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Study on the Innovative Trends of Hydrogen Production: Based on Patent Data

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Hydrogen production is the beginning of the hydrogen energy industry chain. This study focuses on the latest patent situation of hydrogen production technology and comprehensively analyzes the development trend of global hydrogen production technology from the aspects of innovation sources, market layout, etc. The analysis results show that global hydrogen production technology is in an active period of research and development innovation. The main source and target market for hydrogen production technology is China, which currently holds the relative technological advantages in the industrial byproduct hydrogen and water-to-hydrogen. Universities, research institutes and other innovators have played a crucial role in the high level of patents for hydrogen production. Water-to-hydrogen production is a hot technology in the field of hydrogen production and has emerged as one of its most promising alternatives. The research results can assist policymakers and innovators in planning technological pathways and allocating resources in advance, and reveal a clear evolutionary path for the large-scale commercialization of technology.

1. Introduction

Hydrogen energy is an indispensable low-carbon energy carrier (Arras et al., 2024), and hydrogen production is an important part in the entire hydrogen energy industry chain. Hydrogen production patent data plays an important role in the development of hydrogen energy industry. Global hydrogen production stands at around 95 megatons per year (MtH_2/year), and is primarily derived from fossil fuels without carbon capture and storage (IRENA, 2024). Low-emissions hydrogen production has grown marginally over the past 2 years and remains under 1 Mtpa H_2–accounting for less than 1 % of global production (IEA, 2024). This year marks the tenth anniversary of the Paris Agreement, and the realization of the vision still faces huge challenges. What are the current trends in the development of hydrogen production technology? What is the competitiveness of different countries in this field? Who are the key innovators driving research and development? Based on this, we use patent data to analyzed the trend of patent application, regional distribution, innovators. The latest patent data can reveal the key technical direction, help innovators to select technical routes, and avoid repeated investment in research and development, thereby improving efficiency. We hope to provide certain information for the technical layout and support the innovation of hydrogen energy technologies.

2. Method and data

We used statistical analysis and index to study the current innovation of hydrogen production technologies. Firstly, we constructed a search strategy that includes Chinese and English keywords as well as International Patent classification (Table1). Secondly, we conducted a comprehensive and accurate search of the retrieval results. We found 16,524 relevant patent families published at December 31, 2024. Finally, we used the patent data to identify the source of innovation, technology leaders, and competitive advantage through analysis and revealed comparative advantage (RTA) index.

The RTA index (Balassa, 1965) was originally used to determine whether a country has a comparative advantage in international trade, and later expanded to measure a country's comparative advantage in technology composition (Soete et al., 1983). We used the RTA index to reveal the comparative advantage through patent data. The RTA index is described by Eq(1).

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$$RTA = \frac{FP_{ij}/\sum_{i} FP_{ij}}{\sum_{j} F_{ij}/\sum_{ij} FP_{ij}} \quad (1)$$

Table 1: Search strategy (The Definition of IPC can be found in WIPO website)

Technology	Part of English Key words	IPC
Fossil fuels to hydrogen	methane; natural gas; reform; steam; coal gasification; syngas; methanol	C01B3; C10L3; C10J3; B01J8; B01J21; B01J23; B01J25; B01J27; B01J29; B01J3; B01J31; B01J32; B01J33; B01J37; B01J38; B01D53
Industrial byproduct hydrogen	chlor-alkali; PSA; TSA; byproduct gas;	C01B3; B01D53; C01B3; C07C7
Biomass to hydrogen	biomass; waste; garbage straw; gasification; microorganism; bacteria; ferment; gasification; Pyrolysis; reform	C12P3; C12M1; C12N1; C01B3; C10J3; C10B53
Water to hydrogen	electrolysis; seawater; water electrolysis; alkali solution; PEM; proton exchange membrane; Anion Exchange Membrane; AEM; photolysis; photothermal	C25B1; C25B9; C25B11; C25B13; C25B15; C01B3; B01J27; B01J35; B01J23

In our study, the RTA index for each technical branch is defined as the ratio of the number of patents for a specific hydrogen production technology in a country in the total number of patents for hydrogen production in that country divided by the ratio of the number of patents of this technical branch in all countries in the total number of patents in all countries. The RTA index shows different performance in different technological fields of the same country. When it is greater then 1, it means that the country has a relative advantage in this field. Conversely, there is no competitive advantage (Henk et al., 2005).

The data was sourced from the RCESIPat, which is a public service platform that provides global patent information retrieval and analysis. This platform was built by the Technology and Innovation Support Center (TISC) of the Dalian Institute of Chemical Physics, Chinese Academy of Sciences. The TISC is a collaborative project under the framework of World Intellectual Property Organization (WIPO) aiming at helping innovative users in developing countries to enhance their ability to search for technical information, allowing them to grasp industry trends and new technological information quickly (WIPO, 2025). We built the RCESIPat platform with data supports from WIPO and China National Intellectual Property Administration. Since most hydrogen production patents published in China, we used the Chinese data platform for retrieval will be more comprehensive to some extent.

3. The global landscape of hydrogen production

3.1 Patent application trends

As can be seen from Figure 1, global hydrogen production technology has undergone a long period of development. I

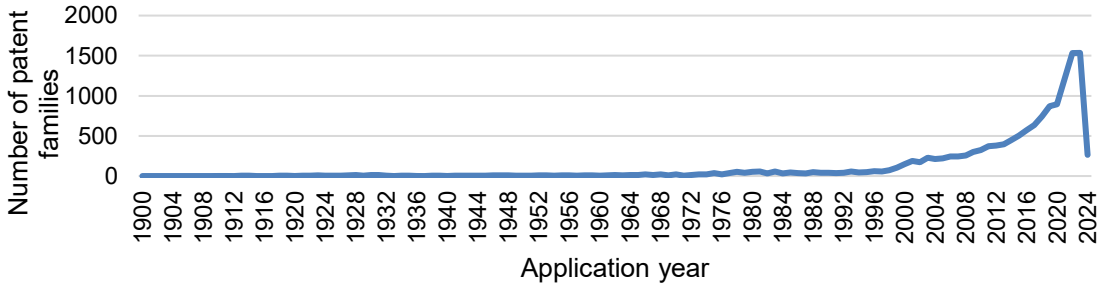

Figure 1: Trends in patent applications for hydrogen production technology (Due to the fact that invention patents are only published 18 months from the date of application, utility model patents are only published after authorization, and PCT patent applications may not enter specific countries until 30 months or even longer from the date of application, the number of patent families after 2023 is lower than the actual number.)

The application trend can be divided into the following three stages.

- 1910-1998: Slow development stage. During this time, global hydrogen production technology was in its nascent stage with less than 10 patent families filed each year.
- 1999-2014: Rapid growth stage. In 1999, the number of global hydrogen production patent families exceeded 100 showing a clear trend of rapid growth.
- From 2015 to the present: Near-vertical growth stage. The development of global hydrogen production technology was advanced at an exponential growth phase after 2015 with the number of patent families surpassing 500.

Global innovation in hydrogen production technology is currently experiencing a period of sustained activity.

3.2 Analysis of technology sources and target market

The global research and development of hydrogen production is very hot, particularly in China (Figure 2). The United States ranks second in the world with nearly 2,200 patent families, and Japan ranks third in the world with 1,773 patents. The number of hydrogen production patent applications in South Korea and Germany is less than 1,000. The main market for global hydrogen production is China (Figure 3). Nearly 10,000 patent families(accounting for 58.5 %) have been published in China, which is 4.6 times the number of the United States. Japan ranks third with 1,433 patent families published.

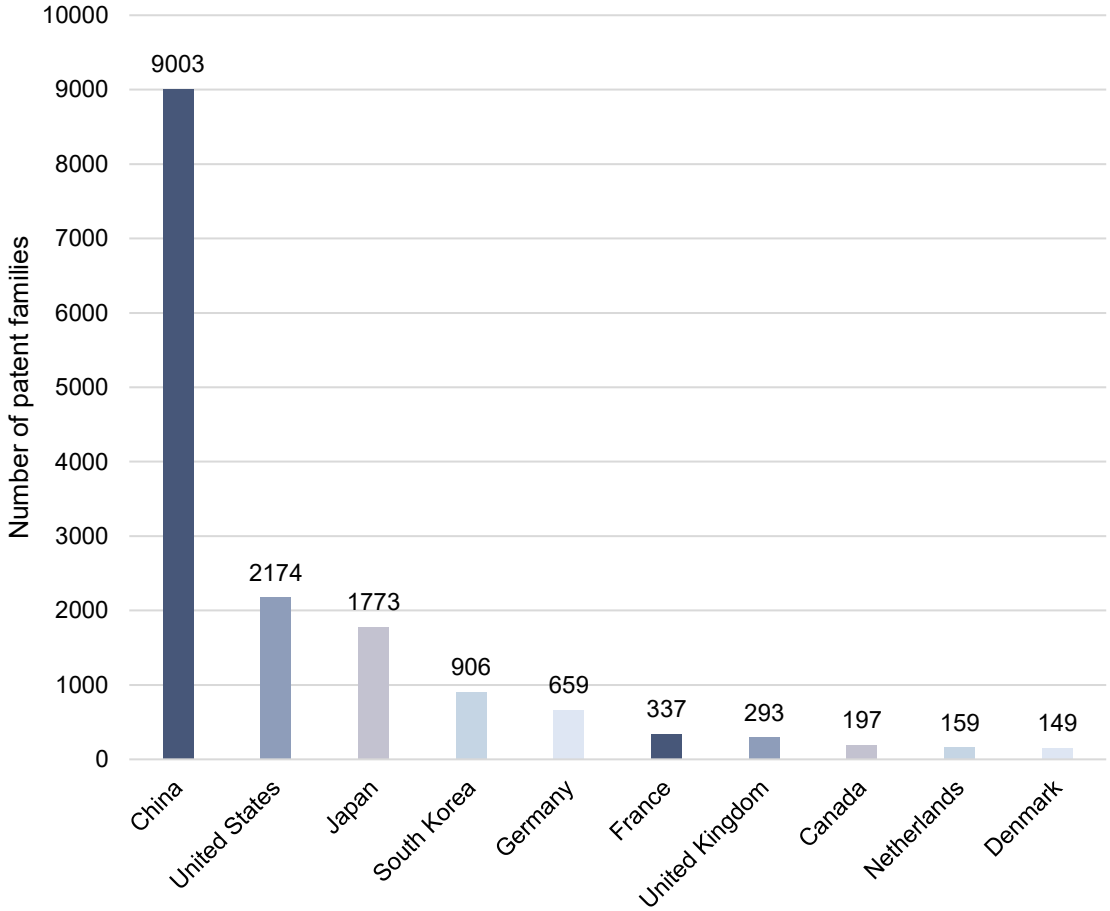

Figure 2: Top 10 sources of hydrogen production technology patent families

China's hydrogen production market is huge in scale and is undergoing rapid changes and development. A large number of hydrogen production patents from China and large patent portfolio deployed in China have, to a certain extent, promoted the continuous growth of China's hydrogen production. In 2023, China has become the world's largest hydrogen producer, accounting for nearly 30 % of the world's total hydrogen production, followed by the United States and the Middle East, each accounting for 14 % (IEA, 2024). Hydrogen production from fossil energy (including coal-to-hydrogen, gas-to-hydrogen, etc.) is still the main methods of hydrogen production.

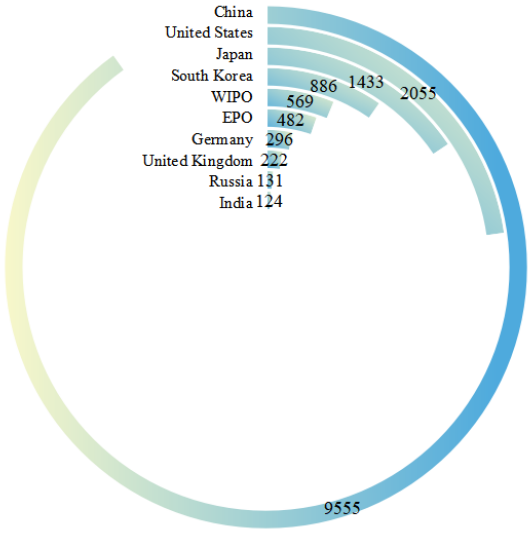

Figure 3: Target markets for hydrogen production technology patent families

3.3 Revealed technological advantage

Based on the patent families statistics from various nations in section 3.2, we analyzed the relative advantages of 4 different hydrogen production technologies in major countries (Table 2) to identify their advantageous technologies. China demonstrates a significant advantage in industrial byproduct hydrogen and water to hydrogen technologies. China's front-running position in water-to-hydrogen technology is backed by its strength in large-scale manufacturing of clean energy technologies. It is home to 60 % of global electrolyser manufacturing capacity (IEA, 2024). The technological advantages reflected through the patent data support China's ongoing expansion of manufacturing capacity and drive down costs. Water-to-hydrogen technology in other countries, however, still lacks a competitive edge over traditional fossil fuels to hydrogen. The United States is gradually moving towards low carbonization and has introduced the Clean Hydrogen Production Standard (CHPS) Guidance from the U.S. Department of Energy. Its technological advantages in fossil fuels to hydrogen and industrial byproduct hydrogen are expected to diminish over time.

Table 2: RTA Index of Hydrogen Production Technology in Major Countries

Countries	Fossil fuels to hydrogen	Industrial byproduct hydrogen	Water to hydrogen	Biomass to hydrogen
China	0.666831	1.022881	1.272160	0.953374
United States	1.565515	1.155395	0.549926	0.96179
Japan	1.097299	0.735879	0.935555	0.982872
South Korea	1.337238	1.061336	0.725831	1.019471
Germany	1.520991	1.005786	0.672342	0.47067

3.4 Main innovation entities

We counted the number of 3 types of patent families of the Top10 applicants (Figure 4). Applicants for hydrogen production technology include the universities, research institutes, and large chemical companies. There are 8 Chinese applicants, Saudi Arabian Oil Company, and the Korea Institute of Energy Research.

The top 10 applicants applied for invention and no design patents which reflects the high level of technological research and development in this field. Dalian Institute of Chemical Physics of the Chinese Academy of Sciences ranks first in the number of invention patent families, with a total of 201. This institute places equal emphasis on basic research and applied research, and has made significant progress in the field of hydrogen production. Recently, the team led by Academician Can Li from the State Key Laboratory of Catalysis and Division of Solar Energy (DNL1600 Group) of the Institute has reported an electron-mediated off-field electrocatalysis approach (OFEC) for complete splitting of H_2S into H_2 and S under ambient conditions, which is possible to replace the

current Claus technology in the industry, realize the elimination and resource utilization of hydrogen sulfide in natural gas extraction, the oil refining industry, and coal chemical processes, and become a new path for low-cost green hydrogen production (Wang et al., 2024).

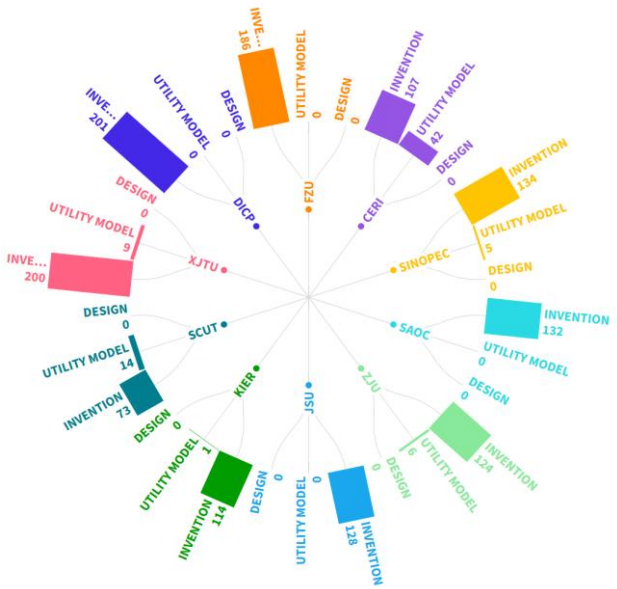

Figure 4: Top 10 applicants in hydrogen production technology(*XJTU=Xi'an Jiaotong University, DICP=Dalian Institute of Chemical Physics, Chinese Academy of Sciences, FZU=Fuzhou University, CERI=China Huaneng Group Clean Energy Technology Research Institute Co., Ltd., SINOPEC=China Petroleum and Chemical Corporation, SAOC=Saudi Arabian Oil Company, ZJU=Zhejiang University, JSU=Jiangsu University, KIER =Korea Institute of Energy Research, SCUT=South China University of Technology.)*

3.5 Key research and development directions

The four hydrogen production technology routes exhibit distinct development characteristics (Figure 5).

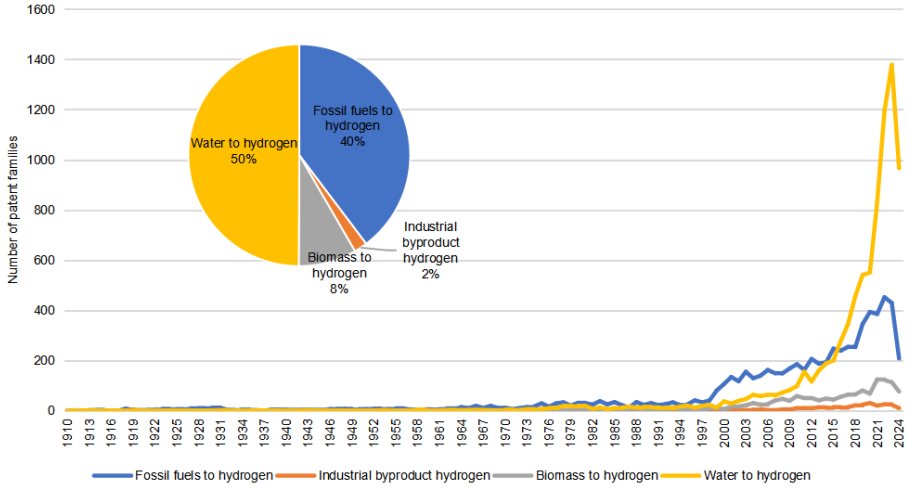

Figure 5: Key research and development directions for hydrogen production technology

Fossil fuels to hydrogen is one of the most traditional routes. After years of development, it has become the primary hydrogen production technology due to its large scale and low cost. Around 2000, the commercial application of fossil fuels to hydrogen had been achieved, and the global energy structure transformation had not yet fully begun, while the number of patent families was growing rapidly. With the global low-carbon transformation, there has been a decline in patent families (as shown by the blue line in Figure 5). However, the cost of producing renewable hydrogen is usually 1.5 to 6 times higher than unabated fossil-based production (IEA, 2024). In the short term, fossil fuels to hydrogen will remain high level and this reliance will decrease over

time. Water to hydrogen is a hot technology (as shown by the yellow line). It has shown explosive growth since 2015, and patent families have exceeded fossil fuels to hydrogen accounting for 50 %.

4. Conclusions

This study has explored the development of hydrogen production technologies and analyzed emerging trends in 4 technology routes. Our findings emphasize that global hydrogen technology is in an active period of research and development and innovation. The main source and target market for the hydrogen technology is China, which currently holds the relative technological advantages in the industrial byproduct hydrogen and water-to-hydrogen technologies. Universities, research institutes and other innovators have primarily contributed to the high level of patents for hydrogen production. Although hydrogen production from fossil fuels is still the dominant route, water to hydrogen has emerged as one of its most promising alternatives. It is a hot technology due to its advantages such as a stable and reliable process. Global water-to-hydrogen technology has entered a period of accelerated capacity growth. Overall, scaling up low-emission hydrogen production has become a key path for the global energy transition, which will require the governments to provide targeted supports for projects to narrow the cost gap between low-emission hydrogen and fossil fuels to hydrogen, during the scale-up phase. China has introduced a series of supportive policies to promote the development of hydrogen production projects. As of December 2024, there are over 160 demonstration and application projects for hydrogen production in China (excluding pilot projects). Other countries have fewer water-to-hydrogen projects, which are located in Europe, including Germany, the Netherlands, Denmark, and Portugal, and in South America, such as Brazil and Chile (RCES, 2025). In the future, as the scale of patents for water-to-hydrogen technology continues to expand and the hydrogen from fossil fuels is gradually phased out, it is essential to deploy and develop hydrogen infrastructure proactively. Governments should take actions to stimulate demand for low-emission hydrogen through quotas and other policies and lay out patents in the main market will help avoid further delays that could slow the growth of low-emission hydrogen production and demand. Patent data reveals a clear evolutionary path, and innovators must pay close attention to the rapid advancements in the water-splitting hydrogen production technology market.

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