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## Article

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## Research Trend on Nuclear Energy from 2008 to 2018: A Bibliometric Analysis

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### ABSTRACT

This paper presents a bibliometric study of the nuclear energy research output from 2008 to 2018, by mean of the Web of Science database. From the 2545 papers published in the period studied, bibliometric indicators were calculated to identify the tendency of this energy source, such as the number of publications by countries, institutions, authors, main keywords reported and the identification of the most cited articles. The results shown the scientific paper as the document type with a more significant number of publications from the total considered (83.4%), and the country with the highest h-index value was the United States, which is also the country with the highest production of articles with a total of (643), followed by China and Germany. An increase in the research outlet was presented in USA (213%) and Germany (182 %) from 2013 to 2017, which is close with the number amount of publication developed by these countries under the figure of international collaboration. Also, the Chinese Academy of Science was the institution with the highest number of publications (79), and the top institution with publications under international network. The results allow to identify the main stakeholders in the nuclear energy research output and determine projections and tendencies on new and complementary topics in this field of study.

**Keywords:** Research Trend, Nuclear Energy, Bibliometric Study, Collaboration Network, H-index

**JEL Classification:** Q42

### 1. INTRODUCTION

The industrial processes that belong to the different economic sectors require different energy processes for their operation, even if this belongs to the industry dedicated to the generation of products or services (Edwards et al., 2019), (Mohammadi et al., 2017). The demographic growth, together with the technological development, made an increase in the consumption of natural resources used to generate energy. It has caused continuous searching for new clean, and renewable energy mechanisms (Lau et al., 2018), (Luqman et al., 2019). Researchers have evaluated the environmental impacts associated with different renewable energy sources (Jin and Kim, 2018), (Khan et al., 2017), as well as the strengthening of global organizations aimed at assessing the effect of CO<sub>2</sub> emissions on the climate change (International Energy

Agency [IEA], 2015), and the establishment of energy policies about the generation of nuclear energy in countries such as China (Long et al., 2015) and USA (Menyah and Wolde-Rufael, 2010).

Nuclear energy emerges as an alternative that seeks to mitigate this problem by covering 11% of global energy demand (Suman et al., 2016; Kim, 2019). Obtaining power from nuclear fission processes is one of the most efficient forms of energy production (Knapp and Pevec, 2018), (Knapp et al., 2010), due to the use of the cohesion of the subatomic particles of radioactive materials (Li et al., 2016), (Joyce, 2018). The interest of nuclear power generation lies in the versatility of generation uses in nuclear power plants in various sectors of the industry (Wang et al., 2019). On the other hand, the implementation of nuclear power plants has been an object of study by many authors worldwide

(Yildiz and Kazimi, 2006) (International Atomic Energy Agency, 2018).

Figure 1 shows the annual behavior of the generated energy derived from nuclear sources in the countries that lead the development of this activity, where an information system of power reactors of the International Atomic Energy Agency was implemented (International Atomic Energy Agency, 2018). It can be seen that the United States of America presented an average production of 96000 MW/h in the last 8 years, in comparison with other countries that have in an average output below 40000 MW/h, except France.

Countries such as the United States and France, presented a constant production of energy for the years 2010, 2015-2017. France was the country that showed a constant production; the rest had small fluctuations over the years. Almost 60% of the creation of nuclear energy was given by the United States and France, while countries such as Japan contribute 17%, China 11%, Germany 6%, and the United Kingdom 5%.

On the other hand, at the research level is the work of Kasahara et al., who studied the thermochemical process of separation of iodine and sulfur, an essential process in the production of hydrogen and widely studied for its chemical effects (Xu et al., 2018), (Gillis et al., 2018), used for the generation of hydrogen with the use of heat from a nuclear reactor (Kasahara et al., 2007). This work was carried out jointly with the Japanese agency of atomic energy, which looks after safety in nuclear power generating sources (Miyauchi et al., 2010), (Matsumoto and Shiraki, 2018).

The phenomenon of global warming made researchers to propose a model for the generation of liquid hydrocarbon fuel, derived from CO<sub>2</sub> emissions (Shin et al., 2004), using a process that separates oxygen and water from carbon dioxide. Thus, Graves et al. proposes a system with an efficiency of 70% where the cost of generating electricity with gasoline varies depending on the location of the study (Graves et al., 2011). Following this work, a study was conducted to establish a direct relationship between the mitigation of carbon emissions, making use of renewable energies compared to nuclear

energy, through a mathematical model that determined the impact of each source (Jin and Kim, 2018), (Dogan and Seker, 2016).

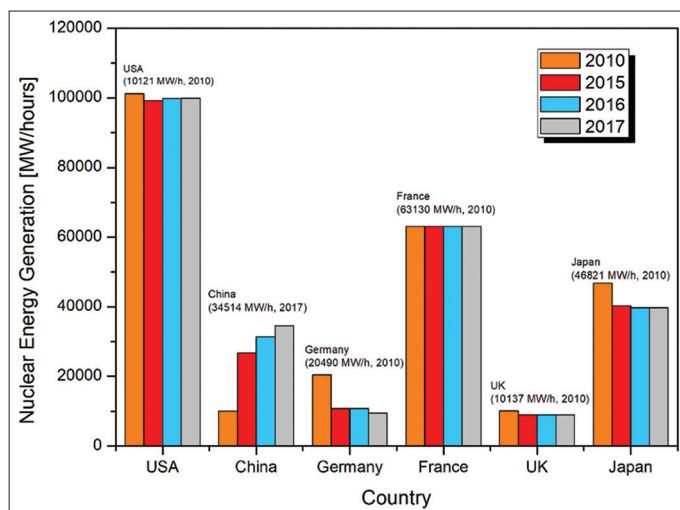
An effective way to know the trends, global interest, and new developments in an area of knowledge is through a review of the specialized literature (Mair et al., 2018). However, the literary revision involves a great effort, long working hours, and long processing times for the volume of publications in the study period considered for the subject under study (Radhakrishnan et al., 2017).

To obtain effective results, bibliometric studies are used, where a systematic process is done to determine not only the most cited articles with the highest impact in the area of knowledge (Yadava et al., 2019), but also the most relevant authors with their latest developments, and the countries with better contribution in the lines of research for the development of technology throughout the period studied (Narin et al., 1994). However, a small number of investigations in nuclear energy are available in the literature (Wang et al., 2018). Moreover, this type of study allows to identify collaborative networks that have been developed over time, through maps of co-authorships, citations, countries and institutions (Dehdarirad and Nasini, 2017). Thus, the main contribution of this article is the presentation of the results of a nuclear energy bibliometric by means of specific indicators in the period from 2008 to 2018. In addition, an analysis of trends in nuclear energy research results was elaborated in an interval of time between the years. The study was developed through an objective and systematic point of view, that give clear and precise perspective of the results contained in the scientific articles about nuclear energy, a source of energy of great growth, thanks to its great capacity of production with few greenhouse gas emissions.

## 2. METHODOLOGY

The bibliometric study developed was based on a statistical method that considers a bibliographic count to define the investigative progress of the topic addressed in the literature (Du et al., 2014), (Yonoff et al., 2019), considering as a point of reference a quantitative analysis of the values of the relevant indicators.

**Figure 1:** Nuclear energy generation of the six most producing countries from 2008 to 2018



### 2.1. The Impact Factor (IF) and the H-index

The present work established the IF and the h-index (h) as measures of influence. The IF is a parameter that measures the average number of citations of an article published in a journal (Huang, 2017). It is necessary to know the quality level of a scientific journal to determine the quality of publications and identify the location of information of great importance in a particular topic. Thus, a good practice is to consult its IF using a complementary tool to the Web of Science (WoS) database called In Cites Journal Citation Reports. On the other hand, the h-index is defined as a parameter that numerically ponders the impact generated by a scientific researcher and their work (Hirsch, 2005). Its use allows quantifying, in the same way, the importance of scientific institutions and journals in multidisciplinary fields.

### 2.2. Research Output Analysis

The research output analysis is a practical research methodology that allows to systematize, analyze, and quantify the research

results included in a large number of articles (Albig, 1952). Researchers often use keywords and expressions that indicate the central content of the literature as the subject of the research. The keywords were examined to quantify their repeatability in the processed articles.

### 2.3. Collaboration Network

The collaboration network is an instrument that allows for discovering the type of relationship among the actors participating in the results of the research. In this document, collaboration networks are presented to establish the cooperation ties in this area and to show explicitly the relations among the 20 countries and institutions with the highest level of production. For its graphic representation, the VOSviewer computer tool (van Eck and Waltman, 2013) was used to build bibliometric networks with different parameters that allow the construction of bibliometric systems with different settings.

## 3. RESULTS AND DISCUSSION

The keywords and words selected for the search in the WoS database were: “Nuclear energy,” “nuclear energy efficiency,” “nuclear reactor.” This search was done on August 18, 2018, to collect documents and information published between 2008 and 2018. The data was analyzed considering characteristics and parameters such as IF, citations, and authors.

### 3.1. Characteristics of the Publications

There were 2545 documents related to nuclear energy from WoS from 2008 to 2018. The largest number of publications were found in the type of document “Article” with an amount of 2123, representing 83.4% of the total sample. It was followed by the type “Proceeding papers” with a total of 246 (9.7%), “Review” with 156 (6.1%), and “Editorial material” with 11 (0.4%). The remaining publications were book chapter, book chapter article, book revision, correction, and letter with percentages lower than 1%. Different types of documents belonging to the topic of nuclear energy available in WoS were processed and distributed in 10 different languages, where English had the highest number with

2487 records. Other languages were also presented in the results with a significant amount, such as Chinese (23), German (14), Russian (11) and Polish (4).

Figure 2 shows the six countries with the highest number of published articles on nuclear energy production, where it is observed that USA and Germany lead the list with a total of 1883 published documents with a contribution of 37.12% for the USA and 33.93% for Germany. In 2017, they reached the maximum number of documents published.

With the analysis of Figures 1 and 2 it can be concluded that the research and technological development mainly takes place in the USA, while France imports the developments for its installation and operation.

On the other hand, we can observe the case of Germany, which is a country that leads the creation of articles related to nuclear energy, with a low production of nuclear energy that can be explained by the fact that it is a producer of technology and scientific developments in the area. Regarding the relationship between the production of articles and energy production, the United States is the most coherent country in maintaining considerably high levels in both parameters, since it dedicates a lot of research resources to the subject, and at the same time, it develops and installs this energy source.

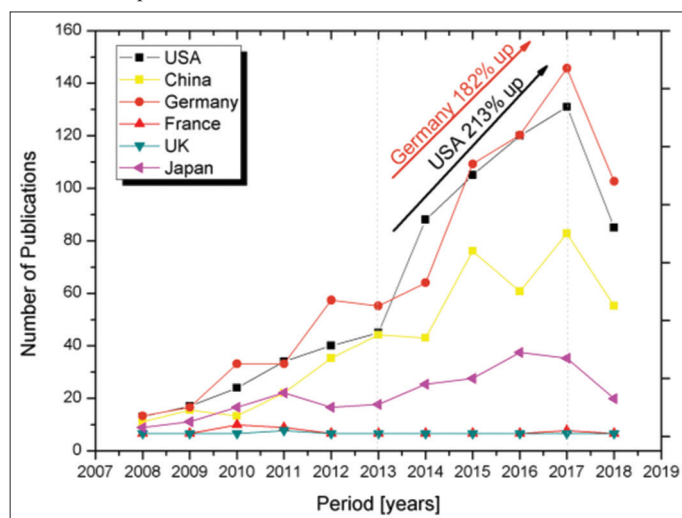
### 3.2. Distribution of Publications in Country

The affiliations and nationality of the authors of the articles of a scientific journal are considered to determine how the countries, institutions, and thematic areas make their contributions in the subject. In scientific research, it is common the collaborations among authors or institutions due to the availability of resources, or infrastructure. Thus, the results show that 50% of the total number of articles was developed jointly by authors or institutions from different countries.

Table 1 shows the characteristics of the publications related to nuclear energy from 2008 to 2018, where the number of papers had an increase of 32% from 2008 to 2011. The average number of authors per article associated with the subject was 4.32 in 2008 and increased to 5.43 in 2017. Regarding the number of references cited, this remained in constant growth from 2008 to 2013, followed by constant growth at a rate of 10% until 2018. The results of the data registered until 2018 had similar trends to the previous years. The increasing rate of change indicates that the theme maintains a high interest and development in the scientific community. The detailed characterization of publications in this area, using bibliometric indicators, allows determining the evolution of the number of publications each year related to the number of authors, which shows the volume of researchers interested in the subject, reaching 1908 by the year 2017. The average of authors per document is shown annually. The extension in average pages of the works was between 4.32 (2008) and 5.93 (2014). Also, it shows the number of times that each article has been referenced 47.58 (2018).

From 2008 to now, 88 countries have generated scientific publications in the WoS database on the topic of nuclear energy.

**Figure 2:** Number of publications of the countries with the highest production of documents from 2008 to 2018



Categorizing the countries by the production of scientific articles on the subject shows that the top 20 of the countries, shown in Table 2, are responsible for 26% of the total production. This analysis was developed considering indicators such as the total number of articles in journals, the number and percentage of articles from a single country and international collaboration, and filiation of the first author.

Additionally, the results show that the geographic location of the top 20 countries belongs to different continental areas, located mainly in Europe, Asia, and North America. There are publications not assigned to a country “unknown,” because the data recorded in the database does not record this information. The position of the countries favors international cooperation; for instance, Germany, France, and the United Kingdom present collaborations in a range of 7-10% of the total number of the publications.

The cooperation networks among the 30 countries and regions with the highest production of articles in the field of nuclear energy can be found in Figure 3, where the United States is the country with the most cooperative works, the most significant bibliographic

production and the highest generation capacity in nuclear energy, which is consistent with the behaviors presented in Figures 1 and 2. The United States has a collaboration network with 29 countries that are located in different continents, which allows reaching a total of 657 publications on the subject. The second country with the most significant collaboration is China, who has worked together with 25 countries for a result of 367 publications. In the case of Germany, an atypical case was presented. In spite of having more collaboration with other countries than China, Germany shows a smaller number of publications for a total of 241.

Also, countries such as Scotland being the country with the lowest production of articles with 13 documents, present the collaboration with 20 countries. A total of 2617 institutions made contributions on the subject of nuclear energy, reaching a total of 2545 publications.

Table 3 shows that 34.67% of the publications were made through international collaboration, where 6 of the 20 most productive institutions, are from the United States, 7 are part of the European continent and 5 of the Asian continents. The results show that six

**Table 1: Characteristics of the publications from 2008 to 2018**

| PY   | TP  | AUTP | #AU  | AU/TP | NR    | NR/TP | PG   | PG/TP |
|------|-----|------|------|-------|-------|-------|------|-------|
| 2008 | 155 | 155  | 699  | 4.32  | 4749  | 30.64 | 1522 | 9.82  |
| 2009 | 177 | 177  | 1016 | 5.74  | 6106  | 34.51 | 1709 | 9.66  |
| 2010 | 175 | 175  | 882  | 5.04  | 6677  | 38.15 | 1799 | 10.28 |
| 2011 | 205 | 205  | 1117 | 5.45  | 7361  | 40.08 | 2047 | 9.99  |
| 2012 | 191 | 191  | 955  | 5.00  | 7656  | 42.68 | 1990 | 10.42 |
| 2013 | 242 | 242  | 1397 | 5.77  | 10328 | 39.33 | 2587 | 10.69 |
| 2014 | 236 | 236  | 1400 | 5.93  | 9282  | 42.03 | 2446 | 10.36 |
| 2015 | 300 | 299  | 1681 | 5.60  | 12609 | 42.03 | 3217 | 10.72 |
| 2016 | 312 | 312  | 1700 | 5.45  | 12554 | 40.24 | 3338 | 10.70 |
| 2017 | 333 | 333  | 1908 | 5.73  | 15334 | 46.05 | 3926 | 11.79 |
| 2018 | 220 | 220  | 1195 | 5.43  | 10468 | 47.58 | 2639 | 12.00 |

PY: Years, TP: Total number of publications, AUTP: Number of publications including names of authors, AU: Number of authors, NR: Number of citations referenced, PG: Number of pages

**Table 2: Top 20 countries with highest production from 2008 to 2018**

| Country     | TP  | TP R (%) | SP R (%)  | FP R (%)  | CPR (%)   | RPR (%)   | h-index |
|-------------|-----|----------|-----------|-----------|-----------|-----------|---------|
| USA         | 643 | 1 (25.3) | 1 (16.84) | 1 (21.43) | 1 (27.69) | 1 (20.12) | 59      |
| PR China    | 367 | 2 (14.4) | 2 (11.25) | 2 (12.12) | 2 (14.62) | 2 (12.48) | 30      |
| Germany     | 241 | 3 (9.5)  | 3 (4.64)  | 8 (4.16)  | 3 (9.67)  | 3 (5.95)  | 38      |
| France      | 205 | 4 (8.1)  | 7 (3.49)  | 4 (4.84)  | 4 (8.64)  | 5 (4.48)  | 30      |
| UK          | 176 | 5 (6.9)  | 10 (3.13) | 8 (4.16)  | 5 (7.41)  | 8 (4.28)  | 31      |
| Japan       | 164 | 6 (6.4)  | 4 (4.28)  | 3 (5.07)  | 6 (6.54)  | 4 (5)     | 18      |
| Italy       | 161 | 7 (6.3)  | 11 (2.9)  | 7 (4.28)  | 7 (6.5)   | 9 (4.16)  | 30      |
| Canada      | 146 | 8 (5.7)  | 6 (3.61)  | 6 (4.48)  | 8 (5.79)  | 7 (4.32)  | 30      |
| Russia      | 136 | 9 (5.3)  | 9 (3.21)  | 11 (3.77) | 9 (5.39)  | 10 (3.57) | 21      |
| India       | 127 | 10 (5.0) | 5 (3.93)  | 5 (4.52)  | 10 (5.19) | 6 (4.44)  | 18      |
| South Korea | 118 | 11 (4.6) | 8 (3.29)  | 10 (3.89) | 11 (4.76) | 19 (0)    | 19      |
| Spain       | 102 | 12 (4.0) | 12 (2.06) | 12 (2.66) | 12 (4.08) | 11 (2.5)  | 22      |
| Switzerland | 97  | 13 (3.8) | 19 (0)    | 19 (0)    | 19 (0)    | 12 (1.47) | 23      |
| Poland      | 65  | 14 (2.6) | 13 (1.43) | 13 (1.75) | 13 (2.7)  | 12 (1.63) | 13      |
| Belgium     | 58  | 15 (2.3) | 18 (0.68) | 16 (1.03) | 14 (2.3)  | 16 (1)    | 17      |
| Australia   | 50  | 16 (2.0) | 16 (0.88) | 17 (1)    | 16 (1.99) | 16 (1)    | 13      |
| Netherlands | 50  | 17 (2.0) | 17 (0.8)  | 18 (0.96) | 16 (1.99) | 18 (0.92) | 13      |
| Unknown     | 46  | 18 (1.8) | 19 (0)    | 19 (0)    | 19 (0)    | 19 (0)    | 9       |
| Iran        | 45  | 19 (1.8) | 14 (1.31) | 14 (1.51) | 15 (2.06) | 13 (1.47) | 13      |
| Brasil      | 43  | 20 (1.7) | 15 (0.92) | 15 (1.11) | 18 (1.71) | 15 (1.19) | 12      |

TP: Total number of publications, SP: Number of publications of a country, CP: Number of publications in international collaboration, FP: Number of publications of the first author of a country, RP: Number of publications corresponding to the author of a country, R (%): Rank and quotient of the number of publications of a country on the total of publications during 2008-2018

countries belong to the top 20 countries with the highest number of publications. However, they do not have any institution within the top 20, which is because the investigations are not done in a particular institution.

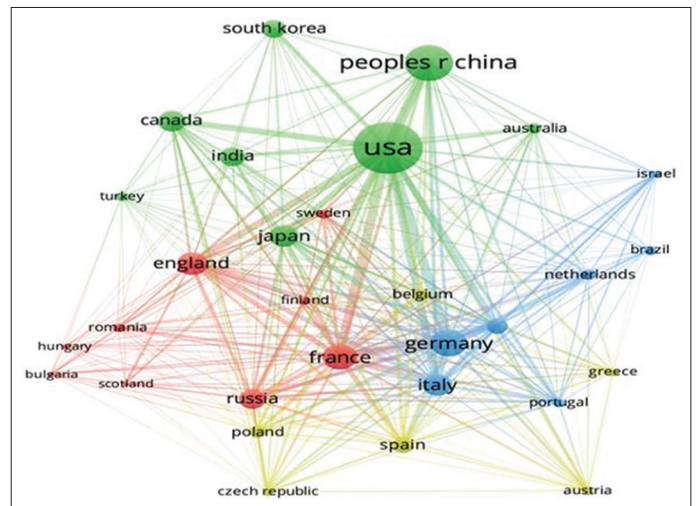
The Chinese Academy of Sciences is the institution that has been consolidated as the institution with the highest rate of publications for a total of 79, reaching 12% of the total publications of the top 20, followed by the National Institute of Nuclear Physics with 53 publications, which represents the 8%. The top 10 institutions of the top 20 cover 59% of the total number of publications, which makes it possible to identify the key players in this topic. Although the Chinese Academy of Sciences ranks first on the list, its value of the h-index (17) does not reach the maximum value of the list.

The institutions that research with the use of resources depends on departments from other institutions. In the analysis of production by institutions, the three institutions with more subordinate departments or institutions shown in Table 4 were evaluated, especially the Institute of Nuclear Technology and New Energies (13), the Laboratory Nazl Sud (9) and the Physics Institute of high energies (9). Furthermore, they have the first places of the Tsinghua University, the National Institute of Nuclear Physics and the Chinese Academy of Sciences respectively. However, the subordinate institution with the highest number of citations is not part of the institution that holds the first place in production.

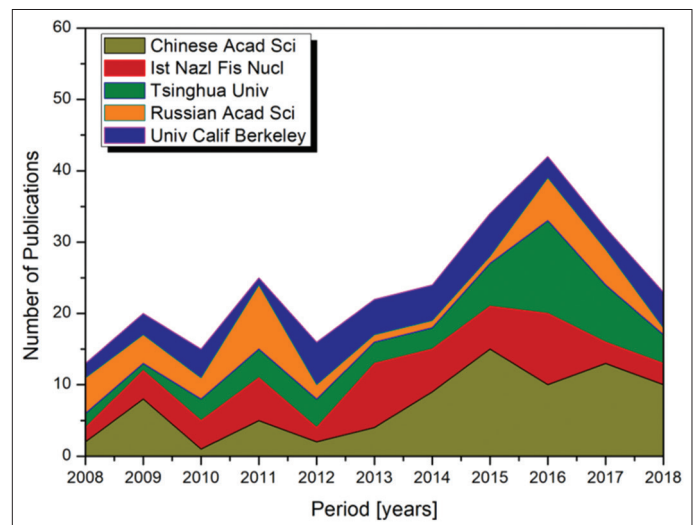
Figure 4 shows the evolution of the publication number in time, where the Chinese Academy of Science of China, the National Institute of Nuclear Physics of Italy and the Tsinghua University of China had an increase in production from 2013 to 2016, thanks to your collaborative work.

Figure 5 shows the network of the 30 most productive institutions in terms of collaboration from 2008 to 2018. The Chinese academy of sciences got the first place in relations of international cooperation, despite having links only with 12 institutions from

**Figure 3:** Cooperation network of the 30 most producing countries



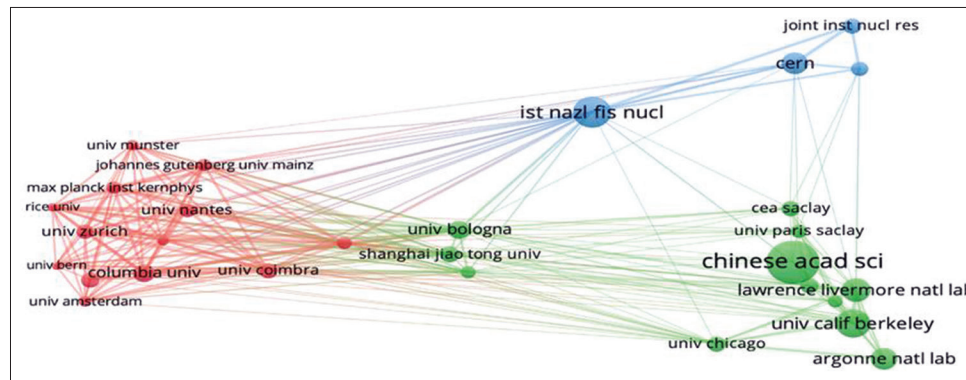
**Figure 4:** Behavior of the top 5 most producing institutions during 2008-2018



**Table 3: Top 20 most productive institutions during 2008-2018**

| Institution name            | TP | TP R (%)  | SP R (%)  | FPR (%)   | CPR (%)   | RPR (%)   | h-index |
|-----------------------------|----|-----------|-----------|-----------|-----------|-----------|---------|
| Chinese Acad Sci            | 79 | 1 (3.12)  | 1 (2.88)  | 1 (3.05)  | 4 (3.13)  | 1 (2.02)  | 17      |
| Ist Nazl Fis Nucl           | 53 | 2 (2.09)  | 7 (1.19)  | 6 (1.51)  | 5 (2.22)  | 7 (0.92)  | 17      |
| Tsinghua Univ               | 50 | 3 (1.92)  | 5 (1.71)  | 5 (1.75)  | 6 (1.91)  | 4 (1.67)  | 9       |
| Russian Acad Sci            | 42 | 4 (1.66)  | 6 (1.39)  | 7 (1.47)  | 8 (1.67)  | 6 (1.27)  | 12      |
| Univ Calif Berkeley         | 40 | 5 (1.58)  | 8 (0.88)  | 8 (1.15)  | 2 (3.61)  | 8 (0.84)  | 18      |
| Lawrence Livermore Natl Lab | 33 | 6 (1.3)   | 12 (0.76) | 12 (0.84) | 10 (1.27) | 12 (0.56) | 13      |
| Univ Ontario                | 33 | 7 (1.3)   | 3 (1.83)  | 4 (1.87)  | 7 (1.87)  | 2 (1.79)  | 17      |
| CERN                        | 32 | 8 (1.26)  | 17 (0.6)  | 9 (1)     | 9 (1.39)  | 16 (0.44) | 11      |
| CEA                         | 31 | 9 (1.22)  | 3 (1.83)  | 3 (2.5)   | 3 (3.45)  | 2 (1.79)  | 9       |
| Los Alamos Natl Lab         | 31 | 10 (1.22) | 14 (0.72) | 10 (0.88) | 11 (1.19) | 9 (0.64)  | 14      |
| Argonne Natl Lab            | 29 | 11 (1.14) | 12 (0.76) | 15 (0.8)  | 12 (1.07) | 9 (0.64)  | 14      |
| Korea AAtom Energy Rec Inst | 26 | 12 (1.02) | 9 (0.84)  | 12 (0.84) | 13 (1.03) | 14 (0.52) | 4       |
| Oak Ridge Natl Lab          | 26 | 13 (1.02) | 9 (0.84)  | 12 (0.84) | 13 (1.03) | 16 (0.44) | 9       |
| Bhabha Atom Res Ctr         | 25 | 14 (0.99) | 9 (0.84)  | 10 (0.88) | 16 (1)    | 9 (0.64)  | 8       |
| Univ Bologna                | 25 | 15 (0.99) | 19 (0.44) | 18 (0.52) | 13 (1.03) | 19 (0.2)  | 12      |
| CNRS                        | 23 | 16 (0.91) | 2 (2.54)  | 2 (3.01)  | 1 (4.28)  | 5 (1.63)  | 8       |
| Texas A&M Univ              | 23 | 17 (0.91) | 18 (0.52) | 18 (0.52) | 19 (0.84) | 18 (0.24) | 8       |
| Univ Tokyo                  | 23 | 18 (0.91) | 15 (0.68) | 16 (0.76) | 18 (0.88) | 12 (0.56) | 8       |
| Japan Atom Energy Agcy      | 22 | 19 (0.87) | 15 (0.68) | 17 (0.72) | 19 (0.84) | 15 (0.48) | 9       |
| Joint Inst Nucl Res         | 21 | 20 (0.83) | 20 (0.28) | 20 (0.4)  | 17 (0.96) | 20 (0.08) | 10      |

TP: Total number of publications, SP: Number of publications of a country, CP: Number of publications in international collaboration, FP: Number of publications of the first author of a country, RP: Number of publications corresponding to the author of a country, R (%): Rank of the number of publications of a country on the total of publications during 2008-2018

**Figure 5:** Cooperation network of the top 30 most productive institutions of the top 5 most producing institutions during 2008-2018**Table 4: Subordinate institutions of the top 3 institutions**

| Institution                                  | Subordinate  | TP |
|--|--|----|
| Chinese Academy of Science, China            | Institute High Energy Physics                              | 9  |
|  | Institute of Modern Physics                                | 7  |
|  | Shanghai Institute of Optics and Fine Mechanics            | 6  |
|  | Shanghai Institute of Applied Physics                      | 5  |
|  | Institute of Nuclear Energy Safety Technology              | 3  |
| Istituto Nazionale di Fisica Nucleare, Italy | Laboratory Nazl Sud  | 9  |
|  | Sez Ferrara  | 4  |
|  | Laboratory Nazl Legnaro                                    | 4  |
|  | Sez Napoli   | 3  |
|  | Sez Roma   | 3  |
| Tsinghua University, China                   | Institute of Nuclear and New Energy Technology             | 13 |
|  | Department of Physics and Engineering Physics              | 12 |
|  | Collaborative Innovation Center of Adv. Nucl. Energy Tech. | 4  |
|  | Department of Mechanical Engineering                       | 4  |
|  | INET   | 3  |

different latitudes, generating a production of (79) documents. The University of Bologna occupies the 15<sup>th</sup> position, in production with a total of 19 publications in international collaboration which were developed in conjunction with 25 countries, surpassing the institution that holds the first place. The institution with the lowest number of publications with international cooperation was the University of Bern (Switzerland) with only five publications, despite having links with 17 countries.

### 3.3. Topics Covered by Nuclear Energy Production

The 2545 articles related to nuclear energy, from the WoS database, made use of 69 sub-topics, with a frequency that can be seen in Table 5, where the first five sub-topics reported in the had 56% of the total records. The performance of the sub-themes makes it clear that the use of the deductive method is the highest used by researchers, (Sampieri et al., n.d.). The subtopic “chemical” has the highest frequency with 452 documents, followed by “physics” with 271 records, and “nuclear science and technology” with 262. It happens because this topic was studied by professionals belonging to the area of the basic sciences.

Figure 6 shows the evolution of the publications in each of the subtopics over time, where the “chemical” subtopic presented an increasing trend until reaching 2016 with a maximum peak value of 75 articles. On the other hand, the subtopic nuclear science and technology obtained its maximum value in 2015 and 2016 with a total of 40 publications each year. The remaining three sub-themes maintained a similar trend with low fluctuations. These results can

**Table 5: Top 20 of the most productive sub-themes during the period 2008-2018**

| Subject                                | TP  | %     |
|--|-----|-------|
| Chemistry                              | 452 | 17.90 |
| Physics                                | 271 | 10.73 |
| Nuclear science and technology         | 262 | 10.38 |
| Instruments and instrumentation        | 261 | 10.34 |
| Engineering                            | 200 | 7.92  |
| Astronomy and astrophysics             | 123 | 4.87  |
| Science and technology – Other topics  | 119 | 4.71  |
| Thermodynamics                         | 117 | 4.63  |
| Energy and Fuels                       | 110 | 4.36  |
| Business and economics                 | 96  | 3.80  |
| Materials science                      | 74  | 2.93  |
| Biochemistry and molecular biology     | 71  | 2.81  |
| Environmental sciences and ecology     | 65  | 2.57  |
| Optics                                 | 22  | 0.87  |
| Plant sciences                         | 19  | 0.75  |
| Polymer sciences                       | 19  | 0.75  |
| Computer sciences                      | 18  | 0.71  |
| International relations                | 18  | 0.71  |
| Biotechnology and applied microbiology | 17  | 0.67  |

be used to select the journals with the highest quantity and quality of articles based on the area of knowledge.

### 3.4. Main Points in Nuclear Energy Efficiency Research

The different articles studied were published in 813 scientific journals related to nuclear energy in the period from 2008 to

2018, whose categorization in the Top 20 of production is shown in Table 6.

The journal Nuclear Instruments and Methods in Physics Research presented the largest number of publications (132) which represents 5.2% of the total volume of publications, followed by the International Journal of Hydrogen Energy with 71 records, and Energy Policy with 61 articles. The journals reviewed by Renewable and Sustainable Energy Reviews and Applied Energy that occupy positions 15 and 16, respectively by article volume have the highest IF values with 9.18 and 7.90 respectively. The presented results allow identifying the top 20 of scientific journals where 33% of the total of publications in the subject under study is concentrated.

Figure 7 shows the behavior of the top 5 most productive scientific journals. The results show that the journal with the highest affinity with the subject studied is “Nuclear Instruments and Methods” with peak production of 22 articles in the year 2011. After that, its production decreased, but always staying in the top positions of the list presented. These results may happen because the technology is in an advanced stage of development, and knowledge is being disseminated through patents and not in research articles.

### 3.4.1. Renewable energy

For a long time, the energy generation has been linked to hydrocarbons, which have a direct negative effect on the environment. This fact has been the object of problems by diverse

sectors of the society due to the scarcity of these resources, and the search to minimize the adverse effects against the environment. Thus, the generation of renewable energies has increased to a large extent due to global energy demand (Ochoa et al., 2018).

### 3.4.2. Nuclear energy efficiency

The concept of energy efficiency was established as the link between the product provided and the amount of energy obtained (Lovins, 2004). Currently, not only energy production is considered, but also the way to do it efficiently. Typically, the capacity factor of a nuclear reactor is misreported as its efficiency value. This capacity factor of a nuclear reactor is the ratio between the maximum amount of energy produced and what it produces, whose average value was 92% in the United States in 2014 (U.S. EIA, 2018). It was followed by natural gas with a value of 50%, whose efficiency can be measured by the thermal efficiency that ranges from 33 to 37% (“Nuclear Reactors | Nuclear Power Plant | Nuclear Reactor Technology - World Nuclear Association,” n.d.).

Figure 6: Top 5 most productive topics from 2008 to 2018

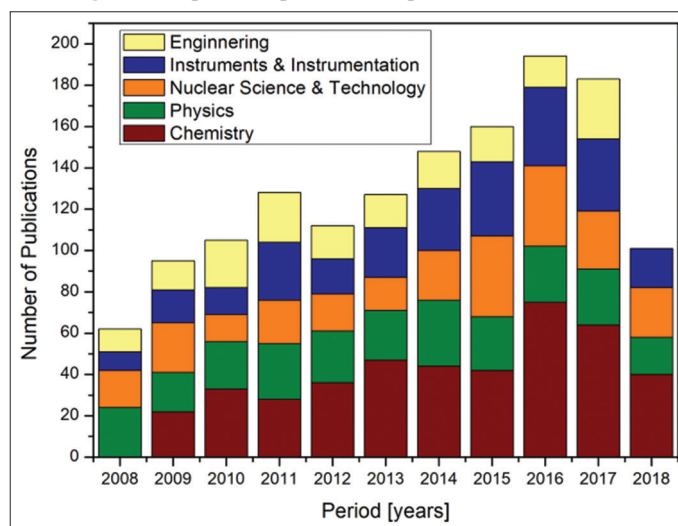


Figure 7: Number of publications of the top 5 scientific journals from 2008 to 2018

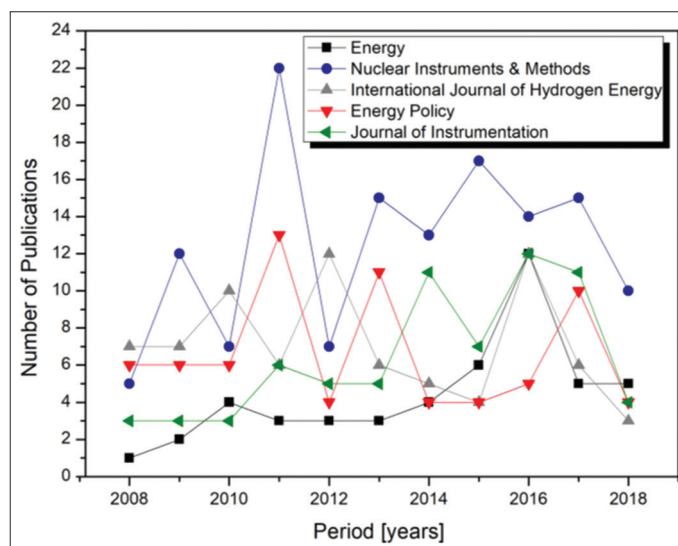


Table 6: Top 20 most productive scientific journals during the period 2008-2018

| Journal name  | R  | TP(%) | IF 2017 |
|---|----|-------|---------|
| Nuclear Instruments and Methods in Physics Research Section A | 1  | 5.2   | 1.33    |
| International Journal of Hydrogen Energy                      | 2  | 2.8   | 4.22    |
| Energy Policy   | 3  | 2.4   | 4.03    |
| Journal of Instrumentation                                    | 4  | 2.3   | 1.25    |
| Energy  | 5  | 2.0   | 4.96    |
| Nuclear Instruments and Methods in Physics Research Section B | 6  | 2.0   | 1.32    |
| Annals of Nuclear Energy                                      | 7  | 1.7   | 1.47    |
| Applied Radiation and Isotopes                                | 8  | 1.7   | 1.12    |
| Physical Review C   | 9  | 1.4   | 3.30    |
| IEEE Transactions Nuclear Science                             | 10 | 1.3   | 1.44    |
| Nuclear Engineering and Design                                | 11 | 1.3   | 1.19    |
| Journal of Radio-analytical and Nuclear Chemistry             | 12 | 1.3   | 1.18    |
| Astrophysical Journal   | 13 | 1.1   | 5.55    |
| Journal of Chemical Physics                                   | 14 | 1.1   | 2.84    |
| Renewable and Sustainable Energy Reviews                      | 15 | 1.0   | 9.18    |
| Applied Energy  | 16 | 1.0   | 7.90    |
| Physical Review D   | 17 | 0.9   | 4.38    |
| International Journal of Energy Research                      | 18 | 0.9   | 3.00    |
| Energy Conversion and Management                              | 19 | 0.8   | 6.37    |
| Progress in Nuclear Energy                                    | 20 | 0.8   | 1.30    |

TP: Total number of publications, R: Range, (%): The relationship between the publications of the number one magazine and the total number of publications during 2008-2018, IF: Impact factor

### 3.4.3. Hydrogen production

Hydrogen is the most abundant chemical element in the universe (75% by mass), and about 95% was produced by fossil fuels, which

require continuous hydrogen generation systems (El-Emam and Khamis, 2018). This source of energy with a low cost of production and minimal impact on the environment has become of great

**Table 7: Number of publications by main topics**

| Main topics and subtopics | Number of publications (2008-2018) | Number of publications (2008-2011) | Number of publications (2012-2015) | Number of publications (2016-2018) |
|---------------------------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|
| Renewable energy          | 61                                 | 15                                 | 25                                 | 21                                 |
| Efficiency                | 60                                 | 20                                 | 23                                 | 17                                 |
| Hydrogen production       | 54                                 | 17                                 | 25                                 | 12                                 |
| Energy                    | 52                                 | 21                                 | 9                                  | 22                                 |
| Nuclear energy            | 44                                 | 12                                 | 21                                 | 11                                 |
| Energy efficiency         | 44                                 | 19                                 | 15                                 | 10                                 |
| Exergy                    | 41                                 | 18                                 | 7                                  | 16                                 |
| Nuclear                   | 38                                 | 12                                 | 15                                 | 11                                 |
| Hydrogen                  | 33                                 | 20                                 | 6                                  | 7                                  |
| Nuclear power             | 28                                 | 6                                  | 13                                 | 9                                  |
| Monte carlo               | 26                                 | 4                                  | 9                                  | 13                                 |
| Climate change            | 25                                 | 11                                 | 7                                  | 7                                  |
| Geant4                    | 23                                 | 4                                  | 8                                  | 11                                 |
| Uranium                   | 18                                 | 3                                  | 5                                  | 10                                 |
| Nuclear power plant       | 18                                 | 4                                  | 7                                  | 7                                  |
| Monte carlo simulation    | 18                                 | 5                                  | 7                                  | 6                                  |
| Sustainability            | 17                                 | 4                                  | 10                                 | 3                                  |
| Simulation                | 17                                 | 4                                  | 9                                  | 4                                  |
| Galaxies: Active          | 16                                 | 5                                  | 6                                  | 5                                  |
| Electricity               | 15                                 | 1                                  | 8                                  | 6                                  |
| Solar energy              | 14                                 | 7                                  | 4                                  | 3                                  |
| Nuclear fusion            | 14                                 | 4                                  | 6                                  | 4                                  |
| Energy policy             | 14                                 | 7                                  | 3                                  | 4                                  |
| Mitochondria              | 14                                 | 4                                  | 7                                  | 3                                  |
| Optimization              | 14                                 | 2                                  | 6                                  | 6                                  |
| HPGe detector             | 13                                 | 3                                  | 7                                  | 3                                  |
| Gamma-ray spectroscopy    | 13                                 | 2                                  | 5                                  | 6                                  |
| Scintillator              | 13                                 | 6                                  | 3                                  | 4                                  |
| Nuclear data              | 13                                 | 3                                  | 5                                  | 5                                  |
| Copper-chlorine cycle     | 12                                 | 5                                  | 6                                  | 3                                  |

**Table 8: Articles with the highest citation during 2008-2018**

| Year | TC 2018 | TC/Y  | Article   | Journal  | Country  |
|------|---------|-------|---|--|----------|
| 2008 | 197     | 17.91 | Electrolyte solutions with a wide electrochemical window for recharge magnesium batteries   | Journal of the Electrochemical Society   | Israel   |
| 2009 | 267     | 26.70 | Solar energy conversion efficiencies in photosynthesis: Minimizing the chlorophyll antennae to maximize efficiency                  | Plant Science  | USA      |
| 2010 | 487     | 54.11 | Genetic engineering of algae for enhanced biofuel production  | Eukaryotic Cell  | USA      |
| 2011 | 658     | 82.55 | A review of applications and challenges of nanofluids   | Renewable and Sustainable Energy Reviews                                       | Malaysia |
| 2012 | 218     | 31.14 | Ammonia and related chemicals as potential indirect hydrogen storage materials  | International Journal of Hydrogen Energy                                       | UK       |
| 2013 | 139     | 23.17 | Lifecycle assessment (LCA) of electricity generation technologies: Overview, comparability, and limitations                         | Renewable and Sustainable Energy Reviews                                       | Denmark  |
| 2014 | 92      | 18.40 | Improved measurements of the neutrino mixing angle theta (13) with the double Chooz detector  | Journal of High Energy Physics   | Japan    |
| 2015 | 107     | 26.75 | Enhancing electrochemical intermediate solvation through electrolyte anion selection to increase nonaqueous Li-O-2 battery capacity | Proceedings of the National Academy of Science of the United States of America | USA      |
| 2016 | 153     | 51.00 | Physics reach of the XENON1T dark matter experiment   | Journal of Cosmology and Astroparticle Physics                                 | Germany  |
| 2017 | 96      | 48.00 | A comparative overview of hydrogen production processes   | Renewable and Sustainable Energy Reviews                                       | Cyprus   |
| 2018 | 3       | 3.00  | Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city                                    | Resources Conservation and Recycling   | Japan    |

interest to many researchers. It is notable with the 54 publications identified in the present study, with a production volume of 25 publications in the period from 2012 to 2015.

Records from the year 2014 report one production of 58 million tons/year, but only a minimum amount is used as fuel (International Atomic Energy Agency, 2016). There are different forms of energy to get hydrogen: Fossil fuels, nuclear power, and renewable energy. Steam and gasification reforming is used in fossil fuels. Thermochemical separation of water and electrolysis at high temperature is used for nuclear energy. Finally, for renewable energy, it is used electrolysis and biomass gasification (Acar and Dincer, 2014).

#### 3.4.4. Nuclear energy

Nuclear energy and its technology make it possible to take advantage of the energy that is released as a result of the division of atoms of certain chemical elements ("Nuclear Power Today | Nuclear Energy - World Nuclear Association," n.d.). This energy is considered non-renewable like the energy obtained from fossil fuels, with a difference that nuclear resources have a longer useful life (Pioro, 2013). Table 7 shows the main topics that correspond to the keywords of each article. The results show that the subtopic nuclear energy with 44 publications is overcome by the topical energy with 52 papers. On another hand, it was found that the essential keywords were renewable energies (61), followed by efficiency (60), production of hydrogen (54) and finally, nuclear energy (52).

There are two ways of obtaining nuclear energy: Fusion and fission. The latter is the method of highest use in nuclear power plants (Şahin and Şahin, 2018), and it is based on the separation of atoms. Nuclear fusion links light elements to form heavy elements (Kembleton, 2019). Currently, an international collaborative project is being developed to make a magnetic fusion device designed to evaluate the possibility of fusion as an energy source (Fiore, 2006).

#### 3.5. Articles with Highest Citation

Table 8 shows the articles with the highest citation from 2008 to 2018. It was considered factors such as annual citations and the total of publications from each country. The results show that the article entitled "A review on applications and challenges of nanofluids" under the authorship of R. Saidur et al., published in the magazine "Renewable and Sustainable Energy Reviews" in 2011, presents the largest amount of citations with a total of 658. It was followed by the article "Genetic Engineering of Algae for Enhanced Biofuel Production" written by Randor Radakovits et al., in the journal *Eukaryotic cell* in 2010. This list allows to locate the articles of highest impact on the subject, and it can be used to prepare bibliographic reviews and state of the art with relevant research results.

The results of this research show the importance of bibliometric analysis in the area of nuclear energy. This paper will serve as a guide for the community in general to see the global aspects of the subject, which cause controversy in society, due to accidents of nuclear power plants. Nuclear energy has its most significant challenge in establishing higher safety standards to make this type of energy more efficient.

## 4. CONCLUSIONS

From the WoS database, the attributes of the bibliography on nuclear energy in the years 2008-2018 were analyzed through a bibliometric study. This article revealed that the topic of nuclear energy had shown growth over the 11 years evaluated. Notably, this trend was maintained constant due to the strengths identified in the networks of collaboration among institutions.

The leading country in research on this subject was the United States with the highest h-index value (59), registering the highest number of publications (643), followed by China and Germany, and the 97% of all the documents were published in the English language.

The United States is also the country with the highest number of international collaborative works being in the top 20 countries with highest collaboration. The institution that produces the highest number of publications was the Chinese Academy of Sciences with 79. On the other hand, the University of Bologna in Italy was the institution with the maximum international connections with institutions from other countries.

The type of document with the highest use was the article, with 83% of the total. The top 5 journals highly used were *Nuclear Instruments and Methods*, followed by *International Journal of Hydrogen Energy*, *Energy Policy*, *Journal of Instrumentation*, and *Energy*.

The document with the highest citation rate was "A review on applications and challenges of nanofluids" from the journal "Renewable and Sustainable Energy Reviews" with 658 citations. The analysis of the keywords showed that renewable energy has the full attention of the scientific community, as well as the efficiency of nuclear reactors.

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