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Research Article

# Trends and future perspectives in wind energy studies: A bibliometric analysis with time-series neural networks

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## ABSTRACT

Energy, which is a fundamental resource for the universe and one of the indispensable requirements of today's modern world, plays an important role in many fields. In contrast to traditional energy sources, the utilization of renewable energy sources that offer a sustainable, clean, environmentally-friendly future is growing rapidly. Wind energy, as one of these sources, has become widespread and a focal point for energy production. This study conducted a bibliometric analysis, a data mining technique, on English publications (articles, reviews, proceedings, and book chapters) indexed in SCI-E, SSCI, and ESCI in Web of Science from 2010 to 2023. The analysis examined publication numbers, citations, authors, institutions, countries, journals, publishers, research areas, and keywords, and investigated their connections. To visualize trends, clusters, spatial distribution, and common interactions, Vosviewer, ArcGIS, and Excel were used. Temporal changes were assessed by dividing the years into three periods, showing an increasing trend in publications and citations in recent years. To forecast future changes, a Nonlinear Autoregressive Exogenous time series method predicted the number of future publications and citations. The analysis predicts continued growth in publications and citations until 2030, with a focus on energy fuels research. Finally, a multidisciplinary assessment was conducted to provide a broad perspective on wind energy and contribute to the versatility of the study. The study aims to be a comprehensive resource and guide for researchers working on wind energy and bibliometric analysis.

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## INTRODUCTION

Throughout history, human beings have questioned life to understand the universe, make progress, and sustain existence. By observing daily life, people discovered that energy is the primary solution source [1]. Defining energy is challenging due to its dynamic structure and interdisciplinary roles. Aristotle's association of the word "entelechia,"

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meaning "complete reality," with the word "energeia" in his work Metaphysics led to the derivation of the word "energy," which modernly formulates in terms of power, force, and work [2, 3]. Energy, generally defined as the capacity to do work, represents all forms that can exist in various ways such as kinetic, potential, mechanical, heat, magnetic, electrical, chemical, and nuclear energy [4].

Energy has played an essential role in the development and evolution of the universe, encompassing both living and non-living entities throughout history [5]. It is possible to categorize energy, one of the most significant factors in the emergence of civilizations, meeting the needs of human beings, and the socio-economic-cultural development of countries, into different resource groups [6]. Energy resources can be divided into two groups: renewable and non-renewable energy resources based on whether they are exhaustible or not. Unsustainable and non-continuous energy resources are at risk of depletion because they cannot renew themselves despite their presence in nature [7]. These resources, which are divided into two as fossil and nuclear energy, are classified into subgroups as coal, oil, natural gas, uranium and thorium.

The energy that is derived from natural processes that are repetitive and permanent is called renewable energy. Solar, wind, hydroelectric, geothermal, biomass and wave are among renewable energy sources [8, 9]. These sources are also known as alternative energy sources and can meet a significant proportion of the world's total energy demand [8]. Population growth, urbanization, industrialization, economic growth, and changes in living standards all contribute to an increase in energy demand. To meet this demand, providing energy supply with renewable energy sources is a sustainable and economically viable solution compared to fossil fuels, which are exhaustible and costly. The production of renewable energy has been on the rise in recent years. In Figure 1, which is based on data from the International Renewable Energy Agency (IRENA), renewable energy production statistics between 2012-2020 are presented both in general and separately for each renewable energy type [10]. Hydroelectric energy stands out as the most produced renewable energy type, with a large production amount that has been on an upward trend over the years. Wind energy production has also significantly increased over time, making it the second most produced renewable energy type after hydroelectric energy. Solar energy production has experienced a significant increase as well, especially after 2015, following a period of stagnation between 2012 and 2015. Biomass, geothermal, and wave energy follow solar energy in terms of production amounts. Overall, there has been a dominant increasing trend in the production of renewable energy. The figure illustrates a growing trend in the production of renewable energy sources, suggesting that their use is likely to increase in proportion.

The sun, which is the main energy source of the earth, is one of the renewable energy sources that influence the emergence of many other energy sources [11]. Solar energy that reaches the earth's atmosphere through reflection is examined in three different ways: solar photovoltaic isolated, photovoltaic grid-connected and thermal solar energy [12-14]. The sun, which causes temperature and pressure differences while heating the earth, is also the main source of winds and thus wind energy. Wind energy, which is easy to generate thanks to turbines and is both climate and environmentally friendly, is a clean resource that is rapidly developing. Solar and wind energy are preferable because they are accessible resources and can be easily produced at an affordable cost. This increases their use significantly and makes them stand out.

Hydroelectric energy is another type of energy produced by utilizing the movement caused by the sun directing the flow of water. This energy is generated from a comprehensive system consisting of a dam, reservoir and power plant. The water stored in hydroelectric power plants is directed to the turbines with a high pressure and thus the mechanical energy is converted into electrical energy by rotating the turbines. In the generation of hydroelectric energy, the sun is utilized as well as the energy generated by waves and tides [15]. Globally, about 1150 GW of hydroelectric energy generation has made it one of the largest renewable energy sources [16].

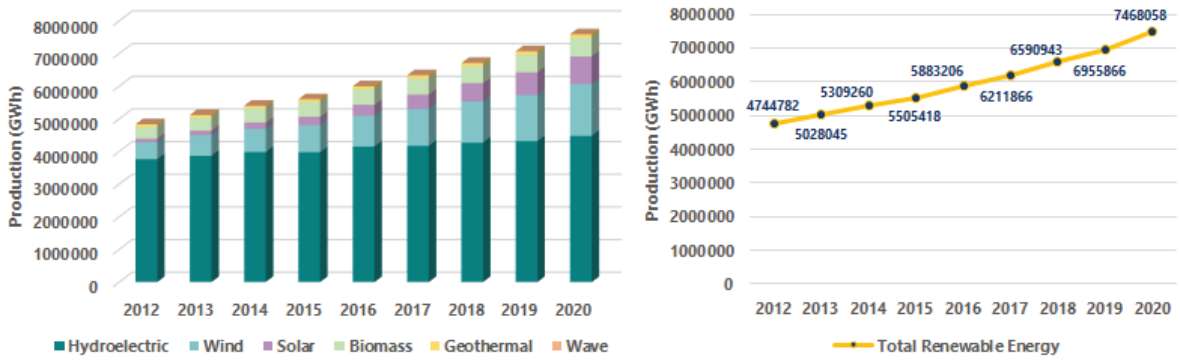


**Figure 1.** Production statistics for renewable energy and resources worldwide between 2012 and 2020.

Obtained by utilizing the internal thermal energy of the earth and independent of solar energy, geothermal energy is one of the renewable energy sources used effectively in electricity generation. Geothermal systems, which consist of three components: a heat source, a carrier fluid that allows the heat to be transferred, and a reservoir, enable the heat to be taken from the source and transferred to the surface [17]. Environmentally friendly geothermal energy is used electricity generation as well as in heating and power applications.

Another renewable energy source influenced by solar energy is biomass. Obtained through plants and animal matter and consisting of carbohydrates, biomass is a special source [18]. Its basic structure includes materials left over

**Table 1.** Applications, advantages and capacities of renewable energy sources

| Renewable Energy Source | Applications | Advantages | Worldwide Capacity (2021) [10] |
|---|---|---|---|
|  **Wind** | • Electricity generation<br>• Electricity demand of factories and industrial areas<br>• Lighting<br>• Water pumping and storage<br>• Grain grinding<br>• Cooling systems<br>• Logistics<br>• Battery and charging stations | • Environmentally friendly<br>• Can be used in small and large scale<br>• Easy maintenance and long lifespan of the system<br>• Quite economical<br>• Abundant and freely available in the atmosphere, thus easily accessible<br>• A clean source | 824 874 MW |
|  **Solar** | • Electricity generation<br>• Heating<br>• Ventilation and cooling systems<br>• Irrigation systems<br>• Electricity for devices<br>• Electric vehicles<br>• Battery and charging stations | • Environmentally friendly<br>• Unlimited<br>• Economical<br>• Reduces greenhouse gas emissions<br>• Easy maintenance and long lifespan of the system<br>• Effective for energy security<br>• A clean source | 849 473 MW |
|  **Hydroelectric** | • Electricity generation<br>• Irrigation systems<br>• Grain grinding<br>• Industrial areas | • A clean energy<br>• Reduces greenhouse gas emissions<br>• Easy maintenance and long lifespan of the system<br>• High energy efficiency<br>• Does not require fuel as it benefits from water, preventing the formation of toxic gases<br>• Benefits agriculture, fishing, tourism, and other fields. | 1 360 054 MW |
|  **Geothermal** | • Electricity generation<br>• Heating and cooling systems<br>• Greenhouse systems<br>• Health tourism<br>• Drying | • A clean source<br>• Reduces greenhouse gas emissions<br>• Energy potential is quite large<br>• Being a natural resource, it does not require fuel<br>• High efficiency | 15 644 MW |
|  **Biomass** | • Electricity generation<br>• Heating and cooling systems<br>• As fuel | • Contributes to recycling<br>• Environmentally friendly<br>• Reduces greenhouse gas emissions<br>• Provides continuous energy supply<br>• Easily stored | 143 371 MW |
|  **Wave** | • Electricity generation<br>• Industrial areas and facilities<br>• Heating systems<br>• Lighting | • Environmentally friendly<br>• Provides continuous energy supply<br>• Has no polluting effect<br>• Helps areas like fishing and water sports<br>• Does not harm the land. | 524 MW |

from agricultural and forestry practices and the residues of industrial and animal products. This makes biomass energy one of the sustainable energy sources globally. While biomass energy is generally used in heating and electricity generation applications, it is also frequently preferred in industrial studies and transportation.

Generated by winds, wave energy is a type of renewable energy whose main source is the sun, since wind is also caused by the sun [19]. The wind passing over the oceans creates waves on the surface. These waves move over long distances depending on the increase in wind speed. The waves rise as the distance increases, thus enhancing the wave energy [20]. The high energy density of waves makes wave energy advantageous compared to other types of energy. Information on the application patterns, advantages and worldwide capacities of these renewable energy sources are given in detail in Table 1.

Considering the world in general, it is seen that most of the countries are dependent on fossil fuels [21]. The use of fossil fuels to meet energy needs brings along the problems of global warming and climate change. The use of renewable energy resources is of great importance in combating these problems that negatively affect our world and all humanity. Using these resources will prevent carbon emissions, reduce environmental destruction and enable clean production, thus contributing to the sustainability of nature. Supporting this is the 7th Sustainable Development Goal, which states. With this goal, which is "Ensure access to affordable, reliable, sustainable and modern energy for all", it is aimed to gain momentum in increasing and expanding the use of renewable energy [22]. The widespread use of green energy for a sustainable nature and life, the construction of green buildings and the development and effective use of conscious policies such as green transportation will contribute to the solution of social problems. The role of renewable energy sources is very important in accelerating all these [23].

In this study, wind energy, which is one of the renewable energy sources that is widely used today and will be more effective in our lives over time, has been detailed. Occurring due to pressure differences caused by the sun, wind is one of the natural, clean and sustainable renewable energy sources. With these features, it contributes to the prevention of problems such as air pollution, global warming and climate change. On the other hand, it makes positive contributions both locally and globally in terms of economic, political and energy efficiency by eliminating foreign dependency, being land-friendly, solving the electricity problem in rural areas, enabling agricultural and industrial practices in the regions where power plants are established, and providing employment opportunities. All these also support the Sustainable Development Goals. Wind turbines are used to generate wind energy. Electricity is generated by wind power plants established because of appropriate site selection based on wind speed, land topography, transportation facilities, socioeconomic and environmental factors. All these opportunities increase the use of wind energy today. According to a report published by the World Wind Energy Association (WWEA), global wind energy capacity reached 874 Gigawatts in June 2022, representing a 13% growth compared to the previous year. On the other hand, it is estimated that it will surpass 955 Gigawatts by the end of 2022 and exceed 1 million Megawatts by the middle of 2023 [24]. These statistics are other indicators of the rapid development of wind energy. Wind energy makes many contributions to our world and human beings and will continue to do so in the future.

When looking at the literature, it is seen that there are thousands of studies on wind energy. These studies have been carried out in various fields of science, using various methods, by many authors at different universities. On the one hand, each study contributes to the literature and our world, as well as its scientific characteristics vary. Examining these studies that have gained a place in the literature in different aspects will provide both an evaluation of the current situation and a direction for future studies. The examinations and evaluations can be carried out effectively through bibliometric analysis.

**Background of Bibliometric Analysis**

The word bibliometrics is derived from two different words of Latin and Greek origin. The concept of bibliometrics, which is used today, has emerged with the combination of the words "biblion" and "metrics", which means "book" and "science of measurement" [25]. Towards the end of the 20th century, it is possible to find many definitions of this concept in the literature. One of these definitions, which can be considered basic, was made by Alan Pritchard in 1969. Pritchard defined bibliometrics as "the application of mathematical and statistical methods to books and other media of communication" [26]. Research, analysis and evaluations based on bibliometrics are called bibliometric analysis. With bibliometric analysis, characteristics such as subject, field of science, author, citation, institution, journal, country, etc. of scientific studies within the scope of a determined discipline are evaluated numerically and statistically and the relationships between them are examined. In this respect, it can be said that bibliometric analysis is a quantitative method.

Although the concept of bibliometrics was introduced to the literature at the end of the 20$^{th}$ century, the beginning of bibliometric analysis applications dates to the 1870s. In 1869 and 1874, Francis Galton took the first steps in this sense with his works "Hereditary Genius" and "English Men of Science" based on the measurement of science [27, 28]. This was followed by the bibliography-themed book "Theory of the National and International Bibliography" written by Frank Cambbell in 1896 [25]. In 1917, Francis Joseph Cole and Nellie Barbara Eales wrote "The History of Comparative Anatomy: Part I- A Statistical Analysis of The Literature", which deals with citation evaluations in the field of anatomy [29].

Today, bibliometric analysis studies have become quite widespread. With this analysis, comprehensive evaluations can be made by considering the relationship between

**Table 2.** Comparison of bibliometric analysis and review

| Bibliometric Analysis | Review |
|---|---|
| • Evaluates the characteristics of publications quantitatively. | • Evaluates the topics and outputs of publications qualitatively. |
| • Examines the relationships between the characteristics of publications. | • Examines the results of publications and the relationships between them. |
| • Enables understanding of trends, distributions, and clustering in a specific field. | • Enables understanding of the quality level of publications in a field. |
| • Uses statistical methods in the analysis process and establishes network relationships between quantitative characteristics. | • The evaluation process involves reading, summarizing, and discussing the results of publications. |
| • As it is based on statistics, the results depend on the relevance and accuracy of the data. | • As it is content-based, the outputs are dependent on the author's perspective and may therefore include a subjective approach. |
| • Evaluates the characteristics of studies conducted in a specific field from a broad perspective. | • Evaluates the results of studies conducted in a specific field from a broad perspective. |

certain characteristics of a scientific study and the outputs obtained can be presented with visualization tools such as graphs, tables and maps. Bibliometric analysis is also a data mining technique because it generates new data from data. As a data mining technique, it sources data from comprehensive databases like Web of Science (WoS), Scopus, and PubMed. These databases provide qualitative and quantitative information on authors, citations, institutions, journals, research areas, indexes, keywords, countries, and publishers. Visualization tools like Vosviewer, Gephi, Citespace, Leximancer, and SciMAT perform network analysis, producing interpretable visuals of distributions, trends, clusters, and their interrelationships. Moreover, the use of artificial intelligence (AI) in today's technology allows for future predictions. Data from bibliometric analysis can forecast future studies and trends through AI techniques. Thanks to the visuals produced, the distributions, trends, clusters and their relationships with each other can be interpreted. On the other hand, the use of artificial intelligence (AI) methods in today's developing technology is gaining importance day by day. Future predictions can be made by utilizing these methods. By using the data obtained because of bibliometric analysis, predictions can be made about future studies through AI techniques, and an idea about how future studies will be affected can be acquired by means of foresights.

The review studies commonly encountered in the literature may seem like bibliometric analysis, but in fact, they are very different from each other. While bibliometric analysis involves the evaluation of certain factors of studies conducted in a specific field using mathematical and statistical methods, review studies focus on the content of existing publications on a specific topic, examine their results, and provide recommendations for the future. Although they have some similarities, these two types of studies are different in terms of their purpose, methods, and results obtained. Table 2 compares bibliometric analysis with review studies.

When conducting a scientific study, utilizing review articles serves as a fundamental means of developing the topic. Bibliometric analyses, on the other hand, enable the evaluation of the global perspective of the field in which the study will be conducted and facilitate the tracking of the existing network of this field worldwide. Therefore, bibliometric analyses provide a broader perspective on a scientific field. This broad perspective enables new studies to be planned in a manner consistent with their purpose, directing these plans, and thus allowing them to directly reach their target audience. It can be understood from this that bibliometric analyses serve as a guide for new studies.

**Research Objective**

This study aims to conduct a bibliometric analysis of wind energy studies indexed in the Web of Science database from 2010 to 2023. Reviewing the literature, it can be observed that there are few bibliometric analysis studies on wind energy. Some of these studies generally focus on the concept of renewable energy, covering other energy types and wind energy, and examining all publication types between certain years. It can be seen that these studies were conducted either in a single country [30, 31] or globally [32-34]. Another group of studies carried out bibliometric analyses on wind energy types [35-37] and components of wind energy systems [38-40]. On the other hand, other studies in the literature have examined the economic and financial aspects of both renewable energy types and wind energy alone through bibliometric analyses [41-45]. Finally, bibliometric studies focusing on specific methods for wind speed prediction can also be found in the literature [46, 47].

In general, these studies were conducted between 2013 and 2023. The differences of this study from the studies in the literature can be listed as "the comprehensive consideration of many features and situations, the use of techniques belonging to today's artificial intelligence technology in addition to basic statistical methods, and the multidisciplinary evaluation of the obtained results." Providing details of all these differences will help to better understand the contribution of the study to the literature. The comprehensive consideration of many features and situations includes providing detailed explanations about the main topic, having highly detailed statistical analyses, turning analysis outputs into effective and interpretable visuals to make them clear and understandable, examining a wide range of time periods, using up-to-date and hardware-strong software in the analysis and visualization processes, and conducting comparative analyses of changes through periodic evaluations.

On the other hand, the outputs obtained from the analysis process were evaluated using Nonlinear autoregressive exogenous (Narx) neural network, which is one of the AI methods. With the Narx method, predictions have been made for the future based on past and current data. Thus, some recommendations have been offered based on future trends and expectations.

Finally, for the study to be multidimensional, multidisciplinary evaluations have been made for the subject, taking into account today's technology, living conditions and the current global situation. In this context, the concepts of environment, engineering, land management, economics, politics and AI are discussed. By establishing the relationship between these concepts and wind energy, remarkable explanations for the current situation and the future have been made and presented with their justifications.

In this study, in Chapter 1, wind energy is discussed, examined in detail from various aspects and comprehensive information about bibliometric analysis is given. In Chapter 2, the materials and methods used in the study are explained and supported with visuals. In Chapter 3, bibliometric analysis was performed, the outputs obtained were evaluated individually and comprehensively, and graphs, figures and maps were produced and presented effectively. In Chapter 4, all outputs and the visuals produced were re-evaluated, changes were observed, comparisons were made and forward-looking predictions were made using Narx time series analysis. With the results obtained from these, future foresights were made and recommendations were presented. In the 5th and final chapter, the entire study is evaluated in general and the purpose and contributions of the study are emphasized.

## MATERIALS AND METHODS

In this study, the studies published within the scope of the subject between certain years in the literature were handled for the purpose of examining them quantitatively. The studies were evaluated by bibliometric analysis, and the results were effectively visualized. Information about each step and details of the study are shown in Figure 2.

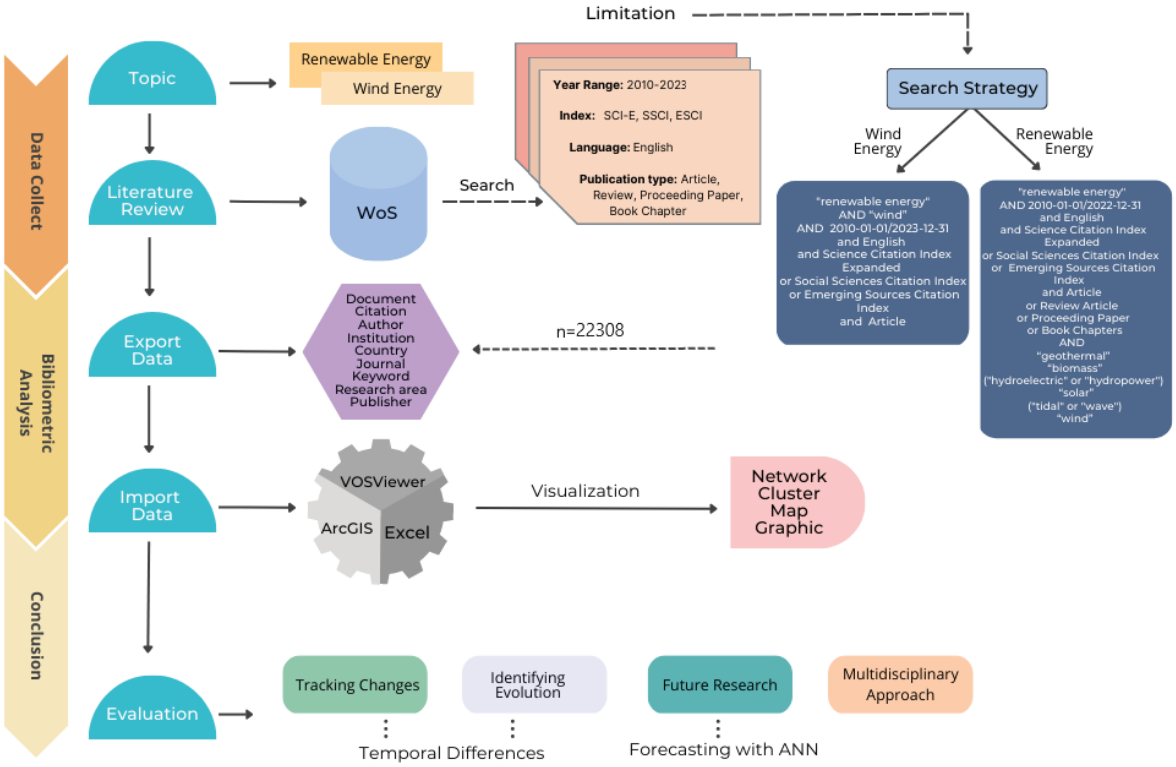


**Figure 2.** Multifaceted bibliometric analysis framework.

**Data Source and Search Strategy**

The study utilized Web of Science (WoS), an academic database that provides access to publications in various fields and offers a wide range of features. The data source for this study was the publications written in English between January 1, 2010, and December 31, 2023, in the form of articles, reviews, proceedings papers, and book chapters, available in the indexes of SCI-E, SSCI, and ESCI. Figure 2 provides a flowchart that gives a detailed overview of the filters and search strategies used in the data acquisition process.

The first part of the study analyzed publications in the five types of renewable energy sources, providing an overview and making evaluations. In the second part, articles published on wind energy were discussed, and a comprehensive analysis of these articles was conducted. The results obtained from the analysis were presented in detail.

**Data Processing, Analysis and Visualization**

After analyzing and processing the data, it is crucial to map and visualize the outputs to present the findings effectively. Various presentation tools were employed in this study to visualize large datasets, display data relationships, and identify trends and patterns. Specifically, Vosviewer 1.6.20 software was utilized to visualize relationships between data, ArcGIS 10.8 was used to create maps, Microsoft Excel 2021 was used for data processing and graphing, and MATLAB 2023b software was used for forecasting based on AI methods.

The main software program used in this study, Vosviewer, was developed by the Science and Technology Research Centre at Leiden University in the Netherlands. The program provides for visualization of authors, institutions, sources, countries, citations, and keywords, as well as their relationships between publications in the form of network analyses [48]. The acronym "VOS" stands for "Visualization of Similarities". The program's fundamental principle is to generate a similarity matrix and utilize the correlation strength to assess the similarity between item pairs in the co-occurrence data. The correlation strength is computed using the formula illustrated in the equation below:

$$S_{ij} = c_{ij}/w_i w_j \tag{1}$$

To assess the similarity between item i and item j, we use Sij, which considers the number of co-occurrences (cij) of the items as well as their individual occurrence counts (ωi and ωj). The program visualizes the data by reducing the weighted sum of the squared Euclidean distance between all item pairs. The squared distance's weight in the sum calculation increases with greater similarity between items. The expectation minimization algorithm aims to minimize the objective function shown in formula (2) while adhering to the constraint conditions in formula (3).

$$\mathrm{V}(x_1, x_2, \ldots x_n) = \sum_{i<j} S_{ij} \left\| \|x_i - x_j\| \right\|^2 \tag{2}$$

$$[2/n(n-1)] \sum_{i<j} \|x_i - x_j\| = 1 \tag{3}$$

The position of item i in the two-dimensional information graph is represented by the vector xi, and the Euclidean norm is indicated by $\| \bullet \|$. ArcGIS 10.8 software was utilized to investigate the global distribution of the data based on countries and analyze them on a location-based basis. Microsoft Excel was used for storing, processing and graphing the data. Additionally, MATLAB software, known for its high capability in mathematical operations, was employed to generate future predictions and create artificial neural networks [49].

**Forecasting with Artificial Neural Network**

Artificial Neural Networks (ANN) are a type of machine learning techniques that draw inspiration from biological neural networks. Composed of neurons, ANN is capable of performing functions such as classification, clustering, prediction, and model building in various fields [50, 51]. The network structure comprises three fundamental components: neurons as the primary units, the network architecture formed by weighted connections between neurons, and the learning algorithm [52, 53]. One of the most significant advantages of ANN is its capacity to handle vast and complex data and generate new data. Consequently, ANN has become a popular data mining technique. The layers in ANN, formed by combining neurons, carry out various operations. ANN comprises three layers: input, hidden, and output layers and provides analytical solutions through the relationships established between them.

This study employed ANN to forecast the number of publications, citations, and research area-specific publications from 2024 to 2030, based on data from 2010 to 2023. The MATLAB programming language was used to create neural networks for future forecasting. Specifically, the Narx (Nonlinear Autoregressive with eXogenous inputs) neural network architecture was used, which is widely recognized for its effectiveness in time series analysis (Fig. 3).

The NARX neural network uses the previous values of the target variable to predict its next values. In this study, the previous three values used for prediction. Different activation functions are used to process input parameters. The hidden layer of the network contains 10 neurons that use the hyperbolic tangent function, while the output layer utilizes a linear function. The Levenberg-Marquardt algorithm was employed to train the network due to its fast-processing speed.

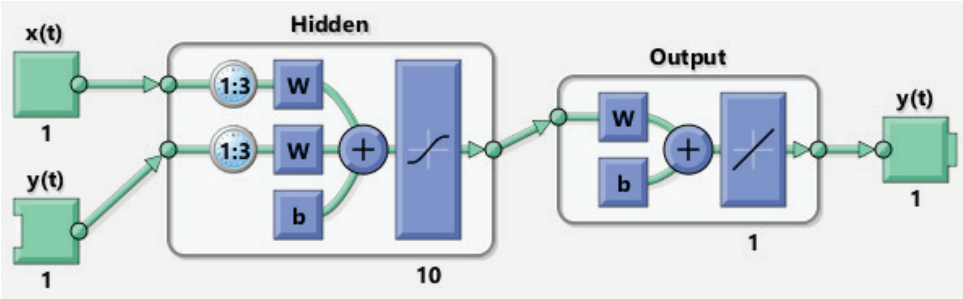


**Figure 3.** Narx architecture used in the study.

## RESULTS AND DISCUSSION

The results of the study are presented in two main sections. The first section includes the number of publications, document types, and research areas related to renewable energy and renewable energy sources. The second section provides a detailed bibliometric analysis of studies on wind energy.

### An Overview of Publications on Renewable Energy

Publications on renewable energy are found in a wide variety of fields and in different categories in the literature. In this section, renewable energy is examined from a general perspective. The information on the publications of each renewable energy type is analyzed quantitatively and evaluated.

### Publication History of Renewable Energy

The graph presented as Figure 4 displays the number of renewable energy-related publications and citations by year, covering the period between 2010 and 2023. During this time, a total of 103234 publications were published, with the number of publications steadily rising from 1382 in 2010 to 17991 in 2023. The year 2023 had the highest number of publications. Over the same period, there were a total of 2944347 citations to these publications, with the highest number of citations, 642025, occurring in 2023. As shown in the figure, both the number of publications and citations have been increasing continuously over the years, indicating that renewable energy is a popular topic of study and research. This trend suggests that studies on renewable energy will likely continue to increase in the future.

Figure 5 presents the quantitative distribution of publications for each type of renewable energy source from 2010 to 2023. The highest number of publications for "hydroelectric", "solar", "wind", "biomass", "geothermal", and "wave" sources were made in 2023. The number of publications for each relevant year were 518, 4425, 3879, 1274, 394, and 473, respectively. As shown in the figure, there has been a general increase in the number of publications in all renewable energy types over time.

### Publication Type Distribution of Renewable Energy

In WoS, all publications are classified into different document types. However, a single study can be assigned to more than one document type if it is categorized under multiple publication types. As a result, the total number of

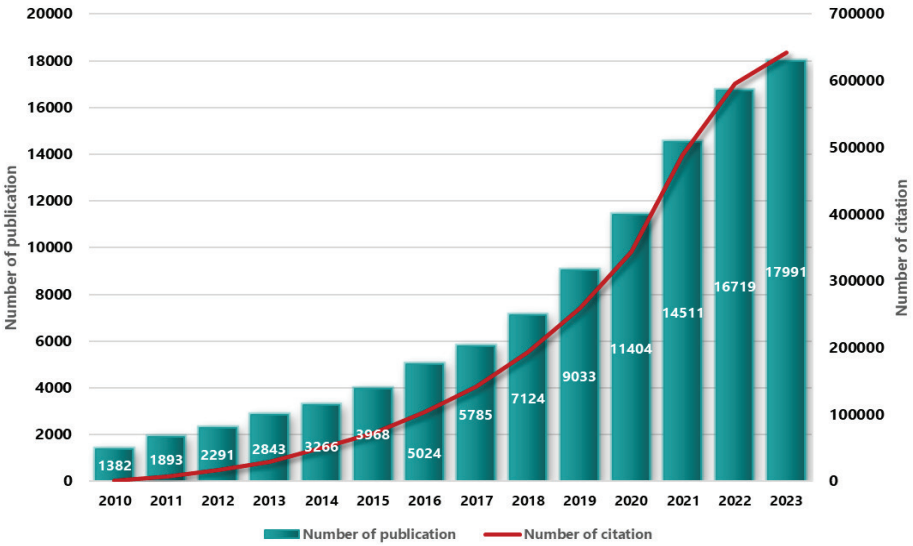


**Figure 4.** Number of publications and citations by year.

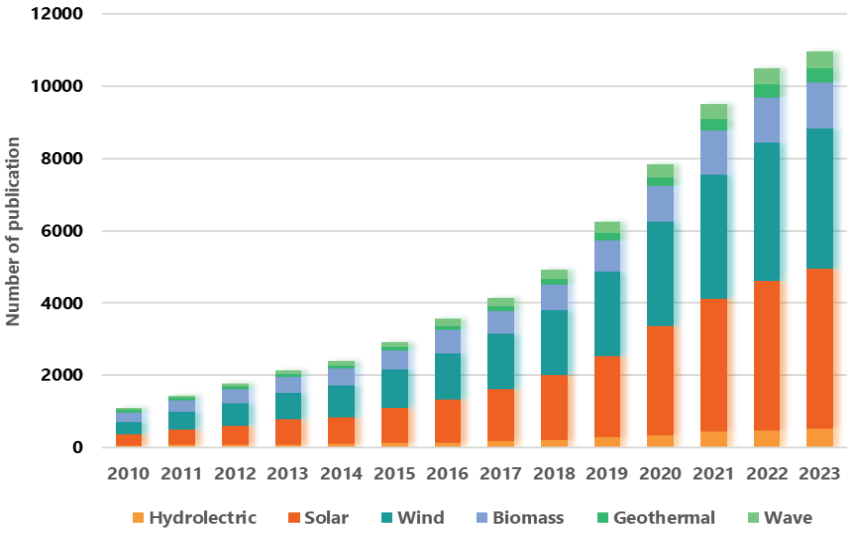


**Figure 5.** Number of publications of renewable energy types by year.

**Table 3.** Distribution of renewable energy types by document types

| Document Types | Renewable Energy | Hydroelectric | Solar | Wind | Biomass | Geothermal | Wave |
|---|---|---|---|---|---|---|---|
| **Article** | 90989 | 2686 | 21988 | 22308 | 8114 | 1933 | 2781 |
| **Review Article** | 12245 | 485 | 3590 | 2750 | 1844 | 483 | 452 |
| **Proceeding Paper** | 2328 | 57 | 608 | 599 | 251 | 64 | 85 |
| **Book Chapter** | 59 | 0 | 15 | 13 | 10 | 2 | 1 |
| **Other** | 1224 | 38 | 285 | 252 | 85 | 20 | 23 |

a particular document type may be affected by another document type. Table 3 shows the distribution of publications, and upon analysis, it becomes clear that articles are the most common type of publication for renewable energy and each type of renewable energy. This is followed by reviews, proceeding papers, and book chapters, in that order.

**Research Area Distribution of Publications in Renewable Energy**

Each publication is associated with at least one research area. However, as a publication may fall within the scope of multiple research areas, this could result in duplicate counts. Figure 6 displays numerical data regarding the top

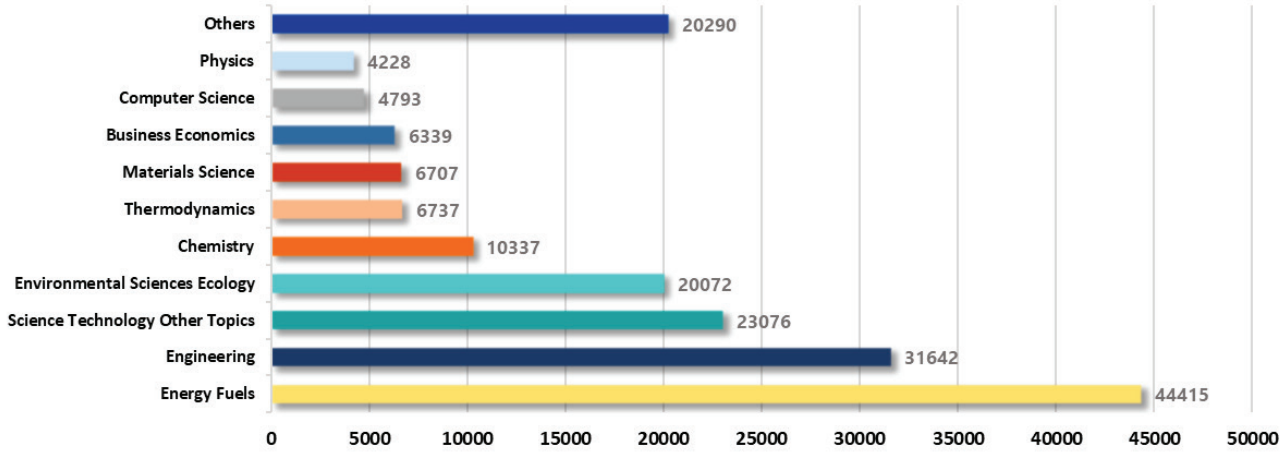


**Figure 6.** Top 10 research areas for renewable energy publications.

10 research areas with the highest number of publications on renewable energy studies.

The most popular research areas are Energy Fuels with 44415 publications and Engineering with 31642 publications. These areas are followed by Science Technology Other Topics with 23076 publications, Environmental Sciences Ecology with 20072 publications, and Chemistry with 10337 publications. Overall, research areas related to energy, engineering, economics, and basic sciences are stand out.

**Evaluation of Wind Energy with Statistical Concepts**

In this section, a comprehensive bibliometric analysis of wind energy studies in the literature is presented in a detailed and effective manner. The publications between 2010 and 2023 were evaluated using the WOS database for the analysis. Through the parameters examined, trends, clusters, networks, and frequency statistics were investigated and analyzed.

The distribution of publications over time between 2010 and 2023 was examined to evaluate the trends and changes from the past to the present. The groups formed based on the relationship between the parameters of the publications were analyzed using cluster analysis, and the characteristics of these groups were investigated. Networks played a crucial role in the formation of clusters and the relationships between them. By evaluating the networks, the bases of these relationships were investigated and inferences were made. Frequency values were also analyzed to investigate the repetitiveness and percentage distribution of the parameters. To present all these statistical analyses, the data used and the outputs obtained were visualized and interpreted using tables, graphs, maps, network structures, and figures.

**Quantitative Information and Temporal Distribution of Publications**

To investigate information on wind energy publications, filtering was carried out from the WoS database, and Section 2 provides detailed information on the filtering process. Quantitative information on all publication types between 2010-2023 shows a total of 24907 publications, with 22177 being articles, 597 proceeding papers, 2730 reviews, 13 book chapters, and 5707 being other types of publications. Most of these studies are articles, followed by reviews and proceeding papers, respectively. Details of the quantitative information of each publication type are given in Figure 7.

Figure 7 clearly shows the continuous increase in the number of publications from 2010 to 2023. Notably, there has been a significant rise in the number of publications, especially after 2018.

In the literature review, it was observed that although there are numerous studies on wind energy, articles are the most used publication type. Analyzing this type of publication will provide more comprehensive information. Therefore, the analysis in the rest of the study focuses on

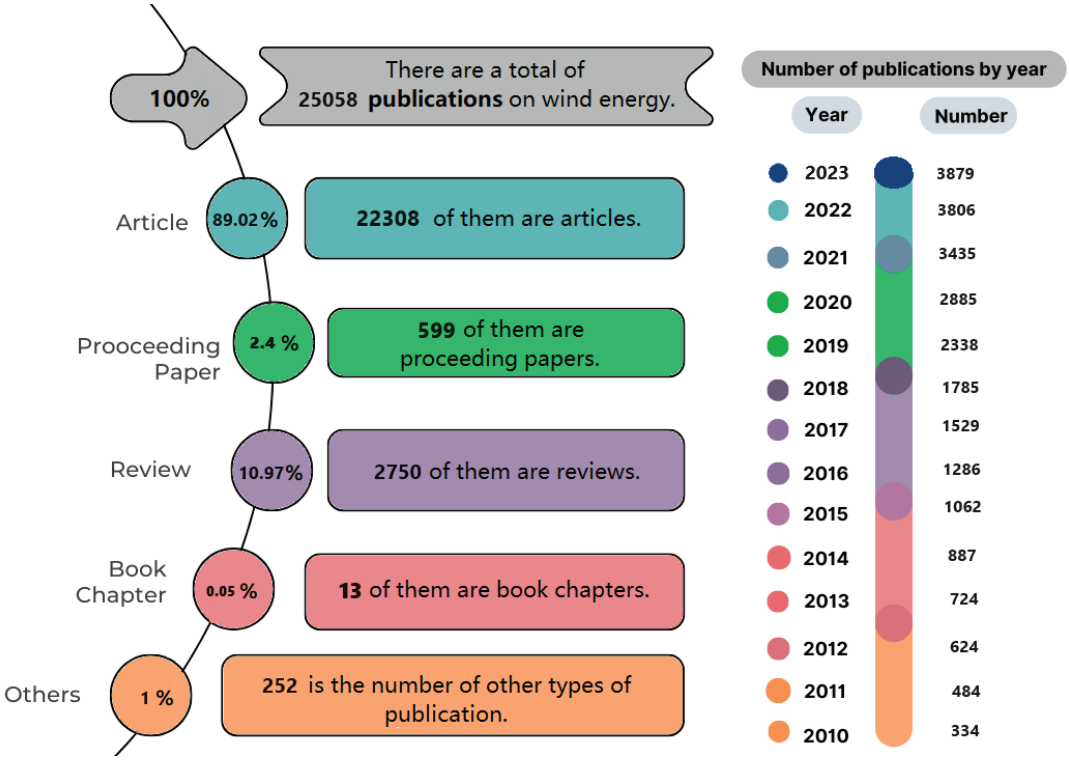


**Figure 7.** Number of publications published on wind energy and their distribution by year between 2010-2023.

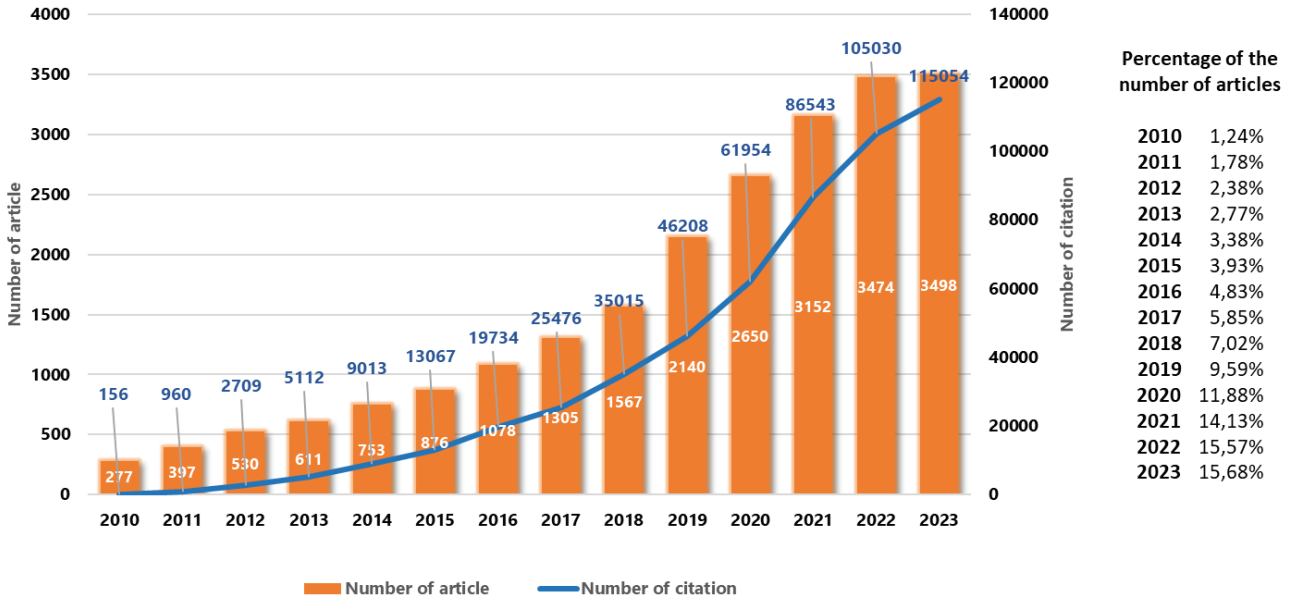


**Figure 8.** Number, percentage, and citations of articles published on wind energy between 2010 and 2023.

articles published between 2010 and 2023. Figure 8 illustrates the distribution of articles over time. The graph clearly indicates that the number of articles has been continuously increasing over the years. It is important to note that some of the proceeding papers are also included in the number of articles. As papers presented at conferences and symposiums are published in journals, they are reflected in the numerical information of both articles and proceeding papers. On the other hand, the number of citations is constantly increasing in proportion to the number of articles.

### Most Productive Authors and Citations Analysis

The analysis of authors working in a research area or subject can provide insights into the popularity, development, and leading researchers of the area. To this end, a total of 47030 authors were identified in the 22308 articles analyzed in the field of wind energy. The high number of authors suggests significant interest in the subject and its research. Notably, 200 authors have more than 16 articles, highlighting the prominence and importance of wind energy research in contemporary times.

Table 4 shows the most productive authors based on the number of publications on wind energy. According to this table, Liu Y (82 papers) from the China University of Petroleum, Kamel S (78 papers) from Aswan University, and Li Y (74 papers) from the Xi'an Jiaotong University are the top three authors. Their universities are located in People's Republic of China , Egypt, and People's Republic of China, respectively. When examining the h-index, which

**Table 4.** Top 10 most productive authors

| Number of Publications | Author | h-index | Institution | Country |
|---|---|---|---|---|
| **82** | Liu Y | 23 | China University of Petroleum | People's Republic of China |
| **78** | Kamel S | 25 | Aswan University | Egypt |
| **74** | Li Y | 21 | Xi'an Jiaotong University | People's Republic of China |
| **69** | Chen Z | 31 | Aalborg University | Denmark |
| **66** | Kumar A | 21 | Maharishi Markandeshwar University | India |
| **66** | Senjyu T | 21 | Univeristy of the Ryukyus | Japan |
| **65** | Mohammadi-ivatloo B | 29 | University of Tabriz | Iran |
| **63** | Breyer C | 37 | Lappeenranta University of Technology | Finland |
| **59** | Wang Y | 29 | Nanjing University | People's Republic of China |
| **56** | Zhang Y | 26 | Hohai University | People's Republic of China |

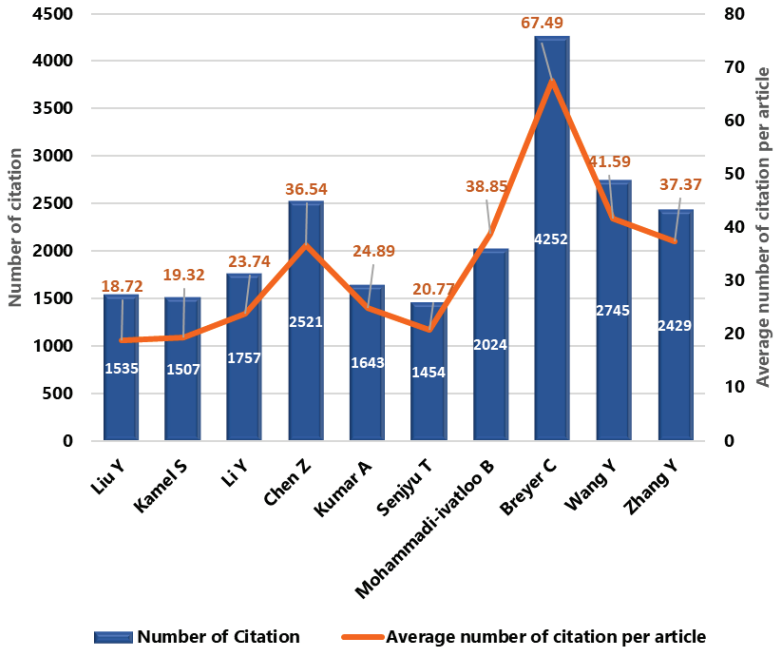


**Figure 9.** Citation frequencies of the top 10 most productive authors.

provides information about the productivity of the author, it is revealed that the value is 23, 25, and 21 for the top three authors, respectively. Figure 9 shows the citation information of the top 10 most productive authors' articles on wind energy.

When considering Table 4 and Figure 9 together, it becomes apparent that the authors are affiliated with various universities, with four authors from People's Republic of China and the rest from different countries. Among the authors, Breyer C stands out with an h-index value of 37. Examining the number of citations, it is evident that Breyer C has the highest citation count with 4252 citations. Breyer C, who is associated with Lappeenranta University of Technology in Finland, has published 63 articles in the wind energy literature.

Figure 10 shows a network of connections and clusters among authors and their collaborating researchers. Each cluster is represented by a different color, the prominent node of each cluster indicates the lead author of the cluster, with node size indicating the number of publications. The network is based on authors who have published more than 5 articles and received more than 5 citations on wind energy, resulting in 39 clusters. Nodes with the same color represent authors who have collaborated. The three most prominent clusters, indicated by the colors red, green, and blue, have 77, 54, and 46 authors, respectively. Furthermore, the top three authors with the most links are Kamel S, Senjyu T, and Breyer C, with 164, 166, and 135 links, respectively.

Table 5 presents information on the top 10 most cited articles on wind energy. The first three articles have 2401, 2232, and 1182 citations, respectively. In 2015, an article was published in Applied Energy by Luo X et al. [54], in which they reviewed and evaluated the technology of electrical energy storage systems. In 2019, Gielen D. et al. [55] conducted research on the energy transition of renewable energy technology from today to 2050, which was published in the journal Energy Strategy Reviews. In 2010, Whipple DT and Kenis PJA [56] presented a number of recommendations for the problem of climate change and sustainable energy production in the Journal of Physical Chemistry Letters. Looking at the table, the top 10 most cited articles were mostly published in 2012 and 2015. Additionally, Applied Energy and Energy Strategy Reviews are the prominent journals in this table.

### Most Prominent Countries, Institutions and Their Spatial Distribution

In the wind energy literature, there are a total of 165 countries with published articles. Figure 11 presents the top 25 countries with the highest number of articles, with People's Republic of China leading at 4476, followed by the USA with 3186 and the United Kingdom with 1971. The map provides a clear view of the spatial distribution of the number of articles about countries, regions and continents, revealing that many countries are working on this topic. Notably, the North American and Australian continents, European continent, and the southern region of the Asian continent stand out in terms of the number of publications. Conversely, the African continent, the northern region of the Asian continent, and the

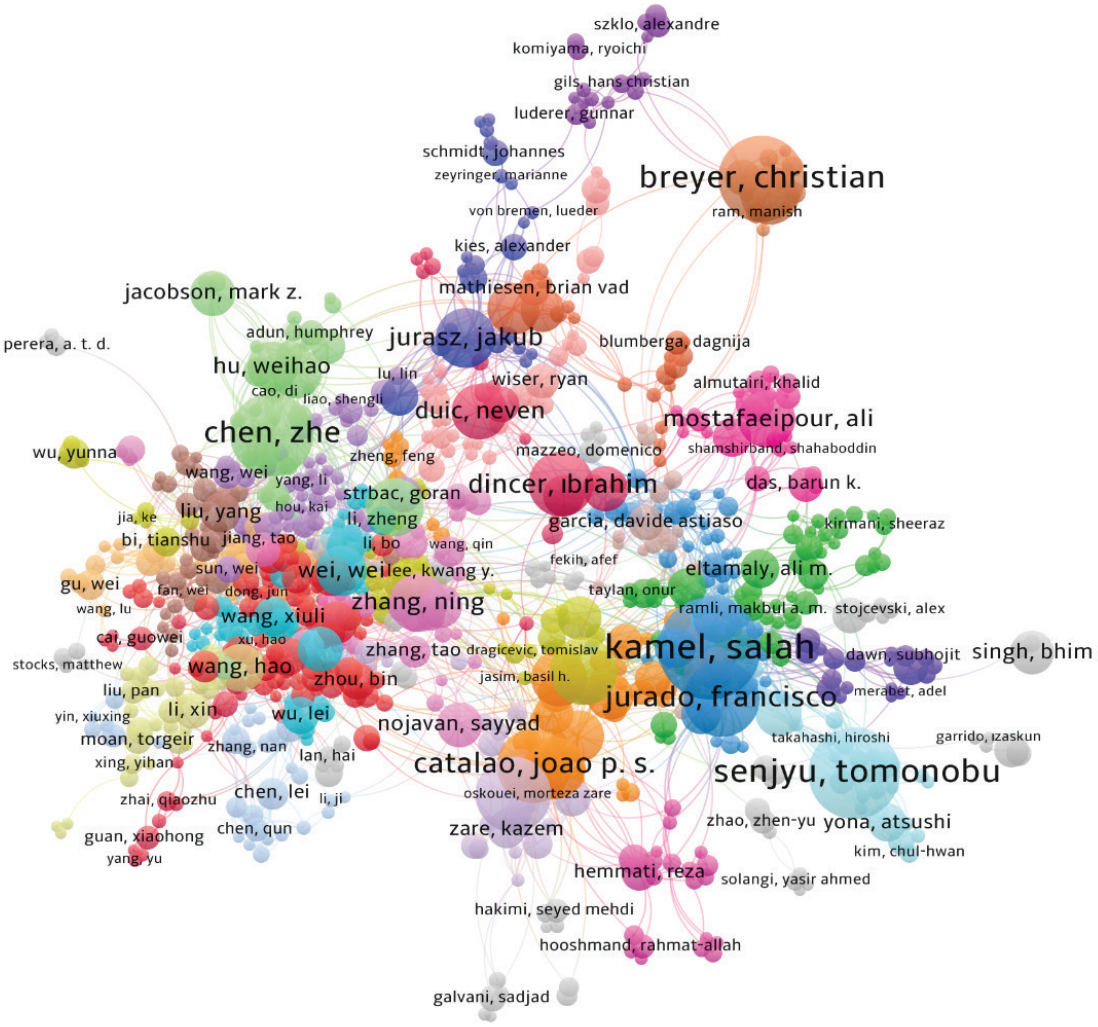


**Figure 10.** Network of co-authorship of authors.

southern region of the South American continent have fewer publications.

Authors can collaborate from the same country or different countries. Figure 12 depicts the links, clusters, and number of co-authorship articles between countries. To ensure visibility, countries with at least 5 articles and 5 citations were included in the network. Out of the 165 countries analyzed, 117 countries met this requirement. Clusters are represented by different colors, with a total of ten clusters. The leading country of each cluster is indicated by the prominent node, and the node size represents the number of publications. The first three clusters with the most countries are represented by the colors red, green, and blue, respectively, with 25, 21, and 14 countries in each cluster. On the other hand, People's Republic of China, USA, and England have the most links to authors in other countries with 2435, 2234, and 1649 links, respectively. The lines between nodes illustrate the co-author links between countries.

According to the literature, there are a total of 12050 institutions working on wind energy. Table 6 shows the top 10 universities with the most publications. The top three universities are North China Electric Power University in People's Republic of China with 534 articles, the National Institute of Technology in India with 409 articles, and Islamic Azad University in Iranian with 358 articles. Upon examining the table, it is seen that most of the universities in the top 10 are in People's Republic of China, Denmark, and India.

Collaborations between authors from different institutions can be analyzed. Figure 13 depicts a network that shows the links, clusters, and number of publications co-authored between institutions. This network was created using institutions with at least 10 articles and 10 citations, resulting in 940 institutions out of 12050 meeting the criteria. The network consists of 15 clusters, represented by different colors, where the prominent node of each cluster indicates the leading institution

**Table 5.** Top 10 most cited articles

| Number of Citation | Authors | Title | Publication Year | Journal |
|---|---|---|---|---|
| **2401** | Luo, X et al. [54] | Overview of current development in electrical energy storage technologies and the application potential in power system operation | 2015 | Applied Energy |
| **2232** | Gielen, D. Et al. [55] | The role of renewable energy in the global energy transformation | 2019 | Energy Strategy Reviews |
| **1182** | Whipple, DT and Kenis PJA [56] | Prospects of co2 utilization via direct heterogeneous electrochemical reduction | 2010 | Journal of Physical Chemistry Letters |
| **1010** | Ursua, A; Gandia, LM and Sanchis, P [57] | Hydrogen production from water electrolysis: current status and future trends | 2012 | Proceedings of the IEEE |
| **969** | Atwa, YM et al. [58] | Optimal renewable resources mix for distribution system energy loss minimization | 2010 | IEEE Transactions on Power Systems |
| **821** | Zhong et al. [59] | Accelerated discovery of CO2 electrocatalysts using active machine learning | 2020 | Nature |
| **812** | Lin, KX et al. [60] | Alkaline quinone flow battery | 2015 | Science |
| **802** | Yan, Y et al. [61] | A survey on smart grid communication infrastructures: motivations, requirements and challenges | 2013 | IEEE communications surveys & tutorials |
| **800** | Mathiesen, BV et al. [62] | Smart energy systems for coherent 100% renewable energy and transport solutions | 2015 | Applied Energy |
| **760** | Hayashi, A et al. [63] | Superionic glass-ceramic electrolytes for room-temperature rechargeable sodium batteries | 2012 | Nature Communications |

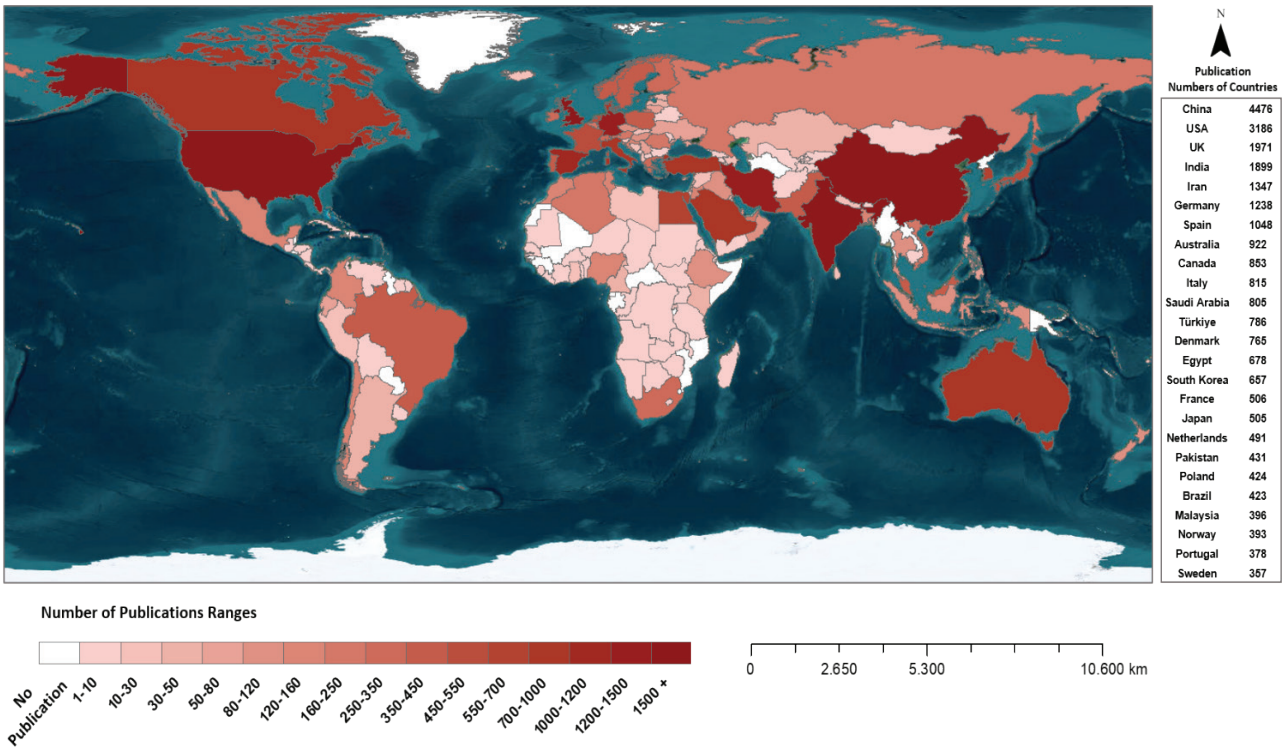


**Figure 11.** Spatial distribution of the number of articles by countries.

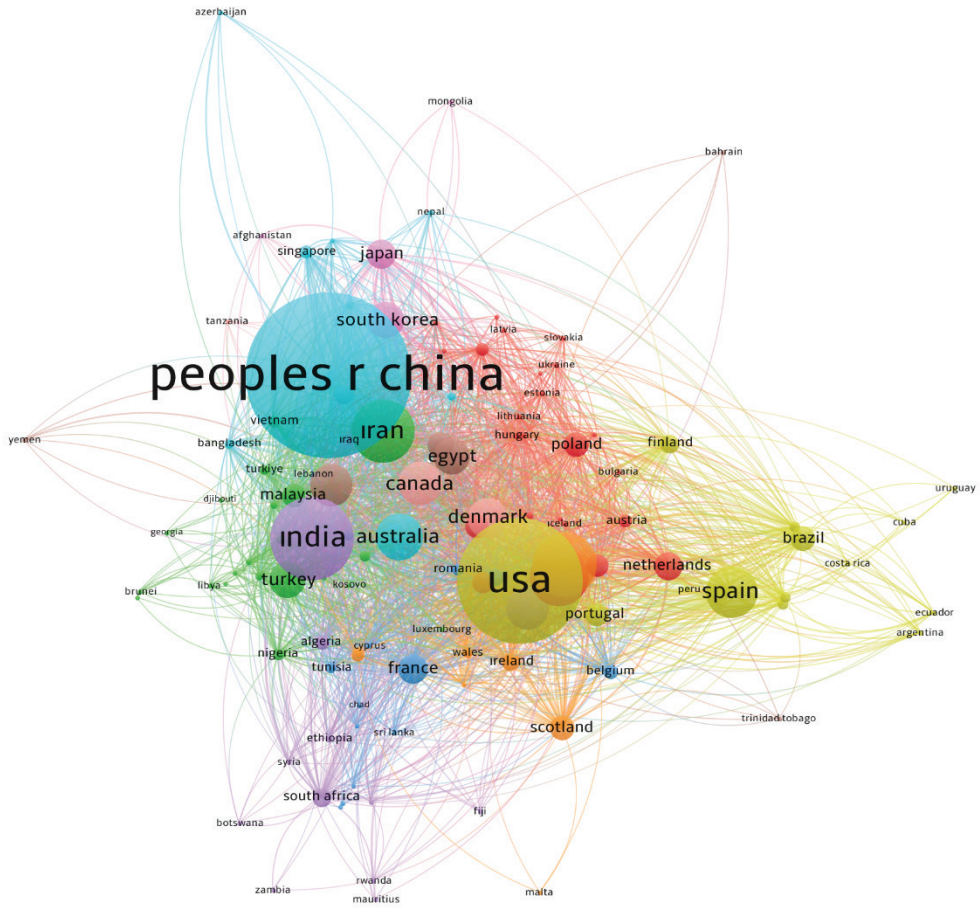


**Figure 12.** The co-author network of countries.

**Table 6.** Top 10 most prominent institutions

| Institutions | Country | Number of Publications |
|---|---|---|
| **North China Electric Power University** | People's Republic of China | 534 |
| **National Institute of Technology** | India | 409 |
| **Islamic Azad University** | Iranian | 358 |
| **Aalborg University** | Denmark | 346 |
| **Indian Institute of Technology System** | India | 311 |
| **Tsinghua University** | People's Republic of China | 285 |
| **Technical University of Denmark** | Denmark | 281 |
| **University of California System** | USA | 212 |
| **Xi'an Jiaotong University** | People's Republic of China | 178 |
| **Norwegian University of Science and Technology** | Norway | 166 |

of the cluster, and the size of the node symbolizes the number of publications. The first three clusters with the most institutions are red, green, and blue, respectively, consisting of 141, 137, and 110 institutions. The top three institutions with the most links to authors from other institutions are Aalborg University in Denmark with 397 links, Islamic Azad University in Iran with 370 links, and North China Electric Power University in People's Republic of China with 336 links. The lines between the nodes indicate the co-author links between the institutions.

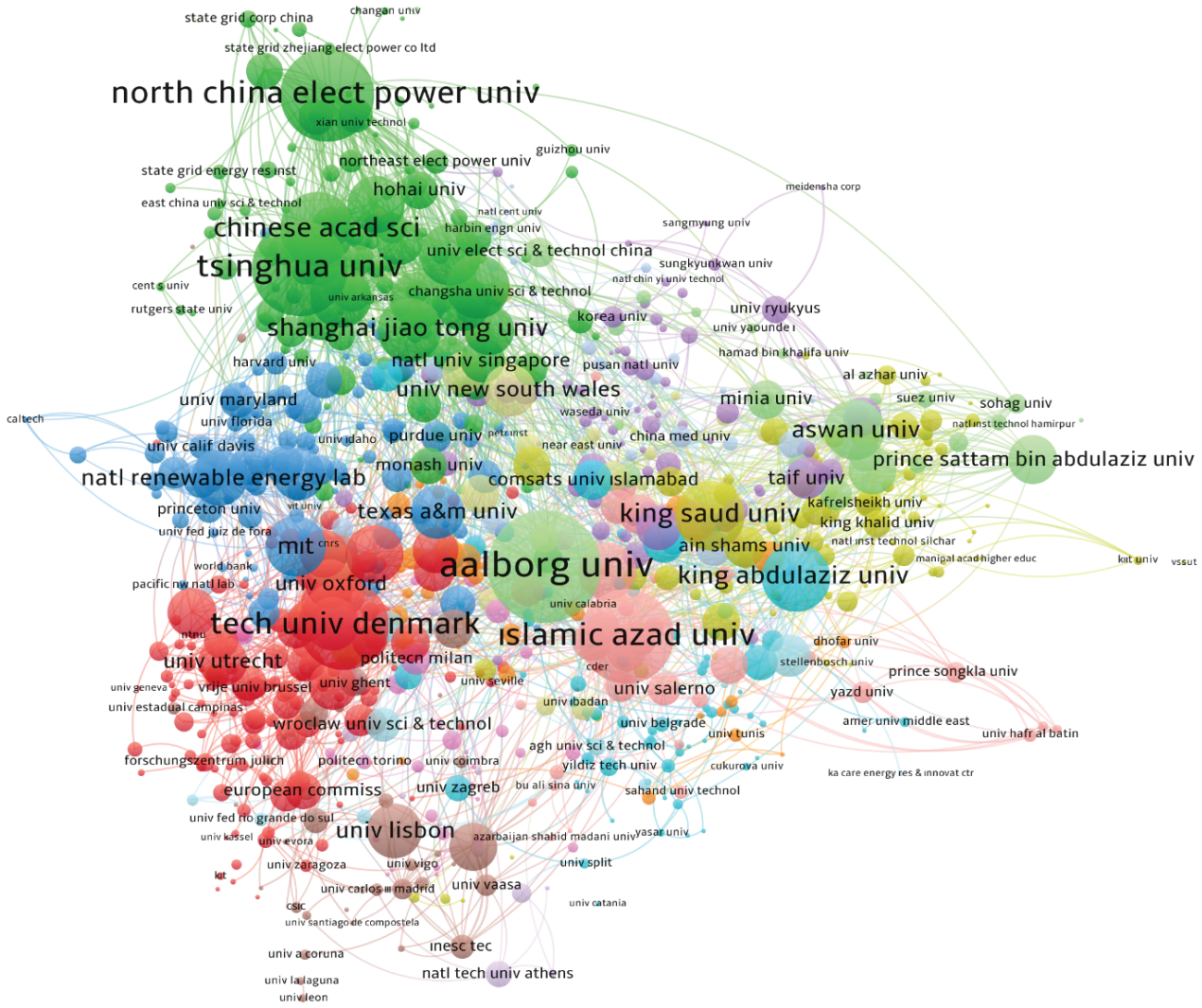


**Figure 13.** The co-author network of institutions.

**Priority Research Areas, Leading Journals and Prominent Publisher**

Wind energy has been studied in various research areas, and an examination of the WoS database shows that there are 93 research areas related to this topic. The top 10 research areas with the most studies are displayed in Figure 14. The most researched areas are Energy Fuels with 12915 articles, Engineering with 8366 articles, and Science Technology Other Topics with 6068 articles, while many studies have also been conducted in Environmental Sciences Ecology. It is evident from Figure 14 that wind energy is a multidisciplinary topic that covers various research areas.

Table 7 shows the top 10 journals that have published the most articles on wind energy. The three leading journals are Energies with 1504 articles, Renewable Energy with 1149 articles, and Energy with 1141 articles. It is evident from the establishment years of the journals that most of them have been operating for many years and are considered the leading journals in the field. In terms of impact factors, Applied Energy, Journal of Cleaner Production, and Energy Conversion and Management hold the top three positions with 11.2, 11.1 and 10,4, respectively. This indicates that these journals are highly influential, prestigious, and successful in their respective areas of research.

Another criterion for understanding the impact of journals is examining their number of citations. Figure 15 shows the citation information for the top 10 journals. The three journals with the highest citation values are Applied Energy with 47086 citations, Renewable Energy with 44329 citations, and Energy with 43275 citations. It is evident from their high citation values that these top three journals are competent and core journals in this field. Moreover, they are also among the journals with the highest number of publications.

Table 8 shows the top 10 publishers that have published the most articles on wind energy. It can be observed that


**Figure 14.** Top 10 priority research areas.

**Table 7.** Leading journals in the Top 10 by number of publications

| Journal | Number of Publication | Foundation Year | IF (2023) |
|---|---|---|---|
| **Energies** | 1504 | 2008 | 3.2 |
| **Renewable Energy** | 1149 | 1991 | 8.7 |
| **Energy** | 1141 | 1976 | 8.9 |
| **Applied Energy** | 879 | 1975 | 11.2 |
| **Energy Policy** | 719 | 1973 | 9 |
| **Sustainability** | 605 | 2009 | 3.9 |
| **Energy Conversion and Management** | 494 | 1961 | 10.4 |
| **IEEE Access** | 466 | 2013 | 3.9 |
| **Journal of Cleaner Production** | 437 | 1993 | 11.1 |
| **International Journal of Hydrogen Energy (IJHE)** | 356 | 1976 | 7.2 |

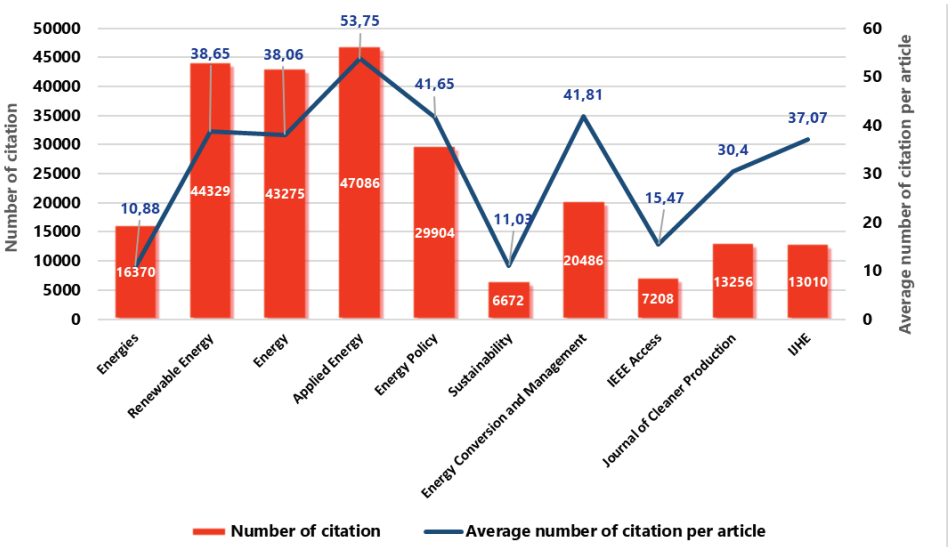


**Figure 15.** The citation frequencies of the leading journals in the top 10 by the number of publications.

**Table 8.** Top 10 prominent publishers by number of publications

| Publisher | Number of publication |
|---|---|
| **Elsevier** | 9612 |
| **MDPI** | 2840 |
| **IEEE** | 1779 |
| **Springer Nature** | 1182 |
| **Wiley** | 929 |
| **Taylor & Francis** | 892 |
| **IET- The Institution of Engineering and Technology** | 461 |
| **SAGE** | 342 |
| **Frontiers** | 250 |
| **ASME** | 157 |

Elsevier, with 9560 articles, MDPI, with 2817 articles, and IEEE, with 1778 articles, are the top 3 publishers in terms of the number of publications. They are then followed by Springer Nature, Wiley, and Taylor & Francis.

### Most Frequent Keywords

The use of keywords is crucial in academic research as they provide information about the content of a publication.

**Table 9.** Top 10 most frequently used keywords

| Keywords | Frequency | Total link |
|---|---|---|
| **Renewable energy** | 5127 | 10737 |
| **Wind energy** | 1671 | 4036 |
| **Renewable energy sources** | 1406 | 5844 |
| **Wind power** | 1061 | 2738 |
| **Optimization** | 814 | 2982 |
| **Energy storage** | 768 | 2676 |
| **Wind turbine** | 717 | 1655 |
| **Solar energy** | 588 | 1758 |
| **Microgrid** | 532 | 1681 |
| **Wind** | 528 | 1921 |

By summarizing the study in words, keywords facilitate easy access to relevant resources for researchers. Moreover, they enable categorization of studies under specific topics or themes.

When examining the articles published on wind energy, a large number of multidisciplinary keywords were found, as the subject is studied in various research areas. Details of the top 10 most frequently used keywords are given in Table 9. The top 3 most used keywords are renewable energy, wind energy, and renewable energy sources, respectively. It


**Figure 16.** The wind rose representing the most used keywords.

can be inferred from this that these keywords form the basis for studies on wind energy.

To see other keywords related to wind energy, a wind rose visualization was created and presented in Figure 16. In this context, the prominence of keywords for different disciplines indicates that multidisciplinary studies are being carried out on wind energy, while at the same time providing an understanding of other fields in which the subject is directed.

To evaluate the co-occurrence of keywords, a network was created as shown in Figure 17. The examination of the literature revealed the usage of a total of 43148 keywords. To create the network, it was assumed that each keyword can co-occur with at least 5 other keywords, based on the approximate number of keywords used in an article. Accordingly, a network comprising of 3030 keywords was generated.

The network shown in Figure 17 consists of 9 clusters, each represented by a different color. The leading keyword of each cluster is highlighted in a prominent frame, while the size of the frame indicates the frequency of co-occurrence with other words. The first three clusters formed by the most frequently co-occurring keywords are colored red, green, and blue, respectively, and contain 275, 172, and 168 keywords, respectively. The keywords that most commonly co-occur with other keywords are renewable energy with 10737 links, renewable energy sources with 5844 links, and wind energy with 4036 links. Additionally, the figure shows other prominent keywords, such as wind turbine, energy transition, energy policy, energy storage, deep learning, optimization, and power system stability.

**Changes, Evaluation, Comparisons and Future Research**

As a result of the bibliometric analysis conducted in the previous section, the studies on wind energy between 2010 and 2023 have been comprehensively analyzed and evaluated in detail. In this evaluation, publications were analyzed both based on each year and holistically. Thus, a general evaluation of the determined year interval was made.

This section divided the evaluated year interval into three periods and analyzed the number of publications and citations in each period to monitor the changes and development in wind energy. Additionally, predictions for the future of wind energy studies were made using artificial

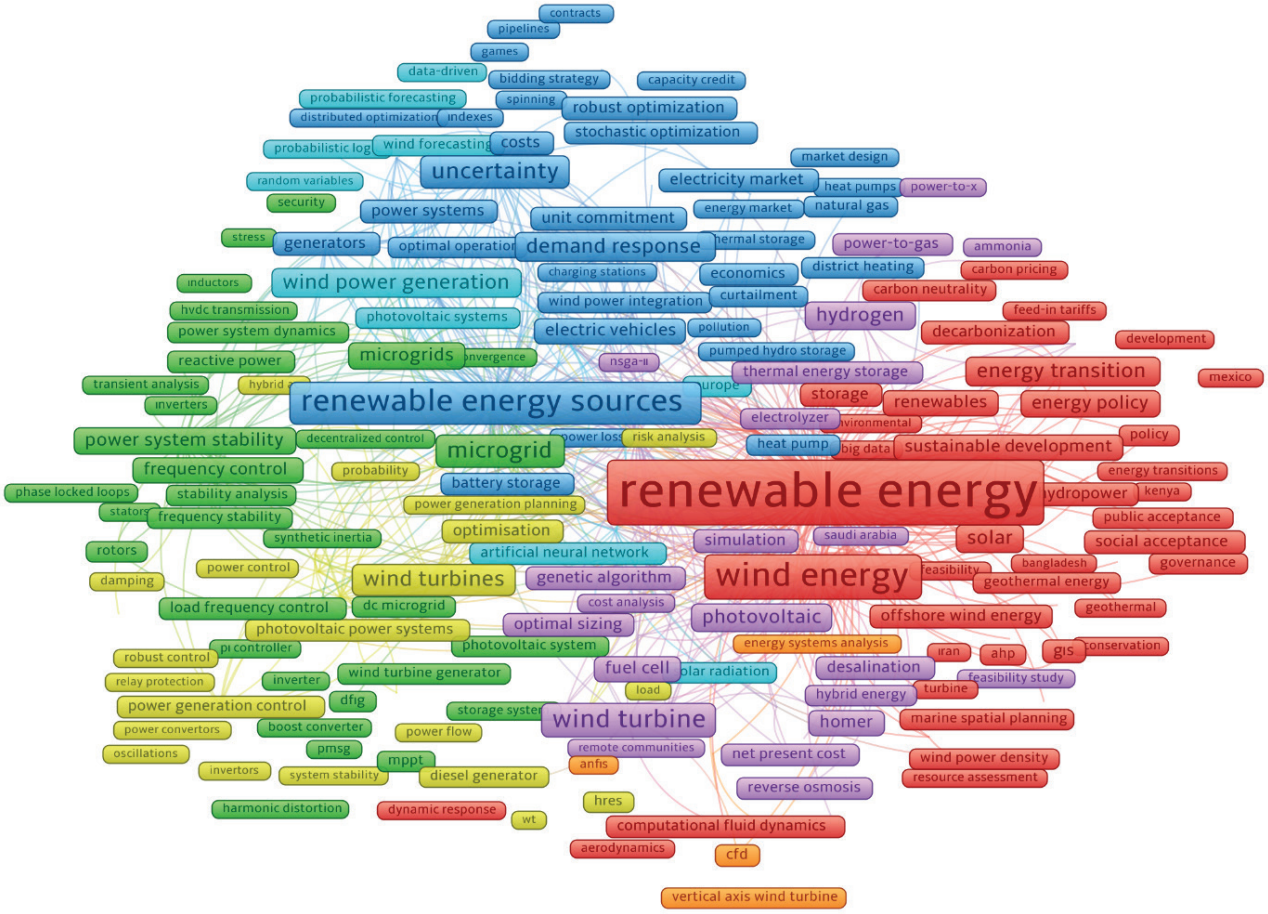


**Figure 17.** Network of co-occurrences of keywords.

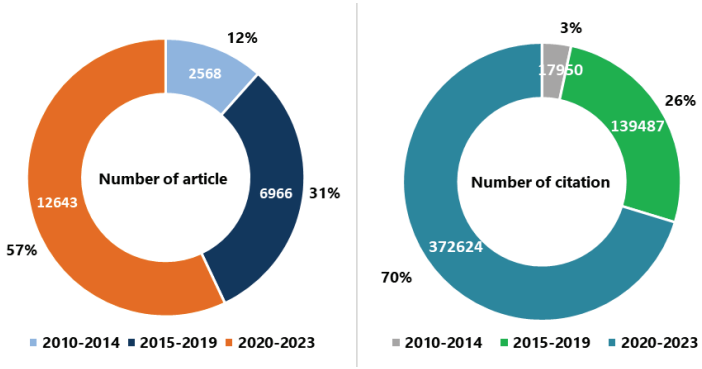


**Figure 18a.** Number of publications for the years 2010-2014, 2015-2019,2020-2023,

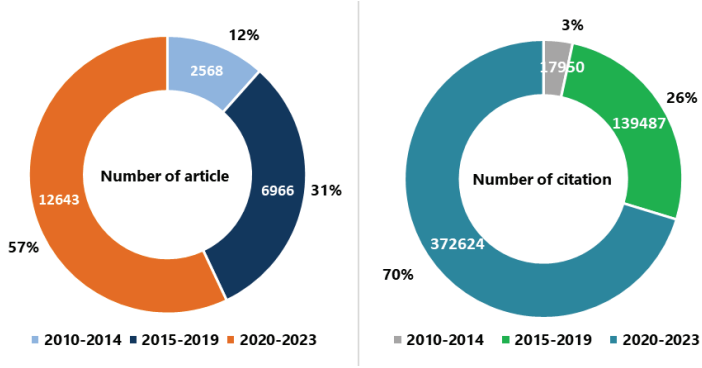


**Figure 18b.** Number of citations for the years 2010-2014, 2015-2019, 2020-2023.

neural networks, a data mining method. The predictions made using ANN include the number of publications and citations between 2024 and 2030, as well as the number of studies that could potentially be published in the top 10 research areas with the most studies. Based on these predictions, evaluations were made regarding the future direction of wind energy.

Figure 18a and Figure 18b analyzes quantitative information on the number of publications and citations between 2010 and 2023, divided into three periods. Figure 18a shows that the number of publications has increased significantly over time. In the second period, the number of publications was almost three times that of the first period, while in the third period it was almost five times that of the first period and almost twice that of the second period. The trend suggests that wind energy has become an increasingly prominent topic, especially between 2020 and 2023. Figure 18b reflects the effects of the data obtained in Figure 18a, showing the number of citations between 2010 and 2023, divided into the same three periods. The data indicates that the number of citations has also increased considerably over time. In the second period, the number of citations is more than nine times higher than in the first period. In the third period, the number of citations is almost three times that of the second period and more than twenty-three times that of the first period. These findings indicate that the number of studies has increased considerably in the last period and that publications in this field have been cited from different areas of study.

Figure 19 illustrates the prediction results obtained by the ANN for the number of publications and citations expected between 2024 and 2030. The graph indicates that both the number of publications and citations will continue to increase steadily. These findings suggest that wind energy will become increasingly popular in the years to come and will continue to evolve as a field of study with the increase in research.

Figure 20 depicts the predicted number of publications from an ANN analysis, providing insight into the top 10 research areas with the most published and prominent research from 2024 to 2030. As shown in the figure, the number of publications is expected to increase in all research areas. Notably, Energy Fuels is projected to be the leading research area during this period, followed by Engineering, Science Technology Other Topics, and Environmental Science Ecology.

Table 10 displays the predicted percentages of publications for the top 10 fields from 2024 to 2030. The table

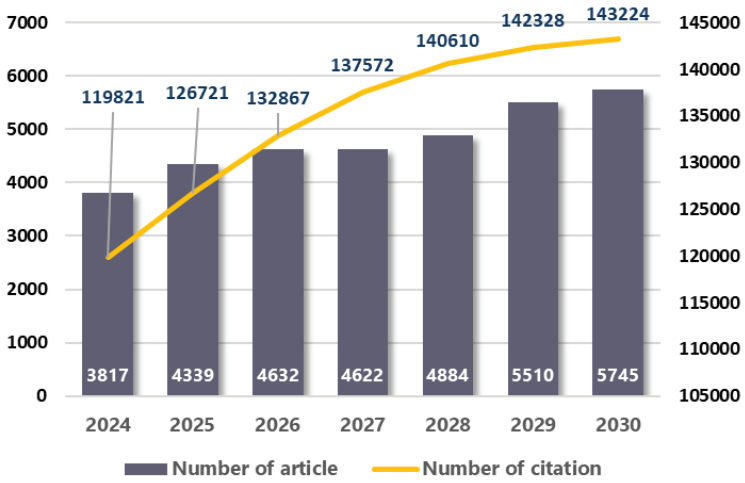


**Figure 19.** Forecasting of number of publication and citation between 2024-2030 with ANN.

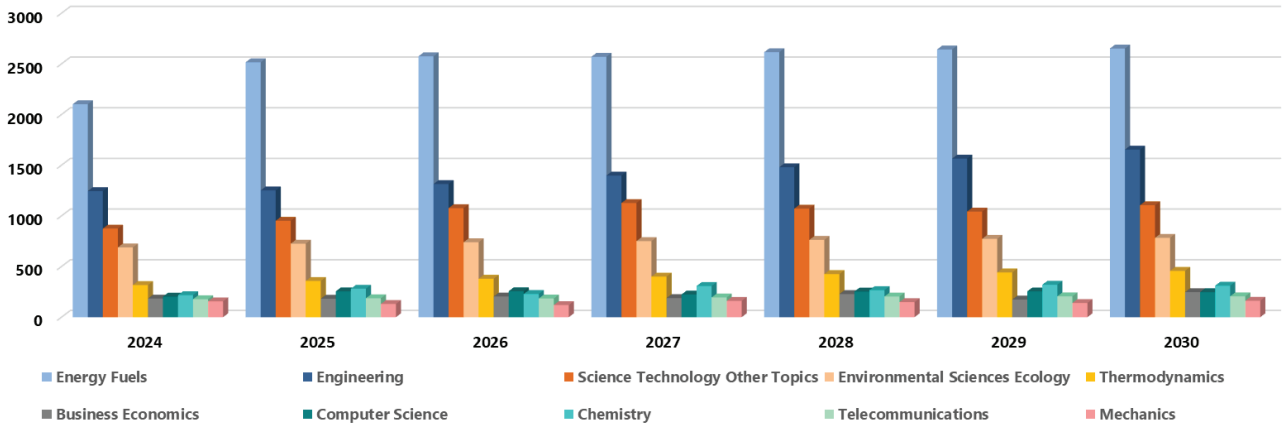


**Figure 20.** Forecasting of the number of publications between 2024-2030 in the top 10 research areas with ANN.

provides for a more effective observation of the differences between fields and the expected trends over the years. Based on the percentage changes, it is expected that research in Engineering, Science Technology Other Topics, Environmental Science Ecology, Chemistry, Telecommunication, and Mechanics will increase in the future, potentially becoming more prominent.

**Multidisciplinary Approach to Wind Energy**

Renewable energy is a versatile resource that encompasses various types of energy and interacts with many factors across multiple disciplines. The use and development of these resources depend on complex and dynamic relationships between disciplines. When considering the versatility of wind energy, various areas become prominent, including the environment, engineering, land management, economy, politics, and artificial intelligence.

The use of renewable energy sources, which are inexhaustible and have the potential to mitigate environmental problems like global warming, climate change, and air pollution, is rapidly increasing as an alternative to fossil fuels. Wind energy, one of the green energy sources, plays an important role in combating these problems. Since wind energy systems do not require the use of fossil fuels during the electricity generation process, they help to reduce greenhouse gas emissions. This, in turn, provides a solution to the adverse effects of these problems while laying the foundation for a sustainable energy future.

The installation of wind energy systems requires collaboration with various engineering disciplines during processes such as design, planning, and utilization. These fields include environmental engineering, which analyzes environmental impacts and creates environmentally friendly designs; mechanical engineering, which focuses on the design, testing, and development of wind turbines; electrical-electronic engineering, which designs and controls the systems necessary for the generation of electricity, efficient

**Table 10.** Percentages of the number of publications forecasts of the research areas between 2024-2030

| Year | Energy Fuels | Eng. | Sci. Tech. Other Top. | Env. Sci. Eco. | Thermo. | Business Eco. | Computer Sci. | Chemistry | Mech. | Telecom. |
|---|---|---|---|---|---|---|---|---|---|---|
| **2024** | 34.10 | 20.19 | 14.18 | 11.18 | 5.14 | 2.98 | 3.29 | 3.53 | 2.88 | 2.53 |
| **2025** | 36.79 | 18.30 | 13.92 | 10.62 | 5.23 | 2.66 | 3.73 | 4.11 | 2.73 | 1.91 |
| **2026** | 36.38 | 18.57 | 15.20 | 10.45 | 5.37 | 2.89 | 3.62 | 3.24 | 2.60 | 1.69 |
| **2027** | 35.10 | 19.09 | 15.38 | 10.26 | 5.47 | 2.58 | 3.06 | 4.20 | 2.66 | 2.20 |
| **2028** | 35.08 | 19.85 | 14.36 | 10.24 | 5.71 | 3.06 | 3.40 | 3.58 | 2.74 | 2.00 |
| **2029** | 34.95 | 20.71 | 13.79 | 10.23 | 5.84 | 2.30 | 3.37 | 4.24 | 2.72 | 1.85 |
| **2030** | 33.89 | 21.14 | 14.12 | 10.01 | 5.84 | 3.16 | 3.15 | 3.98 | 2.63 | 2.07 |

storage, transportation, distribution of energy obtained from turbines, and minimization of energy losses; materials engineering, which develops lightweight and durable materials; structural engineering, which performs the structural analyses necessary for the installation and operation of the system; and finally, geomatics engineering, which selects the most suitable location for the installation of these systems to operate with maximum efficiency.

Selecting the suitable location for wind energy systems is crucial for achieving high energy production potential and maximum environmental protection [64, 65]. Land management is a discipline utilized at this stage, which enables the effective use of land resources, mainly soil, in an environmentally and economically sustainable manner by making and implementing appropriate decisions [66]. Geomatics engineers play a crucial role in determining the site selection according to the principles of land management. Today, Geographic Information Systems (GIS), which enable all these principles and information from other disciplines to be collected, queried and evaluated holistically, have become a frequently used tool for site selection studies [67-70]. GIS tools, which are used effectively by geomatics engineers, provide great easiness in site selection studies.

On the other hand, one of the principles of land management is that a land can be effectively used for more than one purpose, resulting in efficient land use. Installing wind energy systems in areas suitable for other activities such as agriculture, animal husbandry, industry, and tourism means that the lands are used to their full potential, contributing to the economy and creating new areas of employment. These factors highlight the significant impact of wind energy on the economy. Investments in wind energy not only increase economic growth but also support sustainable development [71]. Therefore, countries emphasize wind energy and other renewable energy types by offering various incentives in their energy policies [72].

Recently, artificial intelligence technologies have been increasingly utilized in the renewable energy sector, including the wind energy field. AI allows for designing facilities that can provide high potential and maximum performance, as well as making them smarter and easier to monitor. This enhances the safety and sustainability of the systems. As AI technologies continue to develop and spread, they will play an increasingly important role in optimizing the use of energy resources in the future.

To provide a comprehensive analysis of the scientific areas related to wind energy, a bibliometric analysis was conducted, examining various fields. Today, the fields of Energy Fuels, Engineering, Science Technology Other Topics, and Environmental Science Ecology are prominent in wind energy research, and they are expected to remain the focus in the future. With the growing popularity of AI, it is believed that AI will also play a role in wind energy research and shape the field in the future.

## CONCLUSION

This comprehensive bibliometric analysis highlights the rapid growth and evolving trends in wind energy research from 2010 to 2023. By employing advanced analytical tools and predictive models, this study offers valuable insights into the past, present, and future of wind energy studies. Our findings underscore the increasing prominence of wind energy in scientific research and its critical role in sustainable development. Future research should continue to explore multidisciplinary approaches, integrating technological, environmental, and economic perspectives to advance the field further.

First, the study examined the general distribution, publication and citation numbers of 24907 wind energy studies conducted between 2010-2023. Then, the focus narrowed to article types, where 22177 articles were analyzed using Vosviewer, ArcGIS, and Excel programs. The evaluation included factors such as author, citation, institution, country, journal, publisher, research area, and keywords. The analysis looked at each factor individually and their common connections. Prominent author *Liu Y*, most cited author *Breyer C*, and most cited publication "*Overview of current development in electrical energy storage technologies and the application potential in power system operation*" emerged from the analysis. *People's Republic of China* was the most prominent country, and *North China Electric Power University* was the most cited institution. *Energy Fuels* was the most studied research area, *Energies* was the

most widely published journal, and *Elsevier* was the most used publisher. *Renewable energy* was the most used keyword. The analysis generated statistical outputs, which were presented through graphs, networks, and maps to visualize trends, clusters, spatial distributions, and connections among wind energy studies.

To examine the development process of wind energy, the dataset was evaluated in three periods based on the number of publications and citations. Notably, there was an increase in the number of publications and citations between 2019 and 2022. To forecast the future direction of wind energy, the Artificial Neural Network method was used to predict the number of publications, citations, and research areas from 2024 to 2030. The results of the forecasting study suggest a continuous increase in the number of publications and citations. In terms of research areas, the study predicts an increase in the field of Energy Fuels, while the fields of Environmental Science Ecology, Chemistry, Telecommunication, and Mechanics may also become more prominent. Finally, wind energy was evaluated from a multidisciplinary and broad perspective, considering both the present and the future.

## AUTHORSHIP CONTRIBUTION

**Nihal Genc:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing - original draft;

**Ferdi Ozbilgin:** Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing - original draft;

**Volkan Baser:** Conceptualization; Methodology; Supervision; Writing - review & editing.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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