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Research status of nuclear power: A review

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ABSTRACT

The purpose of this study is to provide the latest research information through atomic power literature analysis for people who are interested in research advancement on nuclear power, and to motivate more discussion and attention on nuclear power. The research on nuclear power has attracted much attention and the literature expanding substantially. This paper characterizes the nuclear power literature during 1996 and 2015 by archiving the data from Science Citation Index Expanded and its implications applying the bibliometric method at country level. Using the bibliometric techniques, we first investigate general spatial distribution, and then explore cross-country comparisons of scientific production, focusing on the country productivity distribution analysis, and institution analysis and research topics analysis. Furthermore, using the bibliometric indicators of the activity index and attractive index, we calculated citation score to further explore research efforts, influence and quality among the 10 most productive countries. First, the results indicate that the USA, Germany and Japan are the three top countries contributing to nuclear power literature, which published 24.34%, 11.04%, 10.87% of all literature, respectively. The great majority of countries come from America and Europe, and there are no African countries significantly involved in this area in the top 30 countries. Second, performance ranking of these countries by institutions echoes the countries' publication performances. U.S. Department of Energy (DOE) is the leading institution by contributing/sponsoring 1061 articles. Overall, American, Japanese and South Korea institutions are the major ones, publishing nuclear power papers. Third, the correlation network and pattern of research topics forms five clusters, the hot and core research topic is model representing simulation. Fourth, we find that Japan holds the leading position with the highest research production, impact and citation score. England and France balance their cost and benefit situation. However, the USA is the only country whose research effort and impact has been continuously declining. China shows a sharp increase in research production but with declining citation score. China should improve production quality and citation score in this field.

1. Introduction

Atomic energy has been an essential part of world energy mix, even though the 2011 Fukushima nuclear disaster shed clouds on the future perspectives on nuclear energy [1–3]. Some 24 reactors are currently being constructed in China, the global biggest energy user [4,5]. And 5 new reactors are considered or being constructed in the USA, the global second biggest energy consumer [6]. Moreover, Japan rebooted the first nuclear reactor in August 2015 since 2011 Fukushima disaster. Being the largest energy consumption country, China has paid more attention on the growing of non-fossil energy [7,8]. In addition, China prefers to develop nuclear power due to the superiority comparing to other clean energy resources [9]. Existing review literature has focused on in the introduction of specific technologies and the development environments. Carlos provides a state-of-the-art review of the SPS / in nuclear engineering [10], Shunsuke elaborates water chemistry control technologies to establish safe and stable operation of nuclear power plants [11]. Advantages in ONPPs have also been reviewed in the literature, containing general arrangement, design parameters, and safety features [12–16] and the application of on-line monitoring [17], martensitic/ferritic steels applied as boiler and turbine materials in power plants [18]. In addition, there are many papers analyzing and presenting the development environments, policies and historical stages [8,19], development statuses, problems, countermeasures, and system dynamics analysis [20–22]. Papers using bibliometric analysis are focused on the alternative energy sources, but not nuclear power. Guozhu Mao

Abbreviations: SCIE, Science Citation Index Expanded; AI, Activity index; AAI, Attractive index; ONPPs, Ocean Nuclear Power Plants; DOE, United States Department of Energy; USA, United States of America; SPS, Seismic protection systems technology

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provides bibliometric analysis of research to carry out scientific production activities, as well as future emphases of alternative energy [23–27].

Bibliometric analysis of nuclear power is not found in the literature, and little is known about the characteristics of utilization literature on nuclear power, including the development and organization in this field of study. Bibliometric method provides a useful quantitative perspective to measure the growing and directions of research in nuclear power field. Awareness of the significance and benefit of technologies related to nuclear power has attracted a growing research attention. Thus, it's essential to measure the sharply increasing literature on the nuclear power.

Using bibliometric method, this study aims to characterize the trends of nuclear power literature in order to study the spectrum and characteristics of nuclear power research, and forecast dynamic directions by investigate nuclear power literature from 1900 to 2015 and its implications. The objectives of this study are: (1) To identify major contributing countries producing most of nuclear energy articles; (2) To discover the growth of nuclear power literatures and recognize the productivity distribution of countries on nuclear power; (3) To identify core institutions that contribute most in journal literature on nuclear power, and to determine the productivity distribution by institutions in this field; (4) To discover relevant research efforts, influence and quality of 10 most productive countries. Based on the analysis results from these four aspects above, we can explore this subject to promote international collaboration and innovations, and more clearly understand the research profiles in the nuclear power technology fields, and provide systemic and current information in nuclear power research.

2. Methodology and data

2.1. Data source

Compared to patent, articles take shorter time from submission to publication with citation on the SCIE database [28,29]. We use journal articles which contain more latest information comparing with patents as the data. The SCIE provided by the Thomson Scientific, is considered as the leader in providing indexing services and literature information in multidiscipline fields [30–32]. It is used to retrieve data from 1900 to 2015, sorted by titles, countries, and institutions. In this study, only the Articles are considered, due to that article is the biggest scientific contributor. Despite review owes more citations, the scientific contribution of reviews are less, and may arise meaningless noise related to vast topics [33]. The earliest research paper on nuclear power was published in the Journal of Naturwissenschaften in 1937 by Jordan, P, from Germany. Although Nuclear power research started a long time ago, it had increased rapidly over the past two decades. In this study, searching the SCIE database using the retrieval conditions, which are "topic = (nuclear power) and document type = (article) and time span = (1996–2015)", 22,224 papers from 1996 to 2015 are collected totally.

In addition, an article may have co-authors from different institutions and countries. Collaboration is identified through the address of every author, "independent" is accessed to papers with authors from the same institution or country, in contrast, 'international collaboration" is accessed to articles with authors from at least two institutions or countries. Therefore, the sum of paper numbers for the three areas (Country productivity distribution, Institution Analysis) published by each institution or country is larger than the total number of publications [34].

2.2. Methods

Bibliometrics, especially the evaluation of bibliometric methods introduced by National Science Council in 1973, are used to measure the scientific and technical profile and performance [35]. Bibliometric has been considered as an effective method for scientific production evaluation [36,37], and is used widely as a quantitative evaluation for many disciplines in the recent years [32,38–41]. The fast and systematic development are attributed to Price and Garfield [39,42]. Later, extended and definite meaning provided by White and McCain [42,43] reflects and explores the further information implicated literature in order to offer evolutionary models of scientific production.

The bibliometric indicators are more urgently demanded due to the sharp growth of scientific production in this century. Numerous literature publications enable bibliometric indicators to characterize research activities [35].

3. Analyses and results

3.1. Country and region productivity distribution

As described above, the data in this paper is extracted from 1996 to 2015. During this period, the SCIE database includes 22,224 papers on nuclear power. The scientific production and contribution of studied country (at least one author from the country published a paper on nuclear power) is measured.

The data indicates that over 133 countries or regions participated in research on nuclear power. Fig. 1 shows that the world map with 30 most productive countries based on the total number of papers on nuclear power, each with more than 170 papers published. The size of each node represents the total number of paper published. The bigger the node, the larger total paper number of papers. The nodes of the USA, Germany and Japan are the biggest, which means they are the top three countries contributing on nuclear power research, 24.34%, 11.04%, and 10.87% of papers, respectively. The following countries include South Korea, France, China, Russia, England, Italy, and India, with published and contributed over half of the papers. In addition, we can see from Fig. 1 that the great majority of countries come from the America and Europe, and there are no countries in African significantly involved in research in this emerging area in the top 30 countries. Two emerging countries play a stronger research role in nuclear power research, namely China and India, which rank in high positions being the 6th and 10th overall.

To provide an overview of nuclear power research, and demonstrate the growth of nuclear power literature, the annual number of articles during 1996 and 2014 is represented in Fig. 2. Fig. 2 reveals that the literature growth rate increases fast over time. USA has always been the largest paper contributor from 1996 to 2014. In addition, since 2011 after Japan's 2011 Tohoku Earthquake, a great deal of studies on nuclear power have been carried out all over the world, including rapid increase in USA and China.

From 2011–2015, research in Japan was growing more sharply than ever before. Particularly, it increases exponentially during 2011–2015 as demonstrated in Fig. 2. The 2011–2015 was crucial stage of development, most articles in Japan were published during this period, which illustrates that nuclear power is really rapid growth subject.

Unsurprisingly, the USA has a leading position in this field, which always predominated, however the share of world publications declines. The USA holds the leading position from 1996 to 2015. The first German paper on nuclear power was published in 1937. However, the second paper appears in 1973. Germany is the second most active nation, where the number of articles grew quickly, Japan ranks the 3rd in the world. After 2012, Japan outrun the Germany ranks 2nd and reaches 355 in 2015, which means that public opinion in Germany is still strongly opposed to nuclear power, and there has been little support for the construction of new nuclear power plants in recent years. Research in Japan, France, South Korea and England on nuclear power started in 1973. The first Russian English-version paper on nuclear energy was published in 1992. China, a rapidly growing country, jumped from the 8th to 6th position in 2014.

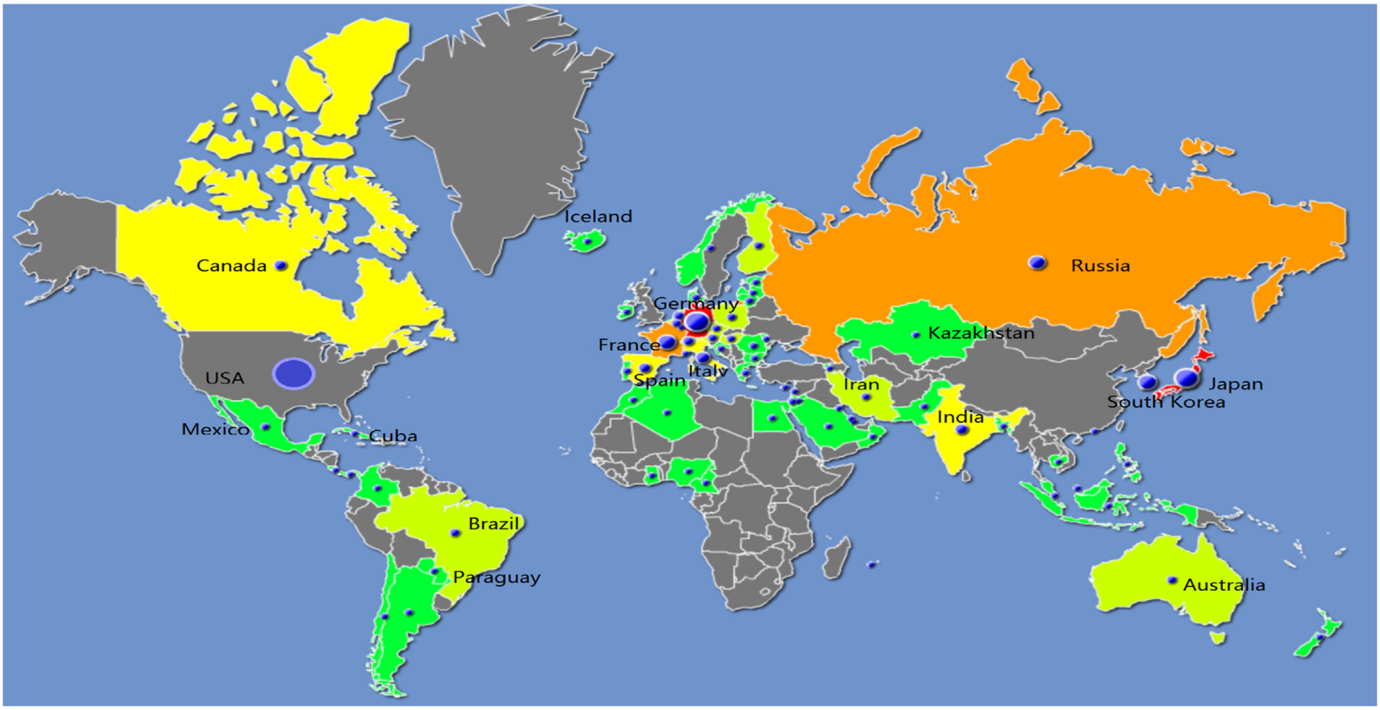

Fig. 1. Country and region productivity distribution of nuclear power literature.

3.2. Institution analysis

The influence of scientific production on country level can be represented from the institutional perspective. As indicated earlier, the SCIE database from 1996 to June 2015 provides institutional affiliation. U.S. DOE is the most productive institution, which contributed 1061 articles. The Korea Atomic Energy Research Institute of South Korea comes next, followed by the Centre National De La Recherche Scientifique Cnrs in France. Overall, American, Japanese and South Korean institutions are the major ones publishing papers on nuclear power. The Chinese Academy of Sciences and the Tsinghua University are the Chinese institutions ranking 11th and ranking 18th, respectively. Six institutions of the top 20 most productive institutions are in the USA. The number of USA institutions among the 20 most productive institutions demonstrates a fruitful yet dispersed research structure. In conclusion, USA has an absolute advantage and position in nuclear power Table 1.

It is worth noting that the number of articles published by Germany ranks the second, only two institutions from Germany is in the list of top 20 institutions. Helmholtz Association and the Karlsruhe Institute of Technology, in Germany are the large contributors publishing 304 and 245 papers respectively. It indicates that the related research is

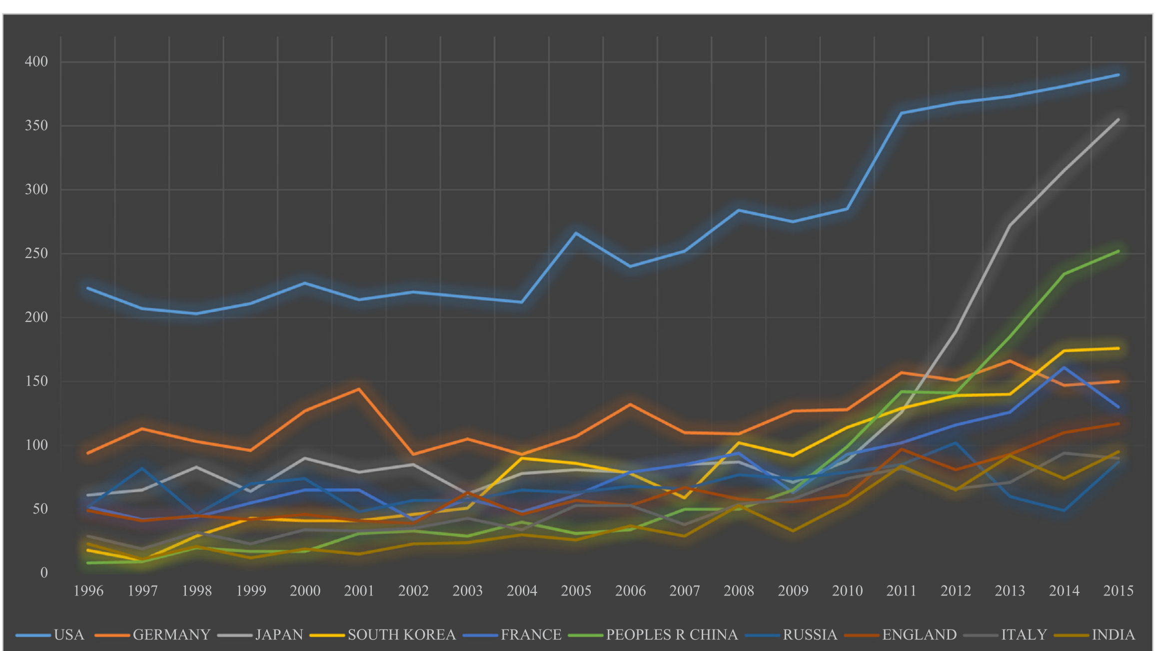

Fig. 2. Characteristics and productivity distribution by year of the top 10 countries from 1996 to 2015.

Table 1
The 20 most productive institutions based on the number of articles.

Institution	Country	Number
United States Department of Energy Doe	USA	1061
Korea Atomic Energy Research Institute	South Korea	559
Centre National De La Recherche Scientifique (CNRS)	France	540
University of California System	USA	514
University of Tokyo	Japan	499
CEA	France	491
Japan Atomic Energy Agency	Japan	402
Russian Academy of Sciences	Russia	397
Helmholtz Association	Germany	294
Max Planck Society	South Korea	284
Chinese Academy of Sciences	China	281
Bhabha Atomic Research Centre	India	270
Korea Advanced Institute of Science Technology Kaist	South Korea	246
Harvard University	USA	232
National Research Centre Kurchatov Institute	Russia	224
University of California Berkeley	USA	222
Massachusetts Institute of Technology (MIT)	USA	222
Tsinghua University	China	208
Karlsruhe Institute of Technology	Germany	207
Pennsylvania Commonwealth System of Higher Education Pcshe	USA	202

relatively concentrated in Germany. The good performance of these countries by institutions echoed the country's publication performances.

3.3. Research topics analysis

In this paper, we use VOSviewer to draw the correlation network of research topic based on the co-occurrence of high frequency keywords [44–46]. Fig. 3 indicates and examines the correlation network and pattern of research topics. We can see that there are five clusters. The first cluster (left side of figure and blue cluster) is focused on the nuclear-power-plant risk research. The second cluster (down of figure and red cluster) is focused on the nuclear power design research. The third cluster (middle of figure and green cluster) is focused on the simulation research. The forth cluster (up of figure and yellow cluster) is focused on the impact of nuclear power on human health research. The fifth cluster (right of figure and purple cluster) is focused on the impact of nuclear power on the study of atomic energy in the evolution of galaxies. There is a very close relationship between the third cluster and other clusters, in contrast, the fifth cluster is only close and related to the third cluster.

The first cluster is centered on nuclear-power-plant and radionuclides, and the research hot topics in the first cluster are nuclear-power-plant, radionuclides, sc-137, Japan, Chernobyl, accident and Fukushima, which are related to nuclear-power-plant risk. There is stronger relationship between the research topics in the first cluster. The research hot topics in the second cluster are around design, energy, nuclear power and nuclear. The core and hot research topic of the third cluster (middle of figure and green cluster) is model, which is the core of simulation research, because the development of nuclear power is based on laboratory experiments simulation, for example, simulating the impact and effects of nuclear power and simulating the atomic energy in the evolution of galaxies, which is the only cluster related to fifth cluster. The key research topics in the fourth cluster are radiation, population, cancer and children, which are closely related to human health. In summary, the hot research topic is model represented stimulation, research related to the nuclear power is mostly based on the model, due to that the nuclear power is highly risky and should do the stimulate and forecast in laboratory before physical construction. Modeling and simulation is a hot research topic and research emphases.

3.4. Cross-country comparisons

3.4.1. Activity index

The activity index (AI) proposed by Frame [47] and set forth by Schubert [48] refers to comparison of one country scientific profile to the world scientific profile, which can be applied to characterize the relevant research effort of one country in a given field [49,50].

$$AI_i^t = \frac{(P_i^t/\sum P)}{(TP^t/\sum TP)}$$

where P_i^t is the nuclear power publications by country i in year t; $\sum P$ is the nuclear power papers published by country i in the given time interval; TP^t is the total nuclear power-papers published by all the countries in the year t; $\sum TP$ is the total nuclear power-papers published by all the countries in the given time interval. AI is widely used to

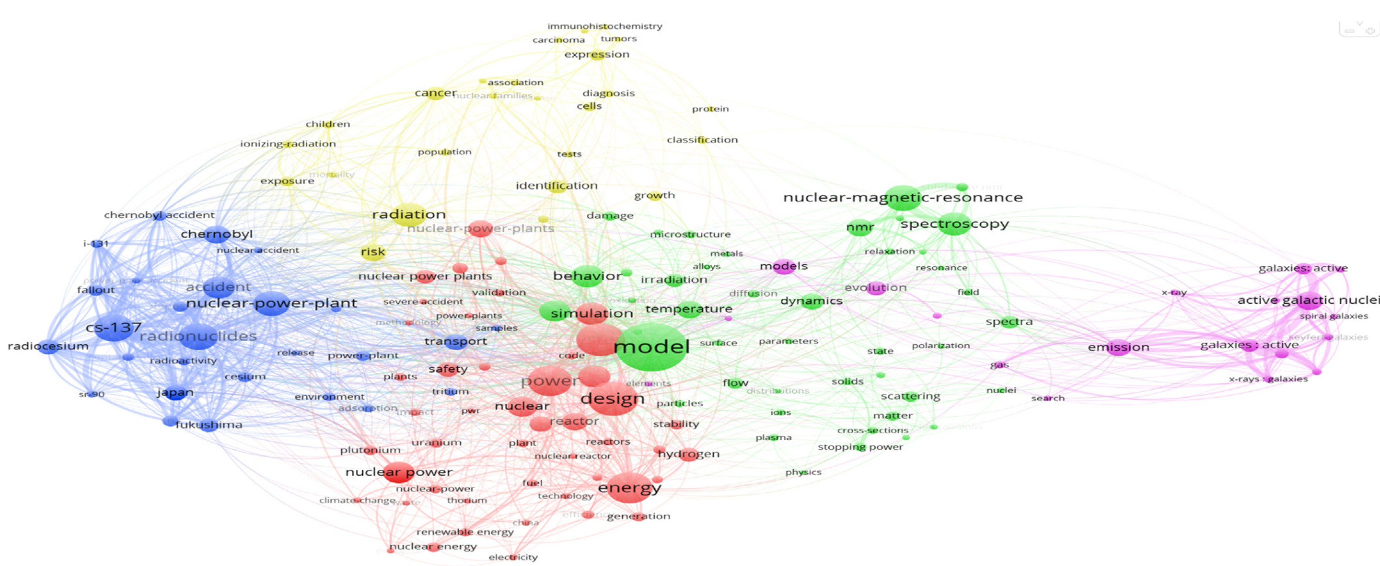

Fig. 3. The correlation network of research topic in atomic energy from 1996 to 2015. Notes:1. The one node represents one research topic. The color means the different clusters, the color of one node is determined by the cluster to which research topic belongs. 2. for each item, the size of the item's circle depends on the weight of the item, the distance between two nodes indicates the relatedness of the two research topics in the correlation network. In general, the closer two modes are located to each other, the stronger their relatedness in terms of correlation links, lines indicate the strongest correlation links between research topics.

Table 2
The activity index (AI) of top ten countries.

	USA	Germany	Japan	South Korea	France	China	Russia	England	Italy	India
2006	0.914634	1.140475	0.701897	1.030395	1.063519	0.490474	1.074306	0.841448	1.117217	1.017442
2007	0.945946	0.936126	0.743867	0.767699	1.127111	0.710455	1.027052	1.047746	0.788996	0.785481
2008	0.947509	0.824455	0.676698	1.179609	1.107834	0.631445	1.064973	0.806136	0.996516	1.275888
2009	0.926550	0.970098	0.557705	1.074476	0.749823	0.828992	1.033596	0.786031	1.080910	0.802273
2010	0.845530	0.860934	0.608663	1.172363	0.974651	1.111783	0.971615	0.753927	1.214343	1.177386
2011	0.875486	0.865610	0.714378	1.087451	0.876252	1.307182	0.856936	0.982730	1.103027	1.474002
2012	0.849754	0.790493	1.017460	1.112585	0.946205	1.232438	0.976401	0.779194	0.842975	1.083005
2013	0.789808	0.796886	1.342740	1.027575	0.942465	1.482809	0.526680	0.820373	0.831566	1.405635
2014	0.768558	0.672272	1.481402	1.216674	1.147254	1.786769	0.409761	0.924400	1.048831	1.077099
2015	0.756205	0.659389	1.604773	1.182934	0.890431	1.849592	0.699321	0.945096	0.965257	1.329139
Mean	0.861998	0.851674	0.944958	1.085176	0.982555	1.143194	0.864064	0.868708	0.998964	1.142735

Table 3
The attractive index (AAI) of top ten countries.

	USA	Germany	Japan	South Korea	France	China	Russia	England	Italy	India
2006	1.020233	1.176825	0.465277	0.804883	0.69506	0.762722	1.041987	1.234577	1.318525	1.917442
2007	1.19403	0.832633	0.492363	0.746004	1.114511	0.892952	0.99702	0.978806	0.803786	0.851433
2008	1.135573	0.833031	0.654921	0.68391	0.821988	0.673332	0.974359	1.230912	0.954394	1.088683
2009	1.022975	0.748114	0.358796	0.806647	0.665286	0.892991	0.417973	0.608584	0.948499	0.565288
2010	1.096907	1.287984	0.533249	1.22735	0.994626	1.220178	1.173771	1.068865	1.142168	1.058781
2011	0.980315	0.941859	1.252479	0.982478	1.239835	1.225931	0.896811	0.978109	1.196915	1.254493
2012	0.892097	1.200038	2.220173	2.025048	1.324639	1.002957	2.269785	1.009437	0.60795	0.574259
2013	0.806097	1.054884	1.835416	0.910113	1.175233	1.305248	0.380031	0.886682	0.75995	0.704246
2014	0.767135	1.127774	1.798666	0.834899	1.301382	1.334387	0.665248	1.129345	1.607831	0.963398
2015	0.540053	0.623413	1.554528	0.453897	0.615281	0.917406	0.374816	0.762682	0.614546	0.677102
Mean	0.945542	0.982656	1.116587	0.947523	0.994784	1.022810	0.919180	0.988800	0.995456	0.965513

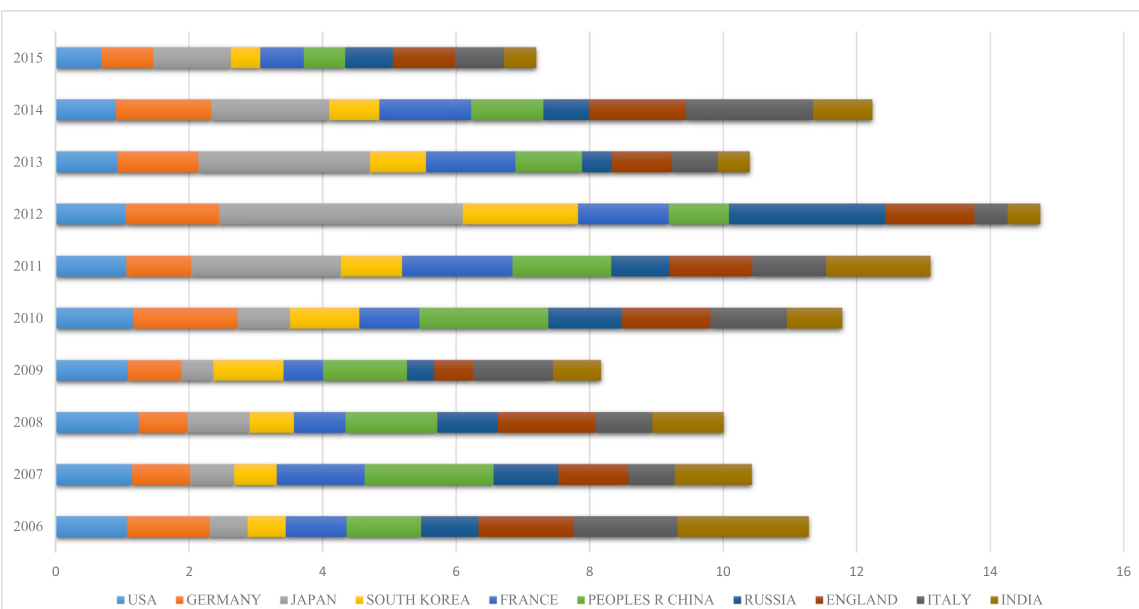

Fig. 4. The values of AAI vs AI of the top ten countries during 2006–2015.

measure the research performance in consideration of the effect of the papers on nuclear power of the evaluated country. There are three conditions, namely, if AI score is 1, the research output of this country is in line with the global average in this area. if AI > 1, the research output of this country is more than the global average in this area, which means that resource inputs of this country is more than the global average in this area, and AI < 1 is completely opposite to AI > 1 [50]. We select the top ten countries from 2006 to 2015 to calculate the AI and attractive index (AAI) and make comparison in Section 3.4.2.

Table 2 represents that the calculated activity indices of 10 most countries during 2006 and 2015. In general, South Korea, China and India have devoted more efforts to nuclear power research compared to the global average, having average values of more than 1 from 2006 to 2015. Contrary to the former countries, the research efforts of USA in the past 10 years are the lowest, with an average value being 0.862, and the Germany shows a sharp decline in investments to nuclear power research. In addition, as indicated by the calculated AI scores, China as the unique nation which keeps a sharp increase of the AI scores during 2006 and 2015, having AI score always greater than 1 since 2010. The following country is Japan since the Fukushima nuclear crisis. South Korea and India still pay stable attention to the nuclear power research, which indicates that China gives more efforts in nuclear power.

3.4.2. Attractive index

The attractive index (AAI) [48] is applied to describe and determine the scientific production influence of nations on nuclear power using citation they attract as a performance measures. There are also three conditions, firstly, AAI is 1 represents that the scientific production influence of this country is just in line with the global average, while AAI greater than 1 and AAI smaller than 1 indicate the scientific production influence of this country is higher and lower than global average, respectively. In mathematics, this AAI of country i in a certain time year t is described as follows:

$$AAI_i^t = \frac{(C_i^t/\sum C)}{(TC^t/\sum TC)}$$

where, C_i^t is the number of nuclear power-citations by country *i* in year *t*; $\sum$ C is the nuclear power citations of country *i* during a certain given time; TC^t is the total nuclear power citations of all countries in the world in year *t*; $\sum$ TC is the total nuclear power citations of all countries in the world during a certain given time.

The AAI scores of 10 most countries from 2006 to 2015 are shown in Table 3. Japan and China are greater than the global average of scientific influence in the nuclear power during the given 10years. The scientific influence of Russian during this period is the lowest, with AAI score being just 0.919. Nevertheless, in accordance with AI performance, only USA always holds a stable decline of AAI scores from 2010 to 2015, having scores higher than 1 before 2010. On contrast, the AII scores of Germany display increasing trend than the AI scores. Since 2011, the USA's AAI is lower than 1, indicating that the USA lost its dominant position in the relative citation impact of nuclear power science research. Japan presents a sharp increase from 2011, and even reached 2.22 in 2012, indicating its absolutely leading position. In addition, we use the "citation score" (AAI vs AI) that presents to what extent the efforts committed to study in a field (the paper efforts) have enough reward in its influence (in terms of citations) on further research. The trends of the values of AAI vs AI of the top ten countries are shown in Fig. 4.

There is a temporal lag between papers and citations, which has been determined by many studies [51,52]. Studies reveal that the number of citations for papers usually can be up to highest point in the second year [49,52], we adopt the 2-year-lag citation structure and applied the two years temporal lag of AAI. Accordingly, we select AI scores from 2004 to 2013, and AAI scores from 2006 to 2015 to calculate the values of AAI vs AI.

The values of "USA (2006–2012)" are a little larger than 1 and "USA (2013–2015)" are continuously decreasing below 1. This means the USA is the unique nation in terms of citation score during 2006–2012. However, the values of AI, AII and AII vs AI are all declining since 2013, which illustrates USA does not put efforts to push the development of nuclear power. On the contrary, Germany shows the high citation score even when the AI and AII are decreasing. Japan shows clear improvements in terms of AI "investments", and the comparative advantages in AAI "returns" since 2011. It is worth noting that their efficiency and citation score are the highest, and even reaches the 3.65 in 2012. However, the citation score of South Korea is still lower, although their publications are higher than the world average. We also see that in China the trend of AI "investments" is in contrast to the trend of AAI "returns", and attributing to due to substantial support in nuclear power [53], China presents a sharp increasing trend in publications. China should improve the quality, effects and citation score in this field. Similarly, England and France their cost and benefit-effectiveness situation.

4. Conclusion

Based on 22,224 articles on nuclear power that were indexed in the SCIE, this bibliometric study provides an overview of research on nuclear energy and analyzes worldwide research activities based on the analysis results of four key aspects, including country and region productivity distribution analysis, institution analysis, research topics analysis, cross-country comparisons analysis, and, and impact and quality analysis at country level for the selected investigation period. We draw the following conclusions:

(1) This study reveals that over 133 countries or regions took part in research on nuclear power. The USA, Germany and Japan are the top three countries contributing to nuclear power literature, sharing 24.34%, 11.04% and 10.87% of papers, respectively. The great majority of countries come from the America and Europe, and there are no countries in Africa significantly involved in this emerging area in the top 30 countries.
(2) The number of paper in the USA has been the largest from 1996 to 2014. Since 2011, after Japan's 2011 Tohoku Earthquake, extensive studies on nuclear power were conducted all over the world and the USA and China extended their studies rapidly. The period from 2011–2015 witnessed significant publications on nuclear power in terms of papers published during this period, which illustrates that nuclear power is really rapid growth subject.
(3) The correlation network and pattern of research topics forms five clusters, which are respectively focused on the nuclear-power-plant risk research, nuclear power design research, simulation research, the impact of nuclear power on human health research and the impact of nuclear power on the study of atomic energy. The hot and core research topic is model representing simulation.
(4) In general, South Korea, China and India paid more attention and efforts on nuclear power research comparing to the global average. In contrast, general efforts of the USA in the past 10 years are the lowest, with the average value 0.862. Germany shows a sharp decline in investments to nuclear power research. China as the unique nation keeps a sharp increasing trend of the AI scores during this period of 2006–2015, with AI score exceeding 1 since 2010. The following country is Japan since the Fukushima nuclear crisis happens. Japan and China have the higher than the world average research influence in nuclear during the given 10 years period. Only the USA still hold a stable decline of AAI scores from 2010 to 2015, in addition, AAI scores are greater than 1 before 2010. In contrast, the AII scores of Germany show an increasing trend than the AI scores.
(5) This means that only the citation score of USA is around 1 during 2006–2012. Japan shows clear improvements in the AI "investments" and comparative advantages in the AAI "returns" since 2011. It is worth noting that the efficiency and citation score are the highest, and even reached 3.65 in 2012. However, the citation score of South Korea is still lower, although their publications are higher than the world average. China should improve the quality, effects and citation score in this field. Similarly, England and France balance between cost and benefit effectiveness.

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