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ARTICLE

Analysis of Renewable Energy Research Hotspots and Trends Based on Bibliometric and Patent Survey

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ABSTRACT

In recent years, renewable energy has taken on an increasingly important role as a result of the depletion of traditional fossil fuels and the pressure of climate change. Due to the advantages of clean energy production and wide availability, research on renewable energy has increased worldwide. We collected data from the *Web of Science* and the *Derwent Innovations Index* to analyze research trends in the field of renewable energy. It was found that the number of research achievements in this field has developed rapidly worldwide since 2005. The United States ranks first in the quantity and quality of literature and fourth in the number of authorized patents. China ranks second and first regarding the quantity of literature and authorized patents, respectively. Biomass energy, wind energy, and solar energy are trending research topics in various stages of development. China has maintained close cooperation with the United States, the United Kingdom, Australia, and other countries.

1. Introduction

Renewable energy is a relatively new type of energy and can be used with a wide range of technologies. It is used increasingly worldwide attention due to the low pollution and low environmental impact [1]. For example, Susana Garrido Azevedo et al. believe that the number of publications related to renewable energy has increased rapidly in recent years [2]. Proskuryakova and Ermolenko used Foresight methodology to study Russia's energy structure and explained through Russia's energy strategy to 2030 that develop renewable energy sector and realize rapid transformation of energy structure are important [3]. On the other hands, the development of renewable energy technology has reduced the power generation cost of solar, wind, and other renewable energy, thereby increasing the competitiveness of renewable

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energy generation [4]. Perea-Moreno et al. believe that by 2050, the use of wind and solar energy will need to increase [5]. And Graus's research shows that people are becoming more interested in biomass energy, reflecting its growing importance [6]. Many countries and regions have recognized the necessity and importance of developing clean and renewable energy due to the global energy transition and climate change [7]. Perea-Moreno et al. concluded that the role of renewable energy in mitigating climate change has affected the world, especially industrialized countries [8]. Yang et al. believe that energy security is one of the key parameters to ensure the stable development of countries and regions [9]. By the middle of this century, renewable energy will account for 77% of the global energy supply (compared with 13% in 2008), according to the Intergovernmental Panel on Climate Change (IPCC) report [10]. In addition, in 2014, Xi Jinping, the chairman of China, responded positively to the concerted global action on emission reduction since the establishment of *the United Nations Framework Convention on Climate Change*. The chairman put forward the concept of an energy revolution, which represents a significant turning point in China's energy development, and proposed the goal of 15% renewable energy by 2020 [11]. Therefore, both China and the world have recognized the importance of developing renewable energy and have put forward relevant policies and development goals. In addition, as part of the primary energy issues in the 17 Sustainable Development Goals, the United Nations and energy exchange platforms, such as the South-South Cooperation, have also promoted the development of renewable energy [12]. Research on the development and utilization of renewable energy is of great practical significance.

This study is an analysis of the renewable energy literature and authorized patents before 2018 to obtain an understanding of current research and development trends in this field and to provide references for the effective utilization of renewable energy.

2. Data Sources and Research Methods

The *Web of Science* and the *Derwent Innovations Index* are reliable databases of international publications and authorized patents, respectively. The *Web of Science* is the world's largest and most extensive comprehensive academic and scientific research database, which list publications in more than 8,700 influential academic journals in various research fields such as natural science, engineering technology, and biomedicine [13]. The database provides clear and accurate information on the retrieved records. The *Derwent Innovations Index* includes more than 38 million authorized patents from 47 countries and institutions, including the United States, China, Japan, the United Kingdom, France, Germany, South Korea, the European Patent Office (EPO), and the World Intellectual Property Organization (WIPO). The database allows for a comprehensive comparative analysis of different countries or regions in the world [14]. A bibliometric analysis is conducted to determine the research and development trends in the field of renewable energy, and the results of the analysis are presented in a visual format.

The literature and authorized patents cover the period 1963-2018. The literature search was conducted as follows: TS= ("Renewable Energy" and "wind power" or ("Large hydro*" or "Small hydro*" or "Micro-hydro*"") or ("Solar power" or "Solar PV" or "Solar thermal") or ("Geothermal" or "Geothermal power") or ("Biomass" or "Biomass power" or "Biogas" or "liquid biofuel*") or "Ocean Energy")). The authorized patents were searched as follows: TI= ("wind power" or ("Hydropower" or "Large hydro*" or "Small hydro*" or "Micro hydro*") or ("Solar power" or "Solar photovoltaic" or "Solar PV" or "Solar thermal") or (or "Geothermal" "Geothermal power") or ("Biomass" or "Biomass power" or "Biogas" or "liquid biofuel*") or "Ocean Energy") "NOT PN = CN2 *"). A total of 11,879 literature records and 7,5208 authorized patent records were obtained. The publications on renewable energy were analyzed from the following aspects: overall trend, country, research trend, and inter-country cooperation. The authorized patents in the field of renewable energy were analyzed from the following aspects: overall trend, country (organization), and trend.

3. Bibliometric Analysis

3.1 Overall Trend

The search of the *Web of Science* database shows that the number of publications worldwide has exhibited an increasing trend from 1982 to 2018, and the rate of increase has risen significantly since 2005 (Figure 1). Research on renewable energy began in the early 1980s. The first paper in this field was published in 1982. Since then, the number of publications increased annually from 1 article in 1982 to 1861 articles in 2018. The growth rate was relatively low before 2005 but began to increase after 2005; there were 118 publications in 2005 and 1861 in 2018, with an average annual growth of 23.6%. Figure 1 reflects the increasing attention and maturity of research in the field of renewable energy worldwide. The large increase in the number of publications shows that renewable energy research is considered essential in many countries and regions [15].

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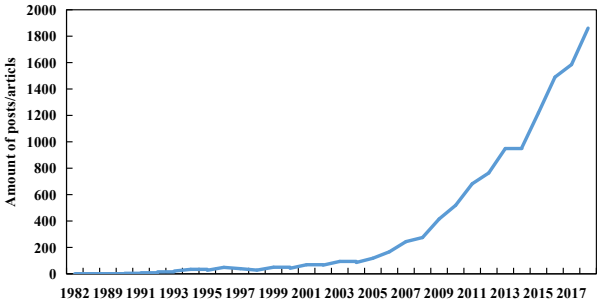

Figure 1. Research publications in the field of renewable energy

3.2 Research by Country

The number of publications in different countries (Figure 2) indicates that some countries conduct significantly more research on renewable energy that other countries. The top 10 countries (the United States, China, Germany, India, Britain, Italy, Spain, Turkey, Canada, and Australia) issued 8218 articles, accounting for 52.5% of the total publications. The United States had the largest number of articles and ranked first, and two countries (The United States and China) accounted for 13% and 9%, respectively, of the total, representing nearly a quarter (22%) of all publications worldwide (22%). Thus, the United States and China contributed most of the research in this field, occupying an important position [16].

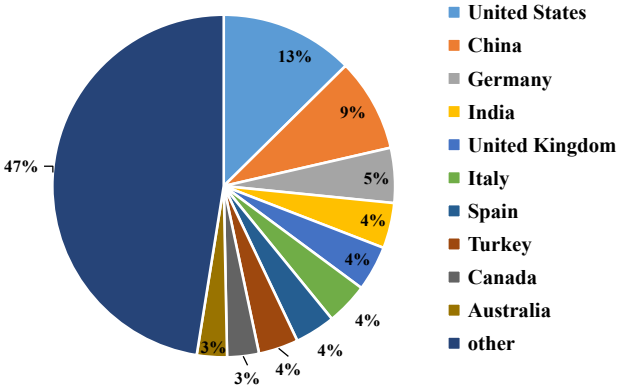

Figure 2. The proportion of publications

As shown in Figure 3, from 2005 to 2017, the United States had the highest number of publications in the field of renewable energy (the number was 260 in 2017), and the United States was the first country to publish research in this field (1990), followed by China, Germany, India, and the United Kingdom. The development of China's renewable energy research occurred relatively late, and the first paper was published in 1994. However, in 2018, the number of papers published in China (334) exceeded that of the United States (275), indicating that China has attached great importance to the development of renewable energy in recent years, and has made achievements and showed continuous progress in research in this field.

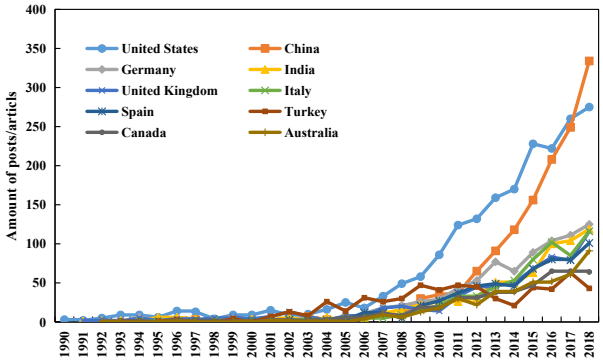

Figure 3. Number of publications in the top ten countries

3.3 Research Trends

For the analysis of the current research topics and trends, the keywords of the article represent the key topics. In the analysis of the frequency of the keywords, the period of 1982 to 2018 was divided into periods, i.e., 1982-2004, 2005-2013, and 2014-2018, as shown in Figure 4. Biomass energy represented the largest proportion in all periods and was 39%, 58%, and 46% in the three periods, respectively. The highest proportion (58%) occurred in 2005-2013. These results indicate that biomass energy has great potential for development in the future [17]. Wind and solar energy represented the second- and third-largest proportions [18]. The proportion of solar energy increased from 14% in the second period to 24% in the third period, indicating an increase in publications in solar energy research. Although the proportion of wind energy publications decreased from 23% in the first period to 21% in the third period, wind energy is an important renewable energy type and is likely to develop further in the future [19].

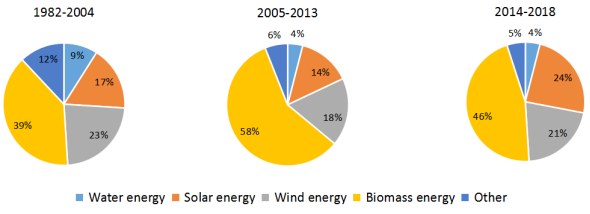

Figure 4. Proportion of research fields in different periods

The keyword frequency in the three periods indicates many studies related to biomass (Table 1), such as methane, biofuels, and anaerobic digestion. Biogas was the most frequent keyword of bioenergy in each stage, and

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the keyword frequency increased rapidly from 21 in the first period to 226 in the second period and 336 in the third period. In the solar energy field, research on photovoltaics has been a trending topic [20]. The keyword photovoltaic increased from 32 in the first period to 107 in the second period and 365 in the third period. The results show a lack of research in the field of solar thermal energy; the keyword only appeared 7 times in the first period and did not occur in the top 10 in the other periods, demonstrating a reduced focus on solar thermal research. The frequency of the keywords indicates that there is relatively little research in the field of wind and hydro energy; these fields should be further explored. In addition, an increasing number of studies included the keyword "China" in recent years. The keyword appeared 91 times in the 2014-2018 period, an increase of 59.6% compared with the 2005-2013 period. This result demonstrates the growing role of China in the field of renewable energy, making the country an important international player.

Table 1. The keyword frequency in the three periods

	1982-2004	2005-2013	2014-2018
1	Photovoltaic(32)	Biogas(226)	Photovoltaic(365)
2	Biogas(21)	Biofuels(219)	Biogas(336)
3	Gasification(18)	Hydrogen(129)	Anaerobic digestion(293)
4	Ethanol(17)	Geothermal energy(121)	Energy storage(289)
5	Rural energy(15)	Photovoltaic(107)	Hydrogen(156)
6	Pyrolysis(14)	Anaerobic digestion(106)	Biofuels(150)
7	Anaerobic treatment(12)	Gasification(82)	Geothermal energy(138)
8	Hydrogen(9)	Biodiesel(57)	China(91)
9	Solar thermal energy(7)	Energy storage(49)	Pyrolysis(90)
10	Wind turbine(5)	Heat energy(45)	Wind turbine(77)

3.4 Analysis of Cooperation between Countries

Figure 5 shows the cooperation between different countries. China cooperates with many other countries, such as the United States, Britain, Australia, Canada, Germany, Spain, Italy, Turkey, and India, most of which closely cooperate with the United States (the wider the line, the greater the cooperation); thus China has become at close partner of many countries in the field of renewable energy, far more than other countries. In addition, China also has close cooperation with the United Kingdom and Australia, but relatively little with other countries.

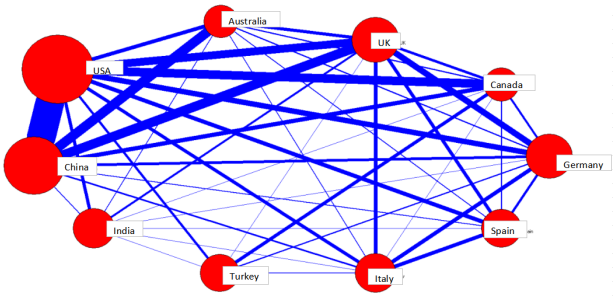

Figure 5. Cooperation between countries

In recent years, the "The Belt and Road" initiative proposed by China has increased the cooperation and exchanges on renewable energy between China and Africa. Figure 6 shows the cooperation between African countries and China. Overall, the African countries have a close cooperative relationship with China, and China has cooperative relations with 13 of the 21 African countries that have publication records, such as Ethiopia, South Africa, Nigeria, Lesotho, Liberia, Zambia, Benin, Egypt, Sierra Leone, Cameroon, Algeria, Ghana, and Kenya. The number of countries of origin (Figure 6) accounts for 61.9% of all countries in Africa. The number of publications on cooperative relationships with countries in Africa was low (1-2 articles) [21]. China's continuous development in the field of renewable energy is conducive to demonstration projects, and China can provide leadership, thereby strengthening the cooperation with African countries and the transfer of renewable energy technologies. This will allow African countries to use their abundant renewable energy resources efficiently and will promote the common development and progress of all parties.

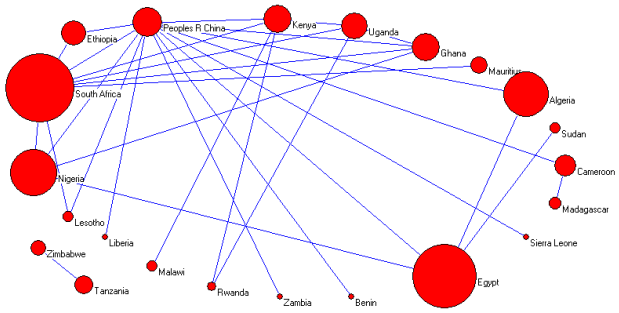

Figure 6. Cooperation between African countries and China

4. Analysis of Authorized Patents

4.1 Overall Trend

The trend in the total number of renewable energy authorized patents worldwide is very similar to that of the number of publications. The number of authorized patents

showed an increasing trend (Figure 7), and slow growth before 2005.The total number of authorized patents increased rapidly after 2005 (the annual number of authorized patents increased from 1,347 in 2005 to 7,305 in 2018), and there was a slight decline in 2012-2013. From 1973 to 2018, a total of 75,208 authorized patents related to renewable energy were issued worldwide. The number of authorized patents exceeded 1,000 for the first time in 2003, and the average annual growth rate was 12.7%. This result shows that the field of renewable energy has good prospects for development, and the number of authorized patents is on the rise.

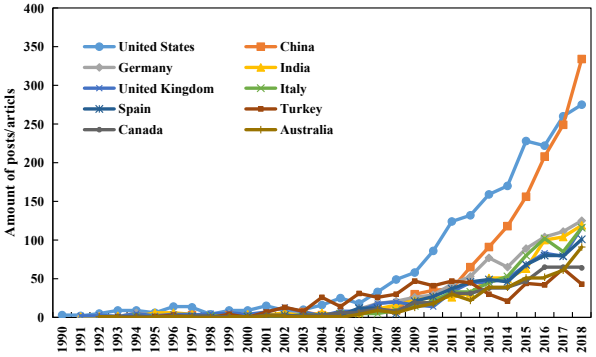

Figure 7. The number of renewable energy authorized patents worldwide

4.2 Patents by Country (Organization)

As shown in Figure 8, China, Japan, the WIPO, the United States, and South Korea are the top five countries in terms of the number of authorized patents, which were 32,993, 8,234, 6,407, 5,493 and 5,185, respectively, accounting for 77.5% of all countries. The number of authorized patents in China has exceeded that in the United States and has continued to grow since 2008. China is currently the country with the largest number of annual authorized patents, which account for 43.9% of the total. China should strengthen cooperation and exchange with other countries or organizations.

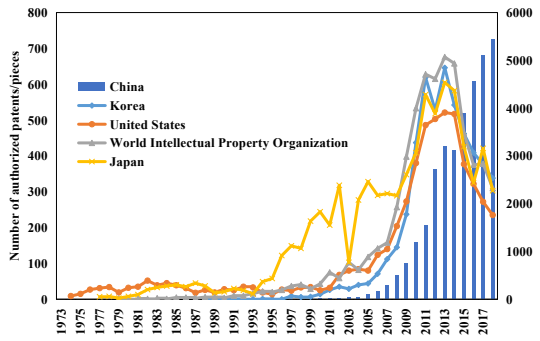

Figure 8. The number of authorized patents in countries with the largest number of authorized patents

4.3 Patents by Category

The analysis of the authorized patents by category (Figure 9) indicates that the largest number of authorized patents is related to wind turbines (9,849), far exceeding the number of authorized patents for other technologies. The number of authorized patents related to biomass energy production is relatively high; examples include patents related to fuel production and clean combustion, sewage treatment, fermentation and synthesis of organic matter, and fertilizer. The results show that theoretical and practical research related to biomass energy is developing rapidly.

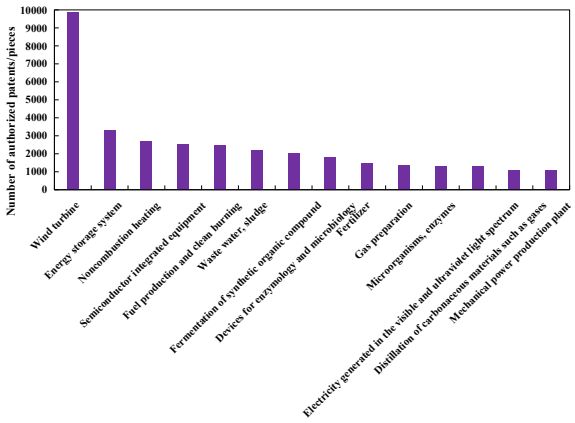

Figure 9. Number of authorized patents in different categories

The trends in the authorized patents in different technology categories (Figure 10) show that the earliest patented technologies included wind turbines, non-combustion heating, and mechanical power production devices (1974), whereas more recent authorized patents were related to electricity generation in the visible or ultraviolet spectrum (2014). Since 1992, the number of different authorized patents has increased rapidly, but the number of authorized patents for wind turbines began to decline in 2013, indicating that the use of wind turbines is gradually being replaced by other types of renewable energy technologies.

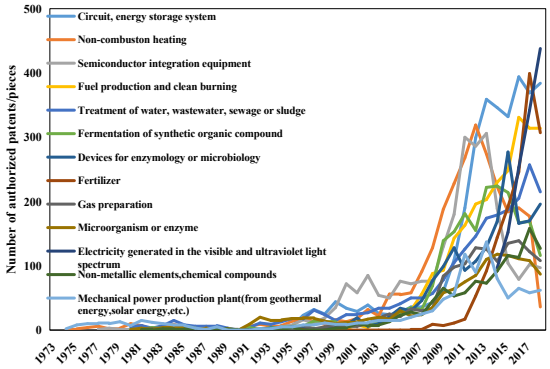

Figure 10. Trends in authorized patents in different categories

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5. Conclusions and Implications

Information obtained from the *Web of Science* and the *Derwent Innovations Index* databases was used to conduct a quantitative analysis of the publications and authorized patents in the field of renewable energy. The status of the current research, the research trends, and the cooperation between countries were analyzed. The main conclusions of this paper are as follows:

(1) A total of 11,879 studies on renewable energy were published before 2018, accounting for 13.6% of the literature achievements in the field of renewable energy. The number of authorized patents was 75,208 before 2018, accounting for 86.4% of the number of authorized patents in the field of renewable energy. A rapid growth in authorized patents occurred after 2005. Although the number of authorized patents was high, it is suggested that the quantity and quality of publications should be higher to make the two develop in a balanced manner.

(2) The overall number of renewable energy publications was highest in the United States, followed by China, and the United States ranked first in the number of publications until 2017. China ranked first worldwide in the number of authorized patents related to renewable energy, accounting for 43.9% of the total. In terms of the number of publications and authorized patents, China overtook the United States in 2018 and 2008, respectively, indicating that China and the United States occupy important positions in the field of renewable energy. China's research achievements in this field are increasing, which is reflected in the number of publications and authorized patents.

(3) The most common topics in renewable energy technologies were biomass energy and wind energy (primarily wind turbines). Biogas was the most common keyword in the publications in each period stage. Therefore, in the field of renewable energy research, biomass energy, wind energy, and others will be future development trends.

(4) Many countries had close cooperative relations based on the number of publications, and most relationships were with developed countries. China had the closest cooperative relationship with the United States, followed by Australia and the United Kingdom. In addition, China actively established cooperative relationships with many African countries through the south-south cooperation and other platforms. This approach represents an effective strategy for cooperation and exchange of renewable energy technology [22], training of renewable energy professionals, and increasing scientific research investment.

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