

Article

# Digitalization—The Engine of Sustainability in the Energy Industry

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**Abstract:** The goal of this paper is to conduct a bibliometric analysis of the scientific literature about the sustainability of digitalization in the energy sector in order to capture the main challenges and trends in the transition towards it. The bibliometric analysis of the scientific literature was carried out by interrogating the Scopus database, using a set of keywords considered relevant for the analyzed field and for the goal of the proposed research. The purpose of the study was, on the one hand, the depth of the research into these topics during the 2013–2021 period, in terms of the number of scientific papers, the topic, abstract and keywords associated, the geographical area of origin and the authors' affiliation and on the other hand, an analysis of the existence of possible links between these topics formulated through three hypotheses. The results obtained reveal the researchers' concerns for digitalization in the energy sector, the existing correlations between the keywords analyzed and the tendencies registered in the field of digitalization in the energy industry in order to ensure higher sustainability.

**Keywords:** digitalization; energy; sustainability; industry 4.0; digital technologies



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## 1. Introduction

All activities carried out, be they economic or otherwise in nature, are influenced by the ever-increasing integration of digital technologies, causing significant changes in all fields, including changes of a social nature [1]. It is a well-known fact that with the emergence of the COVID19 pandemic, the integration of digital technologies in certain fields or activities has become a necessity, and sometimes people have had to start using digital technologies overnight, which they have learned to use on the fly.

Digitalization is often mistaken for the concept of digitization. Generally speaking, digitization means the transformation of data from analogic format into digital format, and digitalization includes digitization elements but also brings about changes due to the integration of digital technologies into organizational, social and economic processes. Digitalization is a means of improving business, optimizing business processes and increasing transparency. As with most industrial processes, the sustainability of the energy sector is influenced by the emergence of new technologies, by processes of innovation through digitalization and not least of all by the protection of the labor force by ensuring adequate social inclusion. There are many instances where digitalization seen just as a means for maximizing profit propagates social exclusion, thus creating imbalances in the economy. The energy sector plays an important role in the transition of economies towards green economies, as energy is vital for the economic and social activities carried out by people. The green economy implies the protection of the environment by using renewable resources and reducing the consumption of fossil fuels in energy production so as to reduce carbon emissions, and the energy obtained in this way is considered green energy [2].

The digitalization of the energy sector in order to increase the degree of sustainability is a complex process that brings about a lot of changes, some of them accelerated by the

COVID19 pandemic. In many cases this has caused the fast adoption of certain solutions to limit or eliminate the interaction between clients and energy producers by providing digital channels for delivering invoices, making collections, payments, installing sensors to limit human travel, redesigning certain technological processes, setting up digital meters, developing intelligent traffic control platforms, platforms for reporting energy issues, etc.

Many EU countries focus on digitalization in their progressive energy policies aiming to transition to intelligent energy systems, in accordance with the European Green Deal from 2017. Smart meters measuring in real time the bidirectional flow of renewable energy between networks and users play an important role within intelligent energy systems. Nowadays, The European Union has implemented numerous pilot projects for such systems, with the support of the Horizon 2020 program of the European Commission [3]. Digitalization comes also with data security and social exclusion risks; therefore, it must be assessed critically in terms of benefits and risks [1].

The sustainable development of the energy sector by means of digitalization entails the use of intelligent technologies that enable the automation of certain processes by using certain software, algorithms and artificial intelligence with a view to optimization. Digitalization may have several implications: from the conversion of data from analogic to digital form to the transformation of organizational, social and economic processes through digital technologies. According to [1] digitalization is performed through interlinking the activities in different sectors and ensures the cross and inter-sectoral dynamics of innovation.

Digitalization results in an efficient management of energy sources, thus facilitating the transition to sustainability in the energy sector. The aim of this article is to identify the researchers' concerns regarding digitalization in the energy sector, the existing correlations between the analyzed keywords and the trends registered in the field of digitalization of the energy industry with a view to ensuring a high level of sustainability.

## 2. Literature Review

As the engine of the economy, the energy industry has always been influenced by technological progress; industrial revolutions originated in the need for access to better and better, cheaper and easier to procure energy sources. Over time, due to stronger concerns for environmental protection, in addition to the need for energy performance, the sustainability of the energy sector also became necessary.

At the Hanover Fair [4] from 2011, a new concept, Industry 4.0, was launched in order to highlight the industrial revolution about to take place, the successor of the previous three industrial revolutions. In the meantime, this concept has gained notoriety among scientific researchers and organizations concerned with innovation in order to increase labor efficiency and productivity [5]. Chronologically, the first industrial revolution was connected to the discovery of steam engines that were used to mechanize industrial operations, the second industrial revolution was related to discovering electricity, and the third industrial revolution was connected to the discovery of nuclear energy. We could say that, one way or the other, the first three industrial revolutions are connected to the discovery of certain forms of energy [6,7]. Unlike the previous ones, the fourth industrial revolution is connected to the internet, essentially to the concept of communication. The fourth industrial revolution is an industrial revolution induced with the help of digitalization [8]. It is practically a revolution of connectivity through digitalization, unrelated to the discovery of a new type of energy but based first of all on energy use; it is a revolution that laid the foundation for the interconnectivity between various equipment, devices, machines, etc., as well as between these and people [9]. In the meantime, applications of artificial intelligence, big data, machine learning, autonomous cars, virtual reality and augmented reality, robots, Internet of Things (IoT), etc., have been introduced [10,11]. In practice, the processes of the economic and social environment have become smarter, the fourth industrial revolution is reaching a whole new level; we already speak of Industry 5.0, a revolution of intelligence, which emphasizes perfecting the interaction between people and equipment, highlighting the importance of research and innovation [4,7].

Given that the energy sector is a fundamental component of Industry 4.0 and Industry 5.0, we must ensure a means towards high sustainability in the context of the migration of the economies towards green economies, which will use more and more energies from renewable sources, with carbon emissions as reduced as possible. The European Parliament adopted on 14 July 2021 several proposals [2] to adapt EU policies in the areas of climate, energy, transportation and taxation in order to reduce net greenhouse gas emissions by at least 55% by 2030, relative to the values from 1990. According to [12], the energy sector is considered an important factor for sustainable development, and the whole of industry, in general, shall remain the main consumer of various forms of energy supplied by an economy. The use of renewable resources is one of the basic objectives of obtaining green energies, together with reducing emissions, considered harmful for the environment. Apart from promoting clean energy, without carbon emissions and reduced emissions, it is deemed that ecological processes occurring in the economy may be used for the benefit of the people, without endangering the sustainability of the ecosystems it contains [13]. The main sources for obtaining renewable energies are connected to capturing solar, wind and running water energy. If Industry 4.0 and Industry 5.0 aim to increase efficiency, this can be accomplished through lower energy consumption due to using efficient digital technologies, thus leading to high sustainability. Against this background, changes in the energy sector are fast and deep. According to a study by Deloitte [14], these can be grouped into: technological changes (artificial intelligence, internet of things—IoT, blockchain, robotics, augmented reality), social changes (energy transition, regulation, volatility of the price of resources, concentration of resources), changes in use (autonomous networks and insular networks), changes to reduce costs (preventive maintenance and operational support), changes for growth (smart homes, production capacity management) and, last but not least, disruptive models (the use of assets from adjacent sectors). Another study on the tendencies in the energy sector [15] conducted in 2018 researched the trends regarding the integration of new technologies in this sector. It showed that by 2022, 85% of the respondent companies indicated the integration of big data analytics and Internet of Things, 77%—machine learning, 73%—cloud computing, 54%—blockchain and 3D printing, 8%—humanoid robots. Other trends for the energy sector revealed by this study were the reduction of the number of employees by expanding automation (56%) and increasing the collaboration with contractors specializing in particular tasks (52%).

In view of their importance and the innovations achieved by integrating digital technologies, the following are considered pillars of Industry 4.0 [16,17]:

- a. Supply Chain
- b. Horizontal and vertical integration
- c. Internet of things
- d. Autonomous robot
- e. Augmented Reality
- f. Additive manufacturing
- g. Cybersecurity
- h. Big data analytics
- i. New Business model
- j. Artificial Intelligence
- k. Cloud computing

The integration of these pillars transforms the production process into a fully integrated, automated and optimized system, [18]. This way, the efficiency of the production process is increased, and the relations between the various actors involved (suppliers, producers, customers, people, machines) are brought to another level.

### 2.1. Supply Chain

Companies may use digital technologies to react faster to changes in the business environment, reduce overproduction, or improve waste management [19]. The integration of smart networks for efficient energy management can provide high sustainability for

companies. The technologies of Industry 4.0 also improve the efficiency of energy resources by integrating supply chains [20] and intelligent process control [21]. The integration of sustainable energy sources in the production supply chain reduces energy consumption to minimize its impact on the environment [22]. Other authors [23] show that managing the energy supply chain, where renewable energy would be obtained from waste processing would be beneficial in terms of environmental protection and could be considered a primary source of renewable energy.

Energy is conveyed almost instantaneously from one location to another, at least in terms of human perception, but one of the biggest issues with electrical energy occurs in periods of overproduction when only the energy produced can be consumed. Electrical energy can be lost in the absence of efficient storage solutions, the storage issue being highlighted ever since it was invented [24].

### 2.2. Horizontal and Vertical Integration

The digitalization of all physical elements in an organization presupposes the interlinking and integration of the processes in a production chain, vertically and horizontally. Vertical integration means digitalization and interlinking of certain internal processes within the same entity. All the information regarding the entire internal manufacturing chain is available in real time, the data being analyzed and optimized within an integrated network [17]. To this end, the use of ERP (Enterprise Resource Planning) systems enables decision making in real time, leading to an increase in productivity and efficiency of processes within organizations [25].

Time as a resource is essential in Industry 4.0, the efficiency of its use is very important. Decentralization, horizontal/vertical integration, interoperability and production capacity in real time are of great interest with regard to the duration of a manufacturing cycle, the duration of a purchasing process, etc., [26].

Horizontal integration means the digitalization of the processes outside the manufacturing entity, the availability of information in real time being very important, as well as the analysis of data from the customers and suppliers in the production chain with a view to integration in the internal processes.

### 2.3. Internet of Things

The revolution of connectivity through the Internet refers to the interconnection of each smart object or device by means of the network. This large-scale interconnection of all objects poses at least three problems in the fields where the Industry 4.0 revolution is applicable: data collection, data transfer and data security. Of these three problems, one of the most important, especially in the context of the energy sector and in particular of the energy market is that of data security. The Mirai malware that took control over the surveillance cameras and DVR devices operating on the TCP 23 port in 2016 [27] is well known. In this context, the use of blockchain technology brings about the decentralization of the IoT. Its use in the IoT ensures that data cannot be manipulated, even if it can be tracked [28].

Regarding the use of the IoT in production processes, these technologies help to monitor them more efficiently, and the use of sensor-based smart meters [29] helps to monitor energy consumption in real time [30].

### 2.4. Autonomous Robot

Autonomous robots are an important part of the future of the industrial revolution. The literature in the field [31] distinguishes between several categories of autonomous robots that could contribute to the reduction of energy consumption and more efficient energy use:

- Robots for autonomous delivery on pedestrian walkways (SADR)
- Autonomous delivery robots (RADR) are those who travel on conventional roads used by other vehicles as well

The use of these categories of robots could significantly reduce the kilometers driven by motor vehicles, which would be reflected in a reduction of the energy consumed, more efficient energy use and reduction of carbon emissions. Certain authors [31] show that there is potential for reducing the delivery times and costs when compared to classic delivery methods. The use of these types of robots could, however, cause issues related to sidewalk or road crowding, which implies issues with their management that can be solved by adequate digitalization solutions. There have been implementations of multifunctional autonomous logistics robots in certain warehouses of big retail suppliers [32], which perform logistical operations automatically for their online stores.

### 2.5. Augmented Reality

Augmented reality may have various applications for reducing energy consumption and efficient energy use. There is consideration in the field of construction, for designs that ensure reduced energy consumption with a minimum impact on the environment, with simulation and augmented reality offering multiple possibilities with regard to finding solutions for optimizing building consumption [33]. Other applications based on augmented reality streamline on-site interventions by energy producers by selecting parts from a warehouse and sending repair instructions using mobile devices. Augmented reality offers employees in the energy sector real time information about repair instructions for replacing a particular part or subassembly [34].

### 2.6. Additive Manufacturing

According to Gao et al. [22], current industrial manufacturing processes make up approximately 15% of the global energy consumption. In practice, the reduction of energy consumption, no matter how small, means progress towards global sustainability. Additive manufacturing (AM) is a process of automated manufacturing of multidimensional structures from digital models made by computer assisted depositing layer upon layer [35]. This results in an optimized manufacturing process with reduced energy consumption, ensuring high sustainability. Other authors [36] have conducted experimental studies on the energy characteristics and the power models of computer-controlled machinery. The results have shown that there are high energy savings to be made in the manufacturing process.

### 2.7. Cybersecurity

Cybersecurity is a component of Industry 4.0 dealing with issues related to the protection of the IoT system, cyberterrorism, hacking, malware, ransomware attacks, etc. The more digitalized the energy sector becomes, the more it can become the target of cyberattacks [37].

Despite the fact that the practices and doctrines of international law on sustainable development are also applicable to cyberspace [38] attacks, such as that on the US fuel pipeline network on the East Coast in 2021, which paralyzed fuel supply have become a matter of common knowledge [39].

Digitalization and hardware and software security in the energy sector must aim for development and ensure environmental protection at the same time. Economic efficiency may suffer due to the need to ensure system redundancy and automation of manual controls in order to limit the effects of possible cyberattacks [37].

### 2.8. Big Data Analytics

Paper [40] proposes an analytic framework based on large data volumes to reduce energy consumption and carbon emissions for big energy consuming manufacturing industries. Big data is a technology that processes large data sets that are too big and too complex to be managed and processed efficiently using traditional technologies and tools [41]. The large data volumes on energy consumption and the advanced analysis techniques have led to the birth of a new area of interdisciplinary research called energy big data [42].

### 2.9. *New Business Model*

Industry 4.0 must value any quantity of energy obtained from renewable sources that does not carry carbon emissions. In general, there is a tendency to overlook small energy producers as they compete with big corporations that produce energy. However, in many instances, there are regulations for small energy producers to co-exist along big energy producers [43]. This extensive approach creates new business models with social implications with regard to the debate on the contribution of newly arrived producers and of other operators in the industry to technological innovation in the energy sector [44].

### 2.10. *Artificial Intelligence*

Forecasting the demand for energy and the energy prices is more and more feasible by integrating artificial intelligence (IA) techniques [45]. As a matter of fact, AI is one of the digital technologies used on a large scale in the energy sector [46], including for energy production and conservation, integration of several renewable energies, etc. The same technology integrated through digitalization can mitigate issues related to electric vehicle access to energy sources [47], including issues related to the batteries, from the production stage to the recovery and recycling stage, this being one of the current concerns in the context of the efforts to reduce net greenhouse gas emissions by at least 55% by 2030, relative to the values from 1990 [2].

### 2.11. *Cloud Computing*

It is one of the important pillars for Industry 4.0, which offers a virtual platform for all services and resources that is accessible online, from anywhere. In order for cloud technologies to be adopted by electricity network operators, they must provide a high level of reliability and security. Any technical or security issue could have serious repercussions for energy consumers. Last but not least, the storage and processing capacity of a cloud system assigned for the energy sector must be very high. Any disruption on the operation and availability of a Cloud system could generate significant energy losses. In 2003, a malfunction of the software for an alarm system in a control room in Ohio led to the interruption of the energy supply to 45 million people in eight states [48].

## 3. **Research Methodology**

The research that we propose is a quantitative, bibliometric analysis of the works published in the field of sustainable digitalization in the energy sector. Bibliometrics is a research method that implies the inventory of scientific articles on particular topics, depending on certain criteria (location, keywords, authors' affiliation, etc.). Bibliometric data shows the scientific interests and the depth of the research on the topics considered. According to [49], scientometric indicators are important in the analysis of scientific research. The analysis of the Scopus database was conducted based on a set of words that indicate the relevant topic for the field of sustainable digitalization of the energy sector in the proposed research: digitalization AND energy AND sustainability.

Given that up to 2013 scientific interest in the field of the topic considered was insignificant (five articles prior to 2013), the analyzed period was from 2013 until October of 2021. The VOSViewer version 1.1.17 software app was used for the bibliometric analysis. VOSviewer makes maps that show graphically the links between the elements that fall under the scope of the research and that occur most frequently in the scientific production analyzed in the Scopus database. The processing performed by VOSViewer is based on data files exported from the Scopus database.

After the research material was collected, a descriptive revision of the collected articles was conducted, and then we proceeded to analyze the data, formulate the conclusions, the research limitations and the main lines for expanding the research.

Apart from the analysis of the scientific impact of each key topic considered by the research we conducted, research hypotheses regarding the possible interdependence

between particular topics were also formulated, based on the analysis of the literature in the field and the fact that digitalization is an important factor for energy sustainability:

**Hypothesis 1.** *There is an interdependence between “Digitalization” and Industry 4.0 pillars.*

**Hypothesis 2.** *There is an interdependence between “Energy” and Industry 4.0 pillars.*

**Hypothesis 3.** *There is an interdependence between “Sustainability” and Industry 4.0 pillars.*

Testing the hypotheses was performed via the correlation matrix. The Pearson correlation coefficient is often used to measure the statistical correlation and the association of certain data.

Higher values of the correlation coefficient indicate a higher dependence of the response variable on the independent variables. If the value of this coefficient is positive, the variables are directly correlated, conversely, if it is negative, they are inversely correlated.

Values of the Pearson correlation coefficient above 0.75 indicate a strong correlation, values between 0.5 and 0.75 indicate a moderate correlation, between 0.25 and 0.50 we have an acceptable correlation, and between 0 and 0.25 we have a small correlation.

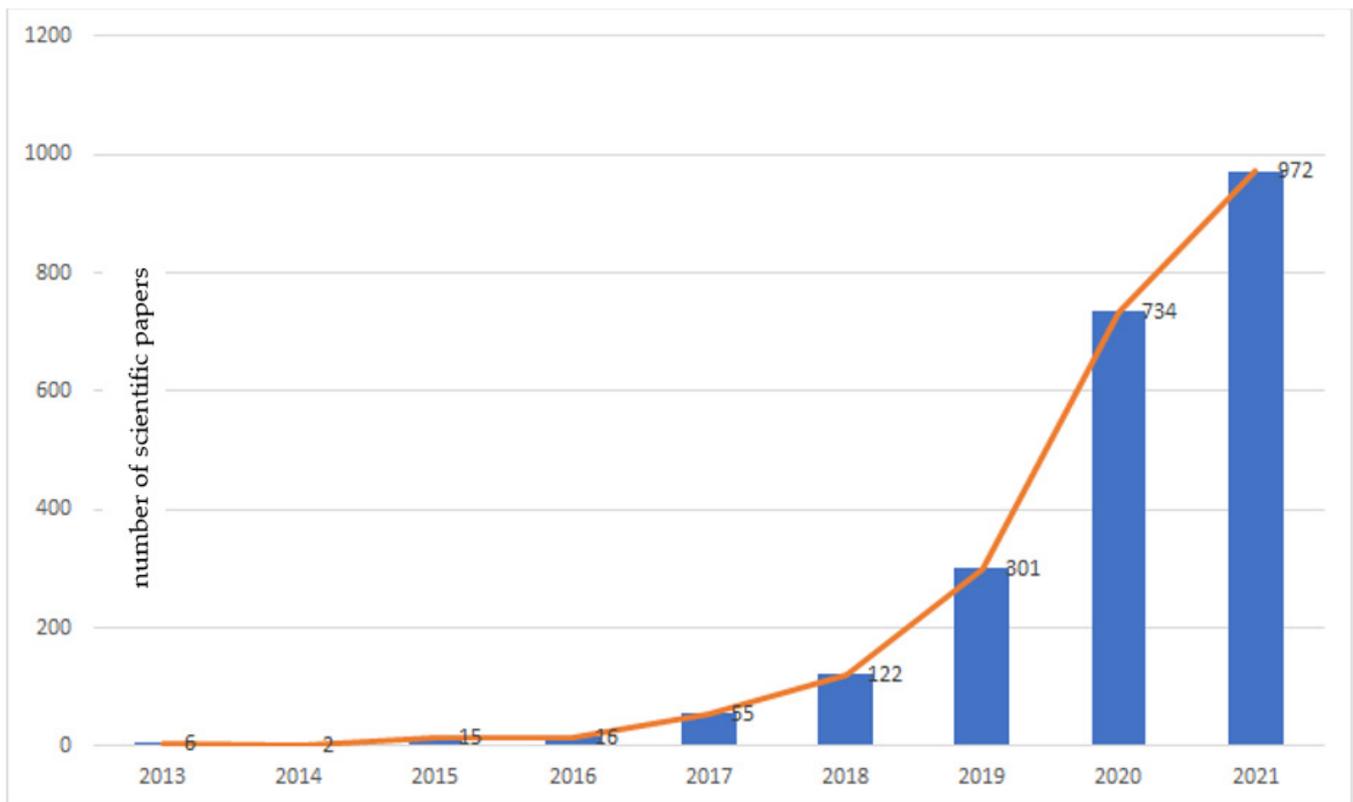
#### 4. Data Analysis

A number of 2223 scientific papers were selected, and identified within the Scopus database based on the set of words digitalization AND energy AND sustainability, and considered relevant in terms of the topic chosen for the research we conducted. The search for these was made in the title, abstract, or keywords. Table 1 indicates the distribution of the scientific papers in the analyzed period, as well as the trend in terms of the interest in the publication of scientific materials on the researched topic.

**Table 1.** The number of scientific documents in the analyzed period and the trend of the scientific interest based on the analyzed keywords. Source: processing done by the authors based on the data interrogated in the Scopus database.

Year	Number of Scientific Papers	Trend of the Scientific Interest Compared to the Year before
2021	972	+132%
2020	734	+244%
2019	301	+247%
2018	122	+222%
2017	55	+344%
2016	16	+107%
2015	15	+750%
2014	2	−33%
2013	6	-

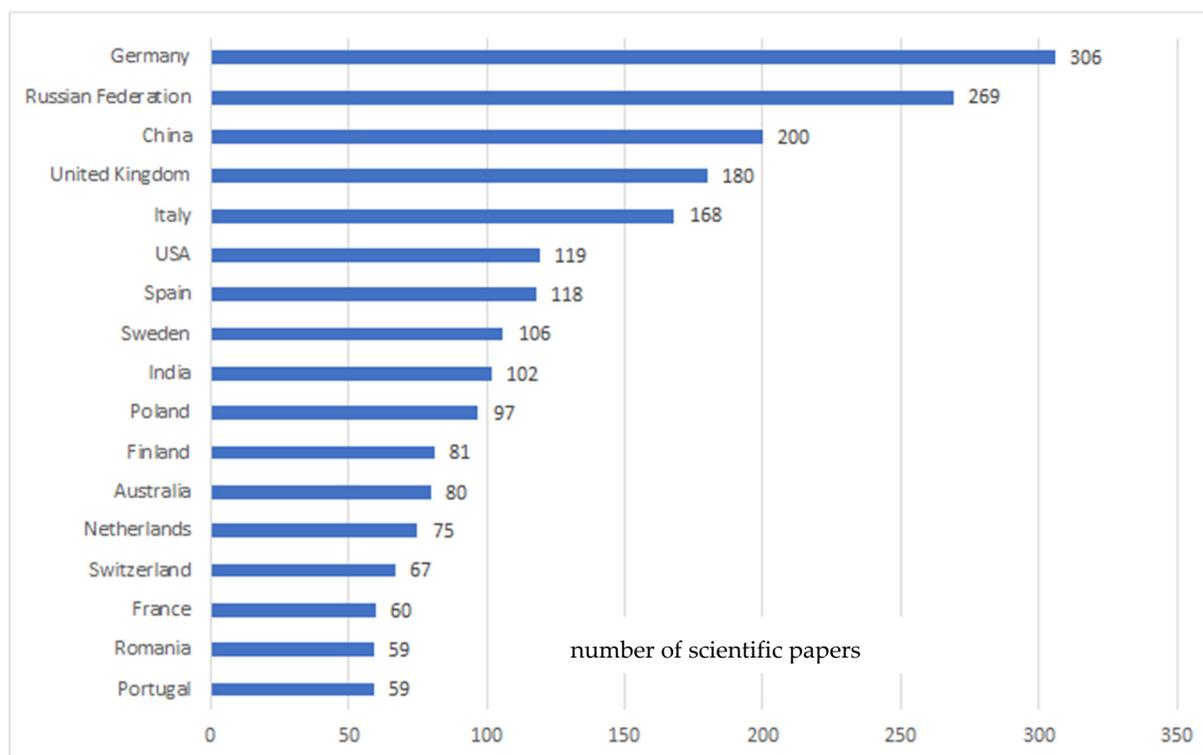
As you can see in Table 1 and Figure 1, in the first 4 years of the analyzed period the interest in publishing scientific materials on the analyzed topic was very low, the number of scientific papers published being very small, with increases from one year to the next of over 100%; between 2014 and 2015 the increase was of 750%. Beginning with the middle of the analyzed period and up to the moment of the study, the number of scientific papers on the analyzed topic began to increase consistently, reaching 972 scientific documents in the first 10 months of 2021.



**Figure 1.** The number of scientific papers and the trend of the scientific interest in the researched topic. Source: processing done by the authors based on the data interrogated in the Scopus database.

In terms of the countries (Figure 2) contributing to the publication of scientific materials on the topic of sustainable digitalization of the energy sector, we can see that the largest contribution comes from Germany with 306 (13.76% of the total) scientific papers, followed by the Russian Federation with 269 (10.10%) and China with 200 (8.9%). Additionally, we can notice that Germany contributes 1.53 times more scientific papers on the researched topic than China. The fact that Germany has the largest scientific production on the chosen topic somewhat confirms the interest of the scientific field in this country, which is actually where the term Industry 4.0 was launched at the la Hanover Fair [4] in the year 2011. Figure 2 shows the ranking of the countries contributing more than 50 scientific papers on the analyzed topic.

Regarding scientific papers benefiting from research funding, the interrogation of the Scopus database reveals that the biggest financial contributor to the research is the European Union, with a total of 93 scientific papers on the researched topic. This highlights the current concerns in the whole of the EU regarding the importance of ensuring the sustainability of the energy sector in the context of the digitalization occurring within the ongoing industrial revolution.



**Figure 2.** Distribution of scientific papers on the researched topic by country. *Source: processing done by the authors based on the data interrogated in the Scopus database.*

#### 4.1. The Bibliometric Analysis

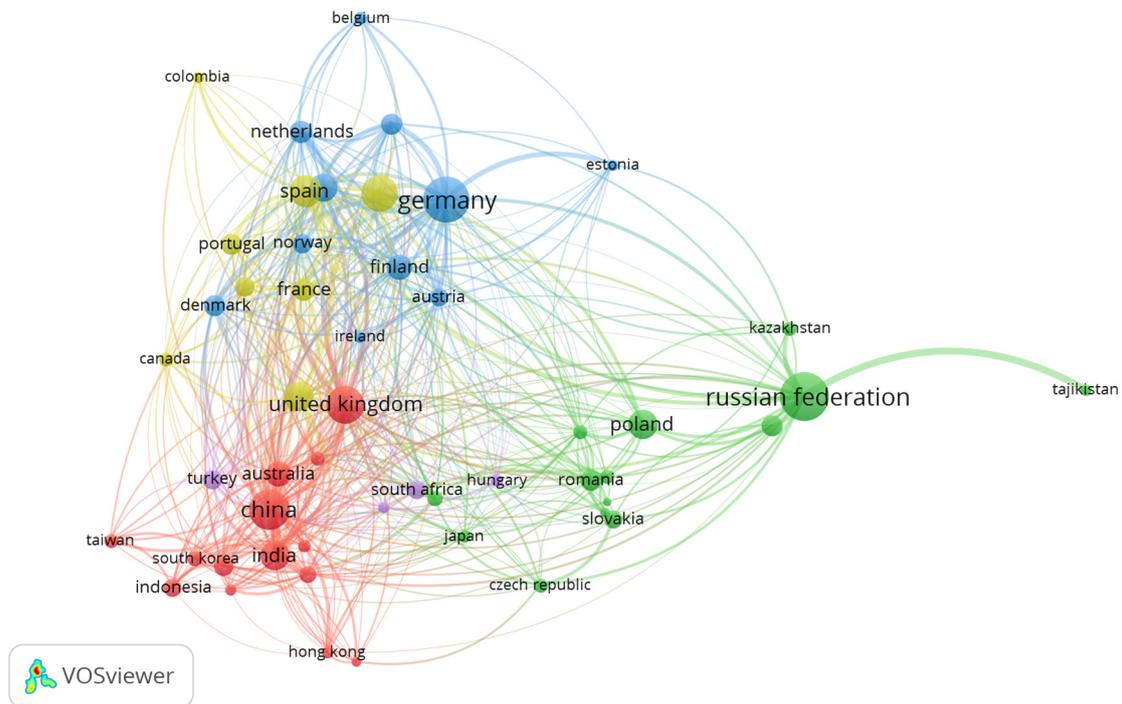
The bibliometric analysis conducted also took into account the quantification of the links between the scientific publications, by country of origin. The analysis was made using the VOSViewer app and captured the existing links between the authors of the publications, by country of origin, using a map (Figure 3). Out of a total of 116 countries, 44.82% (52 countries) had a minimum number of 10 articles and were selected for analysis.

As you can see in Figure 4 and Table 2, there are five main clusters concentrated around the countries with the largest scientific interest in the field of sustainable digitalization of the energy sector: Germany, the Russian Federation, China, and the United Kingdom.

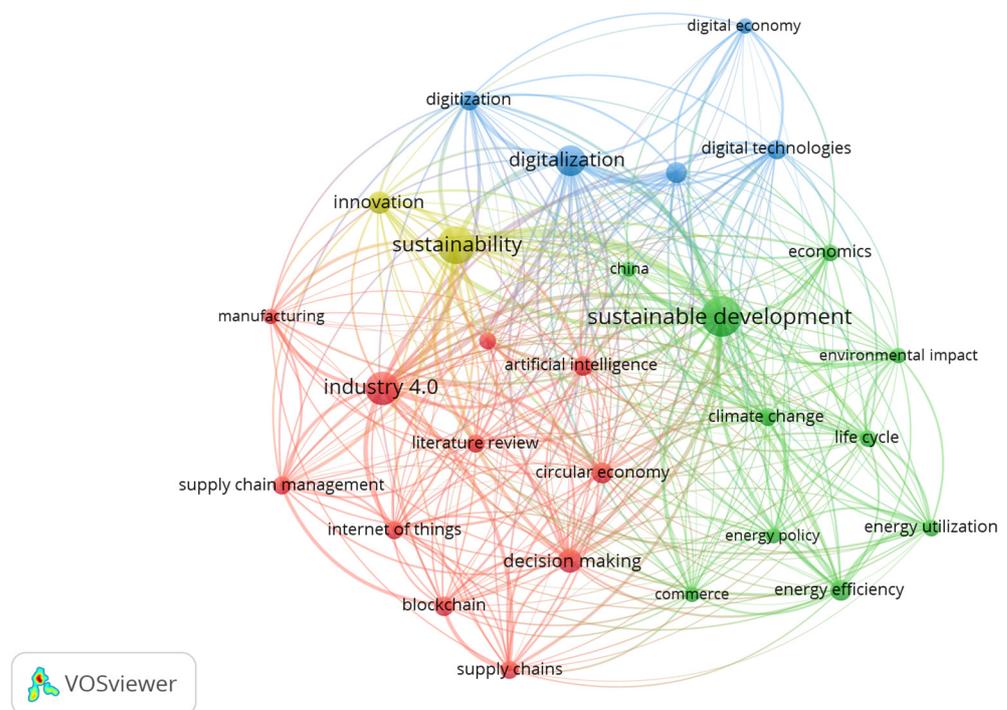
The VOSViewer app was used for the bibliometric analysis of the links between the keywords at the basis of the analyzed topic, the sustainable digitalization of the energy sector. It can generate a map of the links between the keywords with the highest number of occurrences in the title, abstract, or keywords. Practically, the app captures the relevant context of their occurrence within the topic of digitalization and energy and sustainability, considered by the research. The keywords extracted from the Scopus database were integrated into VOSviewer, where the map in Figure 4 was created, which entailed selecting a minimum limit of 50 occurrences for a word. This in turn has caused an estimate of a number of 28 terms (which constitutes 0.16% of the total) that fulfill the aforementioned condition (total number of terms identified at the moment when the Scopus database was interrogated: 12,215).

The keywords that are particularly important for the topic of digitalization and energy and sustainability in the scientific papers analyzed are the following: “industry 4.0”, “decision making”, “innovation”, “circular economy”, “energy efficiency”. The fact that the term “circular economy” was included in the top 5 of the most relevant keywords reveals the organic link between the sustainable digitalization of the energy sector and the concepts pertaining to the circular economy, as part of the green economy. Among the basic principles of the green economy are the use of renewable energies and the reduction

of carbon emissions as components to the sustainability of the economic development of society.



**Figure 3.** Graphical representation of the links between scientific papers, by country. Source: processing done by the authors with VOSViewer, based on the data interrogated in the Scopus database.

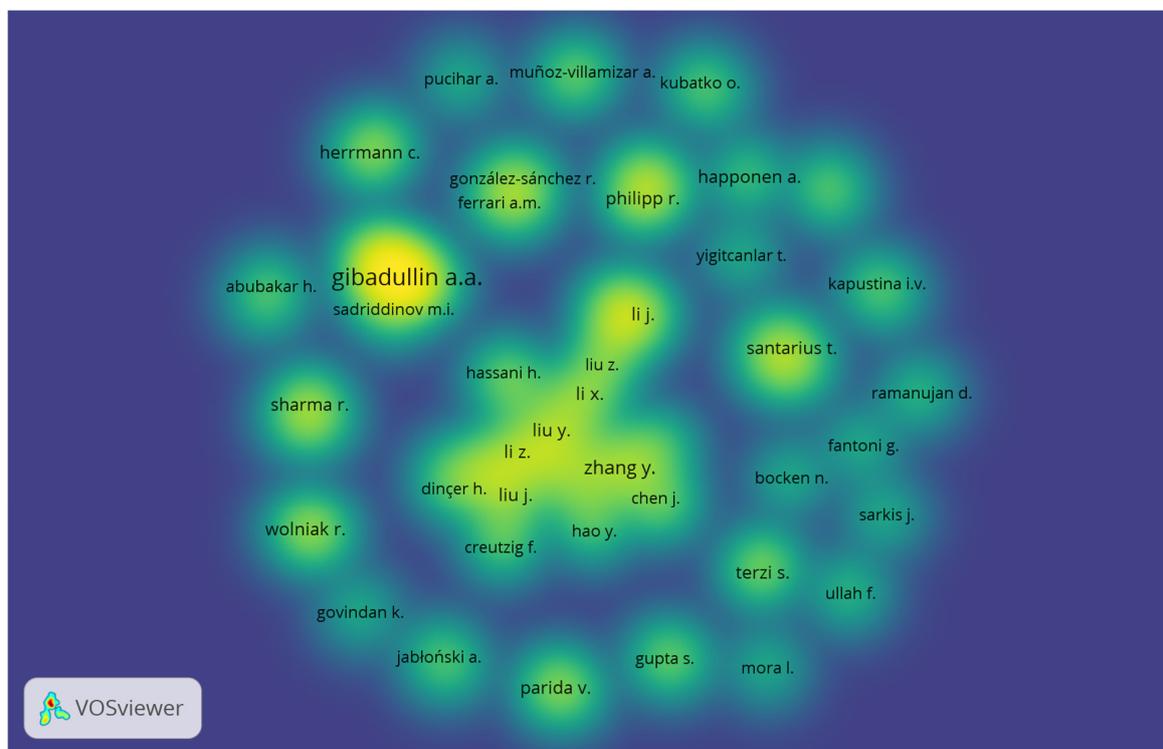


**Figure 4.** Graphical representation of the keywords and the links between them, relevant to the researched topic, resulted from the interrogation of the Scopus database. Source: processing done by the authors with VOSViewer, based on the data interrogated in the Scopus database.

**Table 2.** The main clusters and topics description.

Cluster	Topics	Description
industry 4.0	circular economy	Use of renewable energy and reduction of carbon emissions
	decision making	Making decisions to reduce energy consumption
	artificial intelligence	Energy demand forecasts, energy price forecasts
	supply chain	Supply chain management and energy storage
	blockchain	The use of blockchain technology brings IoT decentralization and provides security to systems.
	Internet of thing (IoT)	The use of IoT in production processes, helps to monitor more efficiently the use of smart meters based on sensors helps to monitor real-time energy consumption
sustainability	innovation	Innovation as an element of sustainability of economic development
digitalisation	digital economy	The positive as well as the negative impact of digitization by increasing energy consumption, waste and emissions from the manufacture, use and disposal of hardware components
sustainable development	energy efficiency	Analysis of economic development based on energy efficiency through the development of business models in the development of the supply chain in order to streamline energy consumption

The research conducted also took into account the bibliometric analysis of the collaboration between the authors of the scientific papers resulting from the interrogation of the Scopus database. The analysis was made using the VOSViewer app. The app generated a map (Figure 5) of the links between the authors who had published a minimum of four scientific documents on the analyzed topic. Out of 6278 authors resulting from the interrogation of the Scopus database, 80 had published a minimum of four scientific papers in the reference period, which represents a percentage of 1.27%.



**Figure 5.** Graphical representation of the authors and the links between them, resulted from the interrogation of the Scopus database. Source: processing done by the authors with VOSViewer, based on the data interrogated in the Scopus database.

From the authors with a strong interest in the field of the researched topic, we notice Gibadullin A.A. (Scopus author ID: 57205376624), affiliated with The State University of Management, Moscow, Russian Federation, with the most published papers (23 publications). The second place is taken by Morkovkin D.E. (Scopus author ID: 57094200800), affiliated with the Financial University under the Government of the Russian Federation, who wrote 13 publications. Likewise, Zhang Y. (Scopus author ID: 42862683500) is the author of another nine de publications on the same topic and is affiliated with the College of Civil Engineering and Architecture, Zhejiang University.

#### 4.2. Testing the Hypotheses Regarding the Interdependence between Key Topics

The correlation matrices under Tables 3–6 were created in order to verify the strength of the links between the analyzed key topics.

**Table 3.** Pearson correlation coefficient.

Pearson Correlation Coefficient	Correlation
$-0.25 < r < 0.25$	small
$-0.5 < r < -0.25$ or $0.25 < r < 0.5$	acceptable
$-0.75 < r < -0.5$ or $0.5 < r < 0.75$	moderate
$r < -0.75$ or $r > 0.75$	strong

**Table 4.** Correlation matrix for “Digitalization” and the Industry 4.0 pillars.

Keyword	Industry 4.0 Pillar	Pearson Correlation Coefficient	Correlation
A. Digitalization	1. Supply Chain	0.95	strong
	2. System Integration	−0.31	acceptable
	3. Internet Of Things	0.98	strong
	4. Robotics	0.97	strong
	5. Augmented Reality	0.63	moderate
	6. Additive Manufacturing	0.10	small
	7. Blockchain	0.87	strong
	8. Big Data	0.98	strong
	9. Business Model	0.61	strong
	10. Artificial Intelligence	0.93	strong
	11. Cloud Computing	0.04	small

According to the data in Table 4, there is a link and a strong synchronization between “Digitalization” and “Supply Chain”, “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence”.

We find a moderate interdependence  $r_{(y/x)} \in [0.5;0.75)$  between “Digitalization” and the “Augmented Reality” and “Business Model” pillars.

An acceptably strong correlation between “Digitalization” and “System Integration” ( $r_{(y/x)} = -0.31$ )

There is a lack of correlation over time between “Digitalization” and “Additive Manufacturing” ( $r_{(y/x)} = 0.10$ ) and between “Digitalization” and “Cloud Computing” ( $r_{(y/x)} = 0.04$ ).

Hypothesis H1 is confirmed for 8 of the Industry 4.0 pillars and is infirmed for 3 of the pillars.

**Table 5.** Correlation matrix for “Energy” and the Industry 4.0 pillars.

Keyword	Industry 4.0 Pillar	Pearson Correlation Coefficient	Correlation
B. Energy	1. Supply Chain	0.98	strong
	2. System Integration	−0.26	acceptable
	3. Internet Of Things	0.99	strong
	4. Robotics	0.99	strong
	5. Augmented Reality	0.35	acceptable
	6. Additive Manufacturing	0.02	small
	7. Blockchain	0.98	strong
	8. Big Data	0.98	strong
	9. Business Model	0.32	acceptable
	10. Artificial Intelligence	0.99	strong
	11. Cloud Computing	−0.03	small

**Table 6.** Correlation matrix for “Sustainability” and the Industry 4.0 pillars.

Keyword	Industry 4.0 Pillar	Pearson Correlation Coefficient	Correlation
C. Sustainability	1. Supply Chain	0.99	strong
	2. System Integration	−0.29	acceptable
	3. Internet Of Things	1.00	strong
	4. Robotics	0.99	strong
	5. Augmented Reality	0.43	moderate
	6. Additive Manufacturing	−0.02	small
	7. Blockchain	0.96	strong
	8. Big Data	0.99	strong
	9. Business Model	0.41	acceptable
	10. Artificial Intelligence	0.99	strong
	11. Cloud Computing	−0.06	small

According to the data in Table 5, there is a link and a strong synchronization between “Energy” and “Supply Chain”, “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence”.

An acceptably strong correlation between “Energy” and “System Integration” ( $r_{(y/x)} = -0.26$ ), between “Energy” and “Business Model” ( $r_{(y/x)} = 0.32$ ) and between “Energy” and “Augmented Reality” ( $r_{(y/x)} = 0.35$ ).

There is a lack of correlation over time between “Energy” and “Additive Manufacturing” ( $r_{(y/x)} = 0.10$ ) and between “Energy” and “Cloud Computing” ( $r_{(y/x)} = -0.03$ ).

Hypothesis H2 is confirmed for 7 of the Industry 4.0 pillars and is infirmed for 4 of the pillars.

According to the data in Table 6, there is a link and a strong synchronization between “Sustainability” and “Supply Chain”, “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence”.

An acceptably strong correlation between “Sustainability” and “System Integration” ( $r_{(y/x)} = -0.29$ ), between “Sustainability” and “Business Model” ( $r_{(y/x)} = 0.41$ ) and between “Sustainability” and “Augmented Reality” ( $r_{(y/x)} = 0.43$ ).

There is a lack of correlation over time between “Sustainability” and “Additive Manufacturing” ( $r_{(y/x)} = 0.02$ ) and between “Sustainability” and “Cloud Computing” ( $r_{(y/x)} = -0.06$ ).

Hypothesis H3 is confirmed for 6 of the Industry 4.0 pillars and is infirmed for 5 of the pillars.

## 5. Discussion

The bibliometric research conducted reveals the very high interest over the last three years (Figure 1) in publishing scientific materials on the topic of sustainable digitalization of the energy sector, as an integral part of Industry 4.0 and Industry 5.0. If in 2013, the first year considered by the study, only six scientific documents were published, in 2020 there were 734 documents (a 122 times increase), and in the first 10 months of 2021, there were 972 scientific materials (a 162 times increase) published. This fact shows that the analyzed topic constitutes the main piece in the new age of sustainable industrial development that we live in.

Regarding the countries that provide increased support for scientific research into the topic of sustainable digitalization of the energy sector, Germany comes in first place with 306 scientific materials out of a total of 2223 documents resulting from the interrogation of the Scopus database, which represents 13.76% of the total. Germany is actually the country that launched the concept of Industry 4.0, at the Hanover Fair in 2011 (Xu et al., 2021), this accomplishment confirms the interest in the world of science in this country in the topic of sustainable digitalization of the energy sector. Additionally, the research shows that the EU encourages and supports sustainable development by funding research in the field; 93 scientific materials published in the reference period benefited from Community financing. The bibliometric analysis of the data actually shows five main clusters grouped around the countries with the highest scientific interest in the field of the researched topic: Germany, the Russian Federation, China, and the United Kingdom.

The bibliometric analysis of the keywords in the field of sustainable digitalization of the energy sector has provided five keywords as an organic part of the research into this topic: “Industry 4.0”, “decision making”, “innovation”, “circular economy”, “energy efficiency”. The link between the sustainable digitalization of the energy sector and the concepts corresponding to the circular economy indicates that the researched topic ranks at the top of worldwide concerns for ensuring a sustainable economy focused on protecting the environment by using renewable energies and reducing carbon emissions. We also notice the term “Industry 4.0”, which confirms the importance of the energy sector in the interdependence with the Industry 4.0 industrial revolution and the fact that the sustainable digitalization of the energy sector is happening as part of it.

In the context of the circular economy, a prime objective of the sustainable energy industry is energy efficiency. This can be achieved by innovation and systems to support decision making, which entails artificial intelligence and big data.

Out of the authors publishing scientific materials on the topic of the sustainable digitalization of the energy sector, it is worth noting three: Gibadullin A.A., affiliated with The State University of Management, Moscow, Russian Federation, Morkovkin D.E., affiliated with the Financial University under the Government of the Russian Federation, Zhang Y., affiliated with the College of Civil Engineering and Architecture, Zhejiang University.

The number of scientific documents published and the ever-rising trend shows that the field of sustainable digitalization is a central one in approaching Industry 4.0 and an insight into Industry 5.0.

The correlation between the digitalization, energy, sustainability topics and the industry 4.0 pillars has shown a strong link between these topics and the “Supply Chain”, “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence” pillars. The keywords digitalization, energy, sustainability occur more rarely together with the “Business Model” and “Augmented Reality” pillars and not at all with “Additive Manufacturing” and “Cloud Computing”. The correlation between the “System Integration”

pillar and the three keywords is negative, the number of occurrences of the term “System Integration” decreases as the number of occurrences for Digitalization, Energy, Sustainability increases. This phenomenon is explained by the increase in the number of scientific papers in the field of energy sustainability through digitalization, with attention focused on “Supply Chain”, “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence” and a decreased interest in system integration.

Industry 4.0 is a revolution that laid the foundation for the interconnectivity between equipment, devices, machines, etc., as well as between these and people. There is an increasing concern about the role that artificial intelligence plays in the digitalization of the energy industry, as well as the role of automation with reference to the Industry 4.0 Robotics and Internet Of Things pillars. The problems in the supply chains and the energy storage methods are a topic of interest for research in the context of sustainability. Data storage and analysis (Big Data), as well as the transfer methods and transaction security (Blockchain) add to the landscape of the digitalization of the energy industry.

In our opinion, all the Industry 4.0 pillars can lead to increased efficiency in the energy field. System integration may constitute an innovative direction of research in the field of energy sustainability.

## 6. Conclusions and Limitations of the Research

The obtained results reveal the researchers’ concerns regarding digitalization in the energy sector, the existing correlations between digitalization, energy, sustainability and the industry 4.0 “Internet Of Things”, “Robotics”, “Blockchain”, “Big data”, “Artificial Intelligence” pillars and the trends observed in the field of digitalization of the energy industry, with a view to ensuring a high level of sustainability.

Systems to support decision making that include artificial intelligence and big data processing functionalities are essential for energy efficiency.

Energy sustainability as a goal of the circular economy implies the use of innovative technologies and automation (robots, IOT).

The digitalization of the energy industry as a sustainable method of obtaining energy efficiency implies the use of artificial intelligence to optimize decision making on the basis of big data analysis and the use of innovative technologies, such as automation and robots (Robotics and Internet Of Things).

However, one of the limitations of the research conducted is the fact that not all databases indexing scientific materials were considered. It is likely that there are publications relevant for the field of the researched topic, indexed in regional or national databases of countries that are not concerned with international visibility, but that yielded important results for research.

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