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Sustainable Energy Research Trend: A Bibliometric Analysis Using VOSviewer, RStudio Bibliometrix, and CiteSpace Software Tools

Abidin Kemeç [1] and Ayşenur Tarakcıoglu Altınay [2,*]

[1] Department of Office Services and Secretariat, Karahallı Vocational School, Usak University, Usak 64000, Turkey
[2] Department of Civil Aviation Transport Management, Civil Aviation Vocatinal High Scholl, Usak University, Campus of Bir Eylul, Usak 64200, Turkey
* Correspondence: aysenur.altinay@usak.edu.tr

Abstract: Purpose: To systematically present the publication trends related to sustainable energy, which is an interdisciplinary concept. Design/methodology/approach: This study performed bibliometric analysis to investigate sustainable energy research between 1980 and 2022 using a sample of 1498 research papers from the Web of Science (WoS) databases, with only published articles on sustainable energy. Findings: A bibliometric analysis reveals trends in sustainable energy research publications, showing sustainable energy as an emerging topic and trends in sustainability and energy research. However, it seems that sustainable energy is still a niche area of study. Within the scope of the study, 2857 publications were included in the analysis. Of the publications included in the analysis, 1498 are articles and 1089 are other publication types. As a result of the analysis, the number of articles on the United Nations' Sustainable Development Goals and the Paris Agreement has significantly increased since 2015. In 2022, the highest number was reached. It is seen that this finding is related to energy supply security and the reflections of geopolitical risks on it. The keyword "sustainable energy" stands out as the most frequently used keyword. Research limitations/implications: This research analysis is based on data from the Web of Science database only; there will be some shortcomings in the findings. Originality/Value: This research contributes to the field by exploring current developments in the field of sustainable energy, highlighting current gaps in the literature, and recommending future research in this field. The fact that the keywords "sustainable energy", "renewable energy", "sustainability", and "sustainable development" are frequently included in the literature shows that interdisciplinary academic studies in these fields are of great importance.

Keywords: sustainable energy; VOSviewer; bibliometrics; CiteSpace; Bibliometrix

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1. Introduction

Sustainability means fulfilling the basic needs of all humans without jeopardizing future generations. Sustainability in terms of energy also adopts the same principles. Sustainable energy (SE), constituting a crucial focal point of sustainability as a priority issue for human development and human activities, was conceptually defined for the first time in the Brundtland Report of the United Nations in 1987 [1]. Although it is stated in the report that SE assumes an important role in sustainable development (SD), the scope and content of such a role have not been clarified in detail. In 2000, a new development paradigm was presented in the United Nations Development Program World Energy Assessment report, and it was stated that that paradigm was linked to Sustainable Energy Development (SED), in which the impacts of energy development on the economy, society, and environment were taken into account [2]. In 2001, the IAEA (International Atomic Energy Agency) presented the first attempt to develop indicators for SED, a complex and multidimensional concept whose meaning is subject to change depending on the applications and the user's

perspective, at the ninth session of the Sustainable Development Commission, which further shaped the concept along with other international organizations and countries [3]. With the introduction of the seventh goal of the SDGs, "to ensure access to affordable, reliable, sustainable and modern energy for all" in 2015, the importance of energy in achieving SD has been defined and become more recognized. Thus, the role of energy in SD and what SED entails have been defined in more detail since the 1987 Report on Our Common Future, also known as the Brundtland Report. Today, it has an important place in the world agenda, especially due to accentuating environmental concerns and depleting fossil fuel resources. Risks aggravate each year in preserving the environment and combating global warming. Sustainable energy is generally accepted as one of the key solutions to prevent risks in the process of protecting the environment and combating global warming [4]. Fossil fuels (e.g., coal, natural gas, and oil) are not sustainable energy sources. Not only do they harm the planet when burned for energy every day, but they are also unsustainable as limited resources [5]. Considering the fact that fossil fuels will be globally depleted someday, the importance of SE is brought forth once again [6]. Because the orientation towards long-term SE systems necessitates the discussion of policy objectives and policy instruments from a more differentiated perspective, and the transition from an economy based on energy stocks to an economy based on energy flows requires a societal paradigm shift.

In association with the aims of the study, six research questions are determined. These research questions are as follows: What is the annual publication trend of the studies? Which developments have been influential in the emergence of such a trend? Which countries are brought forth in the research? What are the levels of cooperation between these countries? What are the recent prominent keywords? What are the most frequently used and strongly linked keywords with high density in the research? Who are the most prolific authors? What is the level of connection between these authors and other authors? Which journals have the highest publication scores?

In order to respond to the research questions, the relevant literature is systematically reviewed. The publications are thematically investigated in order to determine the themes with which the SE concept is associated. Upon making such a review, historical developments that constitute essential turning points for SD and climate change issues (the development of the SE concept) are taken into account.

The study of science, academic research, technologies, and innovation's quantitative traits and attributes is known as scientometrics. The statistical evaluation of publications, such as books, journals, or other study types, is the focus of bibliometrics, a field of science known as "scientometrics" [7]. Since the first article in the field of SE was published in 1980, the year range in the scope of the study was determined as 1980–2022. The current study conducts bibliometric analysis to examine research on SE during this period and utilizes a sample of 1498 research papers, which includes articles published on the concept in the WoS database. Bibliometric methods use a quantitative approach to identify, evaluate, and monitor published research studies. These methods have the potential to provide a systematic, transparent, and reproducible review process, thereby improving the quality of reviews. Bibliometric methods are useful aids in the literature reviews even prior to reading because they guide the researcher to the most influential studies and map the research field without subjective bias.

Upon collecting and analyzing the data for the determined keywords, insights about the structure of the field, social networks, and current interests can be revealed [8]. In bibliometric analysis, large amounts of bibliometric data are summarized to present the state and emerging trends of the intellectual structure of a research topic or field. By meticulously comprehending large amounts of unstructured data, bibliometric analysis is useful for deciphering and mapping the cumulative scientific knowledge and evolutionary nuances of well-established fields. Therefore, well-conducted bibliometric studies can lay solid foundations for the progress of a field in new and significant means, provide a one-stop overview of scholars and strengthen their comments, identify knowledge gaps, derive new ideas for research, and place their intended contributions to the field [9].

2. Conceptual Framework

SE, which is described as the provision of energy to fulfill contemporary needs without jeopardizing the ability of future generations to fulfill their needs [10], also means the power that can be renewed within a human lifetime, and, therefore, does not cause long-term harm to the environment. There are various environmental impacts associated with energy systems [11]. Due to the significance of energy in terms of living standards and economic development, it is of great importance to obtain SE resources, utilize advantageous energy carriers, enhance the efficiency of energy systems, mitigate the lifetime environmental impacts of energy systems, and address the non-technical aspects of SE [12]. SED involves increasing the magnitude of energy resources and managing demands for them so that societal energy needs are fulfilled with a minimal impact on greenhouse gas (GHG) emissions and a nominal outcome contribution to future climate change [13]. Although partial energy transitions have been observed from a historical perspective, a complete transition from a fossil-based energy system to SE systems is historically unprecedented at a large scale [14].

With growing concerns regarding worldwide energy scarcity and carbon emissions, SE and energy recovery are constantly attracting intense attention [15]. In recent years, the increasing demand for resources and energy has attracted the the public's attention toward sustainable energy that can be obtained from biomass, especially biomass waste [16].

Since the SE and systems lead to low carbon emissions [17], it renders the matter an important alternative for conventional energy types with high carbon emissions. Nonetheless, the transition of energy systems to more sustainable forms of energy production and consumption remains a key challenge for politicians, stakeholders, and societies around the world [18]. Because the orientation toward long-term SE systems necessitates the discussion of policy objectives and policy instruments from a more differentiated perspective, and the transition from an economy based on energy stocks to an economy based on energy flows requires a societal paradigm shift [14]. The transition to SE is also closely associated with the transformation of communities to embrace renewable energy (RE) [19]. Recently, the sudden rise in energy usage and carbon dioxide emissions (CO_2) has reached alarming levels. Although many believe that increasing population levels in urban areas account for the rise, others argue that it may be due to the production of goods and services [20,21]. Whatever the case may be, energy remains a determining factor for sustainable development [22]. Therefore, it is predicted that global industrial sector energy usage would increase by approximately 30% in 2050, whereas final product consumption would grow to exceed approximately 310 quadrillion British Thermal Units (BTUs) [23]. Upon considering the projection, the rise in energy usage is likely to affect economic activity, society, and the environment. Therefore, governments and policymakers should pay attention to cleaner energy policies to reduce carbon dioxide emissions. SE and clean production have become the main priorities of European economic policy [24]. The European Commission supports the development of SE to promote the use of energy from renewable sources and mitigate climate change [25]. SE development is recognized by governments and the public worldwide as a component of sustainable development [26].

SE includes any energy resource that is inexhaustible and may last forever. SE is also capable of fulfilling the world's demand for energy without any risk of degradation or exhaustion [27]. Therefore, SE is on the agenda as the most optimal response to the world's energy needs. The fact that SE causes either minimal or no harm to the environment supports the efforts against climate change. Energy resources per se are often free, although generating and building means to obtain SE have a cost since they require the systematic restructuring of SE structures from a new perspective [17]. SE resources, in general, include all renewable resources such as geothermal energy, solar energy, wind energy, biomass, and tidal and wave energy.

The total quantity of power produced by renewable sources in 2019 was 6963 TWh. About 61% of this (4207 TWh) came from renewable hydro, with the remainder coming from wind (1412 TWh), solar (693 TWh), bioenergy (558 TWh), geothermal energy (92 TWh), and marine energy (1 TWh). 389 TWh (69%) of bioenergy was generated from solid biofuels,

92 TWh (20%) from biogas, 69 TWh (10%) from renewable municipal trash, and 8 TWh (1%) from liquid biofuels [28]. Improving the level of SE performance helps reduce GHG emissions that are detrimental to the environment. It is a key element in achieving SDGs at environmental, micro, and macro levels (economic units and countries) [29].

Although there are various themes or pending problems associated with SED, the SE concept has improved and changed over time, similar to other issues with SD. While initially energy was discussed within the framework of reducing GHG emissions and improving air quality [30], as of today the development of SE is being discussed in a more holistic framework that takes into account the three dimensions of SD: economy, society, and environment. At this point, the role that SE assumes in promoting economic growth and social development is also confirmed [6]. Upon considering the increasing demand for energy and depleting fossil fuel resources, energy efficiency and the transition to RE are also seen as being concentrated on with regard to SE [31]. It is of great importance to understand how SE can be used to reduce the impact of increasing demands on climate change while also addressing the future of energy resources [14]. The successful completion of an SE transition (SET) is a decisive process for the long-term sustainability of societies that depend heavily on resource-limited fossil fuels. It points out the transformation of an economy based on (depleted) energy stocks into one based on RE flows [15].

With the issue of energy security on the world's agenda for a while, actions such as the importance of domestic and renewable resources and the diversification of their resources have become important parts of the development of SE as well as SE [32]. Nevertheless, within the last two decades, the issue of sustainability has gone beyond energy security due to growing concerns about the GHG impact, global warming, loss of biodiversity, gradual increase in pollutants, and deterioration of human health [33]. A crucial issue to remember is that as the global economy continues to grow and developing countries become more industrialized, energy security will be compromised through shortages of energy supplies, soaring prices, and environmental degradation caused by the overexploitation and use of fossil fuels [34]. Although a part of the problem is linked to the dispersed but growing nature of energy security threats, increasing energy security involves, in a sense, British Petroleum's Deepwater Horizon, the nuclear meltdown at Fukushima in Japan, the methane explosions in Russia and Mexico, and the Russia-Ukraine war. Energy is the lifeblood of any economy, and a steady energy supply is critical to sustainable economic growth and national security [35]. The introduction of renewable energy reduces the influence of petroleum and gas exporters in global politics. Moreover, it is surpassing the non-renewable resources as a result of the issues of climate change, resource depletion, and diversification. The changing geopolitical interest in the fossil fuel market renders renewable energy an ideal component of the global economy. Nonetheless, energy security has geopolitical implications [36] and readjusts the corresponding parameters of strategic competition [37]. Consideration of the issues pertinent to energy security among the resources reached as a result of the systematic literature review conducted within the scope of the study indicates that demographic and political developments affect publication trends.

3. Research Method and Data Collection

3.1. Research Method

The bibliometric methodology has been employed in various fields. Significant studies have been conducted in the fields of presumption [38]; COVID-19 [39]; integrated reporting [40]; environment [41,42]; blockchain technology [43]; smart cities [44]; materials research [45]; and ecopreneurship [46]. VOSviewer (https://www.vosviewer.com/ (accessed on 4 December 2022)) is free software for generating and viewing bibliometric maps. VOSviewer can be used, for instance, to create maps of authors or journals based on co-citation data, or generate keyword maps based on co-occurrence data. The software offers a visualizer in which bibliometric maps can be viewed in full detail. VOSviewer can display a map in several ways, each highlighting different aspects of the map. It has zoom, pan, and search functions that make it easier to explicate a map. Unlike software such as

SPSS and Pajek, which are widely used for bibliometric mapping, VOSviewer pays special attention to the graphical representation of bibliometric maps [47]. VOSviewer also offers various features; one is a text mining function that can be used to generate and visualize correlations upon citing an article [48].

The Bibliometrix R software package (http://www.bibliometrix.org (accessed on 4 December 2022)) provides a set of tools for quantitative research. It is developed in R language, an open-source environment, and in an ecosystem. Significant and effective statistical algorithms, access to high-quality numerical routines, and the provision of integrated data visualization tools are among the strongest features of the software. Bibliometrix is an open-source tool for quantitative research in scientometrics and bibliometrics that includes all major bibliometric analysis methods [49].

CiteSpace is a free Java application based on network analysis (https://sourceforge.net/projects/citespace// (accessed on 4 December 2022)) and visualization. CiteSpace is designed to respond to questions about the field of knowledge, a broadly defined concept encompassing a scientific field, a research field, or a scientific discipline. By courtesy of computer algorithms and interactive visualization, the overall image of knowledge domains, such as cited publications, collaborative authors, and co-occurring keywords, can be discovered [50].

3.2. Data Collection

The advent of scientific databases such as the WoS has made it relatively easier to obtain large amounts of bibliometric data. By courtesy of bibliometric softwares, such as Gephi, Leximancer, VOSviewer, Bibliometrix, and Citespace, they have provided quite a pragmatic data analysis, thus recently enhancing scientific interest in a bibliometric analysis [9]. The comprehensive platform allows monitoring ideas across disciplines and time, from nearly 1.9 billion cited references out of more than 171 million records. More than 9000 leading academic, institutional, and government institutions and millions of researchers rely on WoS for conducting high-quality research, gaining insights, and making more informed decisions that shape the future of their institutions and research strategies [51]. WoS is a bibliographically used digital database that provides researchers with various types of high-quality publications [52] and is considered the most common [53] and comprehensive data source [54,55].

The methodology part of the study is structured in two phases. In the first phase, the necessary data for the research is collected and the search strategy is determined. In the study, bibliometric research is conducted based on the Web of Science Core Collection (https://www.webofscience.com/wos/woscc/basic-search (accessed on 4 December 2022)). The search routine is as follows: "sustainable energy" (Title) and Article (Document Types). The keyword "sustainable energy" is searched in the search title of the database and the reached studies constitute the dataset. Upon including all publication types in the scope, 2857 documents are reached, and 1498 datasets emerge when the survey is limited to articles. The research is designed to cover 1498 articles belonging to the period between the years 1980 and 2022. The entire records of WoS include the author, document type, Web of Science category, keywords, year of publication, publishers, affiliated institutions, countries/regions, and indexes for each article. The survey was performed on 2 December 2022, to avoid deviations from daily updates of the database.

In the second phase of the study, firstly, all the texts containing "Record Content: Full Record and Cited References" are downloaded in PlainText format by clicking on Export Records to Plain Text File of the 1498 articles reached during the survey. Since the number of document creations at a single time is $\leq$500, 3 different documents with the extension ".txt" are generated. Then, from this meta dataset, three different softwares are utilized to generate, visualize, and analyze bibliometric networks. These tools are VOSviewer (version 1.6.18), Bibliometrix (version R. 4.2.2), and CiteSpace (version 6.1.R3). The Co-occurrence Network and Co-authorship Network are handled with the VOSviewer software—the keywords being Trend Topics, Thematic Map, and Collaboration World Map with the

Bibliometrix software—whereas Strongest Citation Bursts and the Time-Zone Visualization Map with the CiteSpace visualization software. The systematic flow chart of data collection, data analysis, and data visualization processes is illustrated (Figure 1).

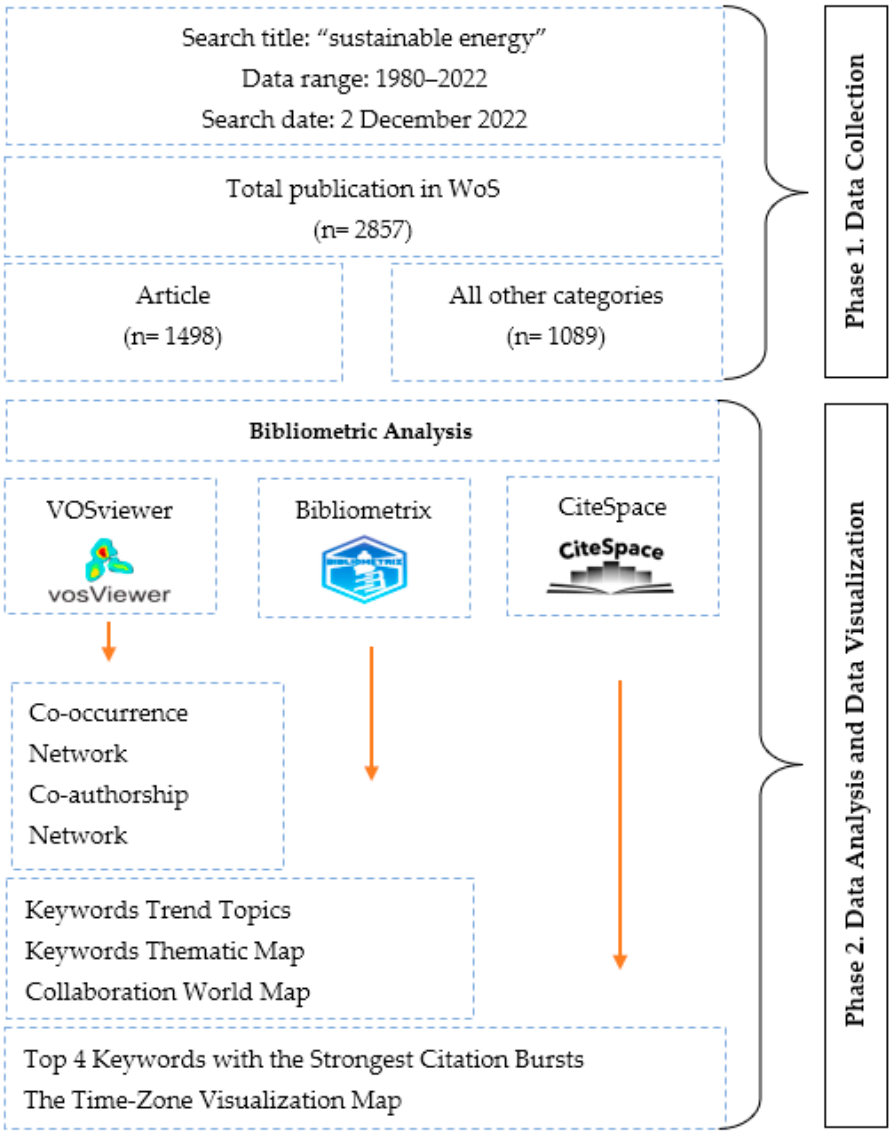


Figure 1. Flowchart of data collection, data analysis, and data visualization.

4. Findings

In this part of the study, the link strength of the keywords, their co-occurrence, their development over time, their centrality and density levels, and the data of the times when they reached the highest number of citations are analyzed and interpreted. The most productive countries in terms of academic collaboration between countries and the number of publications are assessed using different parameters. The authors with the highest number of publications and the links among the authors are discussed. The Sankey Diagram is used to analyze the author, journal, and keywords. Articles conducted on SE are analyzed by ranking by the number of citations, whereas the most productive journals are analyzed by ranking by the number of publications.

4.1. Descriptive Bibliometric Analysis

Table 1 indicates that 1498 articles were published in 636 journals by 4446 authors over the period 1980–2022. The annual average number of publications is 35.66, the average number of citations per document is 21.85, and the number of references cited in the studies is 64,505. The collaboration index in the documents is calculated at 3.35. The number of documents with a single author is 239, whereas the number of documents with multiple authors is 1259.

Table 1. Main information.

Description	Results
Timespan	1980–2022
Sources (Journals)	636
Documents	1498
Document average age	5.99
Years on average since publication	35.66
Per-document average for citations	21.85
References	64,505
Authors	4466
Single-authored documents	239
Multi-authored documents	1259
Collaboration Index [1]	3.35

[1]: Collaboration Index = Total authors of multi-authored articles/total multi-authored articles.

The overall information presented in Table 1 is discussed in detail in the following headlines of the study.

4.2. Annual Scientific Production

Over the period 1980–2022, 1498 articles have been indexed in the WoS database. The first article on SE was published in 1980 by Lewis J. Perelman [56]. Since 1980, there has been an increasing trend in compliance with academic research on SE, studies conducted by international organizations, and the financing and investment commitments provided by the European Union and the United Nations. Although only 56 articles have been conducted within the 15-year period between 1980 and 2004, various articles have been published after 2005. The highest article production was recorded in 2022 with 200 (13.3%). 13.3% of all publications were conducted in 2022. More than half of the articles have been published within the last five years. The annual average growth rate of studies is 2.59% (data were only available through 2 December 2022).

In Figure 2, since the date of the first published article on sustainable energy was 1980, the milestones affecting the sustainable energy issue between 1980 and 2022 are shown. It is seen that the issues brought to the agenda regarding sustainable development also affect the publication trend.

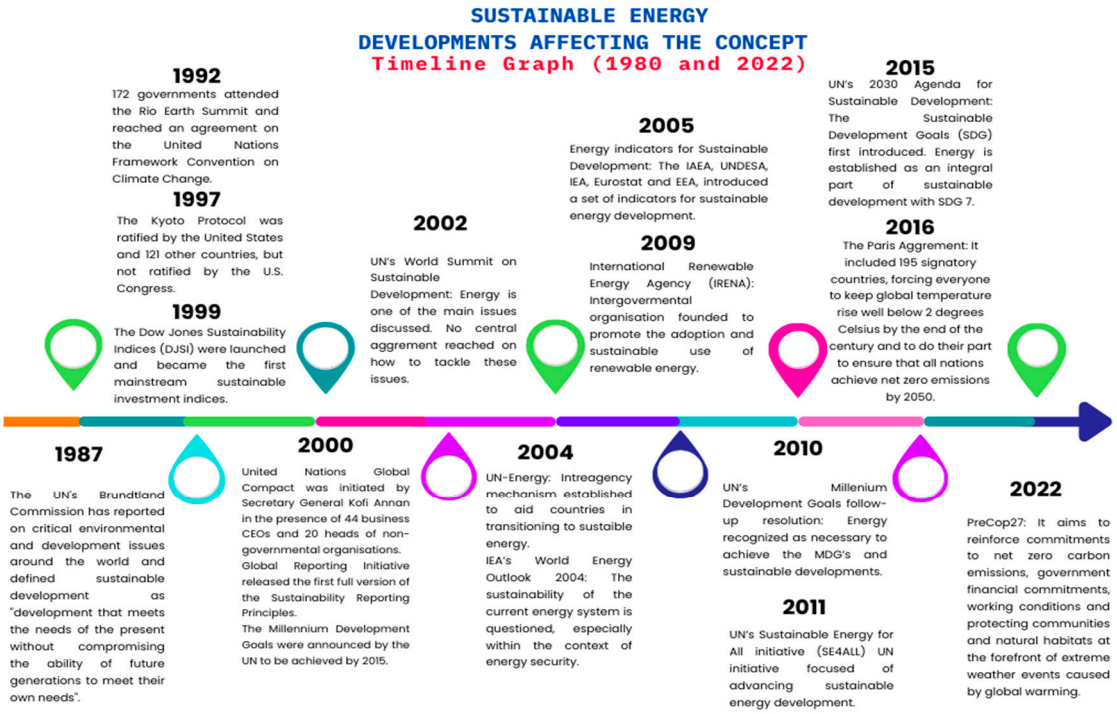


Figure 2. Sustainable development and climate change historical milestones (between 1980 and 2022). Source: authors.

The Kyoto Protocol, which was enacted in 2005, accounts for the rise in the number of publications. Over the period 2005–2015, there has been a moderate increase in the number of publications. Throughout this period, during which 32.5% of all studies have been published, the annual average number of publications was 44.3%.

This protocol aims to combat global warming and climate change on a global scale. The "SDGs" set by the United Nations General Assembly in 2015 and the Paris Agreement that was enacted in 2016 are crucial historical developments. With the impact of these historical developments, a total of 932 articles on SE have been published over the period 2016–2022, and it has been the focal point of scholars. The concept of SE has begun to be studied more frequently. Throughout this period, the annual average number of publications has increased to 133.1 (Figure 3).

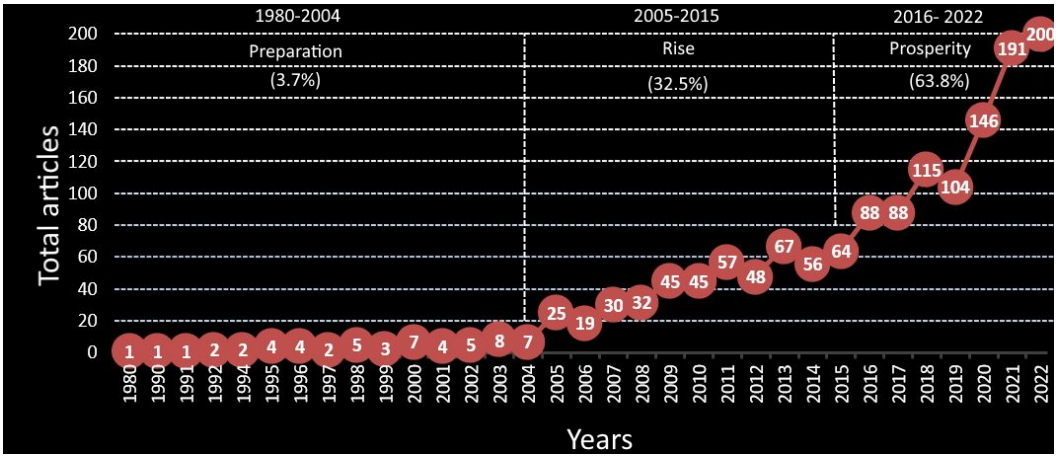


Figure 3. Sustainable Energy Publication Years.

Over the period 1980–2022, 1498 articles have been published in 636 journals by 4446 authors. The annual average number of publications is 35.66, the average number of citations per document is 21.85, and the number of references used in the studies is 64,505. The collaboration index in the documents is calculated at 3.35. The number of documents with a single author is 239, whereas the number of documents with multiple authors is 1259.

4.3. Keywords

"Renewable energy" ranks first in the list of keywords with the strongest links, with a total link strength of 632 SE (550) ranking second, whereas sustainability (476) ranks third (Table 2). The results indicate that the keywords "renewable energy", "sustainable energy", and "sustainability" led the research study. The average year of publication in the list ranges from the last quarter of 2013 to the first quarter of 2018. Generally speaking, there is a direct link between occurrences and total link strength, with two exceptions.

Table 2. Keywords with the strongest links.

R *	C *	K *	A *	TLS *	AP *
1	10	Renewable energy	222	632	2016
2	3	Sustainable energy	344	550	2017
3	6	Sustainability	151	476	2018
4	9	Sustainable development	99	396	2014
5	5	Energy	76	340	2017
6	5	Energy efficiency	73	287	2016
7	7	Energy transition	66	213	2018
8	4	Energy policy	68	210	2017
9	2	Biomass	60	180	2015
10	3	Climate change	34	159	2017

R *—Ranks, C *—Clusters, K *—Keywords, A *—Articles, TLS *—Total Link Strength, and AP *—Years on average since publication.

In network visualization maps (Figure 4), each label is denoted by a colored node. Node size is determined by the frequency of the item's usage. The higher the frequency of item usage, the larger the item's label. Additionally, the thickness of the internode and the connecting line represent the frequency of co-occurrence of the labels. There is a stronger link between nodes with the same color.

The keyword co-occurrence network analysis is one of the most effective approaches that may present scientific trends and issues that have evolved over time due to short, compact visualized maps [57]. The objective of co-occurrence analysis is to sketch the conceptual structure of a framework or summarize it in a bibliographic collection, using a co-occurrence network to map and cluster the terms extracted from keywords [49].

The variety of keywords covered by the SE literature has expanded significantly over time. In the co-occurrence network analysis using the VOSviewer software, 3955 different keywords are listed. The keywords in the list are categorized into 130 clusters. "Renewable energy", as the keyword with the largest node, is also the central node of the 10th cluster. "Sustainable energy" ranks second. The number of links between these two keywords is 14. The strongest link is between the keyword "renewable energy" and the keyword "sustainable development" (24 links).

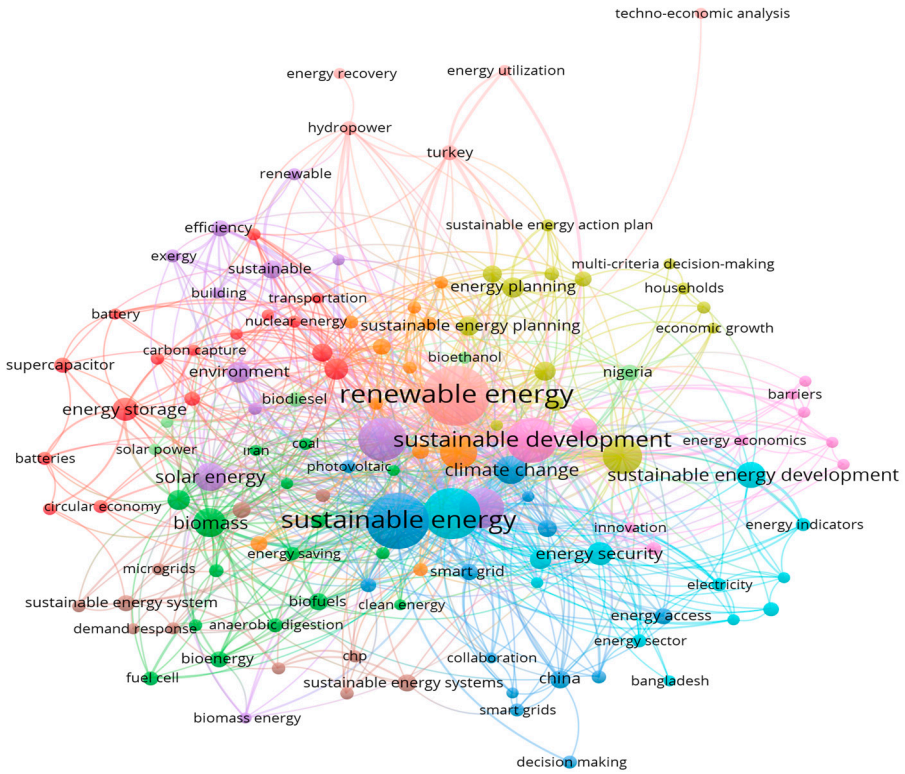


Figure 4. Keyword co-occurrence network map.

Once the threshold value is chosen, 5127 keywords fulfill this value. The keywords in the list are categorized into 11 clusters.

In Figure 5, the development of research articles over time is illustrated in terms of keywords. Although the articles published over the period 2012–2014 concentrated on RE resources, such as wind power and hydropower, the focus shifted to keywords such as "demand-side management" and "barriers" in parallel with the global problems in energy supply in current publications.

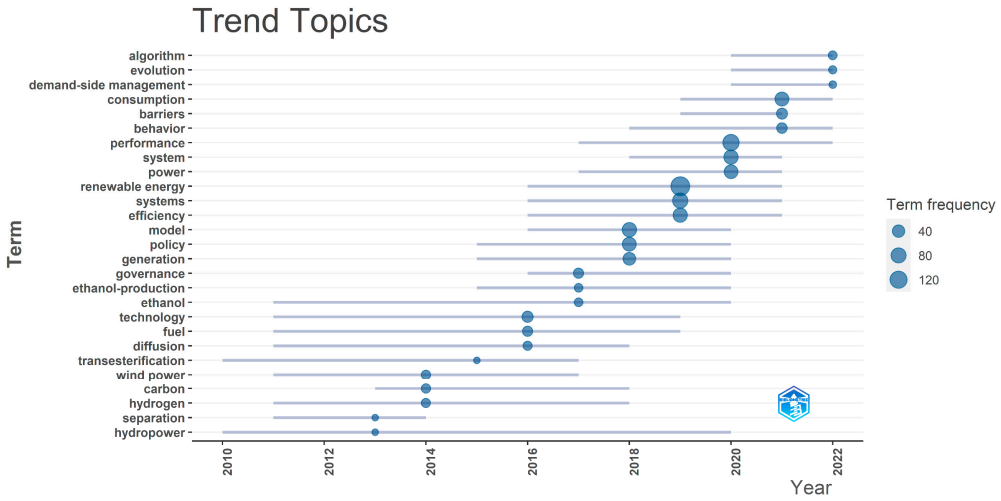


Figure 5. Keywords trend topics.

Figure 6, generated using the CiteSpace software, contains the keywords with the strongest citation bursts. The blue line represents the time interval, whereas the red line stands for the time it was detected that a keyword had a burst. Although the keyword "sustainable development" reached the highest number of citations over the period

1998–2011, the keyword "renewable energy" reached the highest citation level over the period 1996–2015. The most current keyword in terms of Citation Bursts is storage (2017–2022). The extensive penetration of variable renewable energy resources such as wind and solar in power generation ensures the achievement of climate targets as well as the transition to a decarbonized and sustainable energy system [58]. Grid-scale energy storage is required to help balance the supply and demand for energy and to prevent imbalances that may lead to problems at different grid levels. Therefore, the storage of energy produced from sources such as solar [59] and biowaste [21] has become a research topic, and this issue has started to be dealt with predominantly in the literature.



Figure 6. Top four keywords with the strongest citation bursts.

Scientific mapping techniques consist of thematic maps that depict the conceptual structure of a particular research domain (Figure 7). The thematic map consists of a network analysis of word occurrences to explain what science is saying in a field, key themes, and patterns [60]. Density is used to measure consistency between nodes, and centrality is used to measure the degree of correlation among different subjects [61].

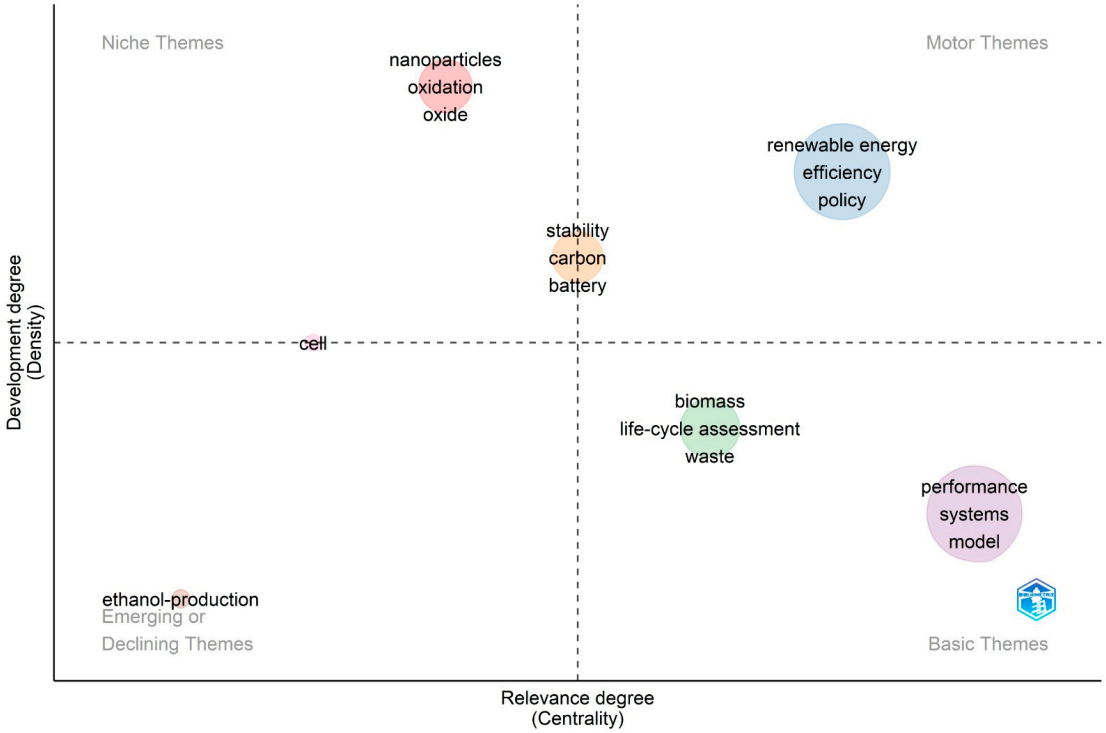


Figure 7. Keywords thematic map.

Most scientific studies and citations on "sustainable energy" belong to keywords in the motor theme group. Although nanoparticles, oxidation, and oxide are considered highly advanced but isolated (niche) themes, they have high centrality and low density. Although the keywords in this group have been more productive in previous years, their connection to the subject has weakened over time. The word "ethanol-production", however, belongs

to the emerging theme group represented by low intensity and low centrality. The connection of this keyword with other words and its relevance to other words are quite low. Performance, model, biomass, and waste are the basic themes with high density and low centrality. Keywords in this group have a low internal connection.

The visual highlighting of the temporal relationships in the keyword network linking with SE is illustrated in Figure 8. In the cluster timeline view, the horizontal axis corresponds to the years, and the vertical axis corresponds to the cluster labels. The studies published over the period 1980–2022 are selected for analysis with a time frame of 1 year. The size of the circle represents the number of studies published by the author. The shorter the distance between the two circles, the greater the collaboration between the two keywords. Cluster #0, the SE information cluster, ranks first since it has had citation bursts in recent years. In this cluster, there are keywords such as "energy efficiency", "sustainable energy", "capacity", "ownership", "power generation", "selection", "sector", "technology", "strategy", "environment", and "energy security". The words "capacity", "selection" and "sector" in this group are the most recent keywords. In recent years, the focal point of research has changed. Global developments have had an impact on the research trend. The words "mint indicator", "hydrogen economy", "energy scenario", "customer preference", and "rural energy policy" do not have up-to-date and high-profile publications.

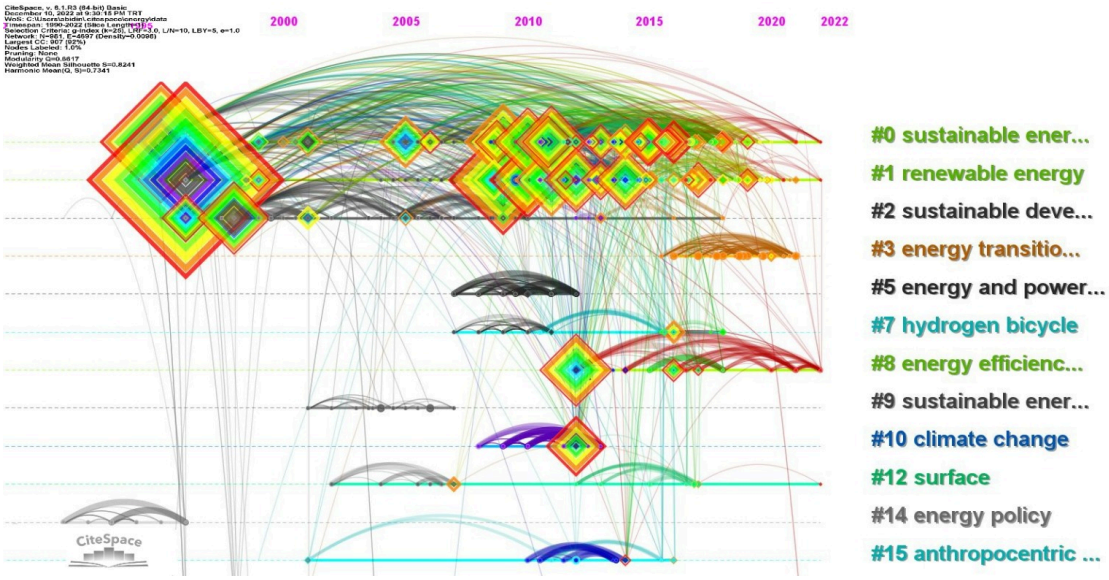


Figure 8. The time zone visualization map.

4.4. Countries/Regions

An analysis of the country/region-based distribution of research can help to comprehend a country's capacity and explore capacity differences among various countries [62]. Academic collaboration among different countries or regions may assume a guiding role in promoting the dissemination of knowledge and academic exchange [63]. The collaboration world map shows the authors' country-based affiliation. The colors on the map show the intensity level of the relationship (light colors indicate weak relationship, dark colors indicate stronger relationship. Gray color indicates no connection) (Figure 9). Upon evaluation in terms of country connections, the countries with the strongest links are China and the USA, each with 20 links. The fact that the link strength ranks first among these countries also has a direct impact on the number of publications conducted by the countries. The intercountry connection map under the title of SE is illustrated in Figure 9. China, as one of the most active countries in SE, has collaborations with Pakistan (12), Canada (9), the United Kingdom (8), and Australia (7), respectively. Four different strong collaborations (with Asia, America, Europe, and Australia) have been established. Despite the different

languages spoken by the contacted countries, Chinese scholars are more likely to establish multinational partnerships.

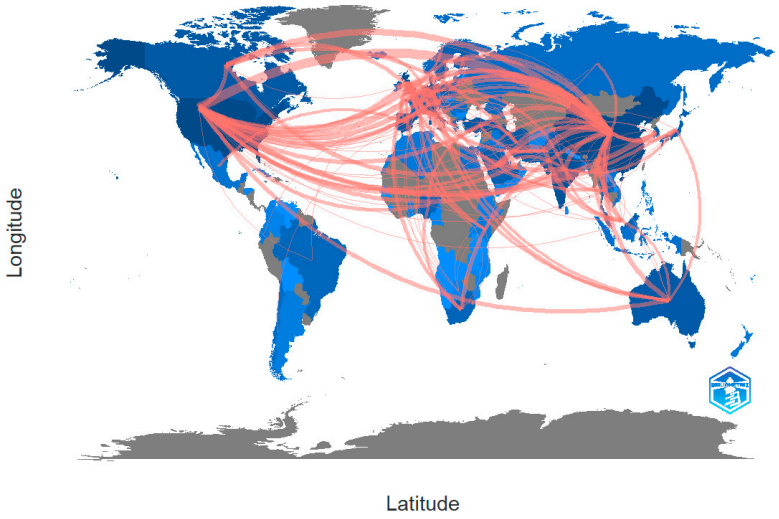


Figure 9. Collaboration world map.

Table 3 lists the top 10 most active nations/regions. Upon ranking countries/regions by the number of publications, the most productive countries are China (153), the USA (147), and the UK (110), respectively. China's share of all publications is higher than 10%. Although the USA lags behind China in the number of publications, it is almost twice as high as China in terms of citations. This proves that American authors are publishing higher-quality articles.

Table 3. Most influential countries.

CR *	C *	A *	TA *	SCP *	MCP *	F *	MCP_Ratio *
China	2	153	3887	87	66	0.102	0.431
USA	7	147	7269	112	35	0.098	0.238
United Kingdom	3	110	3712	84	26	0.073	0.236
India	1	79	877	64	15	0.053	0.190
Germany	6	72	1176	58	14	0.048	0.194
Italy	5	58	1230	46	12	0.039	0.207
The Netherlands	1	48	1682	40	8	0.032	0.167
Canada	6	42	393	28	14	0.028	0.333
Spain	2	42	440	31	11	0.028	0.262
Turkey	2	41	500	37	4	0.027	0.098

CR *—Countries/Regions, C *—Clusters, A *—Articles, TA *—Total articles, SCP *—Single Country Publications, F *—Frequency, MCP *—Multiple Country Publications, and MCP_Ratio *—MCP/Articles, Freq: Articles/Publication.

A large number of high-tech research institutes, attractive government incentives, and a large number of researchers in China, the USA, and the UK are influential in the high number of publications. At the same time, China's energy security would encounter a more serious challenge, and sustainable energy development is considered to affect the publication trend as it becomes a real problem that China needs to solve [64]. Approximately 43% of the Chinese-produced publications have been conducted with authors from more than one country. Turkish researchers, however, have collaborated with authors from other countries at a low rate (9.8%). The USA was the first country to publish on SE.

Upon considering that the negative impacts of global warming and climate change are felt on a global scale and that the adverse impacts will emerge even more in the coming years, it is possible that the number of countries studying in this field and the established collaborations will increase.

4.5. Authors and Co-Authorship

Co-authorship is mainly used to analyze the co-signatures of authors in published articles (Figure 10). If two authors collectively produce a published article, they are considered to have a mutually collaborative relationship, expressed as a link connecting the two authors in a co-authorship network [65]. Such information can also assist individual researchers seeking potential collaboration, and publishers can also utilize co-authorship findings to form editorial teams [66].

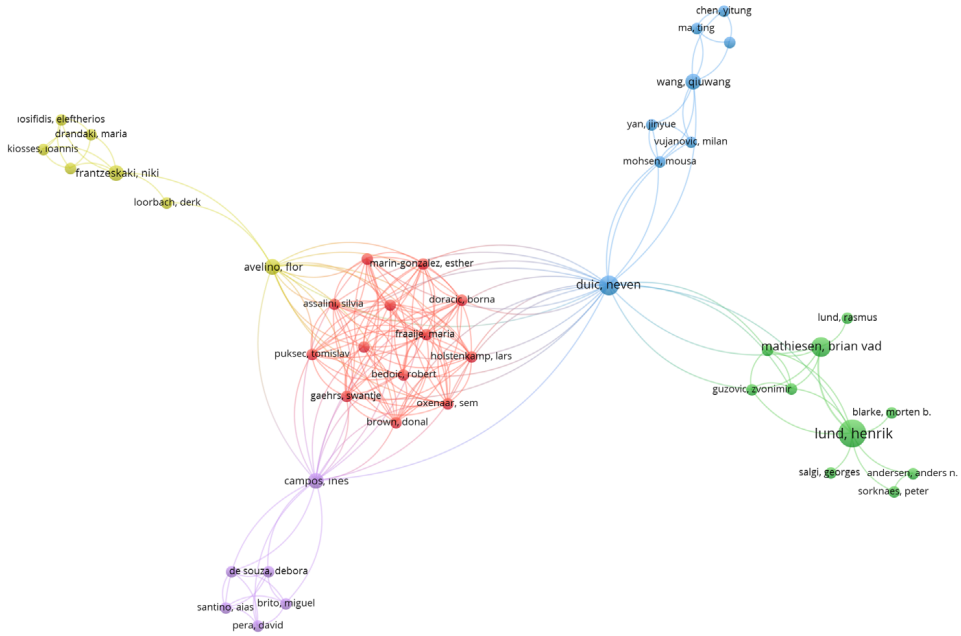


Figure 10. Co-authorship network map.

It is increasingly common today to develop a research project while sharing authorship with field experts from other institutions and even from other countries. The network of professionals currently being created is becoming increasingly intense, so researchers need to conduct more specialized studies and connect with authors who have had a greater influence on research.

In the co-authorship analysis, 44 authors with the strongest link were selected among 4617 authors. These authors are represented in five different clusters. Upon ranking the authors by the number of links, Duic Neven, which is located in the central node of the third cluster (blue), ranks first. Duic Neven works in the Department of Mechanical Engineering at the University of Zagreb. This author has cited 24 different authors from different clusters in 3 publications on the topic. The total number of links of Campos Ines, who ranks second, is 20. Campos Ines is the central node of the fifth cluster (purple). Although there is no central node in the first cluster (red), the authors in the central nodes of the second (green) and fourth (yellow) clusters are Lund Henrik and Avelino Flor, respectively. Štreimikienė, Dalia who ranks first in terms of the number of publications, is not included in the list due to having weak link strength (4). Furthermore, the link strengths of all the authors listed in Table 4 are not sufficient.

Table 4. The Most Productive Authors.

R *	AU *	TA *	CA *	FA *	CR *	H-Index
1	Štreimikienė, Dalia	15	Lithuanian Institute of Agrarian Economics	2005	Lithuania	41
2	Breyer, Christian	9	LUT University	2017	Finland	40
3	Bak, Tadeusz	8	Western Sydney University	2014	Australia	13
4	Nowotny, Janusz	7	Western Sydney University	2014	Australia	39
5	Atanacio, Armand J.	6	Australian Nuclear Science and Technology Organization	2016	Australia	11
6	Kuzemko, Caroline	6	University of Warwick	2016	England	14
7	Balezentis, Tomas	6	Lithuanian Institute of Agrarian Economics	2012	Lithuania	36
8	Ionescu, Mihail	6	Australian Nuclear Science and Technology Organization	2016	Australia	26
9	Wang, Zhong Lin	5	Georgia Institute of Technology	2010	USA	264
10	Rahman, Kazi Akikur	5	United States Department of Energy	2018	USA	4

R *—Ranks, AU *—Authors, TA *—Total articles, CA *—Current affiliations, FA *—First articles, and CR *—Countries/Regions.

The top 10 authors with the highest number of publications among 4466 authors are presented in Table 5. Upon analyzing Table 5, Streimikiene, Dalia from the Lithuanian Institute of Agrarian Economics rank first with 15 research articles on the subject. The author, who conducted his first publication in 2005, ranks fourth in the total number of citations. Štreimikienė, Dalia has concentrated on studies on the analysis of RE resources and their applicability in the Baltic countries [67–70]. The author's last study was on measuring the impact of RE resources, public health expenditures, logistics, and environmental performance on sustainable economic growth [68].

Breyer, Christian, at LUT University, published 9 articles on SE over the period 2017–2022. This author is at the top of the list with an average of 1.8 publications per year. Although his contribution to the number of publications is modest, the author with the highest number (570) in his ranking is Wang, Zhong Lin. The differentiation of the rankings by the number of citations, number of publications, and h-index indicate that no author dominates the field. Upon evaluating the scope of the countries in which the authors are located, researchers from Lithuania and Australia are brought forth.

The Sankey Diagram indicating the relationships among keywords (left), authors (middle), and journals (right) is three-dimensionally illustrated in Figure 11. The figure describes the authors' contribution to the relevant journals and their keyword preferences. According to the Sankey Diagram, the higher the number of links among the variables, the thicker the connection lines. The most prolific writer, Štreimikienė, Dalia, has published in the journals Energy Policy, Energies, the Journal of Cleaner Production, and Sustainability, while using the keywords "sustainability," "sustainable energy," "sustainable development," and "energy transition" most frequently in her studies. Breyer, Christian, who ranks second in productivity, concentrated on the keywords "sustainable development," "energy transition," and "biomass" while working with the Journal of Cleaner Production and Renewable *and* Sustainable Energy Reviews.

Table 5. The most productive journals by the number of publications.

R *	J *	I *	P *	CR *	TA * (%)	TC *	H-Index	IF (2021) [1]	FA *	JCI [2]
1	Energy Policy	SCIE	Elsevier	England	84 (5.6)	3904	212	7.576	1997	1.64
2	Sustainability	SSCI	MDPI	Switzerland	65 (4.3)	530	109	3.889	2009	0.65
3	Energies	SCIE	MDPI	Switzerland	58 (3.8)	497	111	3.252	2008	0.45
4	Journal of Cleaner Production	SCIE	Elsevier	England	56 (3.7)	1234	232	11.072	1993	1.51
5	Renewable Energy	SCIE	Elsevier	England	39 (2.6)	1141	337	8.634	1991	1.38
6	Energy	SCIE	Elsevier	England	35 (2.3)	1705	212	8.857	1976	1.46
7	Applied Energy	SCIE	Elsevier	England	31 (2.06)	1130	235	11.446	1997	1.67
8	Renewable Sustainable Energy Reviews	SCIE	Elsevier	England	25 (1.66)	721	337	16.799	1997	1.26
9	Energy Research Social Science	SSCI	Elsevier	The Netherlands	21 (1.4)	720	76	8.514	2014	1.75
10	Sustainable Energy Technologies and Assessments	SSCI	Elsevier	The Netherlands	19 (1.26)	212	48	7.632	2013	1.07

R *—Ranks, J *—Journals, I *—Indexes, P *—Publishers, CR *—Countries/Regions, TA *—Total articles, TC *—Total citations, and FA *—First articles. [1]: https://www.scimagojr.com/journalrank.php (accessed on 20 December 2022); [2]: JCI is a measure of the mean value of Category Normalized Citation Impact (CNCI) of citable items published by a journal over the past three years.

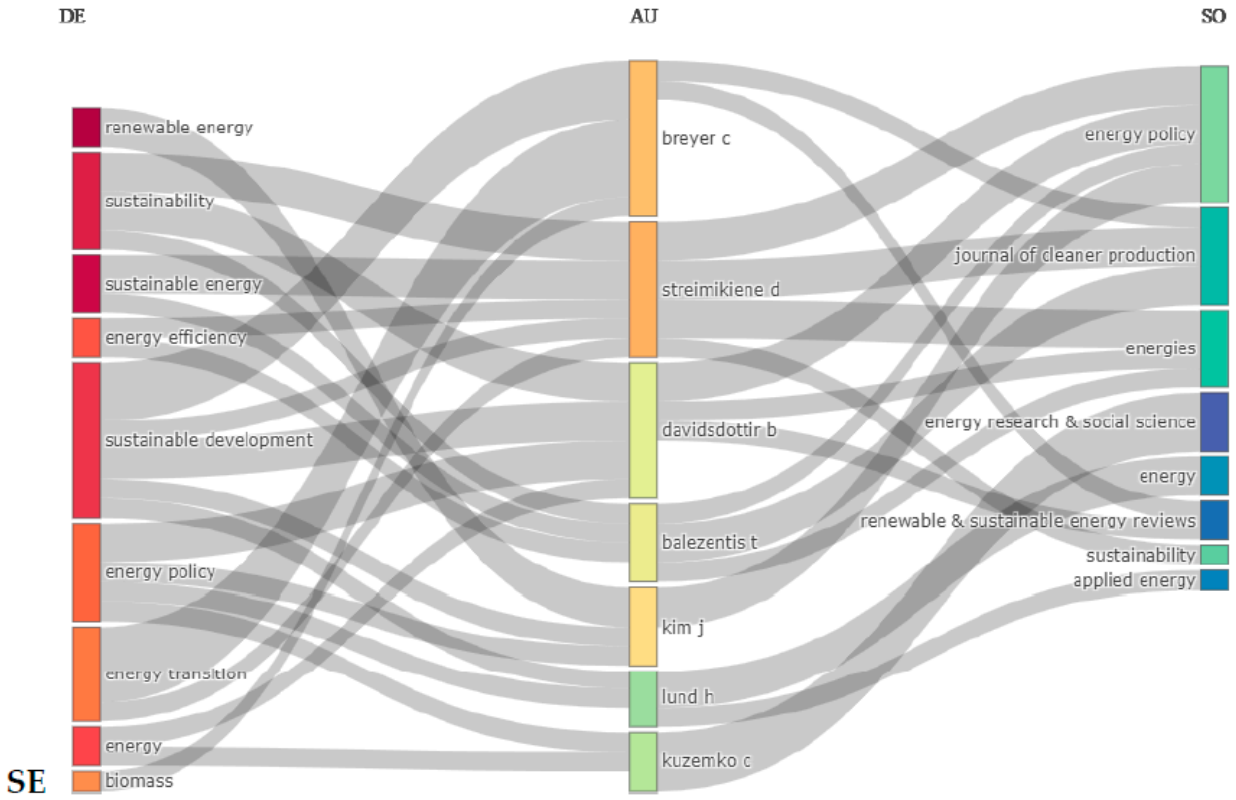


Figure 11. Sankey diagram of author, journal, and keywords.

4.6. The Most Productive Journals

The higher the number of articles and citations a journal has published, the more effective it becomes [71]. Therefore, the number of articles, the number of citations, and the indexes associated with the citations of the journals are analyzed. Table 5 presents the

list of the top 10 most effective journals by the number of publications. Journals in the top 10 constitute 28.68% of all publications.

A total of 1498 articles produced over the period 1980–2022 have been published in 487 different journals. Upon comparing the journals by the number of publications produced (84) and citations (3904), Energy Policy ranks first. The h-index, impact factor, and journal citation indicator of the journal are 212, 7.576, and 1.64, respectively. The Energy Policy journal is owned by the Elsevier group. The journals that rank first and second constitute approximately 10% of all publications. Upon examining the top 10 journals, 8 of them are those of the Elsevier company. The other two journals belong to the MDPI group. These numbers indicate the dominance of Elsevier Company. The ranks of publications and citations in the list tend to differ. For instance, the journal Sustainability, which ranks second in terms of the number of publications, ranks 8th by the number of citations. The Energy Journal, which ranks 6th by the number of publications and began to be published in 1976, ranks second with 1705 citations. The journal with the highest impact factor, Renewable Sustainable Energy Reviews, lags behind by the number of publications (8th place). All of the journals on the list have been published in English.

4.7. The Most Influential Publications

Articles conducted on SE received a total of 32,681 citations. The articles with the highest number of citations, related article titles, authors, DOI number, publication year, total citations, and average citation data are listed in Table 6. The pioneering study in terms of the number of citations (2268) was conducted by Chu, S., Cui, Y., and Liu, N., in 2017 and published in the Journal of Nature Materials. It received 6.94% of all citations. This study concentrated on clean energy generation, transmission, and distribution; storage of electrical and chemical energy; energy efficiency; and better energy management systems. Moreover, the research study with the highest annual average number of citations is also this study. The article, which was published in 2002 and received a total of 1000 citations in 2022, is about hydrogen energy. The studies that rank third and fourth are associated with hydrogen energy. Since there is a temporal impact on the number of citations, publications following the year 2017 are not included in the list.

Table 6. Academic publications with the highest number of citations.

R *	T *	Y *	TC *	CC *	AC *
1	"The path towards sustainable energy" [72].	2017	2268	6.94%	378
2	"Hydrogen futures: toward a sustainable energy system" [73].	2002	1000	3.05%	47.62
3	"The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet" [74].	2005	679	2.07%	37.72
4	"Hydrogen and fuel cells: Towards a sustainable energy future" [75].	2008	635	1.94%	42.33
5	"Growing grassroots innovations: exploring the role of community-based initiatives in governing sustainable energy transitions" [76].	2012	497	1.52%	45.18
6	"Solid acid catalysts for biodiesel production—Towards sustainable energy" [77].	2006	459	1.4%	27.00

Table 6. *Cont.*

R *	T *	Y *	TC *	CC *	AC *
7	"The role of compressed air energy storage (CAES) in future sustainable energy systems" [78].	2009	362	1.1%	25.86
8	"Oil palm biomass as a sustainable energy source: A Malaysian case study" [79].	2009	316	0.96%	22.57
9	"Practical Potential of Reverse Electrodialysis as Process for Sustainable Energy Generation" [80].	2009	249	0.76%	17.79
10	"A grassroots sustainable energy niche? Reflections on community energy in the UK" [81].	2014	241	0.73%	26.78

R *—Ranks, T *—Titles, Y *—Years, TC *—Total citations, CC *—Citation Contribution, and AC *—Average citation.

5. Conclusions

Scientific interest in the concept of sustainable energy has been increasing continuously since 1980 and has continued with an intensifying trend since 2015. Although studies were initiated by American scientists, they are not specific to a particular region, country, or institution and are conducted worldwide. In recent years, in addition to the fact that European scientists are at the forefront of the most productive authors, an increasing trend has been observed in the studies of Chinese scientists on the subject. The most important reason behind this is thought to be the support given by the Chinese government to scientific studies. Interinstitutional collaborations have been intensifying since 2007. The descriptive bibliometrics and visualization in this article revealed that Lithuanian (TA:15) and Finnish (TA:9) scientists are leaders in publishing research on sustainable energy and related topics. As seen in high-impact references, their articles were published in top-ranked journals. Sustainable energy and related issues have attracted great attention over the years, and sustainable energy has become an important part of reducing human impact on the environment. Research can be systematized into different focus sets that differ over time. The current focus (1980–2022) is on storage for sustainable energy, renewable energy sources, and the creation of infrastructure to establish energy supply security.

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