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Review

Energy Supply Chains in the Digital Age: A Review of Current Research and Trends

Agnieszka A. Tubis * and Honorata Poturaj

Department of Technical Systems Operation and Maintenance, Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, Wyspianskiego Street 27, 50-370 Wroclaw, Poland; honorata.poturaj@pwr.edu.pl

* Correspondence: agnieszka.tubis@pwr.edu.pl

Abstract: (1) Background: Digital transformation is critical in further developing the energy supply chain. The attainment of successive levels of digital maturity by chain participants translates into numerous benefits related to the efficiency, cost, and effectiveness of the energy flows implemented. However, the increasing degree of digitalisation and automation generates an increased risk of cyberattacks and other challenges related to the operation of the smart grid. This paper presents the results of a literature review describing the phenomenon of digital transformation in the energy supply chain. (2) Methods: The literature review was performed using two review methods. First, a systematic literature review was conducted using the PRISMA method. However, due to unsatisfactory results, this review was supplemented by a search supporting a narrative review. (3) Results: Analysing the identified publications made it possible to distinguish nine leading research trends related to digital transformation in the energy supply chain. These trends were characterised based on the described research results, and all articles were classified into the corresponding categories. (4) Conclusions: The presented results provide interesting material for further research related to building resilience in the energy supply chain and selected Industry 4.0 tools for assessing and managing risks associated with the operation of the energy sector.

Keywords: digital transformation; COVID-19 pandemic; renewable energy sources; blockchain; internet of things

Academic Editor: Joao Ferreira

Received: 18 December 2024
Revised: 12 January 2025
Accepted: 16 January 2025
Published: 19 January 2025

Citation: Tubis, A.A.; Poturaj, H. Energy Supply Chains in the Digital Age: A Review of Current Research and Trends. *Energies* **2025**, *18*, 430. https://doi.org/10.3390/en18020430

1. Introduction

Digital transformation has been a phenomenon that has been observed for many decades, and like any phenomenon, it goes through successive stages of development. Initially, digital transformation focused primarily on digitising information flows, i.e., the digital reproduction of electronic documents and sounds [1]. The next stage of development was digitalisation, i.e., the use of cyber and data technologies to improve business processes and create new revenue structures and other individual, organisational, and societal contexts [2]. Today, digital transformation focuses on transforming operations, processes, products, and business models to fully exploit digital technologies' capabilities. This perception of digital transformation requires a change in the entire organisation's mindset. Therefore, companies need to understand that the digitalisation process is not only about technological support of processes but also about fundamental changes that relate to the company's strategy, business processes, organisational culture, and the entire organisational socio-technical system [3].

The changes associated with digital transformation are characterised by dynamics depending on the sector under study. Measurements and analyses published in [4], among others, indicate that the leading sectors with the highest level of digital maturity include, first and foremost, the information technology sector, followed by media, insurance and finance, and professional services. The digital maturity of the companies and chains that handle commodity flows in a given sector is usually assessed using dedicated digital maturity assessment models. Examples of such models are described in [5–9], among others. Among the areas of digital maturity assessed, the following are mainly distinguishable [6]: organisation, technology, strategy, culture, employee, customer, processes, and operations (the study included 44 models assessing the digital maturity of an organisation).

Energy supply chains are part of the critical infrastructure, and their efficiency and resilience determine the stability and smooth functioning of industry, the economy, and the state. Indeed, modern industry and society depend heavily on reliable energy supplies to provide comfort and security to the population. However, as Aarland and Gjøsæter [10] note, the degree of this dependence fluctuates with the degree of digitalisation. At the same time, the digitisation of society and industry itself threatens the reliability of the energy supply chain and makes energy supply increasingly difficult. Therefore, analysing digital transformation's impact on the functioning of energy supply chains, particularly in improving supported logistics flows and system security, is becoming an important research avenue. Accordingly, this article presents the results of a literature review conducted to answer the following research questions:

- Q1: What are the main research trends regarding the digitisation of the energy supply chain?
- Q2: Which digital technologies are most frequently described in connection with the digitisation of the energy supply chain?
- Q3: How has digital transformation affected the security of the energy supply chain?
- Q4: As with other sectors of the economy, did the COVID-19 pandemic initiate research into the digitisation of the energy supply chain?
- Q5: How does digital transformation affect the sustainability of the energy supply chain?

The answers formulated based on the critical literature analysis constitute this article's main contribution. These answers are presented in Section 6—Discussion. The structure of the entire article is presented in Figure 1.

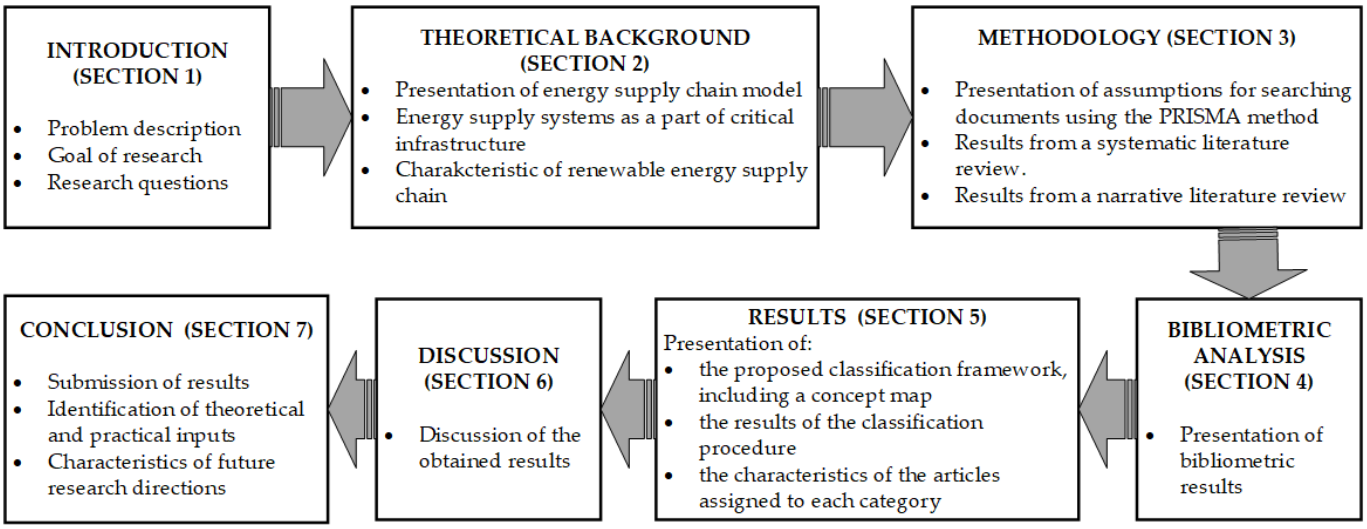

Figure 1. Article structure.

2. Theoretical Background

Energy supply chains (ESCs) are based on a supply network comprising the links responsible for producing, storing, and transporting energy on its way to the consumer. These chains are linked by physical, financial, and IT infrastructures that support energy transfer [11]. A model presentation of the energy supply chain is shown in Figure 2.

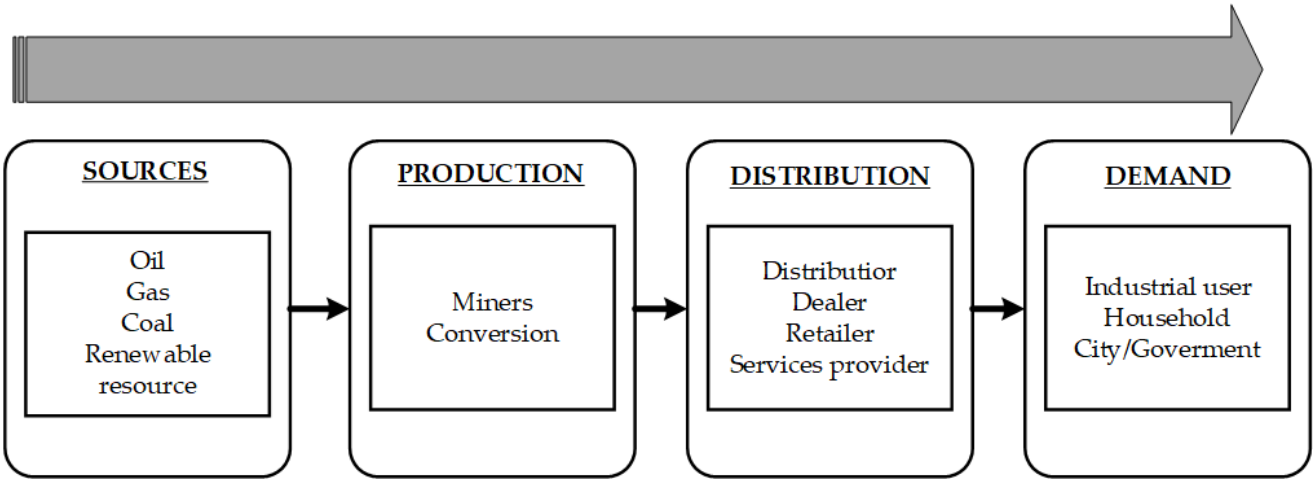

Figure 2. Model presentation of an energy supply chain.

Energy supply systems are part of the critical infrastructure, including real and cyber systems (equipment, facilities, installations) necessary for the minimum functioning of the economy and the state. In the case of critical infrastructure, any disruption can severely impact industry, the population, and the state's core functions. At the same time, the problem of these disruptions is highly complex. This is due to the interdependencies and linkages that occur, resulting in a cascade effect, i.e., the spillover of the effects of the disruptions that occur to other dependent sectors [12]. For this reason, the energy sector is considered highly critical, as many other sectors (including those classified as critical infrastructure) are heavily dependent on energy supply [13]. In doing so, it should be noted that adverse events can occur in the external environment or result from the internal functioning of the supply chain. Many authors consider unstable renewable energy production [14] and extreme weather conditions [15] critical risk factors. In this regard, it is imperative to protect critical elements of the energy infrastructure [16].

Therefore, a critical aspect of managing today's ESCs is ensuring the required functionality and resilience to emerging disruptions. In particular, the resilience of ESCs is critical to guaranteeing energy security. This resilience is usually defined as the readiness of the system to cope with disturbances and shocks in such a way as to ensure continuity of energy supply at the required level [17]. For this reason, current research is directed towards optimising ESCs in the face of increasing energy demands from industry, societies, and governments. Indeed, a growing concern for the modern world is whether current energy supply systems will be able to handle the projected global energy supply, which is expected to grow by 25 per cent in 23 years (2017–2040) [11]. While traditional energy production has met industrial and residential needs for centuries, alternative energy sources are now being sought due to environmental and economic development concerns.

Alternative energy sources are the subject of much research into various aspects of their acquisition and delivery through energy supply chains. Therefore, mainstream research focuses on using renewable energy (RE) and developing chains responsible for its delivery to the consumer market. Renewable energy supply is the answer to protecting the earth's natural resources while enhancing the population's quality of life and further economic

development. In the context of optimising flows in ESCs, supply chains deriving energy from biomass are most commonly described in the literature. Examples of publications include [18–20]. However, in addition to biomass, other renewable energy sources are also described in the literature, as shown in Table 1.

Table 1. Characteristics of renewable energy sources (based on [21]).

Source	Characteristics
Biomass energy	• Diverse organic resources (wood, agricultural, forestry waste). • Technological processes enable waste to be converted into energy resources—primarily biochemical, thermochemical, and extraction processes.
Hydropower and wave energy	• Water flow through mills or turbines is an energy source widely used in industry and agriculture. • Hydropower can be generated by wave and tidal processing, but energy storage systems are required due to their characteristics (constant movement).
Geothermal energy	• This term refers to all the thermal energy stored between the earth's surface and a specified depth in the crust. • In addition to the direct use of the heat resource, this energy must be converted into another form for industrial and agricultural purposes. • A significant limitation is that it can only be obtained in specific locations. • Its collection and conversion require significant financial and technological investments.
Wind energy	• Many wind turbines are located offshore to harvest the vast wind energy and reduce their environmental impact on land. • Wind power is dynamic in nature, so the energy generated must be stored to balance energy demand cycles.
Solar energy	• The Sun's rays and heat are converted into solar energy, which forms the basis for electricity generation. • One of the more popular RE sources, particularly in tropical countries. • Flexible RE source (compared to others), and yet its configuration does not require high capital expenditure. • Energy storage is required in case sunlight is limited.

Wee et al. [21] highlighted that technology is a critical success factor in renewable energy supply chains. Improving the efficiency of renewable energy generation technologies and storage and distribution systems through innovation and digital transformation are important challenges facing today's ESCs. At the same time, renewable energy resources are characterised by three variables, namely intermittency, variability, and manoeuvrability. This creates demands for rational management and increased control of energy flows along supply chains, which digital solutions can effectively support. It is therefore recognised that smart grids are one of the leading technologies being deployed to improve the renewable energy supply chain [22]. This solution integrates information technology with energy networks to optimise energy efficiency through real-time interactive information exchange between suppliers and consumers [21]. This optimisation is possible through the use of information systems that are responsible for monitoring and controlling electricity distribution.

Publications on renewable energy sources are also often located in the area of sustainability research. Therefore, this research aspect plays an important role in ESC improvement research, and continuous changes in the energy markets aimed at increasing green energy consumption further drive the need to publish results from ongoing research [23]. Many

publications in this area are concerned with research conducted under a standard banner integrating three dependent areas: renewable energy sources, sustainability, and environmental protection. An example of such a publication is [24], which, among other things, analysed the application of IT methods in research on renewable energy, environmental protection, and sustainability.

The research trends outlined were discerned from a critical analysis of publications on the design and management of contemporary energy supply chains. The presented characteristics of contemporary energy sector research rendered the use a systematic literature review ineffective. Identifying related publications using verified keywords returned numerous publications that dealt with energy consumption and energy efficiency but did not focus on energy supply chains. Hence, it was necessary to carry out the literature review in a two-pronged manner to achieve a satisfactory count of publications to be analysed.

3. Methodology

The literature review was conducted in two search proceedings using the two most popular knowledge bases, Web of Science and Scopus. The first procedure used a systematic literature review based on the PRISMA method. The selection process for articles on the digitisation of energy supply chains in the systematic review is shown in Figure 3.

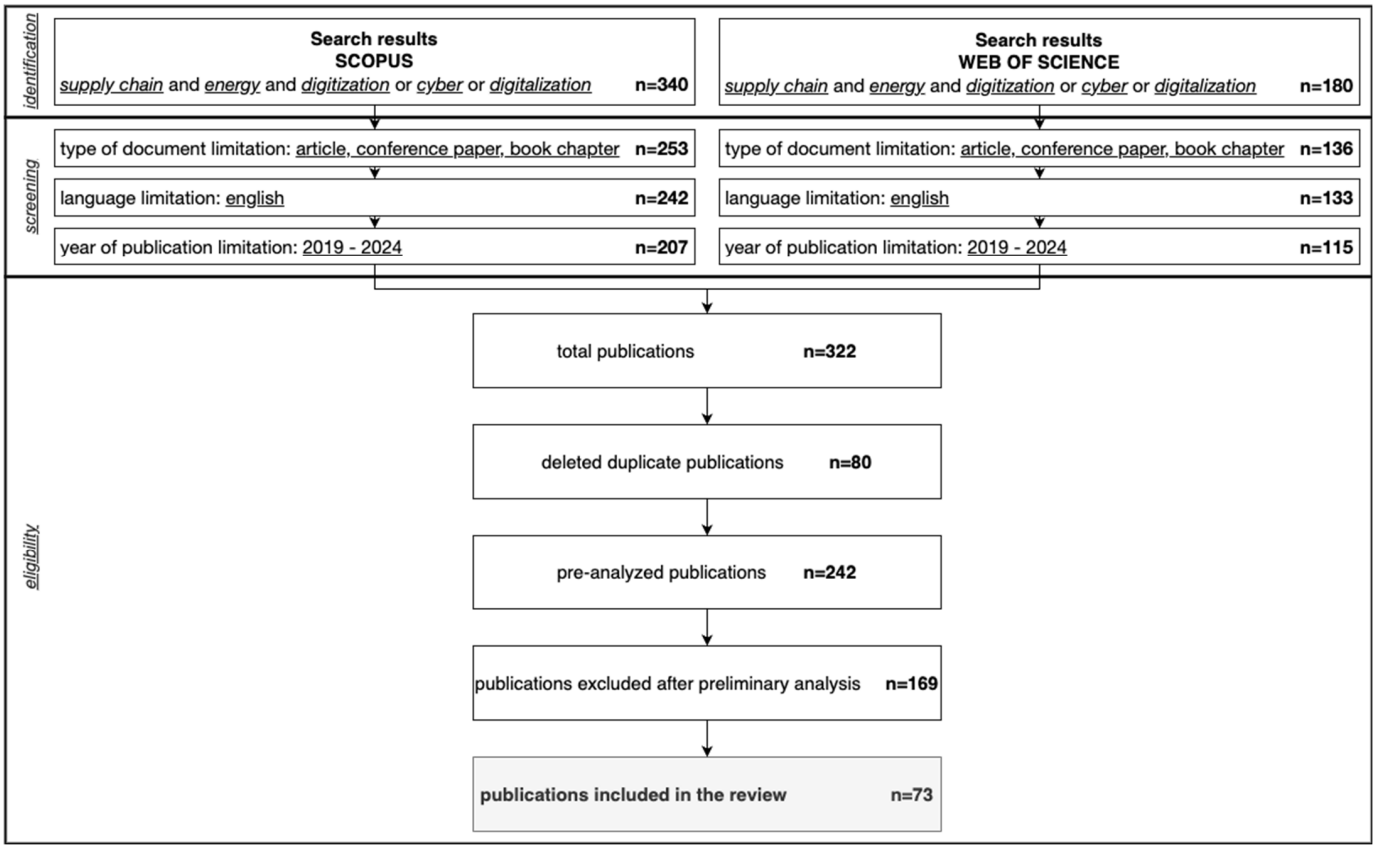

Figure 3. Selection procedure for publications in the systematic review according to the PRISMA method.

As can be seen in Figure 3, the first step in the systematic search using the PRISMA method was to select keywords: supply chain and energy and digitisation or cyber or digitisation. The same words were used in the searches in both databases and were searched among titles, keywords, and abstracts. This was followed by a screening stage in

which publications were restricted to articles, conference papers, or book chapters written in English and published between 2019 and 2024. The restriction in terms of years was introduced to ensure that the most recent publications were analysed, to consider the maturity of Industry 4.0 solutions currently being used in supply chains.

A total of 322 articles were obtained from the two databases, of which 80 were duplicates. The eligibility stage consisted of analysing the abstracts of 242 publications, which made it possible to exclude publications that were not thematically related to the review. A total of 73 papers were included in the analysis. The high percentage of rejected publications was mainly because digital transformation processes are often described as energy efficiency improvements or savings. The combination of the words 'energy' and 'supply chain' is prevalent in documents describing the digital transformation of various economic sectors not directly linked to the energy supply chain.

For this reason, a narrative literature review was used in the second phase of this research. A narrative review is a comprehensive narrative synthesis of previously published information. Narrative reviews do not have a structured search strategy, only an interesting main topic. For this reason, it is important to appropriately select keywords for the conducted document search that meet the researcher's expectations. For this reason, the VOSviewer tool was used to map the leading keywords that should be used during the narrative review. The construction of bibliometric networks was based on keywords (author and index keywords) in publications identified in the systematic literature review. In this way, the systematic literature search using the PRISMA method served as a tool for clarifying the searches on the topic under analysis [24]. A fractional counting method was chosen for the analysis, which makes the weights of the links fractional. The results were visualised using VOSviewer, as shown in Figure 4.

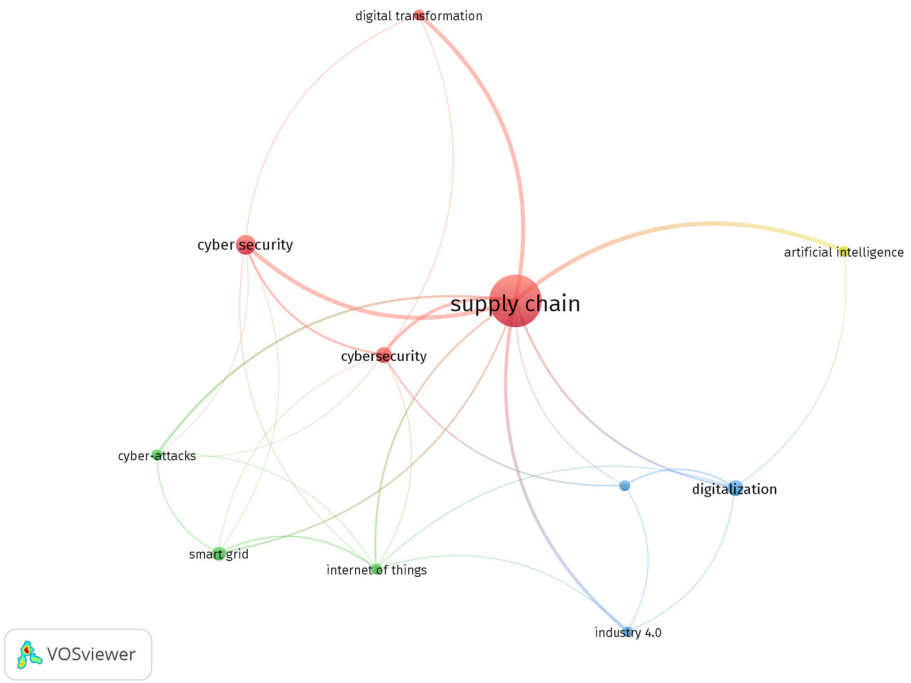

Figure 4. Analysis of leading keywords using the VOSviewer tool.

As can be seen in Figure 4, the leading keyword was "supply chain". However, the authors' focus was primarily on the energy supply chain; therefore, the searches were narrowed down to the selected energy sector. To focus the search on aspects related to digital transformation, the terms "digitalisation" and "Industry 4.0" were chosen to limit the set of searches. As digital transformation includes both digitalisation and digitisation

processes, the second term was also used to search for documents. The terms digital security and leading digital technologies were eliminated from the narrative search, as these were identified as leading research trends, and the narrative review was intended to be general.

The stages of the document search and the selection criteria adopted in the narrative literature review are shown in Figure 5.

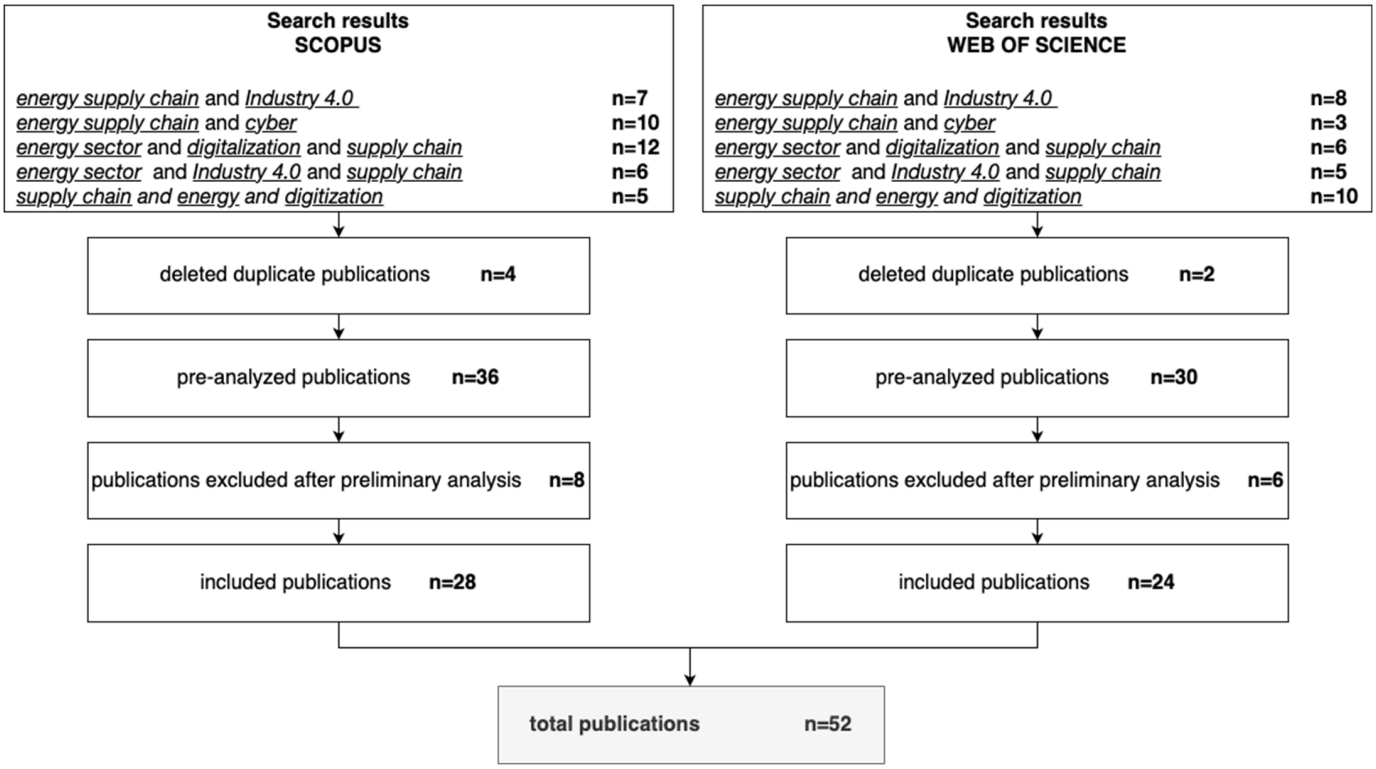

Figure 5. Publication selection procedure using the narrative review technique.

The publications from the narrative review were compared with the systematic review results. Among the 125 publications, 37 republications were identified. The narrative review expanded the list of publications by 15 new items, yielding 88 publications accepted for a final and detailed analysis.

4. Bibliometric Analysis

The collection of publications analysed includes 47 articles, 36 conference papers, and 5 book chapters. Publication trends over the years in the analysed topic are presented in the graph in Figure 6.

The data show a growing interest in the subject under analysis, with a particular increase in publications in recent years. The number of publications has been increasing steadily since 2018. The most dynamic growth occurred between 2021 and 2024, when the number of annual publications increased from 14 in 2021 to 23 in 2024. This trend underlines the growing relevance of the area under study, which is probably linked to technological advances and changing global challenges in the energy sector.

The greatest number of publications were published by Elsevier, which was responsible for 19 articles, accounting for 22% of the material analysed. In second place is IEEE, with 17 publications (19%), followed by Springer, which has 9 publications (10%), and the MDPI publishing house, which has published 6 articles (7%). Other publishers, such as the Society of Petroleum Engineers and ExcelingTech, provided 3 or fewer publications

each. The dominance of Elsevier and IEEE publishers is due to their strong positions in engineering and technology, while MDPI's open-access model attracts authors aiming for a rapid publication cycle. Quantitative data on the publishers are shown in Figure 7.

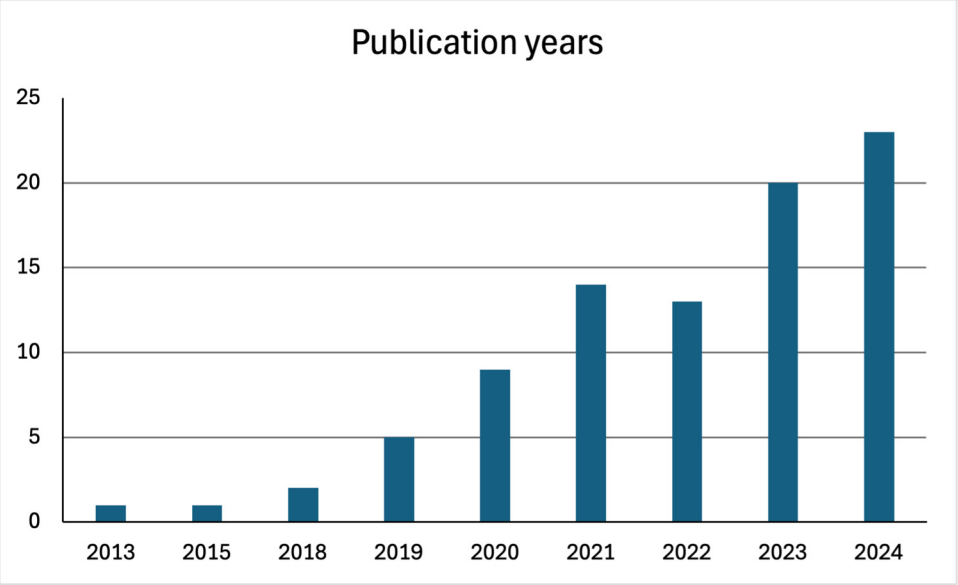

Figure 6. The number of publications from the conducted analysis.

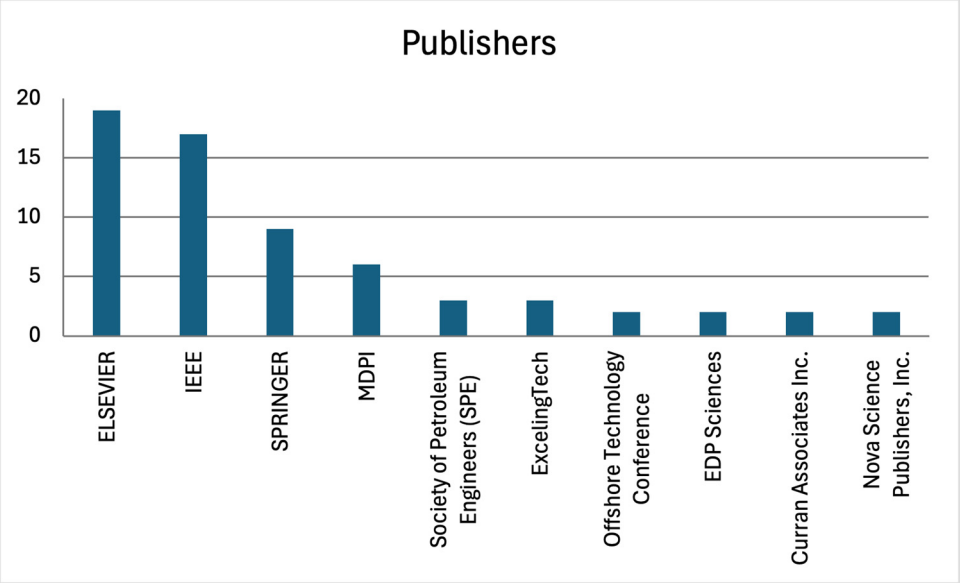

Figure 7. The number of publications by publisher.

Articles were published in a wide range of journals and conference proceedings, reflecting the multidisciplinary nature of the content analysed. The most significant number of articles appeared in *Energies* (5 articles), followed by the *Journal of Cleaner Production* (3 articles) and the International *Journal of Supply Chain Management* (3 articles). Other significant sources included the European Conference on Information Warfare and Security and *Progress in Nuclear Energy*, each providing two articles. The diversity of publication sources underlines the broad applicability and interest in this research area, covering the topics of energy, supply chain management, and security. The distribution of articles in the top sources is shown in Figure 8. The remaining publications were published in various journals and were presented at international conferences.

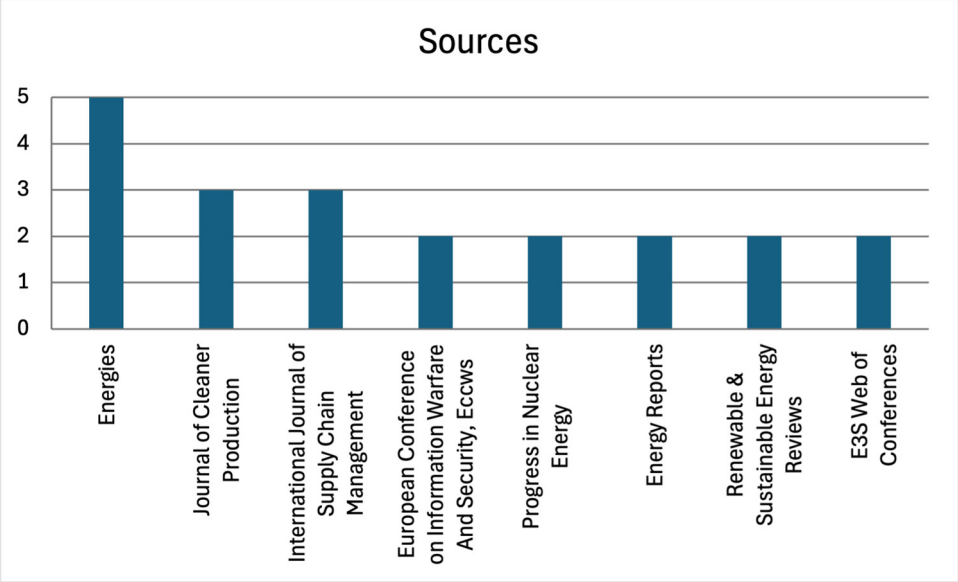

Figure 8. Sources of publications analysed.

The increasing number of publications in recent years underlines the dynamic development of the analysed research area. Contributions from leading publishers such as Elsevier, IEEE, and Springer attest to the importance of developing energy supply chains in the technical and engineering sciences field. A broad interdisciplinary impact characterises research in this area, and journals focusing on energy, sustainability, and technological innovation remain at the forefront. The increase in publications from 2020 onwards may also be linked to the global shift towards solving key challenges through technology.

5. Results

The systematic literature review made it possible to identify nine research trends, presented in Figure 9. Classification procedures were carried out to assign all selected papers for the research trends on the digitisation of the energy supply chain thus defined. Individual publications that could not be classified into any distinguished groups were assigned to the category 'Other'.

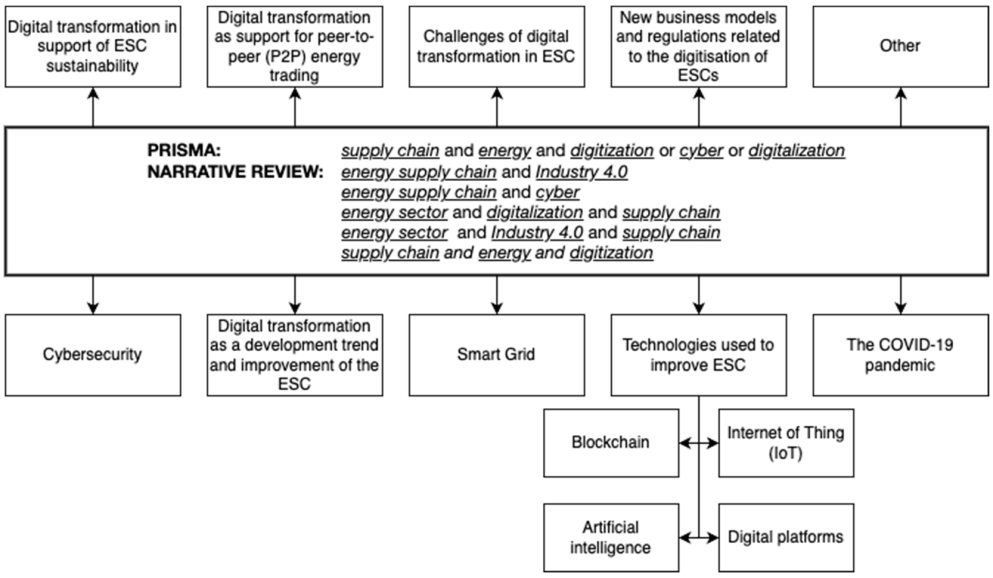

Figure 9. Dominant research trends related to the digitisation of the energy supply chain.

The two leading research trends concern cybersecurity in ESCs and the impact of digital transformation as a development trend aimed at improving ESCs. Therefore, the presentation of the results obtained starts with these two trends.

5.1. Cybersecurity

Many researchers have conducted analyses on the most relevant threats and trends related to cybersecurity [25]. A critical aspect of the digital transformation being implemented is the emerging threat concerning hacking attacks on systems supporting the operation of ESCs, information theft, cybercrimes, and other information anomalies, which have been described in [26], among others. Therefore, new power grid supply chain models based on 'zero trust' assumptions are proposed to facilitate the early detection of potential attacks [27]. Intrusion detection methods based on collaborative learning are also being developed [28], as well as solutions to identify security vulnerabilities, assess the impact of attacks, and test security measures [22,29].

Many publications analyse security in power grids, particularly those vulnerable to hacking of industrial control systems [30]. Therefore, configuration management control systems for measurement and control systems are being developed to protect them [31,32]. Creating a framework for managing cybersecurity in ESCs and defining standards for assessing cybersecurity risks is also becoming a critical aspect [33], and research is being conducted on cybersecurity at the operational and technical levels [34], as well as analyses of various cyber threats, the techniques used by hackers to attack infrastructure, and the consequences of these attacks [35]. An important element of cybersecurity management is creating an appropriate organisational culture. The results presented in [36] indicate that creating the right cybersecurity culture can significantly improve the security of the entire supply chain. The status of the cybersecurity culture among European representatives across the electricity supply chain during the coronavirus pandemic and the war in Ukraine was also assessed in [37]. The cooperation of interdependent organisations is also important for cybersecurity management. Wallis and Dorey [38] emphasise the importance of establishing a mutual commitment to agreed objectives and considering multiple perspectives on supply chain cybersecurity. Establishing an analytical framework for prioritising the protection of critical energy systems in the cyber domain can also be considered a critical aspect of cybersecurity management [39]. The two main research areas related to the cybersecurity trend are shown in Table 2.

Table 2. The main research areas related to the cybersecurity trend.

IDENTIFICATION OF RISKS	[22,25,26,29,30,35]
• identification of cyber threats (cybercrimes, information theft, hacking attacks) • threat level assessment • identification of hacking techniques • evaluation of consequences of hacking attacks	
BUILDING CYBERSECURITY	[22,27–29,31–33,36–39]
• development of models based on the 'zero trust' assumption • development of vulnerability detection methods • development of intrusion detection methods • defining risk management standards • development of a security management framework • security systems testing • development of configuration management control systems • creation of a cybersecurity culture • prioritisation of protection	

Many authors emphasise that cybersecurity in modern ESCs requires process improvement and technological development [40]. These can be achieved through the use of the following:

- Blockchain [40].
- Digital platforms [41].
- E-solutions and Internet of Things [42].
- Deep learning [43].
- Appropriate legislation [44].

5.2. Digital Transformation as a Development Trend and Improvement in the ESC

Digital transformation in ESCs is primarily described as a leading development trend that improves the functioning of the various links in the supply chain. For this reason, digitisation appears in numerous publications as a recommended direction for implemented changes, enabling the following:

- Fuller utilisation of assets [45];
- Increased operational efficiency throughout the supply chain [32,46];
- Improved cost competitiveness [32,47], including by improving cost control and changing the approach to cost management proactively [48];
- Reduced energy losses and greenhouse gas emissions [45,49,50];
- Improved reliability and speed of energy distribution [49];
- Better matching of supply and demand [47];
- Reduction in the grey area associated with energy distribution [20].

Many authors also recommend digital transformation as one of the tools for building ESC resilience [18,51]. In this case, digital transformation primarily aims to improve the risk assessment and management process [52].

Some papers describe general development trends and the importance of digital transformation in current and future energy fields [33]. On the other hand, some authors describe specific solutions dedicated to processes supporting ESC operations, such as offshore logistics [53]. Some of the analysed results described digitalisation as a current development trend for various energy sector representatives, e.g., in petrochemical supply chains [54], as well as its impact on dependent systems, e.g., commercial ports [55].

5.3. Smart Grid

The digital transformation of the energy supply chain has generated the term smart grid, describing intelligent energy networks that use advanced digital solutions to optimise electricity production, transmission, and consumption. Due to the high level of automation concerning critical infrastructure, smart grids are highly vulnerable to cybercrime attacks. For this reason, most of the publications in this group, in addition to the benefits associated with smart grid deployment (self-monitoring and self-repair, among others), focus on aspects relating to securing the energy supply chain against cyberattacks. Therefore, the papers analysed presented methods for detecting hacking intrusions [28]. The vulnerabilities in smart grid security, the types of attacks, and how to secure against them were described [22]. Other studies have focused on aspects of improving functioning smart grids. An example is the paper [56], which proposes a computing system that can integrate many distributed devices. A critical issue for the smart grid is its resilience and possible scalability. In [57], an experimental platform is proposed to enhance the smart grid's resilience, performance, and scalability. Proposed solutions can also target a specific supply chain, such as a gas distribution network [58]. The two main research areas related to the smart grid trend are shown in Table 3.

Table 3. The main research areas related to the smart grid trend.

CYBERSECURITY	[22,28]
• intrusion detection methods • identification of vulnerabilities • characteristics of attacks and recommendations for protection against them	
SMART GRID DEVELOPMENT	[56–58]
• network integration • network scalability • building resilience to disruption • modernisation of distribution systems	

5.4. Technologies Used to Improve ESC

Creating smart grids is usually based on implementing selected digital solutions that support energy generation and distribution processes. Among the most commonly described technologies used in the energy supply chain are the following:

1. Blockchain
    - In [59], three main challenges for applying blockchain are described, and a developed, decentralised peer-to-peer (P2P) energy trading platform is presented.
    - According to [60], the widespread use of blockchain can streamline ESC participants' handling of the many digital procedures, operational tasks, production schedules, and supply chains that affect how the digital well programme and schedules are created.
    - In [61], a blockchain-as-a-service is presented as an evolving platform service. Its popularity could contribute to developing modern energy systems such as battery energy storage systems (BESSs).
    - The research presented in [62] proposes a solution that offers the structure and architecture of a high-level proactive supply chain system based on blockchain and the Internet of Things. The effectiveness of blockchain technology has been confirmed in automating processes in the automotive supply chain, reducing fragmentation and increasing trust between suppliers.
    - The research presented in [63] demonstrates the need to involve government bodies, energy companies, and consumers in adopting blockchain to operate ESCs.
    - The results of the research presented in [64] indicate that blockchain-based applications should be used primarily to integrate IoT devices into the power grid, manage e-mobility infrastructure, automate billing and direct payments, and issue electricity origin certificates.
    - Keivanpour et al. [65] presented the application of blockchain in improving the operation of offshore wind farm systems.
2. Internet of Things (IoT)
    - The research presented in [62] proposed a solution for the structure and architecture of a high-level proactive supply chain system based on blockchain and the IoT. The IoT was used to track the performance of power plant components, ensuring timely maintenance.
    - Dobrowolski [42] researched the risks of using the IoT to support the energy supply chain.
    - In [66], the authors assessed the potential of using the IoT to improve the efficiency of the operation of the renewable energy supply chain
3. Artificial intelligence

- In [67], the application of AI in areas such as demand forecasting, predictive maintenance, energy management, and customer service was presented.
- Seetharam et al. [68] developed a cyber-physical system to create an intelligent energy supply chain.

4. Digital platforms
   - A holistic view of digital platforms in the energy sector, as well as their revenue models, typologies, and regulatory options, is presented in [69].
   - Haouel [70] describes the main trends in the digital transformation of oil and gas supply chains, including using platforms that provide the data needed to collaborate with suppliers.
   - In their publication, Coppolino et al. [71] explain the necessity of integrating and sharing data between ESC stakeholders based on digital platforms and identify directions for improving the data space supporting energy supply chains.
   - In [41], a Cyber Supply Chain Provenance platform for ESCs is proposed to manage cyber risks.

5.5. The COVID-19 Pandemic

The COVID-19 pandemic caused numerous disruptions across the energy sector but also accelerated the digital transformation in many ESCs. Andiappan et al. [18] point out that developing renewable energy supply chains, mainly biomass, has become a critical issue due to the pandemic. Other authors also point to the critical role of technology in pandemic impact management, presenting, among other things, a scenario of a digitised energy model including an integrated energy storage system from various sources [72]. In [73], the authors examined the resilience of power grids to pandemic disruptions. They characterised possible directions for improving ESCs by (a) analysing the impact of COVID-19 on the performance of power grids and actions taken by organisations to minimise the impacts that occur, and (b) presenting machine learning and artificial intelligence tools and concepts that can be applied to enhance the resilience of power systems in typical and extreme scenarios, such as a pandemic.

5.6. Digital Transformation in Support of ESC Sustainability

As highlighted in Section 2, the digitisation of the energy sector is very often linked to the need for ESC sustainability. Most published results confirm that energy market transformation and innovative manufacturing technologies play a significant role in sustainable energy development [74]. They are the main driver for all changes in the energy supply chain aimed at increasing energy efficiency [46]. Durr et al. [75] argue that the increased demand for energy due to more electric vehicles, heat pumps, and other solutions currently used in industry and society will accelerate digitalisation processes and climate-neutral solutions in the energy sector. This is also supported by the research presented in [76], which analyses the impact of digital transformation on the achievement of carbon neutrality by ESC participants. A comprehensive analysis of the critical challenges for the energy sector in achieving carbon neutrality is also presented in [77].

Abdellah [78] presented the results of a survey to assess the role of digitisation in renewable energy development. Also, Ghobakhloo and Fathi [79] investigated the relationship between the functionality of Industry 4.0 solutions and energy sustainability, using, among others, the opinions of experts from both areas. Similar research focused on Green Supply Chain Management was conducted by Labaran and Masood [80]. Their results focus on assessing the impact of Industry 4.0 technologies on the successful implementation of GSCM and identifying the main challenges of renewable energy supply chains supported by I4.0 solutions. In contrast, Fu et al. [49] presented the advantages of using

digital innovation to promote sustainable growth in the energy sector in their research results. They answered how companies can reduce carbon emissions and support global sustainability goals.

Some authors focus their research on specific renewable energy chains. An example of such research is [19], in which the authors analysed digital trends in biomass supply chains and then proposed a residual biomass supply chain model. On the other hand, solutions using Industry 4.0 dedicated to the photovoltaic supply chain are presented in [81]. Based on sustainability concepts, the article's authors [82] proposed a multi-stage model to reduce harmful environmental emissions, power transmission line loss, and pollution-related mortality for a regional energy supply chain in China.

Finally, it is worth noting the research results presented in [83]. In the article, the authors outline the key advantages of implementing the concept of sustainability as part of continuous industrial expansion. Their research also highlights the role of public engagement in creating more sustainable renewable energy supply chains and creating a more resilient energy industry and society based on the concept of Industry 5.0.

5.7. Digital Transformation as Support for Peer-to-Peer (P2P) Energy Trading

Peer-to-peer (P2P) energy trading refers to the sale of renewable energy between different market participants using a predetermined contract based on the automated execution of a transaction and payment for it directly between the participants. Due to its nature, the P2P system is a leading area in which the implementation of digital solutions is observed. Examples of such implementations include the following:

- A decentralised P2P energy trading platform that allows consumers and energy producers to trade directly. Such a platform is described in [59].
- A secure P2P energy trading system that uses federated learning and blockchain. The system predicts energy production and intelligently switches between entities participating in the energy-sharing process [84].
- Using blockchain as a decentralised P2P digital registry technology [60] and as a support to promote P2P trading [64].

Also noteworthy is the research presented in [85], in which the authors investigated the governance features of P2P energy-trading platforms to improve legacy solutions dedicated to energy trading.

5.8. Challenges of Digital Transformation in ESCs

In addition to its many benefits, digital transformation also brings the need for numerous changes, which pose significant challenges for ESC participants and the environment. Anand and Krishna [86] noted that digitising the energy sector brings people, process, and technology challenges. First of all, researchers point out that the digitisation of the energy sector, smart metering, and distribution systems place new demands on the training of IT specialists [87]. In [88], the problems that the sector will have to face when implementing digitisation projects are identified, namely, increased equipment consumption, lack of funding, requirements for technological compatibility of features and parameters of energy equipment and devices, unified switching standards (protocols) and information models, the required number of instruments, hardware, and software. Masood et al. [89], in their study of ESCs serving Pakistan, singles out the lack of compliance with sustainability goals, risk management culture, and awareness of Industry 4.0 as the key challenges. The availability of selected materials, which are in increasing demand due to the development of digital solutions, is also accepted as a critical challenge [90]. Therefore, the challenges of digital transformation in ESCs can be divided into the five areas highlighted in Table 4.

Table 4. The main challenges of digital transformation in ESCs.

PEOPLE	[86,87,89]
• new competence and training requirements for staff • awareness of digital transformation among staff • digitalisation as part of creating an organisational culture	
PROCESSES	[86,89]
• changes in the way operations are carried out • need to implement a culture based on risk management	
TECHNOLOGY	[86,88,89]
• technological compatibility of equipment and devices • unified switching standards and information models • software and hardware requirements	
MATERIALS	[88,90]
• availability of materials used for equipment and devices • increased wear and tear on equipment	
FINANCES	[88]
• increased need for financing new technological solutions	

5.9. New Business Models and Regulations Related to the Digitisation of ESCs

The emerging challenges associated with the digital transformation of ESCs prompt research aimed at developing new business models that meet the requirements of the changes being implemented. At the same time, due to the security of ESCs as critical infrastructure, it is also necessary to modify the operating conditions of ESCs in terms of legal norms. For this reason, publications recommend changes to current state, community, and sector regulations. Examples of such studies are the following:

- Proposed business model and regulatory framework for implementing Industry 4.0 solutions to support improved energy productivity in Australia [91].
- Proposed business model and state regulation for developing cooperative linkages aimed at improving the energy efficiency of production in the petrochemical industry [92].
- Proposal to move from a product-based business model to a service-oriented model in the electricity sector based on ecosystem-level value chain research [93].

5.10. Other

The other papers reviewed dealt with selected issues that were investigated by individual teams. Due to the lack of repetition of the research issues described, they were all included in the 'Other' group. However, the results described in them should be singled out, as they may represent future research trends undertaken by other research teams. This group included the following:

- Research on the creation and operation of smart warehouses [94] and smart factories [95], which constitute ESC links.
- Research using digital technologies as an important solution to support the operation of international ESCs [96].
- Results describing psychological aspects concerning digital adaptation in ESCs [97].
- Research on the impact of digital transformation on future projected energy demand [98,99].

6. Discussion

The literature review was carried out, and the results presented allowed for answers to the research questions posed in the introduction. These responses are shown in Figure 10 and are further characterised below.

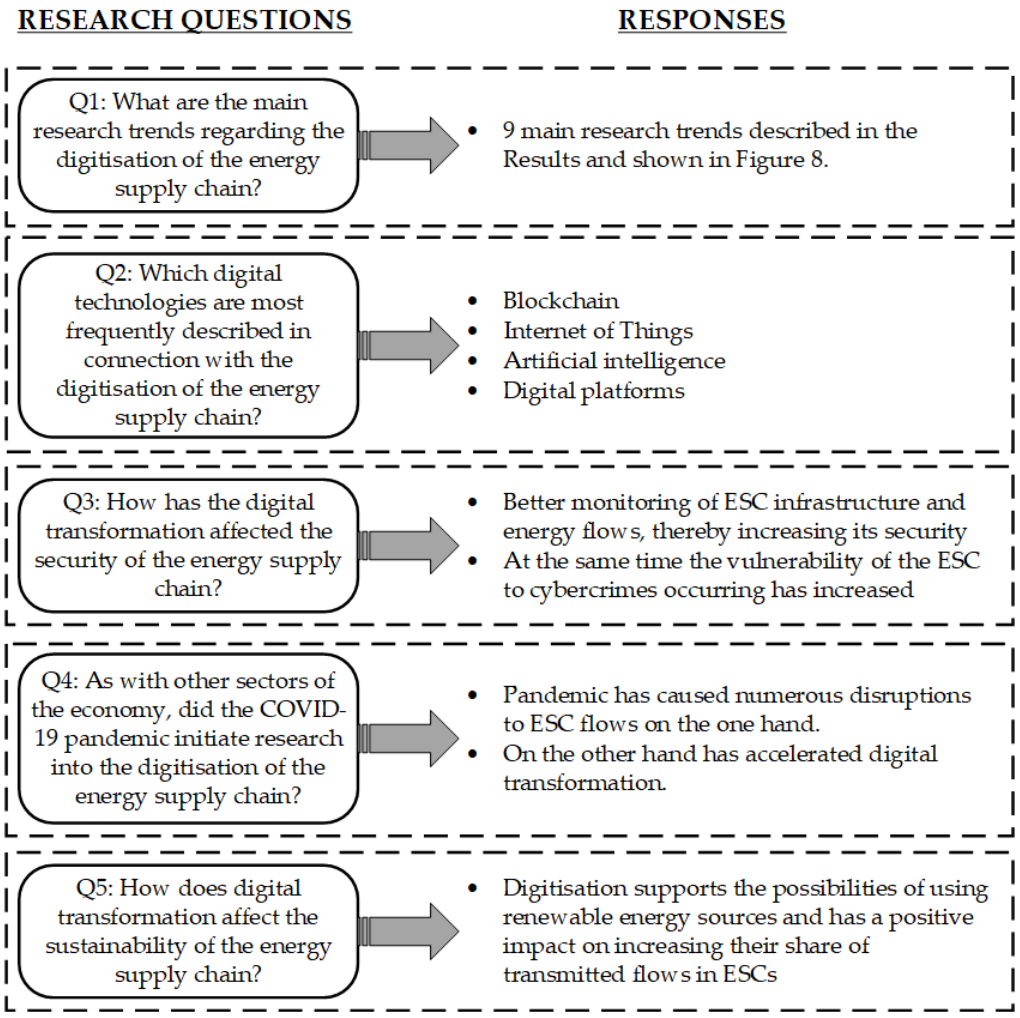

Figure 10. The responses to the research questions.

Dominant research trends on digital transformation could be distinguished in the published papers on the energy supply chain, and the classification results made it possible to define nine dominant research areas and single articles not related to the main trends, which were classified in the 'Other' group. The main research areas formulated are in line with the general directions of contemporary research and concern cybersecurity, supply chain improvement, sustainability, the impact of the COVID-19 pandemic, and the implementation of smart solutions to improve the efficiency and integration of ESCs. Among the dominant technologies dedicated to process improvement in ESCs, blockchain, the Internet of Things, digital platforms, and artificial intelligence stand out. Based on these technologies, intelligent networks are being developed to support the activities of individual links in the energy supply chain. However, most applications described in the literature are related to blockchain, which, combined with the IoT, significantly supports smart grid operations and peer-to-peer transactions.

Implementing digital technologies and automation in energy flow handling processes increases the threat of cyberattacks on smart grids. This threat is particularly high, as energy grids are part of states' critical infrastructure. Therefore, hacking attacks can introduce

significant disruptions to the state, industry, and society. For this reason, cybersecurity is one of the critical research streams that deals with methods of identifying threats, countering cyberattacks, and mitigating their possible effects. Digital solutions are also being used to enhance the resilience of ESCs and monitor the security of energy networks. Therefore, the following can be said:

- On the one hand, digital transformation increases the vulnerability of ESCs to attacks and disruptions;
- On the other hand, digital solutions enable better monitoring of the ESC infrastructure and energy flows, increasing security.

The analysis of the results shows that the energy sector was also affected by the COVID-19 pandemic, as in other sectors of the economy. However, the number of related articles regarding digitalisation is not as high as for other sectors (for example, [100]). The impact of this pandemic, as in other sectors, on the one hand, caused numerous disruptions in the functioning of ESC flows, but on the other hand, accelerated the digital transformation, which is read as a positive effect.

A significant research trend related to digitalisation is the sustainability of ESCs, including, to a large extent, the use of renewable energy sources. For this reason, several authors have researched the role of digitisation in renewable energy development sectorally and concerning a specific energy source, which is characterised in Section 2. Analysis of the published results indicates that digitisation promotes the possibility of using renewable energy sources and positively increases their share of transmitted flows in ESCs. Because of the diminishing natural resources and increasing environmental pollution, if only for this reason, digital transformation should be promoted and developed in the ESC.

As part of the discussion, attention should also be drawn to the described need for a literature review using two methods. The aspects of energy efficiency and energy savings are so strongly linked to digital transformation processes that they often appear as one of the keywords or contents in the abstract. For this reason, the number of documents returned was very high in a systematic search of databases using the PRISMA method. However, the content analysis of these papers proved that the results presented did not relate to the main research area on the digitisation of the energy supply chain. For this reason, many of these publications were rejected in subsequent stages of the proceedings. At the same time, the narrative method proved to be a more effective method for finding relevant publications. This phenomenon, however, makes it clear how important the role of the ESC is in achieving the goals of digital transformation in other sectors of the economy. Hence, there is an added emphasis on the need to digitise the processes of handling flows in ESCs.

7. Conclusions

This literature review shows the great importance of the digital transformation process in the energy supply chain, particularly in improving the functioning of modern ESCs and sustainable development based on the use of renewable energy sources. The research results presented in this article have highlighted leading research issues that researchers worldwide are analysing. These results can be used by academics who, based on the characteristics of the leading research trends, can identify the current gap that needs to be filled concerning the ongoing changes in the environment and functioning supply chain links. Industry representatives may also use the research material presented in this article, which identifies the main developments in ESCs and the digital transformation challenges participants face in these supply chains. The results present the key technologies that can support the development of ESCs and describe the benefits of achieving successive stages of digital maturity for ESC participants.

The conducted literature review represents an initial study identifying leading research trends and research gaps. The results obtained provide a basis for addressing further research challenges. Further research should focus primarily on building ESC resilience by achieving successive levels of digital maturity. To this end, it is necessary to analyse the remaining I4.0 tools that can support the assessment and management of risks occurring in the operation of smart grids. This is because it is necessary to monitor the current state of the infrastructure and the implemented flows and to forecast the potential adverse events. Digital solutions can assist the ESC in collecting the required data, and their subsequent analysis and inference should be aimed at implementing appropriate mechanisms to prevent the occurrence of adverse events or to limit their effects. The literature review results indicate the need for such studies, given the limited number of related publications that have appeared in the last five years. The resilience of the ESC is also built on the workforce and the competencies of the employees at each level of the organisation. Digitalisation significantly impacts their work and the demands placed on them in terms of the knowledge and skills they need to possess. This is another area of research that the authors will undertake to assess the digital maturity of ESCs and build their resilience. The literature review also indicates a limited number of publications assessing the impact of the COVID-19 pandemic on the digitisation of energy supply chains. Publications on other sectors of the economy indicate that the impact is significant. Therefore, this area of analysis, considering not only the impact of COVID-19 on ESCs but also comparing this impact to other sectors, will form a direction of further research.

Author Contributions: Conceptualisation, A.A.T.; methodology, A.A.T. and H.P.; validation, A.A.T. and H.P.; formal analysis, A.A.T. and H.P.; investigation, A.A.T. and H.P.; data curation, A.A.T. and H.P.; writing—original draft preparation, A.A.T. and H.P.; writing—review and editing, A.A.T.; visualisation, A.A.T. and H.P.; supervision, A.A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

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

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