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Review

Digitalization in the Renewable Energy Sector

Musadag El Zein * and Girma Gebresenbet

Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 7032, 75007 Uppsala, Sweden; girma.gebresenbet@slu.se
* Correspondence: musadag.elzein@slu.se

Abstract: This study explored the association between renewable energy uptake and digitalization in the sector by reviewing relevant literature (published 2010–2022), with the aim of identifying the existing utilization of digital technologies within the sector, challenges to adoption, and future prospects. Different search engines (SCOPUS, Web of Science, and Google Scholar) were used to locate relevant papers and documents. The results revealed the high significance of digital technologies in supporting the renewable energy sector, with high costs and security risks representing the key challenges. Most papers reviewed had a positive outlook, but recommended further research and development for effective energy transition and resilient infrastructure. The current drivers of the integration of digital technologies to support the diffusion of renewable energy sources appear to extend beyond energy demand and involve many aspects of sustainability and sustainable development. Compared with previous reviews, this work has unique scope and novelty since it considers the bigger picture of the coupling between digitalization and the renewable energy sector, with a greater focus on critical areas in these two interconnected bodies that need to be addressed. The relatively small sample of relevant papers (69 from 836 hits) located in the literature review confirms the need for more research covering the subject in greater depth.

Keywords: blockchain; digital technologies; renewable energy; security; sustainability

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1. Introduction

1.1. Background of the Study

Digitalization has been defined as "use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business" [1]. Digital technologies are already playing a key role in the diffusion and adoption of renewable energy. Unlike fossil fuels, renewable energy is not "dispatchable", i.e., it is not available where and when needed, and its production is affected by daily and seasonal factors, which poses challenges in terms of reliability of supply. However, the use of digital technologies has helped to overcome these challenges of renewable energy sources, providing great potential for expansion. This has prompted energy companies to invest heavily in digital technologies in recent years. According to the International Energy Agency (IEA), global investment in digital power infrastructure (particularly in grid related) has grown by more than 50% since 2015 [2]. Data for the past decade show 128% growth in the total production of renewable energy between 2010 and 2020 and a simultaneous increase of 147% in terms of devices (digital technologies) introduced to power grids, indicating that these systems are directly coupled [3]. This study analyzed the types and means by which digital technologies have influenced the diffusion and adoption of renewable energy. It also examined the industries that have benefited the most, the geographical regions or countries that have experienced the greatest shift toward renewables with the help of digitalization, and the challenges that arise and how these can be addressed. The interconnectedness between digital technologies and the renewable energy diffusion into the energy sector is still not clearly understood by many stakeholders. This paper, through the literature review, aims to contribute to this research gap by categorizing, assessing, and analyzing the results.

Today, modern society is highly dependent on a constant supply of energy. With the growing global population and increasing modernization and urbanization, the demand for reliable energy sources has increased continuously in recent decades. The global energy sector is now in a period of transition, where renewable and low-carbon energy sources such as wind and solar energy are expected to replace the common fossil fuels (oil, gas, and coal) [4]. The key drivers of this transition are the resilience of renewable energy during times of crisis and commitments to using clean and sustainable sources of energy.

The recent crisis of the Russia–Ukraine war confirmed the significance and impacts of renewable energy transition. The geo-political risks of reliance on fossil fuels have led a few countries and regions to consider huge investments in clean energy and the adoption of energy transition strategies [5]. For instance, Germany was formerly a country with high dependence on fossil fuel imports, but has accelerated its transition to renewable energy in order to cope with the possible ban on energy imports from Russia [5]. At a global scale, overall investment in renewable power capacity (excluding mega 50 MW large hydro-electric dams) in 2020 reached 281 billion USD, compared with only 111 billion for the conventional fossil fuel industry [5].

Other than increasing resilience in addressing various crises, the call for low-carbon energy sources through renewables is driven by factors such as health impacts from air pollution, market forces, energy security, and climate change mitigation efforts [6]. Although global long-term energy transition (LTE), i.e., the shift away from the production and consumption of non-renewable fuels toward renewable energy, is underway, transition is still considered a complex challenge for both firms and countries [7]. Four main drivers for LTE, and their associated challenges, are:

- Economics, i.e., supply and demand. Although there is still strong demand for non-renewable sources of energy, demand for renewable sources is growing, with public utilities relying less on non-renewable sources. However, this increase in demand for renewable energy requires new infrastructure to be built, and firms and governments to make strategic decisions on the energy path they will take in both consumption and production [7].
- Societal aspects: Individual preferences and the collective behaviors of a range of stakeholders, from individual consumers to investor and firms, act as drivers and barriers in the transition toward renewable energy. Deciding factors include the reliability of the source of energy, the services provided, and the overall cost [7].
- Technology: Overall technological developments in recent years have resulted in the diffusion of new sources of energy, greater accessibility, improvements in energy efficiency, and cost reductions, e.g., a 20% drop in the cost of solar panels between 2010 and 2019 [7]. Supporting technologies that have enhanced renewable energy use include the employment of smart grids, solid-state batteries, and overall digitalization of energy systems, with the latter considered to be the catalyst in restructuring the energy transformation infrastructure [8].
- Regulatory framework: Changes in regulations have been made over the past decade to enhance LTE, but the regulatory framework varies between countries [7]. Different continents and countries have introduced different measures to incentivize energy transition and the use of renewables, based on varying natural resources, set priorities, and even the capacities of each country and region of the world.

1.2. Key Forces in Energy Transition

The above drivers act in parallel with five categories of key forces that facilitate energy transformation in general. Before discussing these categories, it is important to acknowledge that energy transition (in this case from conventional to renewable energy sources) is just one form of energy transformation from a physical perspective. Other forms of energy transformation coupled to this may include wider social, organizational, and political changes [8].

The five categories of forces, known as the ‘5 Ds’, are Decentralization, Decarbonization, Democratization, Deregulation, and Digitalization [9]. These are expected to play a key role in enhancing the contribution of renewable energy to global electricity generation by 2035, with an expected 2.7-fold increase compared with 2010 [10]. Important factors concerning these categories are:

➢ Decentralization: Today, decentralization is a defining feature of the ongoing energy transition, driven by falling technology costs, climate change concerns, and social innovation [11]. Unlike centralized systems, decentralized energy infrastructures offer opportunities for many consumers to become “prosumers” (those who can consume and produce electricity). Factors affecting the success of energy decentralization include the rescaling of governance functions, inclusion, capacity building, coherence, adaptiveness, and transparency [11].

➢ Decarbonization: This entails the exploitation and use of clean energy sources to reduce average carbon intensity worldwide. Many countries have set individual energy development plans in order to meet their international commitment on decarbonization. For instance, the USA has committed to a greenhouse gas (GHG) emissions reduction of 2 percentage points (from 28% to 26%) by 2025 compared with 2005, while EU countries (28 members) have pledged to reduce their emissions by 40% by 2030 compared with 1990 levels [1]. According to COP21, some key measures need to be taken to support the 17 Sustainable Development Goals (SDGs). Typical measures include increasing access to information, the internet, and communications technology, providing enabling technologies for several business models, and improving existing systems within the areas of energy efficiency or infrastructures [1].

➢ Democratization: This basically involves strengthening the participation of stakeholders (e.g., social actors), to foster acceptance [8]. Potential measures that energy companies or municipal utilities can take to increase democratization include the following:
   - Establishing participation models in which customers can invest (e.g., local wind or solar farms);
   - Customer empowerment (e.g., supporting prosumers);
   - Being transparent with regard to strategies, goals, and milestones;
   - Establishment of on-site discussion formats with relevant social groups [8].

The inclusion and involvement of affected stakeholders in any decision-making process is regarded as the key factor in achieving democratization [8].

➢ Diversification: This is equally important as the other categories of forces and aims to reduce the risks in energy resource supply disruption and to prevent the creation of monopolies in the supply of certain energy forms, using a variety of technological methods/forms and energy production management models. Examples include the following:
   - Expanding the range of primary energy sources (e.g., wind, solar, etc.);
   - Introducing new power types and supply schemes (e.g., combined-cycle gas turbine units using gas and solid fuel with different thermal schemes);
   - Using new energy-saving methods (e.g., implementation of energy and power-saving reserves in consumption and creation of powerful energy storage units);
   - Introducing additional sources of attractive fuel and energy sources (e.g., expansion of the reserve base of natural gas based on its replacement with electricity in electricity-consuming processes) [12].

Challenges to diversification involve the need for anticipation of technical possibilities at an early stage in order to develop beneficial services with added value [8].

➢ Digitalization: In the past decade, digital-based infrastructures or so-called new digital infrastructures (NDI), formed by the new generation of information technologies, have emerged [13]. Services provided by NDI penetrate the production and operation models of enterprises, allowing improved efficiency of industrial resource allocation and, most importantly, providing new ideas for solving problems in energy transition [13]. In fact, it has been argued that the transformation of energy infrastructure with the services provided by NDI can accelerate energy transition [13].

1.3. Digitalization Categories and Applications

When assessing the contributions of digital technologies, it is important to recognize that digitalization infrastructure comprises varying types serving different purposes within the energy sector. The main types of digital technologies and their corresponding applications within the energy sector are summarized below.

- Artificial Intelligence (AI): This is the most widely adopted digital technology within the energy sector [14]. In a widely accepted broad definition, AI is a "collection of all kinds of technologies and methods, which are used to execute human brain-related tasks, especially cognitive tasks such as learning and problem solving" [14]. It involves the development of algorithms and computer programs that can perform tasks that formerly typically required human intelligence. Areas of application of AI within the energy sector include predictive maintenance, renewable energy integration, energy predictions and optimization, and grid management [15].
- Blockchain: This emerging technology is attracting considerable interest from energy supply firms, technology developers, national governments, financial institutions, and even start-ups [16]. Blockchain comprises shared and distributed data structures that can securely store digital transactions without using a central point of authority. These allow for the automated execution of smart contracts in peer-to-peer (P2P) networks [16]. Typical areas of application of blockchain within the energy sector are renewable energy management, grid management, energy trading, and decentralized microgrid creation [16].
- Internet of Things (IoT): This technology uses the internet to provide connectivity between physical devices or "things" [17]. By employing sensors and communication technologies for sensing and transmitting real-time data, which enable fast computations and optimal decision making, IoT technology helps to improve energy efficiency, the diffusion of renewable energy, and smart metering, and to minimize adverse impacts on the environment [17].
- Big Data Analytics: This plays an important role in the whole process of smart grid management, including power generation, transmission, distribution, and transformation [18]. Big data, i.e., enormous volumes of data collected for the purpose of processing, are described in terms of three characteristics, volume, velocity, and variety, where volume is the amount of data being processed, velocity is the speed at which data arrive, and variety refers to the different formats and types of data being processed [19]. Key areas of application for this digital technology include predictive maintenance, energy consumption optimization, energy usage pattern analysis, fault detection, and supply chain optimization in energy organizations [15].
- Robotics: This form of digital technology lies at the intersection of computer science and engineering and involves design, construction, and use of robots [14] to control, provide sensory feedback, and process information [14]. Areas of applications include inspection and maintenance of energy infrastructure, renewable energy production and distribution, and manufacture and maintenance of energy storage systems (e.g., batteries and fuel cells) [15].
- Additive Manufacturing (AM): This technology, also known as 3D printing, is the process of building objects bottom-up one layer at a time [20]. Computer-aided design (CAD) technology, which has grown rapidly in terms of market size and applications over the past few years, helps in many areas within the energy sector. Key areas of application include rapid prototyping and production of spare parts, customized production of parts including renewable energy components, improved monitoring and control of equipment, and production of high-temperature parts [15].

- Digital Twin (DT): This involves using combined physics-based and analytical methods to model individual components of the power plant and the system. Models applied can provide the design limits of power production units under varying operating conditions, such as different loads, fuel mix, weather data, ambient temperatures, etc. The DT architecture in place today is being used to achieve high reliability, availability, and maintainability (RAM) within the complexity of the energy sector, all at a lower cost [21].
- Cloud computing: The technology for hosting online services has received much attention in recent years due to its promising computing service model, which requires a limited amount of resources on the customer's side [22]. Installations supported by cloud computing use virtualization to separate the software from the characteristics of physical servers. This enables optimization and reductions in certain energy-costly features [22]. Typical applications supported by cloud computing include predictive maintenance, grid optimization, customer engagement, data analytics, and renewable energy monitoring [15].
- Internet of Service: This technology involves the systematic use of the internet to generate new value by materializing the Product-as-a-Service (PaaS) business model. Areas of applications of the technology include support within energy efficiency enhancement, predictive maintenance, smart grids, renewable energy integration, and energy data management [15].
- Augmented Reality: This allows computer graphics to be displayed in a real-time, real-world setting [15]. It offers employees within the energy sector and smart cities real-time information on repair instructions for replacing a particular part or subassembly [23]. Other areas of applications include training and simulation, customer engagement, monitoring and control, and predictive maintenance [15].
- Cyber-security: This technology deals with issues related to protection of the IoT system, such as ransomware attacks, cyberterrorism, and hacking [23]. Key areas of application include the protection of energy infrastructures, including data protection, and enabling secure communications.

2. Objective of the Present Review

The overall aim of this study was to review the recent literature (published 2010–2022) within the area of digitalization and renewable energy, in order to identify the current utilization of digital technologies within the renewable energy sector and challenges to adoption. The specific objectives of the review were to identify the following:

(1) The dominant digital technologies adopted within the renewable energy sector (RES);
(2) The dominant field within the RES where digitalization is being adopted;
(3) The geographical distribution of digital technologies within the RES;
(4) The main challenges to the use of digital technologies within the RES;
(5) Implications of the adoption and diffusion of digital technologies within the RES.

3. Methodology

3.1. Literature Review Approach

The methodology used for collecting data was a literature review, which involved searching, identifying, reading, summarizing, compiling, analyzing, interpreting, and referencing published data [24]. There are three main approaches available, a systematic review, semi-systematic review, and integrative review. The integrative review approach was selected for use in this study due to its compatibility with the purpose of the analysis. Key components of the integrative approach are addressing mature topics by overviewing the knowledge base, and critically reviewing, potentially re-conceptualizing, and expanding the theoretical foundation of a topic as it develops. For newly emerging topics, the aim is to create initial conceptualizations and theoretical models, rather than to review old models [25]. However, the most important aspect of the integrative review lies in its potential contribution to the advancement of knowledge and theoretical frameworks [25], a rather significant characteristic for the present study.

3.2. Search Strategy

This study explored the key connections between digitalization and renewable energy by scrutinizing the recent literature. To identify relevant articles covering the subject of digitalization overall and the use of renewable energy within various fields of operation and industries, the following key search string was used in different search engines:

"*Renewable Energy AND Digital Technology OR Digitalization OR Digital Transformation AND Agriculture OR Rural OR Off-grid*"

Figure 1 summarizes the methodological approach used. To cover a wider spectrum of journal articles, three search engines (SCOPUS, Web of Science, and Google Scholar) were used. With the selected search string, the following parameter boundaries and set filter options were used:

- Subject areas limited to: Engineering, Energy, Environmental Science, Technology, and Agricultural and Biological Sciences;
- Range of years limited to: 2010 to 2022;
- Type of publications: Peer-reviewed, research paper, and review paper;
- Words found in both: Abstract and title;
- Language: Only English.

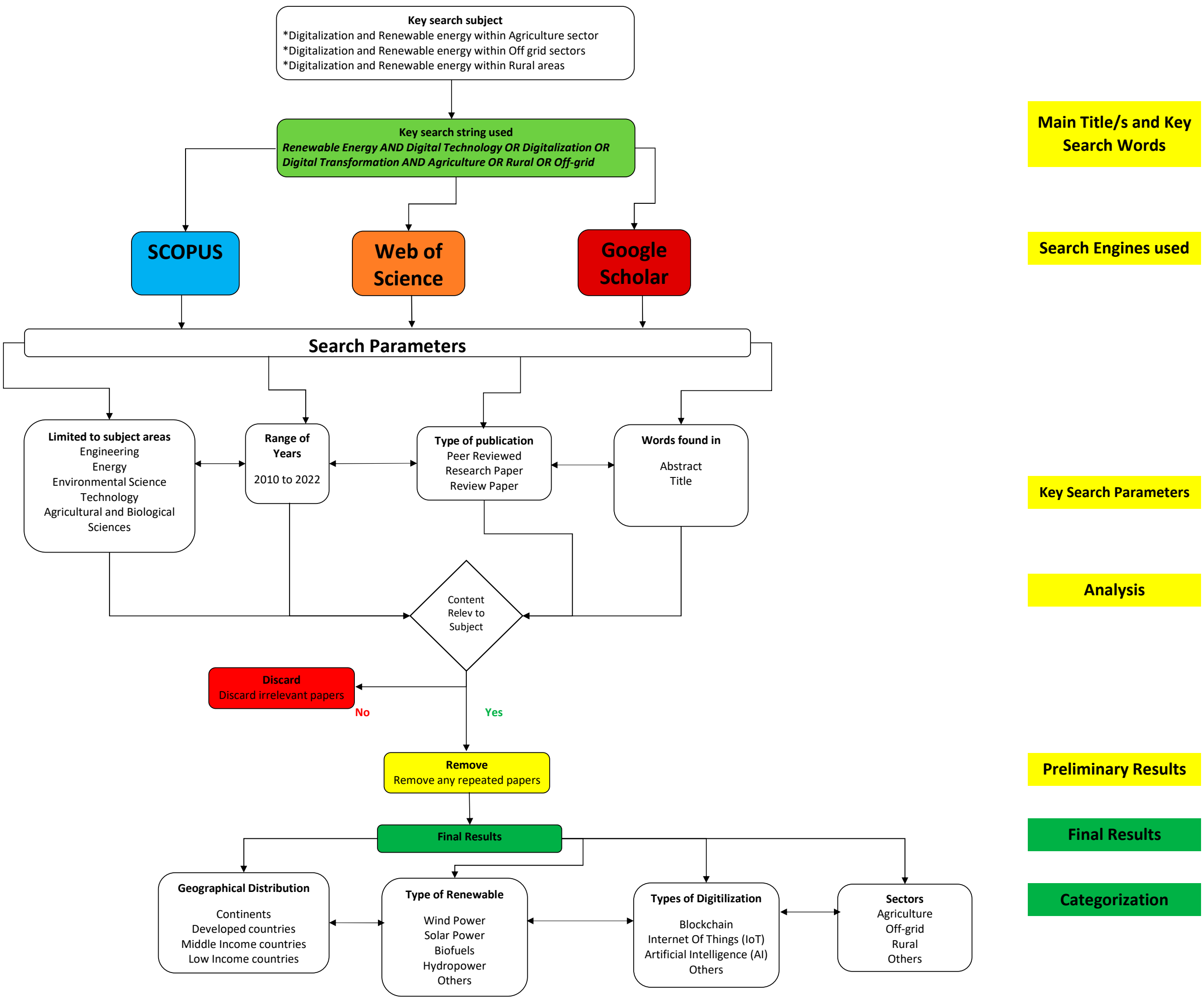

Figure 1. Summary of the methodological approach used in the literature review.

The hits obtained in each search engine were examined and their content relevance was verified. Non-relevant papers were removed from the list obtained from each search engine. Verification of subject relevance was cross-checked first, based on the title of the paper and abstract. In cases of doubt, further text screening was performed on the main text. After verification of relevance, comparisons and cross-checks were made between the lists of papers from all search engines, to ensure that no duplicates were present in the final combined list of papers retrieved using the search string. A check was also made to ensure that only journal articles were retained (i.e., conference proceedings, book chapters, and reports were not included in the final list).

The final step involved categorization and division of the retained papers into five main categories as follows:

- Geographical distribution: Continents, developed countries, middle-income countries and low-income countries;
- Type of renewable/s: Wind Power, Solar Power, Biofuels, etc.;
- Type of digitalization: Blockchain, Internet of Things, Artificial Intelligence, etc.;
- Sector: Agriculture, Off-grid, Rural, etc.;
- Challenges arising.

4. Results

4.1. Papers Identified

The results obtained from the three search engines are summarized in Table 1. There was an initial total of 836 hits from all three engines. After a rigorous review of the content of these hits and the removal of irrelevant papers and duplicates, a total of 69 journal articles were selected for analysis. Papers were considered irrelevant if they did not cover the subject of concern (i.e., digitalization within the renewable energy sector) or addressed only one of these two areas (i.e., only digitalization or renewable energy). Papers coupling the two fields were identified by screening the title, abstract and, when in doubt, the conclusions section. A large proportion of the hits focused solely on agriculture, off-grid systems, renewable energy, or digital technologies in general, and did not address the links or correlations between digital technologies and renewable energies, and were thus considered irrelevant. Of the 69 relevant journal articles found among the 836 initial hits, over 60% were from two sources (32% were published by the Multidisciplinary Digital Publishing Institute (MDPI) and 29% by Elsevier journals).

Table 1. Summary of initial hits obtained in SCOPUS, Web of Science, and Google Scholar and total retained at different steps.

Search Engines/Parameters	Number of Hits
SCOPUS	432
Web Of Science	289
Google	115
Total (All search engines combined)	836
Total (After removing irrelevant articles)	100
Total (After removing duplicates)	69

4.2. Country of Affiliation of Authors

The countries of affiliation of the authors of the selected papers are indicated in Figure 2. A total of 52 countries were identified based on the authors' country of affiliation (typically work address). In order to obtain a fair representation, each country of affiliation of the authors of an individual paper was counted only once. As shown in Figure 2, the USA was the dominant country of origin of the authors of the selected papers. followed by India and then Australia, Austria, China, Saudi Arabia, and the UK. Thus, most of the authors of the papers were based in North America, while the least represented continent was Africa.

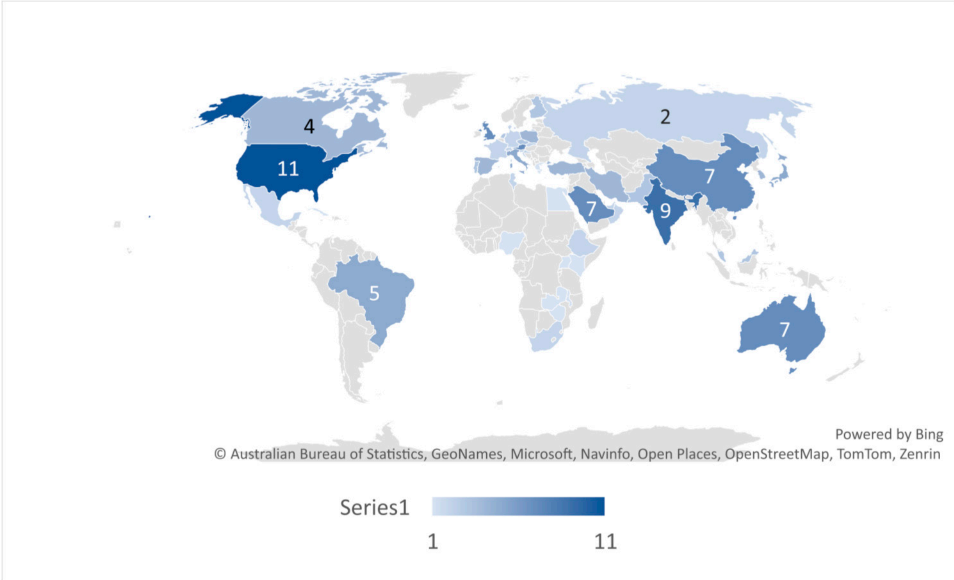

Figure 2. Countries of affiliation of the authors of different papers in the final set retained for analysis.

4.3. Geographical Regions Covered by the Papers

In addition to the authors' countries of affiliation, the regions and countries targeted and discussed in the papers were identified. Reading both the abstract and conclusions section proved to be sufficient in most cases to identify the geographical region or country covered by a paper. The geographical distribution of the study areas identified is summarized in Figure 3. A total of eight countries were discussed specifically in the papers, with Malaysia being the most common study country (addressed in three papers). However, the majority of the papers (55/69) did not confine the study to a specific region or country and hence were categorized as 'global' (Figure 3).

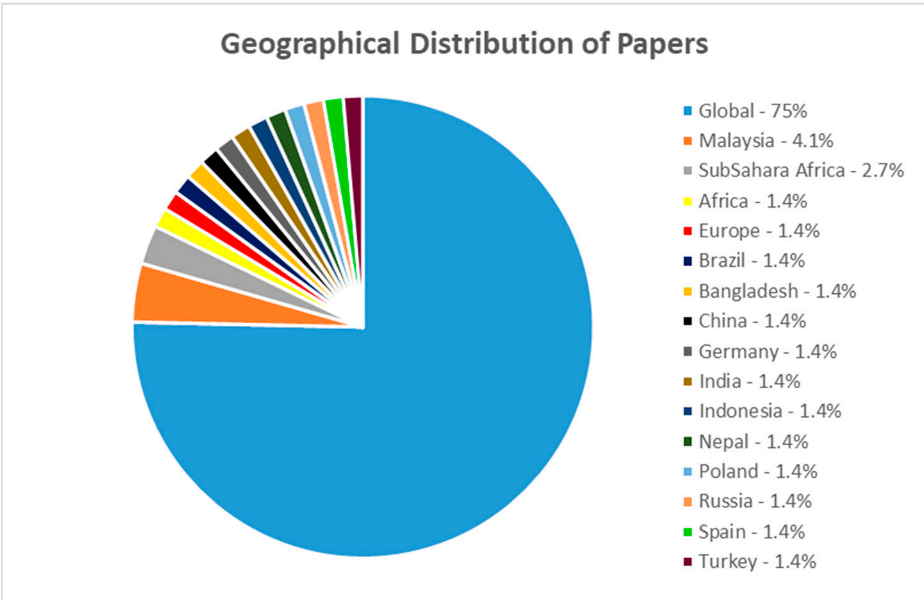

Figure 3. Pie-chart showing geographical regions/countries covered by the papers.

4.4. Keywords

Some of the keywords listed in the different papers were not relevant to the present analysis. Words that were not relevant to the main subject or the search string were removed, e.g., keywords such as "bitcoin", "Russian Federation", "regime change", and so on, in order to focus on subject-related keywords in the analysis. A word cloud of the keywords in the 69 papers retained for analysis is presented in Figure 4. Unsurprisingly, the word "energy" dominated the keywords list since it was used in many terms, including "energy systems, "distributed energy resources", "energy decentralization", and so on. Other significant keywords were "renewable grid", "smart", "microgrid", "sustainable", and "distributed", which were also used in many different terms, such as "sustainable development", "smart contracts", "smart grids", and so on. It is worth noting that the most frequently recurring digital technology type in the keywords was "blockchain". Present also were three of the 5 D forces discussed earlier ("decentralized", "distributed", and "digital"). These are the forces that are thought to play a key role in the integration of renewables into global electricity generation by 2035.

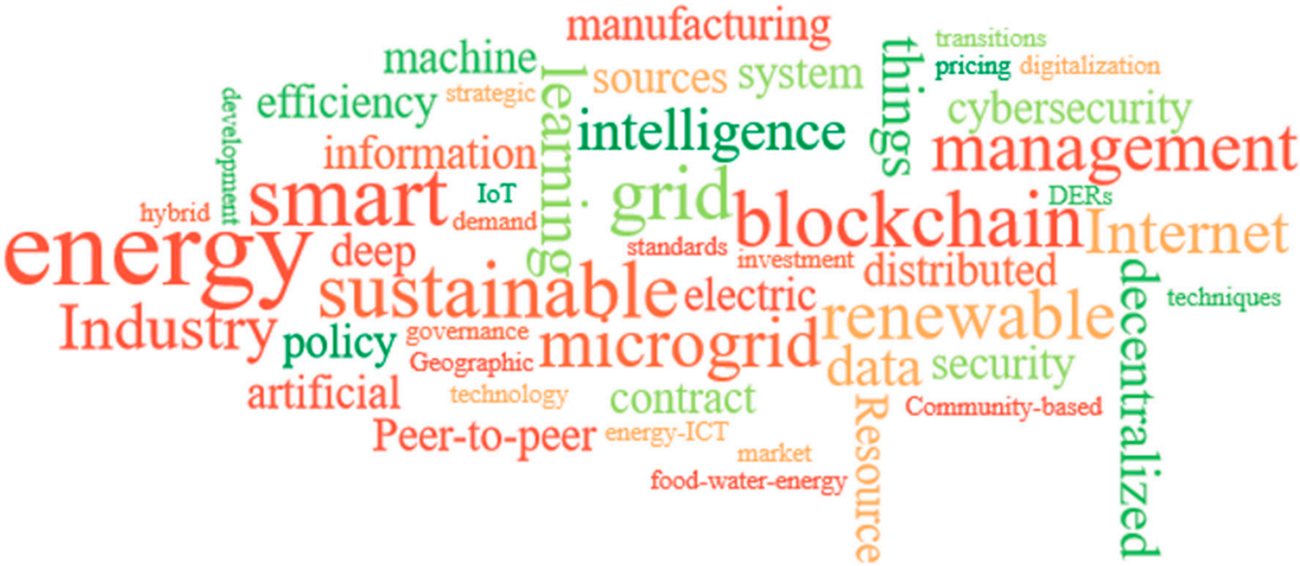

Figure 4. Word cloud of keywords from the set of 69 papers retained from the literature search, with font size indicating frequency of mention.

4.5. Other Words Mentioned in Paper Abstracts

In addition to the keywords, some other words mentioned in the paper abstracts were analyzed for their re-occurrence. These included words used in the original key search string (i.e., renewable energy and digital), any coupled words (agriculture, rural, and off-grid), and the 5 Ds (Decentralization, Decarbonization, Democratization, Deregulation, and Digitalization). To simplify the analysis, repeated mentions of the same word or terms in an abstract were considered as one count (e.g., digital technology, digitalization, etc. were represented by one count for digitalization).

Tracking these words specifically served two purposes. First, it helped identify the overall topics covered by the papers in terms of the research aim, the factors coupled to the issue studied, the categories/industries covered, or even recommendations. Second, it helped determine whether the 5 D forces were addressed or not, an important consideration since these are expected to provide strong leverage for the diffusion of renewables in coming years. Use of the abstract section to track these words was the most obvious approach, since abstracts are usually concise, state the problem/argument, describe the methodology, and provide concluding statements of findings and sometimes recommendations.

Figure 5 shows the number of counts for these supplementary words. As seen for the keywords (Figure 4), "renewable energy" once again dominated the list, with a total of 38 papers mentioning this term in their abstract. The second most frequently mentioned words were those related to "sustainability", appearing in 32 papers. Excerpts of sustainability-related statements from the papers are provided in Table S2 in Supplementary Materials.

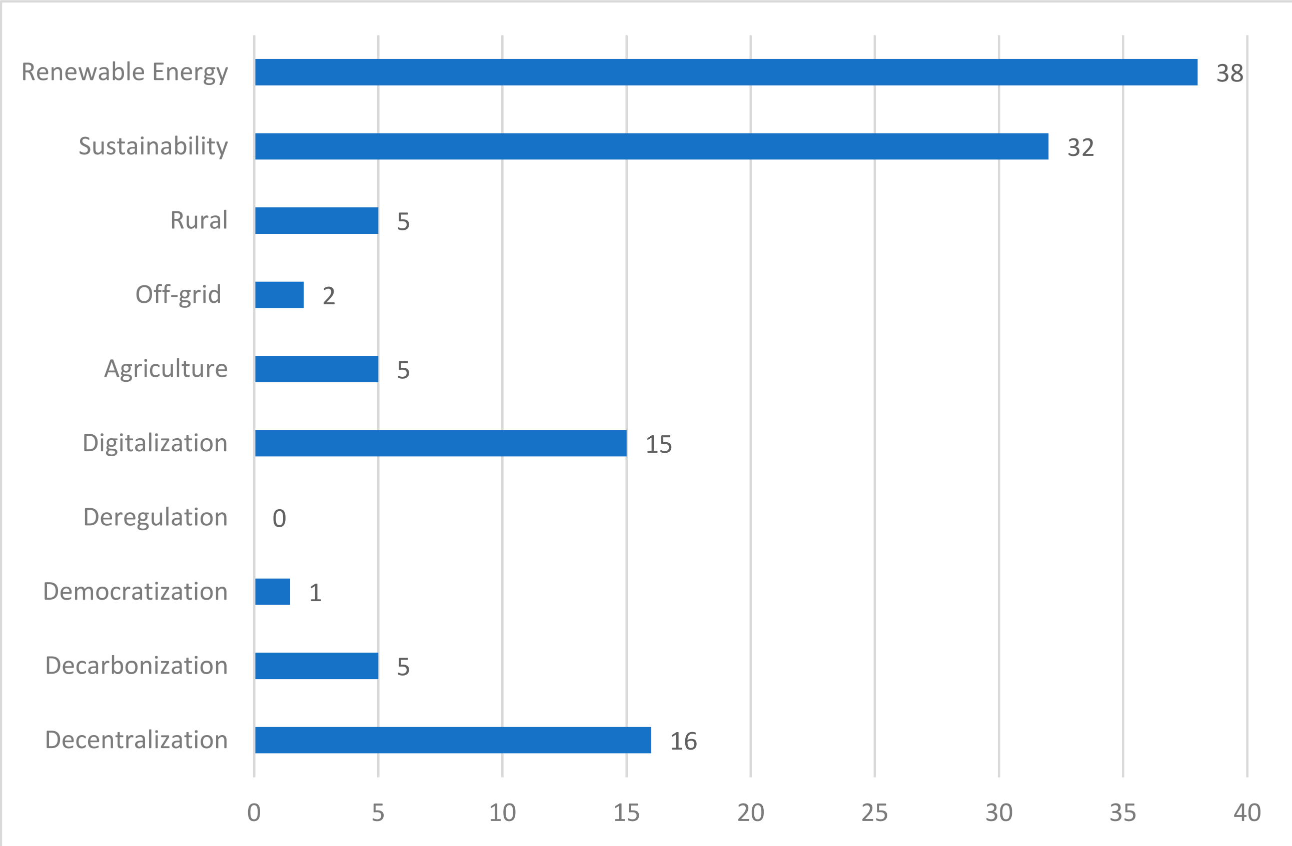

Figure 5. Frequency of mention in paper abstracts of words used in the key search string and the 5 Ds.

In terms of industries and fields represented, rural areas and agriculture-related industries dominated. "Decentralization", followed by "Digitalization", dominated among the 5 Ds, with 16 and 15 counts, respectively, whereas there was no mention at all of the term "Deregulation".

4.6. Types of Digitalization

A significant part of the literature review involved identifying the main digital technology considered in the papers and its coupling to the RES. This was done by reading both the abstract and conclusions section of the 69 journal articles retained in the final set. A mention of a specific technology several times in a paper abstract and/or in the conclusions section was taken as one count, as was each mention of a technology in either the abstract or conclusions section.

Failure to identify any indicative digitalization technologies in the abstract or conclusions meant that a full screening of the paper was necessary. If this revealed that no specific technology was addressed, then a single count was given to the category "Digitalization in General". Specific digital technologies that were discussed in only one paper were placed in the category "Others".

Blockchain technology was the leading single digital technology covered, discussed in 18 papers (Figure 6). It was also the most frequently mentioned digital technology in the keywords (see Figure 4). "IoT technology" and "Digitalization in general" were in second place, with 17 papers addressing these. The least addressed single technology was "Digital twin", which was mentioned in only two papers out of the 69.

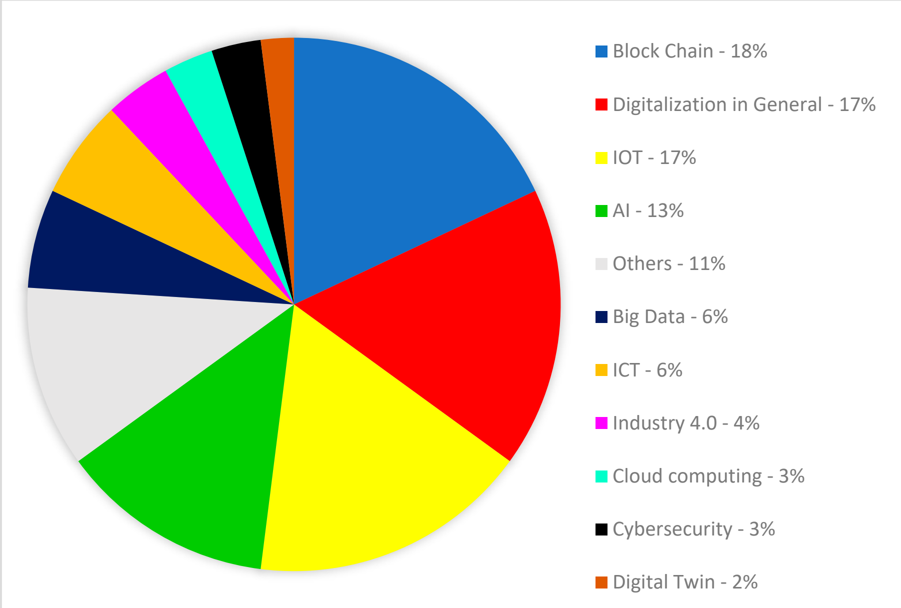

Figure 6. Pie-chart showing frequency of mention of different types of digital technology in the 69 papers reviewed.

4.7. Types of Renewable Energy

Another important component of the literature review was to determine which renewables were covered most and least in relation to digitalization. By applying the same approach as that used for frequency of mention of digital technologies, a donut chart of frequencies was established (Figure 7). "Renewables in general" was by far the most frequently discussed type of renewable energy in relation to digitalization, followed by "Solar power" and "Wind power", while "Biofuels" were the least discussed renewable energy type.

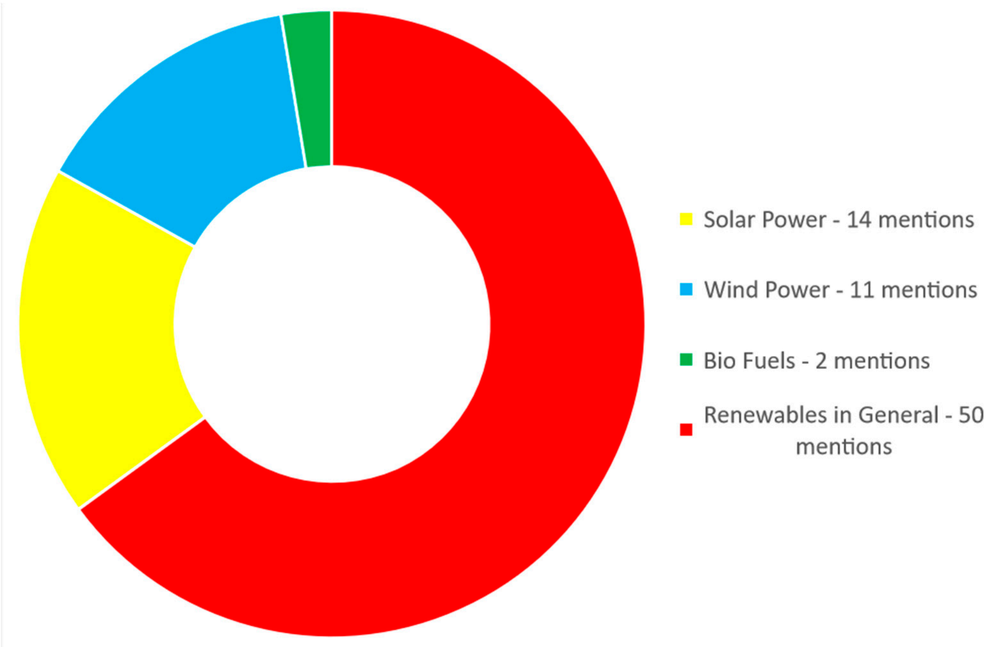

Figure 7. Donut chart showing frequency of mention of different renewable energy types in the 69 papers reviewed.

4.8. Types of Challenges Identified

Despite the perceived benefits and opportunities of digitalization in the energy sector and evidence of how these technologies can support the diffusion of renewables, there are major challenges associated with this energy transition. Challenges mentioned in the set of 69 papers reviewed were identified and divided into two main categories, technology-associated challenges and economics and management challenges. Each type of challenge mentioned or discussed in the papers was awarded a count. Table S1 in Supplementary Materials provides excerpts of statements on challenges and concerns taken from the papers reviewed.

4.8.1. Technology-Associated Challenges

The technology-associated challenges raised in the papers were allocated to seven different categories (Figure 8), to help pinpoint the type of challenges identified in relation to digitalization. Three of these sub-categories, namely "Cyber-security", "Security", and "Privacy", related to digital security in one form or another, reflecting the terminology used in the respective papers. It should be noted that although these terms are commonly used interchangeably, they differ in terms of the aspect of security they represent. Cybersecurity refers to protection from cyber-attacks. Information security, or simply security, refers to protecting information and data from any form of threat, digital or physical (and thus includes cyber-security as one of its components). Privacy refers to mishandling of data (energy data in this case) that can infringe upon individuals' privacy rights [26].

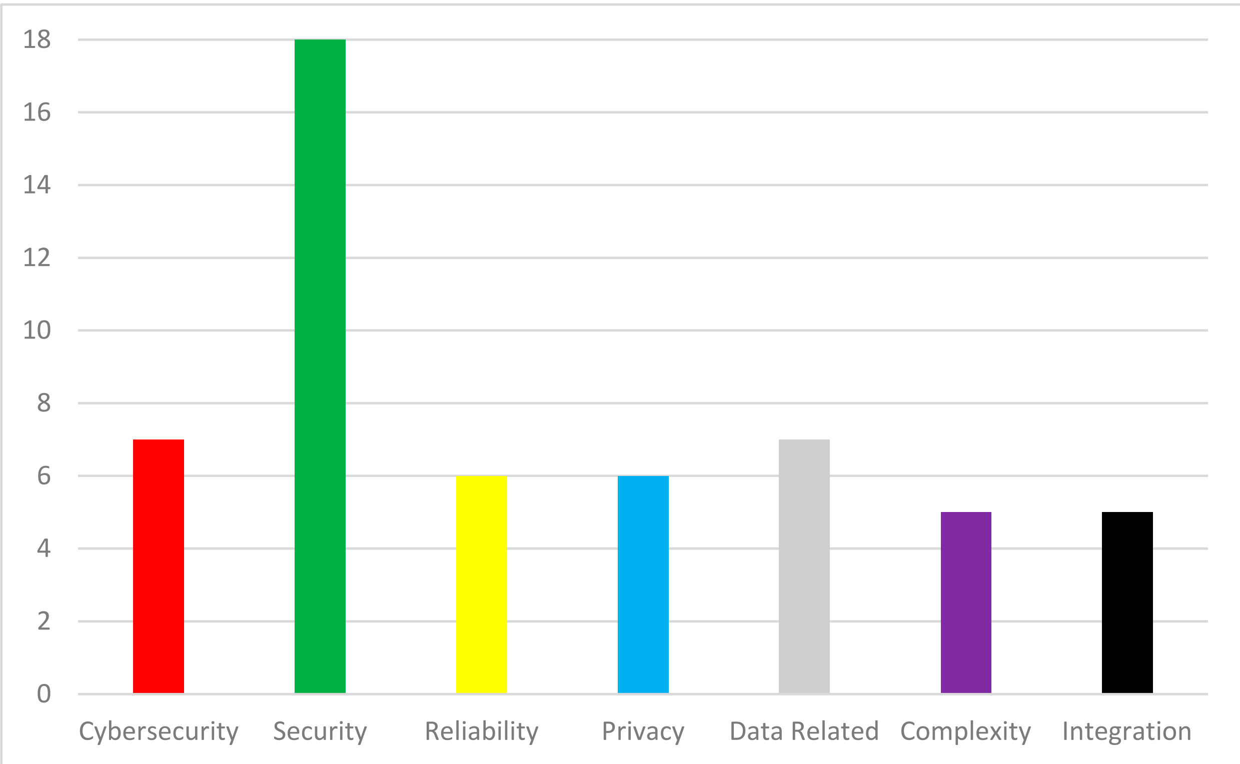

Figure 8. Bar chart showing frequency of mention of different categories of technology-associated challenges in the 69 papers reviewed.

The "Data related" category of challenges involved other aspects concerning data, e.g., lack of a data-driven framework enabling digital technology, data collection and communication with energy customers, data labeling, and so on. The "Reliability" category mainly comprised stability and quality issues between the grid and the power supply. The "Complexity" and "Integration" categories addressed challenges in other aspects of the grid, namely the complexity of the grid in terms of control, monitoring, and operation, and the integration of digital technologies into existing grids and energy infrastructures, respectively.

As can be seen in Figure 8, security challenges were the category most frequently brought up in the papers reviewed. Other challenges were more or less equally frequently raised.

4.8.2. Economics and Management-Associated Challenges

The most frequently raised economics- and management-associated challenge was "Costs", e.g., lack of investment and funding of projects, and high operating and maintenance or transaction costs (Figure 9). The second most frequently raised challenge was "Regulation" (lack of an appropriate regulatory framework), followed by other challenges associated with "Management", "Human factors", and "Policy". Typical management challenges mentioned were failing approaches (e.g., a top-down approach), existing bureaucracy processes, and problems with managing energy storage or overheads. Human factor-related challenges included social acceptance, employment, and conflict resolution.

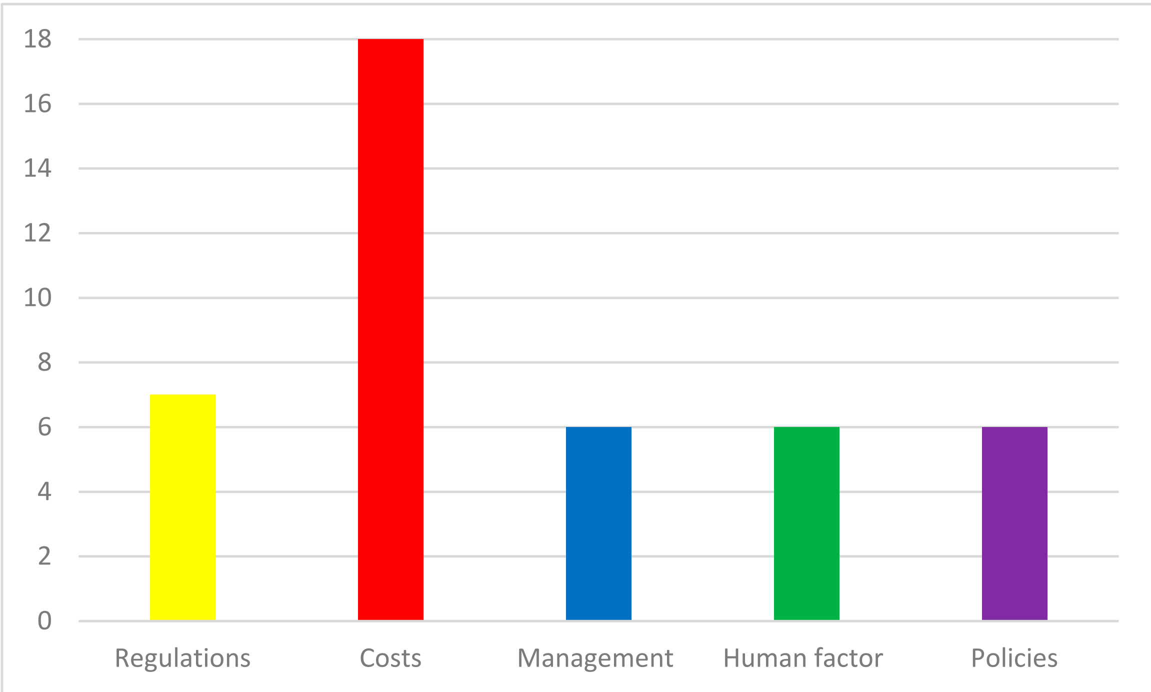

Figure 9. Bar chart showing frequency of mention of different categories of economics- and management-associated challenges in the 69 papers reviewed.

4.9. Conclusions Reached in Papers

The conclusions section of the papers were scrutinized to identify the key findings and any recommendations made (some excerpts are provided in Table S3 in Supplementary Materials). Most papers highlighted the significance of integrating digital technologies into the energy sector and were optimistic about future adoption, but concerns were also raised regarding barriers and challenges hindering the process. Further research and development (R&D) was one of the most common solutions recommended to overcome the barriers identified.

5. Discussion

The aim of this review was to assess the existing utilization of digital technologies within the renewable energy sector and expected progress in coming years. Analysis of the selected set of papers provided a comprehensive overview of the main drivers of progress (supporting factors) and the main challenges to digitalization of the renewable energy sector. Understanding the geographical distribution of both the country of affiliation of the authors of the papers and the study area/country also provided a sense of where the technology is heading in terms of diffusion and scalability. Identifying the dominant digital technology coupled to the renewable energy sector was a significant outcome.

Detailed analysis revealed that most of the papers (75%) published to date on the subject of the digitalization of renewable energy considered the issue on a global scale, and showed that digitalization of the renewable energy sector is advancing at a steady pace. This was reflected in a wide spread of the author affiliation countries, which indicated that interest in the subject is no longer restricted to North America or western Europe and extends to countries in the Middle East and Far East, e.g., Saudi Arabia, India, and China, and the southern hemisphere, e.g., Brazil and Australia.

Although the papers covered a vast number of digital technologies, the analysis of abstracts and keywords revealed that blockchain was the main technology discussed, followed by IoT. Therefore, blockchain was examined in greater depth in order to learn what distinguishes this technology from the rest and to help understand other important parameters identified in this literature review.

Blockchain technology was first introduced rather recently (in 2008), but it has been rapidly adopted by various sectors (e.g., cryptocurrency, healthcare, etc.) [27]. The renewable energy sector has also undergone improvements provided by this technology, through several successful blockchain applications that are believed to have helped foster energy transition and circular economy initiatives, included smart metering, smart grid management, P2P energy-trading platforms, electromobility, etc. [27]. One of the most significant features of the technology is decentralization, which improves information legitimacy [27]. Decentralization is also one of the known 5 Ds and it provides a substantial additional advantage in terms of providing transparency of information, while simultaneously safeguarding the anonymity of participants. This minimizes any human, social, or behavioral misconduct, thus guaranteeing the security and integrity of the network [27]. Interestingly, the term "decentralization" was the most frequently mentioned of the 5 D forces and the third most frequently mentioned supplementary word. This was related to mentions of blockchain, which is a distributed, decentralized database of individual transaction records.

Understanding the fluctuating and unpredictable properties of renewable energy sources and addressing these through blockchain-based smart grids has improved the overall diffusion of renewables. Tracking and monitoring energy production and consumption provide more effective management and better distribution of energy resources (renewables in particular) [28].

Taking the solar and wind industries as examples within the RES, the following services can be achieved through blockchain adoption:

- Use of smart devices to sell excess energy at a better price in a decentralized market, thus creating new business models in the energy industry;
- Increased the security and transparency of energy transactional processes;
- Elimination of middlemen, and lower costs;
- Registering and authenticating sources of renewable energy to ensure effective and sustainable use [28].

The most discussed form of renewable energy in the papers reviewed in this study was solar power, followed by wind power (see Figure 7). A previous survey of the literature relating to the application of blockchain in the energy sector found that 82% of the publications analyzed mentioned solar energy, followed by wind energy (12%) [28].

According to Statista, a German online platform that specializes in data collection and visualization, the annual growth rate of blockchain in the global energy market in the period 2019–2024 was highest in the Asia-Pacific energy market (60.01%), followed by the rest of the world, Europe, and North America (60.02%, 53.41%, and 51.15%, respectively) [28]. This was confirmed by the findings on the regions/countries most frequently discussed in the papers reviewed in the present study, where the Asia-Pacific countries (Bangladesh, China, India, Indonesia, Malaysia, and Nepal) were the most commonly addressed (11.1% of the papers).

Sustainability was one of the most commonly mentioned words in the papers reviewed. This is unsurprising, since renewable energies and digital technologies go hand in hand and act positively together, in one form or the other, in various areas of sustainable development.

Today, digital infrastructure and renewable energy are viewed as integral to transition toward a low-carbon economy and as vital for achieving sustainable development [29]. Significant attention has been paid to digitalization by researchers and policy makers, as it is a primary factor in mitigating pollution and can be a key enhancer of the achievement of the SDGs. Although the concepts of sustainability and digitalization may seem distinct, they exhibit strong interconnectedness [29]. The adoption of digital technologies provides a gateway for both firms and industries to shift from conventional energy sources to green, environmentally friendly technologies that enhance the environment and society and ensure sustainable economic growth.

Again taking blockchain as an example, and considering the UN-adopted Sustainable Development Goals (SDGs), blockchain applications in the energy sector can help enhance sustainability in the following ways:

- SDG 7—Affordable and Clean Energy: "Decentralized energy markets, facilitated by blockchain technology, empower individuals and businesses in peer-to-peer energy trading, fostering cleaner energy choices and local economic growth" [30];
- SDG 9—Industry, Innovation and Infrastructure: "Microgrid development and management through blockchain advances energy access in remote regions and establishes resilient infrastructure" [30];
- SDG 11—Sustainable cities and communities: "Blockchain integration into electric vehicles and green mobility addresses and encourages responsible energy practices and sustainable urban transportation" [30];
- SDG 12—Responsible Consumption and Production: "Blockchain traceability ensures certificates for sustainable production and consumption" [30].

It should also be noted that the adoption of digital technologies does not always lead to positive outcomes. Taking environmental sustainability as an example, digitalization influences environmental sustainability through three mechanisms: use-effect, rebound effect, and substitution effect. The impact of the use-effect mechanism derives from the production of digital tools that increase energy and resource consumption, while their installation, distribution, and utilization generate adverse environmental impacts, with waste being a key issue. Through the rebound effect, digital-driven systems that stimulate efficiency gains, and hence energy savings, can also lead to counteracting effects, such as increasing energy consumption rates and associated increases in carbon emissions. The substitution effect encompasses dematerialization, decarbonization, and demobilization. Dematerialization involves decreasing material consumption and replacing conventional physical products with virtual products (e.g., e-mails, e-books, etc.). Decarbonization uses smart technologies to benefit energy supply, demand management, and productivity. Demobilization represents the diffusion of e-commerce and teleworking, which helps reduce transportation and adverse transport-related emissions and pollution [29]. The main disadvantage of the substitution effect is the risk of unemployment, especially among an unskilled labor force that lacks technological knowhow [31].

Although digitalization provides numerous advantages and has tackled many problems within the energy sector, some key challenges still need to be addressed. According to the papers reviewed, there are two main types of challenges posing barriers and threats to progress. These are technological challenges, particularly concerning the security of the infrastructures involved, and economic and management challenges, particularly concerning the costs associated with the adoption of the technologies. Due to the lucrative nature of cybercrime, criminals are constantly seeking new means of attack and the vulnerability of critical energy infrastructures continues to be an issue of concern, especially since there is no such a thing as a 100% secure system [32]. Cost-related challenges include capital investment in purchasing, implementing, and using digital technologies. With regard to implementation, there may be high costs involved in making radical changes to existing legacy systems and infrastructures that are not compatible with new technologies [33].

The findings in this study indicate that digital technologies are expanding within the renewable energy sector and undoubtedly make a positive contribution to the sector's diffusion and efficiency. The analysis of relevant papers showed that wind and solar power were the most frequently discussed forms of renewable energy. This is unsurprising, since both are predicted to be the most critical contributors to low-carbon energy consumption in the near future. On a global scale, solar energy is likely to become the largest single energy source by 2040, accounting for 40% of renewable energy, through strong deployment in the Global South (primarily in China and India). According to the IEA, by 2028, renewable energy sources are projected to account for over 42% of the global electricity generation. The largest share of this RES contribution (25%) will be represented by wind and solar PV sources combined [34]. From an environmental perspective, by 2050 Europe alone is projected to have over 450 GW capacity in wind power, with avoided emissions of 462 Mt CO_2 per year, and 4500 TWh capacity in solar photovoltaics (PV), with avoided emissions of 2.3 Gt of CO_2 per year [35].

Considering their significance globally, it is important to identify the challenges facing wind and solar energy today and whether digitalization, geographical region, or field play any role in their diffusion. According to a recent research paper [36], published on behalf of the European Academy of Wind Energy and reviewed extensively by members of the IEA, digital technologies will be a key factor in shaping the industry's future and adoption by improving safety, efficiency, and reliability, while also reducing costs. However, the study identified three main challenges to the digitalization of wind energy: (1) Data: creating FAIR (Findability, Accessibility, Interoperability, Reusability) data frameworks; (2) Culture: connecting people and data to foster innovation; and (3) Coopetition: enabling collaboration and competition between organizations [36]. The study, which involved a literature survey and expert consultation through semi-structured interviews with 44 digitalization experts, mainly from the wind energy sector, made the following key recommendations to address the digitalization challenges facing the sector:

1. Data: "Funding agencies should require that all data collected and produced by FAIR organizations should ensure that data systems follow cyber-security best practices. Funding agencies should fund research on the needs of under-presented groups specifically affected by digitalization of wind energy" [36];
2. Culture: "Businesses should implement DEI best practices such as developing recruiting strategies, mentoring programmes, and personal training. Funding agencies should fund research on the needs of under-presented groups specifically affected by digitalization of wind energy" [36];
3. Coopetition: "Governments and regulators should encourage transparent public energy data which protects personal privacy whilst facilitating innovation and benchmarking. Businesses and funding agencies should support R&D projects that showcase the use of data marketplaces and public energy data" [36].

In another study covering the EU, an analysis was made of the dynamics of the present and projected diffusion of wind and solar technologies [35]. The study, which adopted a "learning curves" approach, covered various areas and factors shaping the EU region. These included company levels, national policies, global scenarios for a selected technology development, and energy and climate change models. Learning curves deliver a phenomenological description of the connections between different values, e.g., cumulative production and past costs, and are useful for estimating future cost reductions by simple extrapolation [35]. The analysis concluded that the two following opposing forces will influence the deployment of wind and solar energies: (1) changes in capital costs; and (2) integration of challenges for the technologies, comprising typically techno-economic parameters, capital costs, operation and maintenance costs, efficiencies, capacity factors, and lifetimes [35].

A recent study using existing literature and a questionnaire distributed to solar and energy industry experts (429 respondents from Pakistan) to investigate barriers to solar PV adoption in developing countries identified the following critical elements for success: financial stability, motivating policies, technological knowhow, organizational support, societal awareness, and market steadiness [37].

Another study on developing countries analyzed a number of case studies concerning renewable energy adoption and found that the following five challenges were present in all four countries studied (Albania, India, Brazil, and Kenya): (1) a need for continuous innovative approaches to address the intermittent nature of renewable energy sources; (2) a need for grid infrastructure upgrades; (3) consideration of social and environmental factors; (4) budget constraints; and (5) a need for cross-border cooperation (i.e., practice and technological sharing and successful policies) [38].

A comparison of two countries (Poland and Finland) differing in terms of perceived renewable energy diffusion barriers found that both were experiencing setbacks to their current policy schemes, despite relatively large societal, environmental, and economic differences. Other barriers to diffusion identified in both countries were high initial investment and transaction costs, doubts concerning Renewable Energy Target (RET) efficiency and reliability, and community-based issues such as NIMBYism (Not In My Back Yard) or unwillingness to pay more for renewable solutions [39]. The study recommended addressing the societal issues through multidimensional awareness-raising actions, such as professional training, conferences, activist movements etc., and the issues with a lack of financial and managerial resources through business angles or venture capital (VC). Catching up with technological development through the so-called ‘Energy 3Ds’ (Decarbonization, Decentralization, and Digitalization) was also identified as critical for success [39].

Based on the studies summarized above, the term “digital technologies”, or “digitalization” in general, is not necessarily explicitly mentioned in papers addressing diffusion of renewables into the energy sector. Terms associated with ‘technology’ could be hinting at digitalization, but this cannot be assumed in every case. This explains the high proportion of irrelevant papers (92%) found among the 836 initial hits. Aligning with the challenges to digitalization noted in the 69 reviewed papers, other papers examining the diffusion of renewables report similar techno-economic and management-related concerns.

The findings in this study reflect the significance of digitalization for the renewable energy sector, but the success of the digitalization process relies on other key factors, in particular economic aspects, represented by capital and running costs, and security-related concerns. However, it appears that societal and regulatory frameworks are also critical for enabling digitalization of the sector. It is important to ensure that drivers of digitalization extend beyond the technical aspect and aim for higher contributions to society and the environment. Contributions to sustainability and to enhancing environmentally friendly sources of energy may secure more stakeholders and have a higher probability of attracting funding.

More R&D and funding for the leading renewable sectors (i.e., solar and wind energies) and digital technologies (represented by blockchain and IoT) will also be needed, although this should not be at the expense of other renewables or other means of digitalization. Greater efforts need to be devoted mainly to attaining FAIR data and addressing cybersecurity issues.

Due to their expanding population, expanding economy, and accelerating urbanization, developing countries are likely to be the key players determining the global energy picture in the near future [38]. These countries need to work on several fronts simultaneously to address digitalization of their renewable energy sector (RES). Issues such as raising societal awareness concerning the significance and coupling between digital technologies, renewable energies, and sustainability must be resolved for a smooth, rapid energy transition. Increasing RES incentives, creating or adjusting regulatory frameworks, and providing training and education (i.e., within digital and renewable technologies) for all levels of stakeholders could be one way of tackling the present and future challenges deriving from lack of funds or skilled labor.

6. Conclusions

Compared with previous reviews, this work has unique scope and novelty since it considers the bigger picture regarding the coupling between digitalization and the renewable energy sector, but with more focus on critical areas in these two interconnected bodies that need to be addressed. While identifying particular pressing technical issues, the study also highlighted the significance of the sustainability aspect in achieving better goals. The relatively small sample of relevant papers included in this literature review (69 from 836 hits) reflects the need for more research covering the subject in greater depth. Many of the research papers deemed irrelevant addressed digital technologies under the rather generic ambiguous term "technology" or "technology development", which is non-explanatory and may in fact create confusion among readers.

The integration of digitalization has obviously helped to promote the diffusion of renewable energy sources in the energy sector, where there is growing interest in various digital technologies, e.g., blockchain, IoT, and AI. These are being applied not only across developed countries, where advanced energy infrastructures exist, but also in many developing nations. The current drivers of the integration of digital technologies to support the diffusion of renewable energy sources appear to extend beyond energy demand and involve addressing many aspects of sustainability and sustainable development.

Further integration of digital technologies into the renewable energy sector still faces technological challenges (security breaches) and economic and management challenges (high costs and appropriate enhancing policies). Addressing these challenges from a holistic approach with sustainability in mind and continuing R&D work can create a better environment for effective energy transition and a resilient infrastructure.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17091985/s1, List S1: Analyzed References; Table S1: Excerpts of Challenges and Concern quotes from the journals; Table S2: Excerpts of Sustainability quotes from the journals. Table S3: Excerpts of Concluding Remarks and Recommendation quotes from the journals.

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