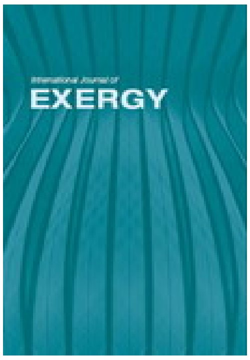

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Historical research trends and overview about exergy: a comprehensive analysis

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Historical research trends and overview about exergy: a comprehensive analysis

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Abstract: This study examines the contributions of researchers from around the world in the field of exergy over the past 30 years (1/1/1992–1/1/2022). Various aspects of the studies have been analysed such as publication type, research areas, and keywords. In addition, countries, authors, journals, and institutions that have worked in the field of exergy were examined. Thus, the detailed results of the five most influential authors, seven journals, and 15 institutions in the field of exergy in terms of publication, citation, PIP, and h-indexes are presented over the years. The effects of all countries broadcasting from the field of exergy in terms of publication and citation are shown. As a result of the analysis of all parameters, it has been shown that the most effective countries are China, Iran, and Turkey. Besides, it has been determined that Dr. Ibrahim Dincer is the most influential author in the terms of contributing authors.

Keywords: exergy; bibliometric analysis; energy systems; research trends; altmetric; scientometric.

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Biographical notes: Ibrahim Ozsari obtained his Bachelor's with high honour in Naval Architecture and Marine Engineering in 2013 from the Yildiz Technical University, Istanbul, Turkey. He obtained his Master's and PhD degrees in 2015 and 2021 respectively from the Yildiz Technical University. He is presently an Assistant Professor Doctor in the Naval Architecture and Marine Engineering Department at Bursa Technical University, Bursa. His main research areas are energy, exergy, gas turbine, oxy-combustion, and thermodynamics.

1 Introduction

Energy is an indispensable requirement for countries' agricultural, industrial, transportation, and housing needs and is also one of the biggest factors in their economic development. While more than half of the electrical energy produced in the world is met from power plants, the other half is obtained from sources such as nuclear energy, hydroelectricity, geothermal energy, solar energy, and other forms of energy (Erdem et al., 2009). The world uses renewable power plants, nuclear power plants and thermal power plants to supply electrical energy. Optimisation studies of power plants are very important for increasing efficiency. Energy supply in developing countries draws attention due to its expensive costs. The need has been found to reconsider energy options with the least cost due to the first law analysis being insufficient in terms of energy performance. Therefore, the importance of exergy analysis has increased regarding thermodynamic analyses for all systems (Utlu and Hepbasli, 2007). Research on energy has been made over the years over two basic concepts: exergy and irreversibility. Exergy is directly linked to the initial formulation of the second law of thermodynamics. Beginning in 1868, the first contributions to transforming energy into work were made by Clausius, Tait, Thomson, Maxwell, and Gibbs. In addition, Gouy's article 'On usable energy', published in 1889, was accepted by scientists upon being subjected to long debate. Later on in 1898, Stodola developed the concept of *free technical energy* as applicable to continuous flow processes. Also, Bosnjakovic's articles published in 1939 marked a new era in the development of exergy analyses. These articles made important contributions to the formulation of new performance criteria. Rant's 1956 paper had a major impact on exergy terminology, as he coined the now generally accepted term of exergy, replacing the colloquial terms of usability, usable energy, and work ability. Later on in 1965, Baehr described exergy as the part of energy that is converted into all other forms of energy. Exergy is based on the second law of thermodynamics and the concept of irreversible entropy generation (Kotas, 1985; Brodyansky et al., 1994; Dincer and Rosen, 2013). The impossibility of completely converting heat to work is a known fact. Therefore, the part that is suitable for transformation may be called exergy. Distinguishing between internal irreversibility and energy losses in a system is a very useful concept in relation to the state of the system and its environment (Dincer and Cengel, 2001). Exergy analysis is a useful method for designing, evaluating, optimising, and improving thermal power plants. In other words, it analyses the useful work potential of energy. Exergy analysis helps find the losses that occur in a system. This method pays attention to various component efficiencies and large losses at various points. As a result, necessary measures can be taken to reduce system losses (Rosen and Bulucea, 2009; Dincer and Acar, 2015). Exergy analysis has been shown to be the best way to optimise a system using the available information (Rosen and Dincer, 2001). Exergy analyses and the obtained benefits have been studied in detail (Szargut, 1980; Pavelka et al., 2015) and has additionally been stated to be the most accurate way to measure energy quality. Exergy analysis enables complex energy systems to be made more efficient (Dincer, 2002; Stanek and Budnik, 2010). Comprehensive research activities have been conducted in the field of exergy between 1992 and 2021. Both research articles and review studies on exergy have been studied over a very broad perspective. Historical research studies provide a great opportunity to see the scientific trends in the field of exergy.

Alan Pritchard's study was the first in this field to use bibliometrics as a historical research and technical term to refer to the statistical bibliography (Pritchard, 1969). Bibliometrics uses mathematics and statistics to analyse books, articles, and publications in terms of quantity, performance, and structure. Quantity indicators measure the productivity of researchers and institutions by counting the number of articles published and citations made over a period of time. Performance indicator usage is mandatory for measuring researchers' and institutions' quality of work. Meanwhile, performance indicators are useful for measuring the impact an article or journal has on a scientific field. The impact factor (IF) is used as a performance indicator to measure journals' importance in their field. Popularity, citation habits, and 5-year journal IFs are all factors that affect the accuracy of journal performance indicators (Durieux and Gevenois, 2010). Many bibliometric studies have been conducted on how to present performance indicators. Imran et al. (2018) studied organic Rankine cycle technology from the point of view of bibliometric analysis. Bodnariuk and Melentiev (2019) used various databases for performing a bibliometric analysis of micro-nanomanufacturing technologies. Amin et al. (2019) studied a bibliometric review of process safety and risk analysis. Omoregbe et al. (2020) carried out a bibliometric study over 20 years on the field of carbon capture technologies for mitigating climate change. Su et al. (2020) performed a bibliometric study that focused on carbon emissions and environmental management. Secinaro et al. (2020) carried out a bibliometric study for identifying business models for electric cars. Andreo-Martínez et al. (2020) used bibliometric analysis to examine the production of biodiesel under supercritical conditions. Kumar et al. (2020) revealed a quantitative analysis of artificial neural network applications regarding materials and engineering issues. Laengle et al. (2021) performed a bibliometric study over approximately 40 years' worth of fuzzy sets and systems. The most popular work in this field is van Eck and Waltman's bibliometric publication in 2010.

Upon examining the literature, no historical research study is seen to have occurred regarding such an important concept as exergy. A comprehensive analysis study can provide information about which energy studies have focused on exergy and where these studies are likely to go in the future. Therefore, this study quantitatively and qualitatively evaluates the global trend regarding research activities in the field of exergy by taking into account the scientific research articles published between 1992 and 2021. In order to comparatively evaluate the contributions of authors, institutions, and countries, we've researched publication statistics, the geographical distributions of authors and institutions, author lists, institutions with significant contributions in the field of exergy, citations, and authorship models and selected effective performance parameters. This study is a comprehensive analysis of the exergy field and has the potential to identify future research topics by providing researchers with a very useful overview.

2 Data collection and analysis method

Scopus provided the data used in this bibliometric analysis. In May 2022, I accessed the Scopus database records between 1992 and 2021 and searched for the keyword 'exergy'. The Scopus database then listed the articles that contain the word 'exergy' in the article title, abstract, and/or keywords. As a result, I obtained 21,441 publications for analysis. I created and visualised bibliometric networks for these publications, with these data including information such as journals, researchers, and individual publications. Quantitative analysis of the literature on exergy articles can demonstrate the international status of global exergy research from a macro perspective and provide an overview of the exergy topics that have been researched. This study considers primary and co-authorship as the inclusion criteria. The geographical origins and institutions of the authors in each article have been derived from the Scopus database. If an article has more than one author from the same geographic origin or institution, only one was included in the calculation. In the visualisations, the figures show the more popular geographical origins or institutions using larger fonts and bolder connection lines. In addition, the visualisations reveal that the geographical origins, institutes, and keywords of an article are linearly related to one another. Conducting a citation-based bibliometric analysis has been a subjective constraint for proving the quality of a study, for determining the number of publications by year, and also for evaluating authors' scientific efficiency (i.e.., h-index). I have also performed the analyses in this article only using the Scopus database: using another database may provide different results.

This bibliometric analysis study used four different drawing and analysis programs for making the visualisations after summarising the obtained data. The larger the size and darker the colour in a visualisation shows the studies that have had greater effects. VOSviewer is a program used to create and visualise bibliometric networks (van Eck and Waltman, 2010) and was also used as another analysis program. The networks created in VOSviewer can include journals, researchers, or specific publications and are creatable based on relationships such as number of citations, bibliographic matching, co-citations, or co-authorship. The network visualisations represent the elements with their own labels and a circle. The size of label and the circle for an item's tag is determined by the item's weight. The higher an item's weight, the larger the item's label and circle. Labels may not be displayed for some items. This is done to avoid overlapping labels. The colour of an item is determined by the set to which the item belongs. Lines between elements represent connections.

3 Results and discussion

The results from the bibliometric analyses on exergy in terms of publication type, citations, fundamental research areas, keywords, countries, authors, journals, and institutions are presented in Figures 1–11. The results are shown in detail according to year, distribution by country, percentage, and impact.

The analysis that was performed to determine the trends of recent studies on exergy first determined the number of articles on the subject over the last 30 years, and Figure 1 shows the total number of citations these articles received. As can be seen in the figure, while a similar number of articles were produced annually between 1992-2003, an increasing number of annual publications occurred between 2003-2022, ultimately reaching 2,500 publications for 2022. Similarly, the number of received citations increased from 1992 to 2017, reaching over 20,000 annually. The reason for the decrease in the number of annual citations after 2017 is that recent studies have yet to be cited. This trend will continue to increase with the these publications being cited in the coming years.

When analysing the number of publications by type, 75% are seen to be research articles, followed respectively by conference papers, book chapters, and reviews (see Figure 2). The remaining types of publications are described in the figure as 'others' and include notes, conference reviews, business articles, short surveys, books, abstract reports, editorial errata, and letters.

Figure 3 portrays the results from examining the subject categories on Scopus. Study areas on exergy are seen to mostly involve energy (28.3%) and engineering (26%). Some studies have additionally focused on environmental science issues for reasons such as finding materials that are more resistant to higher temperatures or for problems such as corrosion cracking and fatigue. Due to exergy being related to the second law of thermodynamics and expressing energy usability, it has also been the subject of many studies in the fields of physics and astronomy, environmental engineering, and chemical engineering. In addition to these, Figure 3 show many other subjects to be in the field of interest, with the larger the size of the circle showing the greater the frequency of the subjects.

Figure 1 Timeline of publications and citations in the exergy field from 1992 to 2021 (see online version for colours)

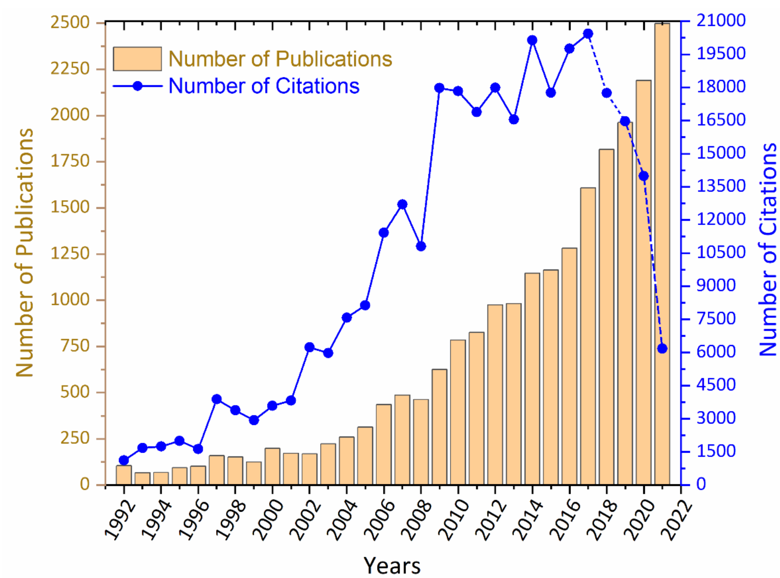
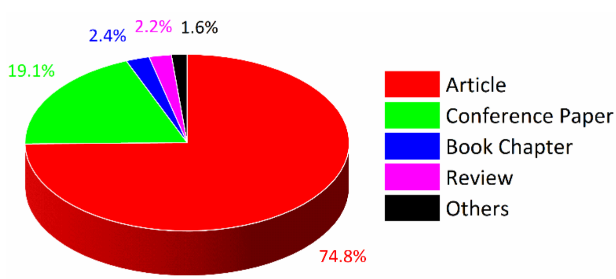


Figure 2 Types of publications in the exergy field from 1992 to 2021 (see online version for colours)



The 160 most-used keywords in the field of exergy were identified in 21,441 studies conducted between 1992 and 2022. The word exergy was the most used keyword at 15,220 studies, followed by energy efficiency (*f* = 4,664), exergy analysis (*f* = 4,341), and exergy efficiencies (*f* = 3,488), respectively. When examined in detail, Figure 4 shows the importance of exergy analyses in regard to energy systems analyses, system components, fuel, and working fluids. Analysing keywords is also very important in terms of identifying new study areas and topics. Thus, this analysis will offer many ideas to future researchers.

Figure 3 Publication distribution by subjects as classified by Scopus proportional representation of all subjects (see online version for colours)

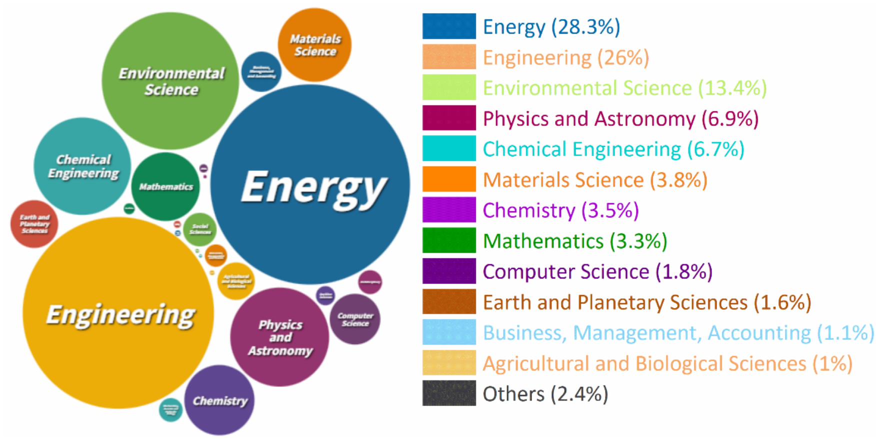
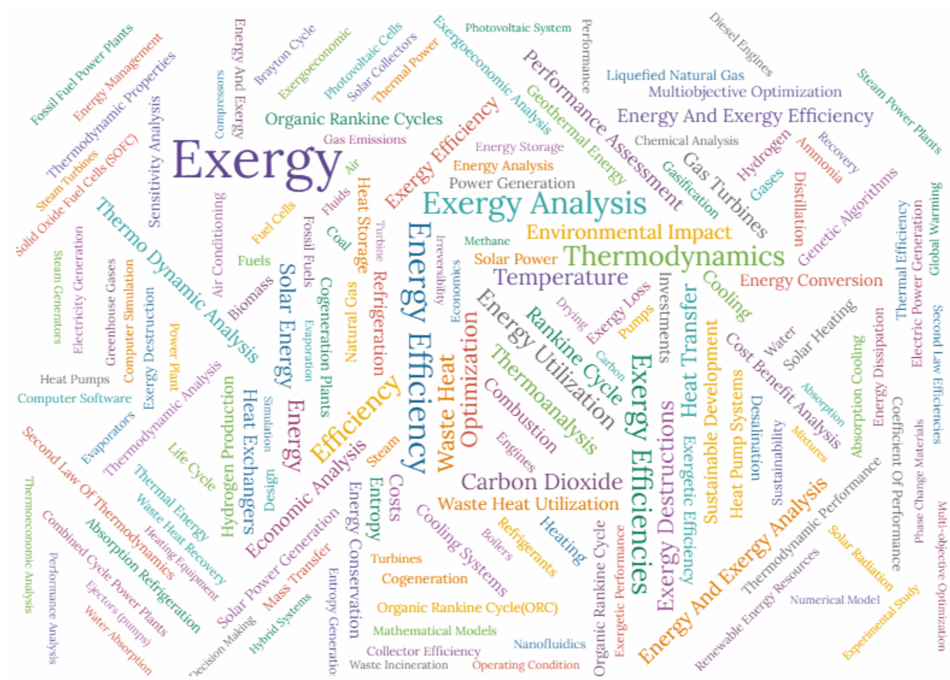
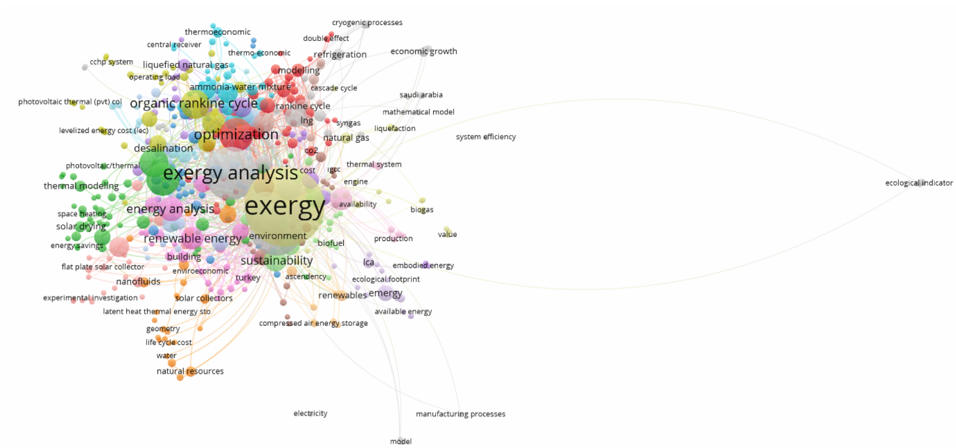


Figure 4 Proportional display of the most used keywords in all publications in the field of exergy in the last 30 years (see online version for colours)



I selected the 1,000 most influential publications from among the 21,441 studies. Figure 5 shows the most common keywords used in the 1,000 most influential publications in the field of exergy and their relations with each other. The colours in Figure 5 refer to different clusters and/or related topics, with larger size circles showing the keywords that appeared more frequently. The closer the circles are, the more often the two keywords were found in the same publications. The minimum number of occurrences for a keyword was selected as one. As a result, Figure 5 is a map for researchers who want to publish effectively in the field of exergy.

Figure 5 Top keywords that obtained with data mining in the top 1,000 publications (see online version for colours)



Figures 6(a) and 6(b) respectively show the number of publications and number of citations regarding exergy by country. When analysing Figure 6(a), in which darker colours indicate higher numbers of publications/citations, China performed the highest with 4,968 publications, followed respectively by Iran with 2,341 publications and Turkey with 1,904 publications. These countries have the greatest number of publications on exergy and are followed respectively by India, USA, Canada, Italy, Germany, UK, and Japan. When analysing Figure 6b, China similarly performs highest with 47,392 citations (12.2%), followed respectively by the USA with 31,264 citations (8%), Iran with 29,010 citations (7.5%), Canada with 26,385 citations (6.8%), and Turkey with 23,760 citations (6.1%). also, analysing the data with respect to the paper impact parameter (PIP = citations/publications) (Ozsari, 2021), the situations change for countries. Countries with at least 50 articles on exergy were taken into account while making this analysis. Accordingly, Switzerland leads the PIP ranking with 245 publications and 8,461 citations (PIP = 34.53), followed respectively by Sweden with 213 publications and 6,355 citations (PIP = 29.84), Australia with 308 publications and 7,349 citations (PIP = 23.86), and Denmark with 304 publications and 7,116 citations (PIP = 23.41). China has a PIP of only 9.54, with 4,968 publications and 47,392 citations. As an important note, stating that the total number of publications and citations for some countries in all these analyses is thought to be low because they mostly prefer to publish articles not in English but in their own language may be helpful.

Figure 7 shows the universities and institutes with the most publications on exergy. As can be seen, this figure shows the geographical distributions for the number of publications; 8 of the 15 most influential institutions in the field of exergy are located in China, followed respectively by Iranian institutions and universities from Canada, Germany, Turkey, and India. The graphs clearly show the most influential institution to be Ontario Tech University. Compared to other institutions, it is by far the leader in both the number of publications and citations. The publications produced in the last 20 years have continued to increase steadily each year. This increase is also seen in all institutions except for a few. The most effective ones in terms of this increase are seen to be Ontario Tech University and University of Tehran. While universities seem to be quite influential in the field of exergy, industrial companies pitifully lag behind in this regard. The second law of thermodynamics should be considered in all energy and engineering projects. In this way, both more efficient and more environmentally friendly projects will be put forward.

Figure 6 Distribution of publications with respect to country in the exergy field for the last 30 years (1992-2021) by (a) number of publications and (b) citations (see online version for colours)

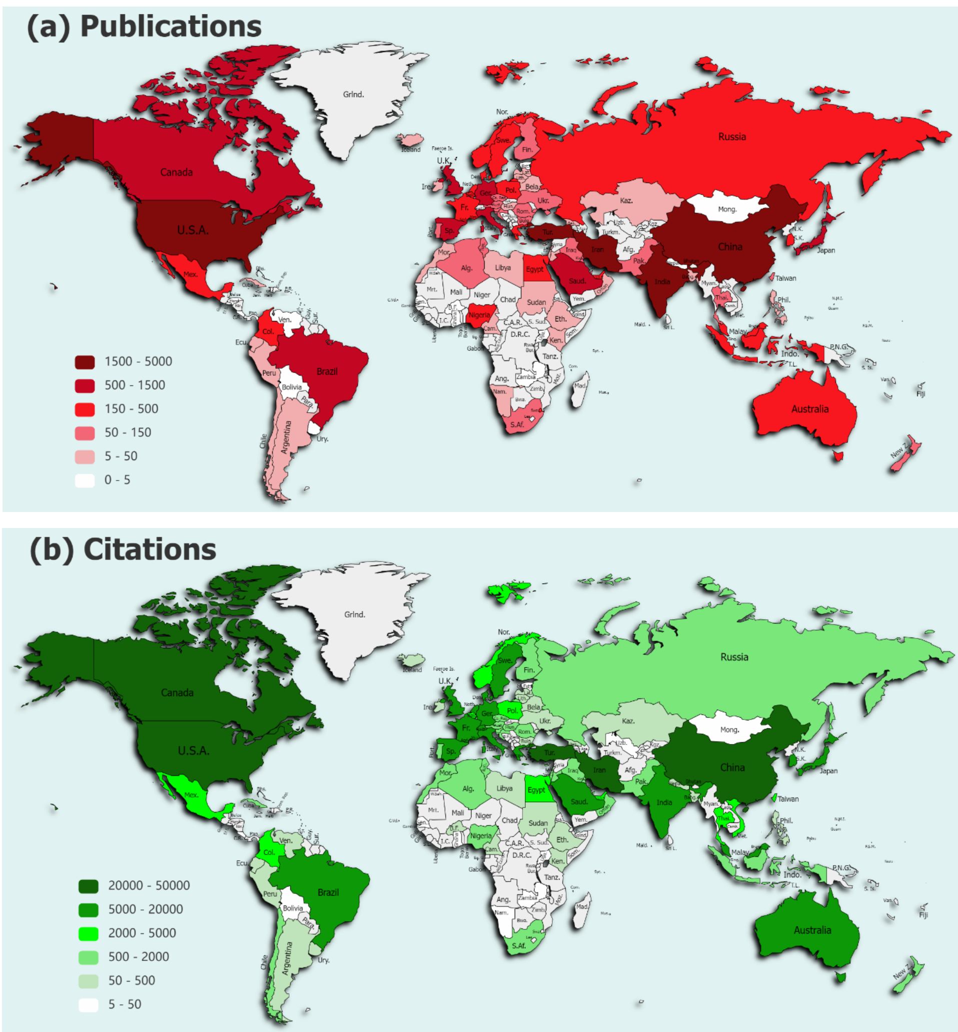
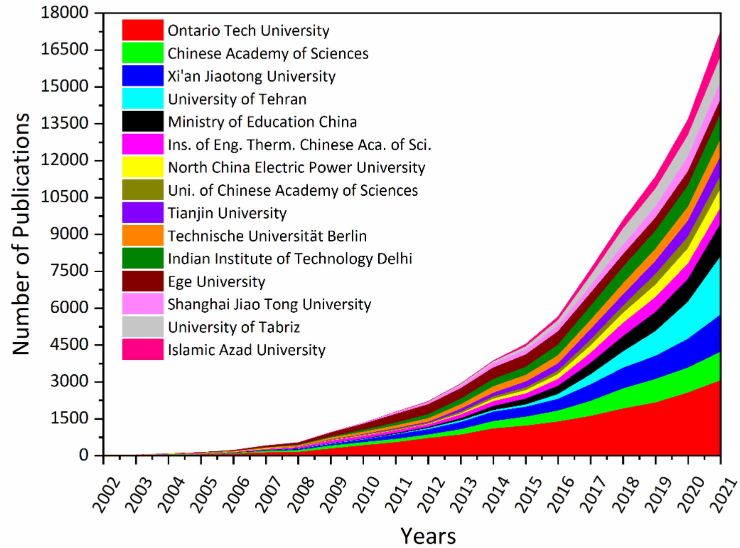
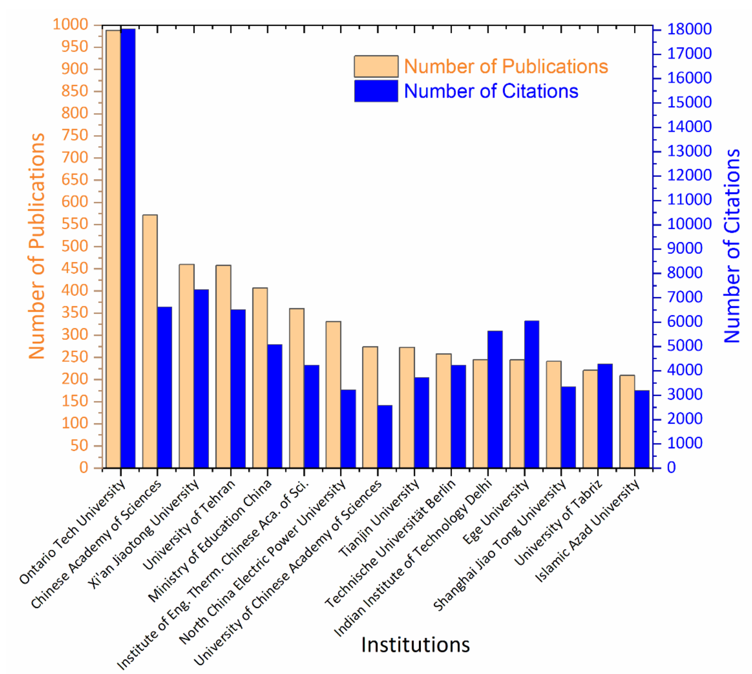


Figure 7 (a) Publication productivity of the most influential institutions in the field of exergy by years (b) Publication citation relationship of institutions (see online version for colours)



(a)



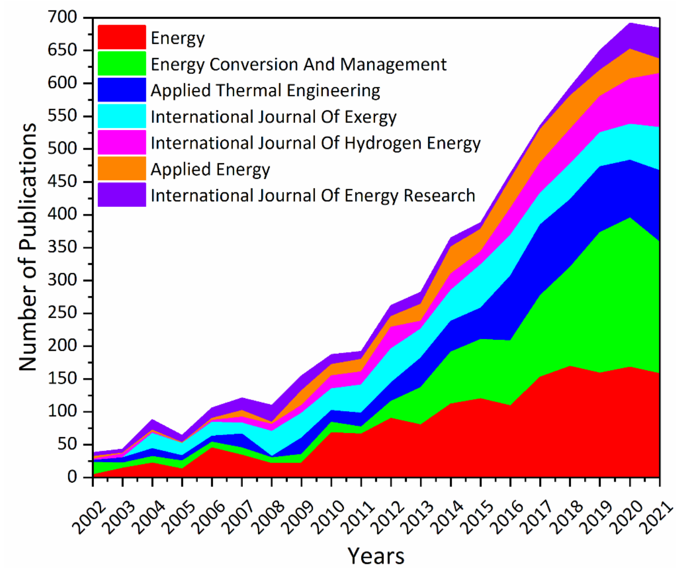
(b)

Table 1 Top 20 productive journals in the exergy field from 1992 to 2021

Publication name	*Publications*	*Citations*	*PIP*	*h index*	*CS 2020*	*SJR 2020*	*SNIP 2020*
Energy	1,694	36,810	21.73	193	11.5	1.961	2.014
Energy Conversion and Management	1,445	27,553	19.07	192	15.9	2.743	2.375
Applied Thermal Engineering	925	20,344	21.99	158	10.1	1.714	1.927
International Journal of Exergy	778	4,155	5.34	31	1.9	0.36	0.544
International Journal of Hydrogen Energy	536	11,722	21.87	215	9	1.212	1.335
Applied Energy	458	18,177	39.69	212	17.6	3.035	2.696
International Journal of Energy Research	380	8,524	22.43	95	5	0.808	1.239
Journal of Cleaner Production	373	7,926	21.25	200	13.1	1.937	2.475
Renewable Energy	344	9,728	28.28	191	10.8	1.825	2.381
Energies	293	2,579	8.80	93	4.7	0.598	1.161
Solar Energy	260	7,438	28.61	181	8.9	1.337	1.614
Energy Procedia	216	1,628	7.54	81	4.4	0.474	1.079
Journal of Thermal Analysis and Calorimetry	204	1,913	9.38	92	5.1	0.521	1.142
International Journal of Refrigeration	203	4,330	21.33	116	6.5	1.497	1.649
Energy and Buildings	198	5,960	30.10	184	10.9	1.737	2.129
Desalination	180	4,072	22.62	184	14.3	1.794	2.108
Renewable and Sustainable Energy Reviews	180	10,625	59.03	295	30.5	3.522	4.684
Entropy	176	2,324	13.20	74	4	0.468	1.059
K.C.J.W.L.H.P. Journal of Engineering Thermophysics	167	420	2.51	23	0.4	0.153	0.241
Ecological Modelling	162	3,842	23.72	156	4.9	0.876	1.095

Table 1 shows the top 20 journals to have published the most articles on exergy, as well as the number of articles they've published and cited. The following is a list of the top five journals that can be created with respect to the number of publications: *Energy*, *Energy Conversion and Management*, *Applied Thermal Engineering*, *International Journal of Exergy* and *International Journal of Hydrogen Energy*. With respect to the number of citations, the top three are: *Energy*, *Energy Conversion and Management* and *Applied Thermal Engineering*. Lastly, with respect to PIP, the top three journals are: *Renewable and Sustainable Energy Reviews*, *Applied Energy* and *Energy and Buildings*. The most cited journals can also be seen to have high PIP scores, which also shows the number of quality papers they publish.

Figure 8 Most productive journals or proceedings in the exergy field (see online version for colours)



Because almost all the studies in the field of exergy are in the field of energy and engineering, the studies have been published in the most popular journals of this field. As can be seen, Figure 8 presents the performances of the top seven most published journals in the field of exergy over the last 20 years. After 2009 in particular, performance increases were seen in these seven journals. When individually examining the performances of these journals, studies on productivity and exergy are concluded to have increased over the years. This performance reached its peak in 2020. In other words, this is concrete proof showing the importance of exergy in today's world of science and technology.

The most productive authors are shown in Figures 9(a) and 9(b) with respect to their publication, citation, h-index, and PIP numbers regarding exergy. The most productive authors according to the number of publications are I. Dincer, M.A. Rosen, and A. Hepbasli, with 790, 352, and 249 publications, respectively. In terms of the number of citations, the most productive authors are again I. Dincer, M.A. Rosen, and A. Hepbasli with 17,367, 9,517, and 6,410 citations, respectively. In terms of the h-index, the most productive authors are still I. Dincer, M.A. Rosen, and A. Hepbasli with h-index values of 106, 86, and 67, respectively. Sorting by the number of publications or citations individually can actually give misleading information about these authors' productivity. For this reason, I feel the PIP as well as the h-index should also be taken into consideration in addition to the number of publications and citations because some authors are found who have few publications but many citations. However, evaluating these indicators on their own would also be wrong. Therefore, publication, citation, and PIP should all be evaluated together. As a result of examining all these parameters together, I. Dincer is clearly seen by far to be the most productive scientist in the field of exergy. Researchers who will work in the field of exergy should closely follow the work of these valuable scientists.

Figure 9 The most productive authors and their scores from 1992 to 2021 by (a) numbers of citations and publications and (b) h-index and PIP values (see online version for colours)

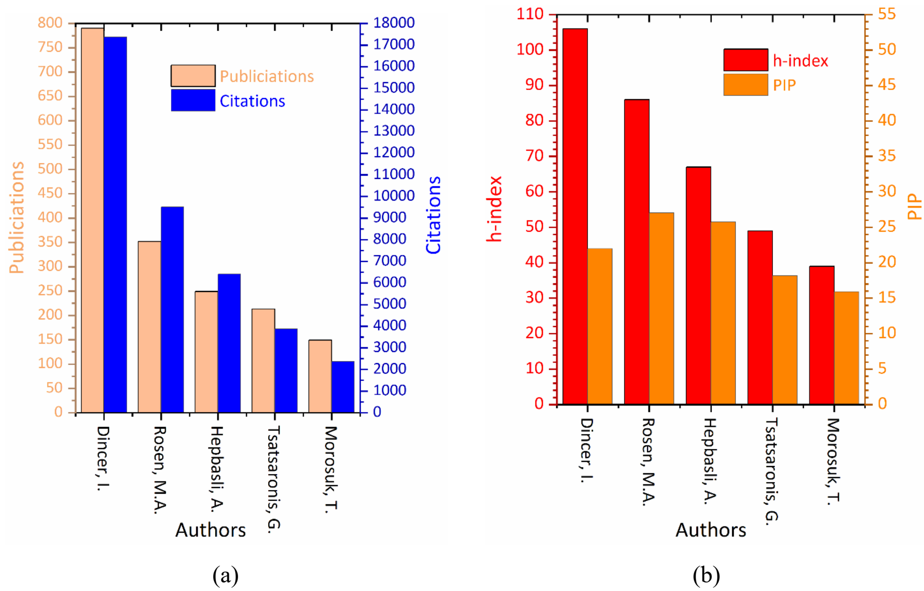


Figure 10 Demonstrating the share of the most influential scientists in the field of exergy in science (see online version for colours)

Figure 11 All authorship analysis connected items for exergy fields studies (see online version for colours)

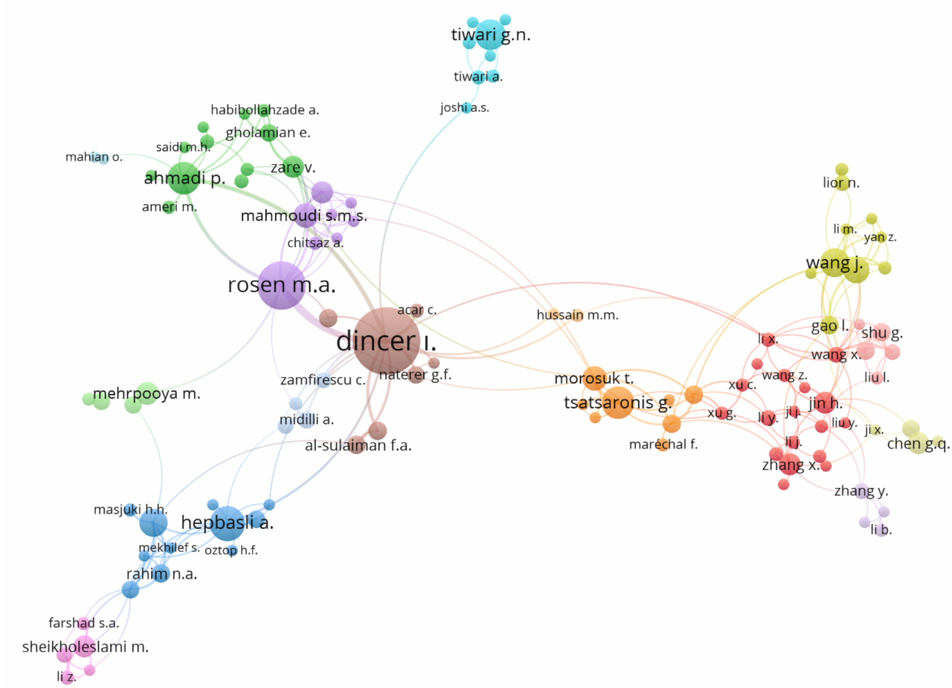


Figure 10 shows the status of the 132 most influential authors in the field of exergy. The software program that visualised the more effective authors in the field of exergy with greater visibility and size, thus showing their share in this field according to publications, citations, and PIP status. Meanwhile, a separate software program was used to examine and extract the relationships among these influential authors. Figure 11 shows the co-authorship analysis results, which was performed using a full counting method by selecting authors as the analysis unit. In this analysis, authors with less than 40 studies remained in the background due to the complexity of the analysis calculations. By selecting the minimum number of documents of an author based on this, 132 authors were obtained. The total strength of an author's co-authorship link with other authors was calculated for each of the 132 authors. The authors with the greatest total link strength were selected. Dr. Ibrahim Dincer ranked highest with 790 documents and 17,367 citations, a total effective link strength of 20. When examining his connections, Dr. Ibrahim Dincer's colleagues and students are seen to collaborate in the field of exergy. This study has presented the scientists who do a lot of work in the field of exergy on the basis of effective studies, and many different working networks are also obviously formed with the relations developed through teamwork.

4 Conclusions

With the industrial revolution, physics and muscle power left their place to mechanical power. With the rapid spread of industrialisation in many countries, industrial inventions began to be seen everywhere. The only goal to initially be achieved was to invent power-generating machines. With the increase in the number of inventions, the power systems from which energy was obtained began to be categorised according to their energy performance. Systems with low performance in terms of energy were either taken into development or ceased being used. With the widespread popularisation of industrialisation all over the world, an international competitive environment emerged. With the start of technology exchanges in this competitive environment, obtaining being good at obtaining outputs from power systems just in terms of energy performance is not enough. Thus, the concept of exergy and exergy analyses became very important. The current study has examined studies in the field of exergy over the last 30 years and obtained results regarding the following. By showing the distributions of publications and citations made between 1992 and 2021 according to year, this study has presented its results in detail in terms of the types of studies and their fields according to their activity status. This research uses figures to display the most used keywords in the field of exergy, as well as their impact rates and other links. The study also presented the publications and citations from countries around the world in the field of exergy and showed the 15 most influential institutions and their outputs by year, as well as their total impact. This study analysed in four different ways the authors who've contributed to the field of exergy, showing the performances of the most influential authors in terms of number of publications, number of citations, h-index values, and PIP values. The names of the 132 authors who contributed the most to this field have been displayed according to their impact scores. In addition, this study has presented these authors' collaborations regarding academic study with others. All these analysis results will be of great benefit to new researchers who will work in the field of exergy. With the guidance of this study, the most productive institutions, journals, and authors will be able to quickly learn and benefit for their research related to the subject of exergy.

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