by forming local energy communities, such as so-called crowds. Crowd energy can be understood as the enhanced cooperation of energy prosumers where their resources are traded with the use of ICT solutions [68]. This concept could be further described as a "decentralized autonomous organization", a distributed network of sovereign agents, based on flawless and reliable operation. Therefore, the crowd energy idea seems to perfectly fit as the background for blockchain, enhancing for example, direct peer-to-peer (P2P) energy transactions, traceability and provenance of energy, smart contracts, etc. Furthermore, according to the seminal study by Andoni et al., decentralized energy trading appeared to be the most common application of blockchain in the energy sector, followed by (2) cryptocurrencies and energy tokens and (3) IoT, automation, and asset management [13]. It has gained the attention of energy companies due to its capability to significantly reduce transaction costs and trading volumes, which attracts smaller-sized prosumers to actively participate in the energy markets. Moreover, prosumer-oriented energy markets can provide more flexibility to the grid, but also the transparency which could result in a significant increase in the customer awareness about the source and quality of chosen energy services. Such an improvement could lead to enhanced competition and so-called energy democratization. Lastly, local energy trading platforms, by forming microgrids, can generate novel revenue streams and potentially decrease the total cost of energy for end customers [13].

2.3.2. Cryptocurrencies and Energy Tokens

The mainstream of initial know-how about blockchain technology links DLT with cryptocurrencies, such as Bitcoin or Ethereum. Therefore, as this is one of the most acknowledged applications of blockchain in general, new cryptocurrencies and tokens are emerging in the energy industry. They can serve as an incentive for low-carbon energy generation, hence some cryptocurrencies act as a reward for most socially and/or environmentally sound practices in the system and, therefore, can enhance clean energy investments. Furthermore, cryptocurrencies can serve to tokenize resources, which creates a possibility to shape novel markets and innovative business models, based on the division of assets and ownership. Interestingly, numerous companies are applying cryptocurrencies to allure new investors and organize additional financing options, such as, for instance, Initial Coin Offering (ICO). There are already several examples of inventing new cryptocurrencies and energy tokens aimed at fostering IoT, sustainable and renewable energy investments, such as SolarCoin, EverGreenCoin, EECoin, EcoCoin, or NRGcoin [69–73], to name a few most popular ones as well as numerous Ethereum-based tokens and platforms.

2.3.3. Enabling IoT and Asset Management

The application of innovative ICT solutions such as the Internet of Things (IoT) can bring numerous benefits to energy companies [74]. The rapidly growing number of smart devices, such as smart meters and ICT tools, fostered by automation processes and big data management results in the potential to remodel the energy sector's value chain. Such innovative digital support can improve the energy system's overall performance and resources analytics which could help the companies to cut down operational costs [75]. Especially in the instance of electricity generators, smart technologies grant the capability of boosting the network efficiency through enhancing billing automation, optimization of demand control (i.e., aggregation and response) mechanisms, and revolutionizing the existing supply chains [18]. Moreover, an introduction of innovative digitalization solutions such as IoT and/or ICT- and blockchain-based technologies can inspire companies to seek innovation paths and to innovate their current business models [14,15,17]. As it is claimed in the literature, the energy sector digitalization will require the reconsideration of existing structures and business models, mainly due to the decentralization of authority, entirely virtual, and new local, self-sufficient markets where consumers are more motivated to actively participate [76,77].

Primarily, IoT solutions are associated with hardware and software smart automation technologies, such as sensors, meters, cloud connectivity and controlling tools, etc. which could, among other things, significantly limit the maintenance and management costs for smaller-sized RET companies [75,78]. Notably, the application of smart grids can improve the grid management and grid stability through smart devices, and enhance real-time coordination and adjustment of the energy demand and supply, and electricity prices accordingly to the current power consumption levels [11]. Finally, it is important to note that blockchains can strongly support further IoT-based solutions' development as blockchains can be used as a solid technological base for creating and sustaining IoT platforms, and provide the reciprocity and interoperability of IoT operations [79,80].

2.3.4. Smart Metering and Smart Grid Management

Blockchains, mainly due to the rising number of smart meters, can play a key role in fostering more efficient, automated methods for metering and billing procedures. The principal benefit coming from such automation is the potential of cutting down administrative costs within the grid and market. Moreover, it provides transparency and trackability of the energy generated and consumed, informing the customers about the source, price, and provenance of the particular energy supplied to them (renewable energy tracking), which positively affects the competition in the market and societal awareness about the environmental aspects of energy. Furthermore, through its data security feature, blockchain can ensure personal and business fragile data privacy and protection against cyber-attacks. Another aspect concerning hazardous events such as power outages and wastes can be tackled by using blockchain's smart contracts while forming a new smart grid [41,67,80].

Interestingly, one of the initial utilizations of blockchain in the energy industry was the introduction of cryptocurrencies as a payment method for electricity and energy bills [13]. Nowadays, an increasing number of companies permit payments for their services through cryptocurrencies, including those of the energy companies, where BAS Nederland is perceived as a leader in this matter, by allowing payments for the energy bills issued by them in Bitcoins, the most globally popular cryptocurrency [81], which was rapidly followed by other companies like German Enercity [82] or Japanese Marubeni [83].

Smart meters and smart contracts provide numerous benefits for the energy sector while administered through blockchain. Another important example of a possible improvement opportunity is the automated and decentralized grid management system through smart grids [10]. Such a smart grid management method, which is based on blockchain's main feature—smart contract—can ameliorate, for example, supply to demand balancing, distribution system coordination, grid assets verification and visibility, through smart contract's capability to effectively control energy network, which is based on pre-established rules and performed in an automated and reliable way [11,26,84,85].

2.3.5. Green Certificates and Carbon Trading—Automation

Importantly, blockchains can contribute to the energy transition toward renewables by facilitating and promoting carbon emissions and cleaner energy trading [86]. Notably, DLTs can foster innovative renewable energy financing by introducing green energy tokens or other tradable digital assets in the energy market or developing P2P energy trading platforms where information about the provenance of the given energy source as well as funds allocation are easily trackable and accessible due to blockchain's transparency and interoperability [87,88]. It is even more important for small-scale energy producers, which are often excluded from the carbon credits procedures due to their relatively complex nature and high claiming costs.

Blockchains, independently of the trading volumes, can automate the issuance of green energy certificates, generate international, transparent markets for green assets trading, and decrease transaction expenses also through preventing double-spending [76,89].

2.3.6. Fostering Electric Transportation

Electric e-mobility is one of the most promoted ways to mitigate the adverse impacts of climate change and to make the transport industry more environmentally friendly. Moreover, digitalization, as a central differentiating factor from conventional, fuel-based vehicles, strongly fosters and enhances electric transportation [90]. Therefore, the inevitable future fast-paced development of electric vehicles (EV) will require improvements in cost efficiency and vehicle performance, but most importantly, in charging speed, the convenience of use, availability and shared charging infrastructure, etc. The decentralized nature of modern transportation trends (on-demand car renting or automated mobility applications, such as Uber) makes blockchain a natural application in this field [13]. In fact, EV charging and shared charging infrastructure are one of the most promising scenarios for blockchain utilization in the energy sector [84]. Blockchains can enable transparency for the EV owners about the charging prices and energy source selection. Moreover, local grid operators and energy suppliers could establish charging prices by the use of blockchain microgrids [91,92]. Furthermore, blockchain wallets could be implemented to facilitate payments at charging stations [15]. Importantly, what is blockchain's unique capability, is to deliver a one-of-a-kind validation and communication platform that is universal despite of location, which would be suitable for cross-border mobility as well. Furthermore, blockchains can provide a market-oriented mechanism for management optimization and EV charging coordination. Charging station operators, with the help of blockchains, could improve the easiness of use for EV owners, but also infrastructure management, the security level of the system as well as promotion of the shared energy concept [93]. Finally, blockchain can serve to guarantee tamper-proof vehicle security and defend programmed cars from being hacked [94], which is often a major concern while employing self-driving cars. Such a guarantee of safety could boost electric and automatic car consumption, which would result in a significant reduction in fuel usage and GHG emissions in the transport industry [95].

2.3.7. Contribution to the Circular Economy

As previously mentioned, blockchains, by providing multidimensional benefits for the RET companies, can play a key role in strengthening the energy transition and promoting more sustainable practices in the energy sector. Notably, a study led by Upadhyay claims that blockchains can contribute to the circular economy concept by facilitating transaction costs reduction, performance and communication improvement within supply chains, human rights protection safeguarding, healthcare patient confidentiality, and welfare enhancement, and carbon footprint reduction [22]. Blockchains, by enabling automation of transactions in a permanent and verifiable way [96], can also serve to optimize time and resources, which could effectively eliminate operational disorganizations or production waste. According to Ghisellini et al., the goal of the Circular Economy approach is to promote greener production measures, the implementation of renewable energy technologies as well as the advancement of optimal strategies and mechanisms [97]. Blockchain can help to achieve these objectives through its ability to generate more sustainable commercial transactional procedures and assist in attaining the necessary equilibrium and harmony between the environmental, economic, and societal dimensions of sustainability.

Blockchain, by its revolutionary decentralized nature, could have a major impact on supply chain management [18,59,60]. For example, blockchain can be used to track and verify the origin of raw materials, production locations, product carriers, storage, and retailers to buy products. Moreover, blockchain enables an efficient tracking and transparency of defective and substandard goods [18]. It also helps to verify the provenance of a product and related sustainability practices, that is, if there are any fraudulent and unethical labor practices involved [98]. In manufacturing processes, blockchains can be utilized for spare parts tracking and monitoring of the current equipment, but also for shipping automation, which has the major potential to provide more time efficiency and reduce operational and repairing costs [44,61,62].

Blockchain can promote circular economy practices, which include reducing materials and waste, reusing products, and recycling. The traceability and transparency features mean that operating costs decreases and so can waste be reduced. Blockchain can be used to incentivize new behaviors by verifying social sustainability claims, tokenizing sustainable purchases, and creating new systems for pricing and trading. Furthermore, the transparency proposed by blockchain can aid in achieving more sustainable practices and controlling contractors to avoid human rights violations, child labor, inhuman working conditions, or corruption.

Within the concept of the circular economy, we may consider blockchain technology as a social tool for coordination, by its ability to join and coordinate numerous distributed databases, where they could all be updated instantaneously and available to all the network participants [22,99]. This can also transform the current concept of value creation and value appropriation by proposing a decentralized convention of value creation and circulation [100]. This fundamental aspect of DLT could substantially help in accomplishing the circular economy principles through its attributes of decentralization, distributiveness, and tamper-protection, in addition to its suitability for smart contracts and tokenization [26,96,100].

2.4. Barriers and Limitations

Even though the potential benefits provide a promising development perspective for the renewable energy sector, blockchain implementation is still associated with some technological, societal, and economic risks and bottlenecks. The major technology-oriented challenges associated with decentralized energy trading are the scalability and speed of blockchain-supported transactions, low initial digitalization levels as well as grid infrastructure innovation requirement. Social concerns are related to data protection, low level of know-how as well as lack of legal compliance or supportive regulations, which strongly hinder the development of new use cases of blockchain adoption that could lead the way and clear the pathway for the hesitant stakeholders to follow. The key economic constraint refers to the high electricity costs of required huge computational power to execute common consensus algorithms, such as the proof-of-work as well as costs of infrastructural innovation necessary for blockchain enhancement. Next, we will discuss major barriers to widespread blockchain technology diffusion within the renewable energy industry in detail.

2.4.1. Scalability and Speed of Transactions

Mainly due to the initial stage of development and applications, a fundamental technical issue is the scalability and performance of blockchain-based transactions. With the growing number of participants, the blockchain faces performance efficiency challenges. It is challenging to ensure the network's coherence via decentralization while sustaining the system's speed [24]. It is important to note that the degree of decentralization strongly influences the overall blockchain's performance. Therefore, every new additional node in the system makes it more challenging to achieve a common consensus. Currently, in a Bitcoin system, there is a limit of 1 MB for the maximum block size, which hampers the network to add just one single block per 10 min. In consequence, the network speed is negatively affected as it can process seven transactions per second at its peak [101].

Moreover, as a study by Di Silvestre et al. suggested, operations can be controlled in a decentralized manner only to some extent as several technical matters are managed centrally (i.e., balancing). According to the so-called blockchain trilemma [102,103], higher scalability is required while high intensity, which results in the necessity of limiting either decentralization or security levels. The blockchain trilemma concept claims that a blockchain-based network can offer a maximum of two of the following three features:

- Ultimate decentralization of block construction;
- System security (its resilience to cyberattacks);
- Scalability of the system (its capacity to process an ever-growing number of transactions during a certain period of time) [104].

2.4.2. Lack of Legal and Regulatory Compliance

As suggested by Teufel et al., policy and regulatory factors might have either positive [105] or negative [106] influence on the further development and diffusion of blockchain-based energy. Concerning the latter, the main challenge is the harmful side effects triggered by a political transformation [47]. However, the lack of prevailing regulatory frameworks opens the opportunity for local or regional policymakers to support the formation of early-stage proto-markets [105].

Importantly, apart from the technical problems mentioned above that need to be solved, the lack of legal compliance and supportive regulations are perceived as a major hindrance to the widespread adoption of blockchain in the energy sector. The most problematic legal and regulatory aspects are related to the smart contract's legal status, energy law, or data security and independence. Moreover, as there exists the risk of cyberthreats and system malfunction, the potential leakage of sensitive and personal data would cause serious privacy issues. This challenge must be solved especially in public blockchains, where all customer and business data are widely open, and there is a need to develop legal solutions to fit under the GDPR requirements, for instance [24,47].

2.4.3. Infancy Stage of Technological Development

Apart from the above-discussed regulatory and strictly technical issues, the disruptive technology of blockchain is hampered by the lack of growing numbers of its applications. This issue is actually resulting from the barriers presented previously, but it strongly affects the low level of technological maturity and consequently know-how or trust about the blockchain technology among the society. Pilot projects, often led by big companies and corporations, can encourage governments to provide supportive regulatory frameworks for new technologies and financing options for their development. Therefore, a low number of use cases results in significantly limited successful examples to follow by other energy companies and the lack of standards causes the interoperability of various technologies extremely challenging [15,24].

3. Materials and Methods

In this curiosity study, we adopt a mixed methodology of seminal academic literature analysis and multiple qualitative case studies. To perform our empirical analysis, we conducted semi-structured interviews with executives representing Finnish RET companies as well as associated consulting agencies focusing on fostering RET-based business clusters. At the initial stage of data collection, we contacted managers from purposefully selected 30 leading RET-focused Finnish companies, using the long-lasting fruitful university-industry collaboration with our extensive professional networks; we received a positive response on their willingness to collaborate from 10 of them, therefore, our positive response rate is 33%. According to the reports, there are approximately 47 RET companies or successful start-ups operating in Finland [107,108], therefore, we have contacted most of them. The relatively low response rate could be explained for example, by the infancy stage of the technological development of blockchain, lack of supportive regulations, and a rather low level of know-how or interest in blockchain at the moment. The interviews were starting with a multilateral consent to record the meeting as well as to ensure the anonymity of both the executives and their companies' names. Therefore, the companies' names were replaced with A, B, C, etc. This approach serves to follow the GDPR requirements as well as ensure the ethical transparency and integrity of this research. Table 2 briefly describes the companies included in our case study.

Table 2. Details of the companies in the case study.

Company	Technology Focus	Interviewee's Role	Length of the Interview
A	Wind Power	Head of Project Development	1 h 10 min
B	Wind Power	Vice President, Energy Management	1 h
C	Automation and Electrification of Wind Power	Executive Vice President, Marketing and Sales	55 min
D	Wind and Solar Power	CEO	55 min
E	Solar PV	CEO	1 h 20 min
F	Circular Economy, Waste to Energy	CEO	1 h
G	Energy hub; Smart Grids, Energy Efficiency, Marine	Communications and Brand Manager	1 h 10 min
H	Cluster management; Electricity from Wind and Hydrogen	(1) CEO/Managing Director (2) Head of Digitalization (3) Project Manager	1 h 45 min
I	Smart energy solutions	CEO	1 h
J	Electricity and district heating from renewables	Development Director	1 h 20 min

Built upon theoretical convenience sampling criteria, the selected cases become relevant to our study as they empower the availability and information richness [109] and to identify cases purposefully which supports in imitating or outspreading emergent theory from the case in which the process of interest is 'transparently observable' [110]. Moreover, the purposeful sampling technique was employed to attain maximum variation, which occurs in adapting to different conditions [110]. The selection of the respondents was based on multiple criteria, for example, characteristics of the population, objectives, and research questions [111]. This criterion guaranteed that our interviewees have rich knowledge about the topic and adequate experience. Thus, the purposeful sampling approach, as an effective technique with limited resources [112], is suitable for our research as it is supported in the selection of the information-rich cases and the identification of individuals that are particularly relevant, knowledgeable, and experienced [113] with the phenomenon of blockchain. This sampling strategy allowed for in-depth multiple case exploration of blockchain-related topics with interviewees, thereby contributing to the reliability and consistency of the findings.

The recorded interviews were transcribed, and as the length of the meetings varied from 55 min to almost two hours, the amount of gathered information was different in every case. However, the overall number of pages per case amounted to approximately 10 pages, which resulted in a total of 105 pages of materials to analyze. This has served to analyze the different factors mentioned during the interviews and seeking for some patterns or common viewpoints, which has also supported our thematic analysis, primarily based on the questionnaire form.

Methods adopted in this research serve to provide the overview of blockchain technology—its main principles and applications in the renewable energy sector, including main possible benefits as well as key barriers to its widespread diffusion. The thorough literature review has served as a theoretical and practical foundation to develop our semi-structured interview protocol named Blockchain Maturity Questionnaire which was created before the data collection stage and was shared with the interviewees in advance to familiarize themselves with the main aspects of the study. The questionnaire form can be found in Appendix A. The empirical part, which is based on this survey, allows expressing the viewpoint of the RET industry experts on the future possible impact of DLT on the daily operations of their companies. Therefore, the results of this study have the potential to provide novel theoretical and practical implications for the interest groups in the fields of blockchain and (renewable) energy.

4. Results

The literature review has served us to categorize possible benefits and barriers of blockchain implementation for our analysis. The outcomes of our interviews with Finnish RET industry experts will be presented in this section, following our developed Blockchain Maturity Questionnaire, which can be found in Appendix A.

4.1. Initial Level of Know-How about Blockchain Technology

At the starting point of our interviews, after briefly introducing themselves and their companies, our respondents were asked an introductory, basic question about their level of familiarity with blockchain technology. As it is an emerging technology with a reasonably limited number of use cases, the overall level of know-how about blockchain and its applicability in the renewable energy sector was intermediate. Some experts were interested in novel technologies in general, so they were aware of this solution, but the degree of knowledge of most of our respondents was limited to the name and its connection to cryptocurrencies like Bitcoin or Ethereum, as the latter strictly relates to energy.

Like the managers from the companies A and D mentioned: "*I am familiar with the concept in general, as we all relate blockchain with Bitcoin and cryptocurrencies*", and "*I've heard some applications in fintech, but I don't know how we could use it in our renewable energy sector*". However, as the expert running the digitalization academy in the company H claimed: "*Yes, we have projects for students' theses. We are reading about it and studying it but from the industry, it has been a little bit hard to find any use cases so far (. . .) big companies—they surely* *have it. But they don't tell it outside. They are testing it still. I mean, it would be unwise if they're not investigating it*".

4.2. Biggest Benefits from the Experts' Perspective

Next, we asked our interviewees about the major possible benefits associated with blockchain adoption in their companies. The process of content analysis has helped us to identify, categorize and list the most commonly mentioned benefits, which can be seen in Table 3.

Table 3. The most common benefits identified in the case study.

Benefit Category	Favorable Implications	Mentioned by Companies
Decentralization of authority	Transparency, cost- and time-efficiency, P2P energy trading platforms, novel markets creation, energy democratization	A, B, C, D, F, G, H, J (80%)
Smart contracts, smart meters, IoE	Automation, integrity, trust, security, energy digitalization	A, B, C, D, E, F, G, H, I (90%)
Traceability	Energy provenance, auditability, green certification, CSR and image improvement, circular economy practices	C, D, E, F, G, H, J (70%)

For instance, the CEO of company D said: "*I think that the most critical benefit is the cost-efficient way to sell the energy products for the customers. And of course, everybody has to trust the system. And there are two major advantages: one advantage is that everybody has to trust the way how we or everybody is working. And another reason is that what is the cost-efficiency rate? Also, for the customer*".

Moreover, as the expert from company A highlighted: "*if I take out the main words: integrity, transparency, and security—that is what also maybe adding up flexibility and speed, I would add that the Finnish market especially needs the well-developed permitting process*".

Decentralization and transparency that blockchains offer have been also appreciated, as the CEO of company F added: "*if it can support these types of transactions in a transparent way, that might be revolutionary, for the whole business, not only in ours but in general. Blockchain might be a technological solution that saves cost and time and effort from technology companies like us*". Similarly, a manager from the company H stated: "*Decentralization, smart contracts offer many benefits as middlemen could be avoided to a great degree, especially when selling your technology abroad, and the whole process is more efficient, transparent and automated*".

Energy traceability has been strongly highlighted as a key potential favorable outcome of DLT adoption, in the viewpoint of experts from companies H: "*I think it's this traceability to see where the energy is actually coming from*", and E: "*There's a huge potential in traceability so that you can trace the energy source and consumption and link them together*".

4.3. Application of Blockchain in Specific Business Areas or Departments

Blockchains can have applications in many different business areas and company departments, therefore we asked the managers to estimate in which aspects blockchains could improve their companies' performance.

As the expert from company H mentioned: "*Well, it probably starts from the accounting and agreements—legal department. So, the ways of handling customer relations, customer usage, customer invoicing, and such. And then the bigger agreements between business to business, international especially. So, they are probably the first ones to come. And the anti-counterfeiting will be the second one and probably the spear parts business will be the biggest solution for all logistics, namely international shipping and tracking of high-value parts. Also, the transparency about the ethically correct manufacturing could be significantly boosted*". Similarly, as the expert from company B confirmed: "*If I have to guess something, I'd say it might one day somehow be related to energy accounting or energy settlements. It is a huge Finnish and Nordic issue, as it's not in our* *own hands to decide how the national and Nordic energy clearing and settlement are done. Perhaps one day blockchain technology will be a way to replace this centralized clearing and settlement*".

Moreover, experts perceived the opportunity to create novel markets for renewable energy trading, as the CEO of company D said: "*If there is some solution to sell that renewable energy for the customers using the blockchain technology if we can make some kind of deals with some example special deals with the only one of a kind-customers in Finland or in Europe or even all over the world. And how we handle it, I think that there is a lot of room to develop that kind of technology or that kind of new philosophy*". And the company's J executive added: "*New P2P energy platforms, especially local ones, would transform the way electricity is sold to the customers and it will challenge companies like us to be even more customer-oriented*".

Case company's G manager highlighted the opportunity to improve transparency in spare parts tracking: "*As we're talking about future, I'm forced to speculate all of these and basically make it up as I go along. But this is the kind of application where I can see is tracking of service, verifying the parts are correct, they're authentic, and so on. Because blockchain offers a really good digital signature, basically, that this part is authentic, you cannot really fake it in such a way, you can also trace where it's been, who has been there fixing it, add stuff to it, and so on*".

4.4. Impact on Business Models

As it is claimed in the literature, the implementation of highly disruptive blockchain technology would require business model innovation [14–17,66,76]. Hence, the experts were invited to present their perspective on the blockchain's potential impact on current business models in general as well as their specific components.

Most experts perceived the blockchain's ability to revolutionize supply chains, as, for example, case company's G executive stated: "*The energy value chain at the moment, it's extremely long, there is a lot of different players. And I think that if we can use blockchain technology, that value chain can be much shorter and we could have easier access to more customers. Therefore, I think that the way how the whole market works at the moment might be changed in a radical way*".

However, there have been other interesting insights from the RET industry experts, such as from case companies A: "*If it is a new product, it is principally the sales and marketing that would affect our business model. But if it would be a more efficient way of working in our traditional business then it would require the training of personnel*".

F: "*I would still consider this as more in the kind of customer interface and then secondly, in the supply chain, so the effects probably could be the not in the value proposition as such, but probably kind of how to make more effective business if we can cut some something from the overall value chain and replace it with blockchain. So, it's more like business model fine-tuning and optimization rather than revolution, in my mind*".

Or E: "*Blockchains could help to automate and improve customer interfaces and standardized systems, which would save a lot of time and effort for us*".

4.5. Role in Fostering CSR, Sustainability, and Circular Economy

Blockchains can foster environmentally friendly practices, which can be a source of multidimensional benefits for the companies. In addition to the aspects mentioned in the literature review, the leading advantages in the experts' views about the potential of blockchain's adoption, such as were the tracking of spare parts, detecting their status for either repair or replacement, or efficiency boost in recycling. As recycling and reusing is the most common idea associated with the circular economy concept, some managers identified blockchain's potential to improve such practices, as confirmed by the expert from the case company C: "*As you may know, we are forerunners for recycling things in Finland. And if you compare kinds of wind parks, nowadays, about 70% of the materials are renewable and can be reused. Blockchains can provide this data transparency on depending what kind of technology they are using and can it be replaced or does it need to be totally renewed during the time life lifecycle, and so on. Overall, I can see that recycling part is a very big part of the whole blockchain thinking and way of working in the process*". This traceability of spare parts and manufacturing processes has been also appreciated by the company's H expert: "*Companies will need to show some certain percentage of how much they are reusing things and the origin is like, where are their materials coming from? They need to see also the life span of the products. So, if you're selling something, when is it destroyed or reused, or made with new materials? So, I think that is one of the first places where blockchains will be used*".

Moreover, blockchains can bring transparency to the ethical and sustainable production and other social actions that might positively affect the company's CSR (Corporate Societal Responsibility) level and thus, gain more recognition among the growing number of environmentally conscious customers and stakeholders. In fact, many managers perceived a possibly beneficial outcome of blockchain's transparency and integrity on their companies' future image, just like in the case of company G: "*Nowadays, every company is starting to give out their plans officially, how are we doing things for the environment—and it will be the new generations that are now in school and will be in the workplace in five or 10 years, they are more environmentally-conscious in their buying decisions, who are they are buying from, they're looking into more of these things. So then, if blockchain can certify that you have a proven track record for 10 years, that you have done these green things, you are environmentally conscious, you don't use low-cost labor and these other things, then you have a much better opportunity of being their company or provider of choice*". Company's D manager added: "*First of all, such practices can save time, improve our performance and reduce our transaction costs. But also, if we use block blockchain technologies in the right way, I hope it will be easier to say this is the real renewable energy that you buy and that is the reason why it might be a little bit extra expensive or all that kind of things. But if, we can use that technology and increase the trust among other counterparties—that is a huge advantage for everybody*".

4.6. Most Challenging Barriers

As blockchain is a disruptive and immature technology, its widespread diffusion within the renewable energy sector is reasonably limited by multifarious factors. Overall, it can be said that the biggest constraints presented in the literature review have been confirmed by the doubts and constructive criticism expressed by our interviewees. The most challenging barriers were identified in the lack of a sufficient amount of use cases within the RET industry as well as the lack of supportive regulations. For instance, in the viewpoint of the company's D representative: "*Of course, legal questions are the ones which we have to solve first. because I think that the most critical thing is that counterparties trust each other. Especially in the energy area—it takes time to implement new solutions. (...) I think that huge companies have to start using blockchain first. And after that, smaller companies can use the same rules and same systems*". Managers from the case company H also highlighted: "*The question is, if some countries or regions regulate in one way—will the others follow the same way. Business is global nowadays, companies sell the same stuff all around the world. And they will not want to have maybe regional-sized blockchain systems. So, the standardization, making it global—it's going to be a big problem*".

A manager from the case company G also confirmed the significance of the legal issues but mentioned some technical transition difficulties as well: "*You can't play with your own rules on this side. So, either everybody takes this technology or nobody. (...) I think there is a big barrier to replacing the whole infrastructure with some new technology, like blockchain technology, it's a huge effort, it won't be easy*".

Moreover, several managers referred to the low levels of trust and negative reputation of blockchains at the moment, just as case company's G executive stated: "*If we take Bitcoin that is very computationally heavy at the moment, is that you're using energy, and the only outcome is heat. Basically, when a computer is calculating the bitcoins, it will become hotter. But to make this electricity, you have also gotten a lot of other wasted heat, and emissions. So, this, this is really the problem. (...) Right now, blockchain carries along with a very negative reputation. And really, if you're going to have something using blockchain, you actually have to have the proof somehow that this is not an environmental disaster*". These concerns have been followed by the company's F CEO: "*I think blockchain's image is somehow still connected to crypto. And crypto is still for many* *people, a mystery or very insecure and something new and scary. So, it's also for us. So probably the main thing why we haven't investigated this more is that, you know, if the cryptocurrency can drop 50% in one day, if that is somehow linked to the blockchain, then it's not secure. Because, for example, in the energy business, everything has to be double-checked*".

4.7. Requirements for Improvement—"Roadmap for BC Adoption"

Most of the case companies suggested the need for increasing the level of technological know-how and introducing more successful use cases that could foster the development of blockchain in the renewable energy industry, as stated by an expert from the company E: "*The first obstacle I see is the lack of education or understanding of the system, and the other one is that there are not many available systems where the blockchain would be implemented at that at the moment*". Experts from the case company H added to that: "*As long as nobody knows anything about it—it's really hard to be implemented. (. . .) if we could get one project at the university, that would produce a practical thing, at least doesn't need to be a real product, but a real case about how to use it for the energy industry, a good example of how to implement blockchain in there. For example, students would be doing a thesis work about it, I think that would be really important because then we could refer to that okay, there's a successful example about it*". Furthermore, as an executive from the company C stated: "*Well, it's interesting to see that how these political and country-wise barriers are going to take down and what is going to be the speed for those legal things that are obstacles for nowadays. (. . .) But what are the drivers for the change? If there are big companies running those drivers further, it will happen quite soon. If this kind of development goes on, it will take time before the legislation will change, and enable this kind of change overall, but I think the world has changed so much already, that it will go much faster than we expect*".

Moreover, the successful examples of blockchain adoption would act as the information provider about the benefits for the companies and other sectors of society B: "*The benefits must be very clear (. . .) Anything you are doing with directly your customers, I think there is a low barrier to implement blockchain technology. If there is some benefit for the reseller around the customer. For us, it has to primarily provide more efficiency and cost reduction*". Furthermore, there is a strong need to solve the legal issues through standardization as suggested by the company's G expert: "*First, we do require some sort of standardization, which blockchain standard, which type of everything to use, and then getting everybody to use it. It should be something that the European Commission wants to implement, not just one country like Finland. This standardization, legal framework, it would need to be European or perhaps even global*". This was also firmly stressed by the CEO of the case company F: "*I think the biggest bottleneck is that we need to have this standardized regulation. (. . .) but also, people are skeptical and there's a need to educate society about the technology, that it's not just related to cryptocurrencies, and so on. So, if the blockchain's image will improve, it will have more chances. I would say it's a marketing problem. I don't think it's a technology problem. The technology looks good, efficient, and new*". The initial steps of change are often the most difficult ones to arrange, therefore, besides the overall viewpoint of starting from big companies, an expert from the company A suggested: "*Well, I see some options—academic commercial first or and some kind of seed somewhere like a seeding in the academic world and through the network building up to the commercial world*". Importantly, it mentions the requirement of involvement from different sectors of society in fostering the widespread implementation of blockchain in the renewable energy industry.

Such insights from the RET industry experts as well as a theoretical foundation based on literature review have served to develop a "Roadmap for Blockchain Adoption", which is presented in Figure 3. It proposes measures that could significantly boost the DLT adoption perhaps not only in the renewable energy sector but in other fields as well. We suggest that multi-sector involvement is needed to implement this disruptive technology. We believe that the university-industry collaboration could lead to introducing several pilot projects aiming to show the practical applications of blockchain and to reveal the most burdensome challenges during its performance. Such actions could raise the interest of the R&D or digitalization departments of the leading energy companies, including the ones focused chiefly on renewables. In fact, the so-called 'big players', which are often partly country-owned or strongly supported by the government, have a reasonably higher possible influence on the policy makers, which could result in the introduction of supporting regulations, that are inevitably a *sine qua non* for the functioning of blockchain in a given country or region. This would result in growing numbers of new use cases, to which—with the help of training and information activities—the society could swiftly adapt.

Figure 3. Roadmap for Blockchain Adoption.

4.8. Future of Blockchain within the Finnish RET Industry

Lastly, we asked the RET industry experts how they perceived the potential of blockchain utilization in future energy systems. Most of the companies expressed a positive perspective on blockchain's future, realizing its capability to transform and innovate the whole industry, even though the barriers are meaningful at the moment. As previously mentioned, there is a critical need to implement favorable legal frameworks and to let the leading energy companies initiate this change. Here are some testimonies supporting these promising scenarios for the RET sector:

Case company A: "*Well, as always, there are two scenarios that whether it is a game-changer or it is fading out technology that didn't do enough. But in mind, it can be a game-changer in energy trading markets, especially*".

Case company C: "*I believe that it's possible to make it and it ought to be used in renewable energy. I see that there is a good opportunity to run blockchain-based business in renewables, overall*".

Case company J: "*There is huge potential to innovate this industry and I believe the benefits are much bigger than the challenges. However, the prerequisite is the digitalization of the whole energy sector, which might take some time*".

Case company F: "*Well, I think renewable energy might be in the front end. You know, of this whole change. Now, governments are spending a huge amount of money on renewable energy, and then you have to find new ways to get grants, etc. So, if they would be smart, they would introduce also new ways of doing transactions and this blockchain is part of that. Definitely. (...) I think there has never been a better momentum for renewable energy than now because of the issues like COVID, and so on*".

Case company D: "*I think so that there is a huge opportunity to mainly have an effect on business models and in value propositions because at the moment there is a very long decision-making chain, so there's a lot of different profit-oriented players on market. But if blockchains can change the models, that might be more effective for the deals. For example, energy producers, the customers could make deals only with them. Nowadays we need five or 10 different players between producers and customers. So, I think that might be a huge change in the business models in the future*".

Case company B: "*There might be good possibilities on the end-user side because in the future, they are generating power themselves and they are also storing it. So, there might be different players, some player is offering storage services some player is offering solar panels, and so on. So, they need to exchange that customer data and measure data from different consumption and production streams. That data exchange might be a place for blockchain technology*".

5. Discussion

After fulfilling the requirements for facilitating blockchain adoption and following the proposed roadmap, there is an increased opportunity of introducing DLT at a large scale within the RET sector. However, these measures are proposed at a very general level and the initial stage of blockchain's technological development. It should be noted that at present, we were restricted to conduct a so-called curiosity study, exploring the future beliefs and viewpoints of the RET industry experts. Even though the results appear to be relatively concise and comprehensive, a study on a bigger sample could perhaps shed some new light on the Finnish or European state of affairs. Especially when based on real use cases or even pilot projects, which we were not able to do now.

Future research should examine further use cases of blockchain in the (renewable) energy sector in different geographical areas, and explore new applications, which will inevitably be associated with specific benefits and challenges to define. Studies around the world show that developed countries have more resources, higher R&D rates, modernized infrastructure (including microgrids or smart meters), and stronger governmental support for distributed energy technologies like blockchain. Therefore, these countries will probably be the initiators of this technological change, and Finland is among them. On the other hand, developing countries are still based on centralized energy systems, which makes the widespread adoption of DLT in the global energy systems more challenging, as the digital transformation there might take years, or even decades [67].

The potential of blockchain application in the (renewable) energy sector is reasonably high and multidimensional [10]. Future studies could further explore for example, more effective methods of blockchain application in the Internet of Energy (IoE), smart grids, microgrids, and distributed energy trading markets, or how to improve the efficiency and security of the blockchain-based transaction. In fact, the biggest potential lies in the electricity part of the energy, which is already noticeably digitalized. Moreover, a central feature of blockchains, smart contracts, but also local P2P trading platforms, will be research hotspots as well [88]. Furthermore, the role of blockchain in fostering renewable energy technologies, circular economy, as well as electric mobility, and charging will remain an important area of future research in the blockchain and energy fields [84]. Lastly, as blockchain is expected to revolutionize supply chains, future research should examine its impact on global and local energy supply chains and the concept of sustainable supply chain management [18,19,39,43,52–64].

6. Conclusions

The goal of this article was to introduce blockchain technology, present its applications in the renewable energy industry and evaluate the potential benefits and challenges associated with its utilization. Building upon a thorough literature review, we have conducted our empirical analysis based on semi-structured interviews with Finnish RET industry experts.

The analysis reveals that the level of technological know-how about DLT and its applicability in the RET sector is reasonably limited. This was further mentioned as one of the biggest barriers to be overcome through education and other awareness-raising actions. The experts, after realizing the potential impact of blockchain on their daily operations, detected numerous possible advantages of blockchain application (which were summarized in Table 3), and these are, for example, increased overall cost-efficiency and performance of the companies, higher trust among the trading partners, energy decentralization and democratization, as well as transparency and traceability of energy and automation of complex transactions and procedures. The business areas where blockchains could have the biggest impact were identified as well, such as energy accounting and legal agreements, anti-counterfeiting, logistics, spear parts tracking transparency, or creating novel energy trading markets. We also asked the experts about the impact of blockchains on their business models, and they have acknowledged, *inter alia*, improved and automated customer interface thanks to much shorter value chains or enhanced marketing and sales opportunities.

The study also examined the role of blockchains in fostering a circular economy, and such influence has been strongly detected in the areas such as spear parts management (quality reports, repair or reuse real-time status, etc.), enhanced transparency, and traceability of manufacturing processes, or integrity and verifiability of ethical working practices, which positively affects the company's CSR. Moreover, blockchains can provide unbiased and auditable information about the energy provenance, which in other words, serves to verify if the energy generated and sold to the customers comes from renewable energy sources or not.

Mainly due to its infancy stage of technological development and low level of industrial application, blockchain technology is hampered by various obstacles on its way to being widely implemented within the renewable energy sector. Our interviewees determined the following most challenging bottlenecks: lack of regulatory and legal compliance, global standardization issues, infrastructural transformation challenges, or blockchain's trust and reputation problems. In response to that, we have asked the managers to propose measures to tackle these barriers and to enable blockchain implementation, which served us to develop a "*Roadmap for Blockchain Adoption in the RET Industry*". According to this framework, multi-sectoral involvement is required to promote DLT as a source of numerous benefits for the sector. The proposed change should be initiated by big energy companies that would lead a way for the rest of the energy industry. This would encourage governments to implement supportive policies for such innovative solutions. However, without a sufficient level of know-how about blockchain technology, its potential could not be recognized in the first place. Therefore, there is a strong need to organize information and education events for all the sectors of society, including academia, where seed and pilot projects could facilitate the transition from theory into practice.

It can be concluded that the potential of blockchain to disrupt the renewable energy industry is meaningful and the benefits far outweigh the challenges [10,22]. Even though this study only estimates future possible benefits coming from blockchain's adoption in the RET sector, the vast majority of the interviewed industry experts expressed a promising will to implement this technology in their future operations.

We believe that the insight and practical contributions provided by this research will help the interest groups from the blockchain and (renewable) energy fields to realize the potential of this technology as well as major barriers to be overcome while using it, and ultimately, to adopt DLT in their daily operations.

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Appendix A. Blockchain Maturity Questionnaire

1. What kind of renewable energy technology is your company focused on?
2. Are you familiar with Blockchain technology and do you use it in your day-to-day business operations?
3. If YES, please explain the main reason why.
4. If NO, please explain the main reason why.

5. If YES—What kind of factors convinced you to implement BC in your company? If NO what kind of BC features do you perceive as potentially beneficial for your company in future?
6. If YES—In which departments of your company are you using Blockchain? If NO—in which departments of your company could you use BC in future (where exactly is the need in the company, in which department, or business area etc. and why?
7. If—How significant was the influence of BC technology on your business model? If NOT—how would it influence your BM?
8. [. . . on specific BM components, such as:
    8.1 key resources (infrastructure),
    8.2 value proposition,
    8.3 revenue streams,
    8.4 client interface,
    8.5 external value chain.
9. How do you perceive the possible impact of BC on the issues such as Sustainability or Circular Economy in your organization and in overall?
10. If YES—What kind of major barriers have you experienced so far while using BC? If NO—What are the main possible disadvantages coming from BC usage (factors that keep your company away from implementing BC)?
11. In your opinion, what kind of measures should be taken to improve the current state of affairs—how to overcome the main possible barriers?
12. How do you see the future of BC in the renewable energy sector? How do you foresee the role of blockchain in renewable energy sector and how would it impact on operational excellence, business models and value propositions?
13. If YES—On a scale 1–5, how would you estimate your experience of using BC? if NO—On a scale 1–5, how is it likely that you will use Blockchain in future, and why?

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