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SCIENTIFIC REPORT

TECHNOLOGY TREND ANALYSIS

Moving towards a Hydrogen Society: Hydrogen Production

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Hydrogen is garnering more and more attention as a clean energy source because of its water-only emissions when used as a fuel. In recent years, it has become even more prominent due to its use in residential fuel cells and fuel-cell vehicles.

The use of hydrogen as an energy source is also being actively considered in policy matters. In 2014, the Japanese Ministry of Economy, Trade and Industry formulated a strategic road map for hydrogen and fuel cells, setting 2020 targets for the nationwide installation of 1.4 million residential fuel cells, 40,000 fuel-cell vehicles, and 160 hydrogen fuel stations. By 2040, the ministry aims for Japan to have established a completely CO2-free hydrogen supply system[1]. The shift in policy focus to a hydrogen society is not confined to Japan. Hydrogen initiatives are occurring worldwide, with the US and the EU establishing the Hydrogen Fuel Initiative and the Fuel Cell and Hydrogen Initiative, respectively.

While hydrogen energy holds great promise, this contrasts with the fact that hydrogen rarely occurs independently in nature, which means that there needs to be some means of extracting it from hydrogen-containing sources, such as water or hydrocarbons. Furthermore, gaseous hydrogen ignites at roughly 299°C; its flammability limits range from 4% to 75%; and its minimum ignition energy is 0.02 mJ, meaning that hydrogen ignites more easily than methane (5%–15% and 0.33 mJ), the primary component of household gas[2]. In addition, hydrogen has a small atomic radius, is highly transparent, and causes hydrogen embrittlement in steel, making it a difficult substance to handle. Therefore, if we are to realize a hydrogen society, it is essential that concerned parties conduct research and development on the key elements of producing, transporting, and storing hydrogen.

Although hydrogen energy is garnering attention, we should know how much its research and development has progressed. For this report, we focused on hydrogen production—one of the three key elements needed for a hydrogen society—and used

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[1] Council for a Strategy for Hydrogen and Fuel Cells, “Hydrogen and Fuel Cells Strategic Road Map: Accelerating

[2] Miake, Atsumi, “Hydrogen Explosions and Safety,” Hydrogen Energy Systems, Vol. 22, No. 2, p9–17 (1997)

academic citations as a resource for our analysis of research and development trends in hydrogen production.

When gathering articles on hydrogen production, we used Scopus, the publisher Elsevier's bibliographic database. We looked for peer-reviewed articles that were published in English since 2001. We used title, abstract, and keyword searches for the occurrence of any of the following words within two words of each other: hydrogen, production, evolution, and generation. There were roughly 25,000 relevant articles.

PANORAMIC VIEW ANALYSIS

Macro Trends in Hydrogen Production

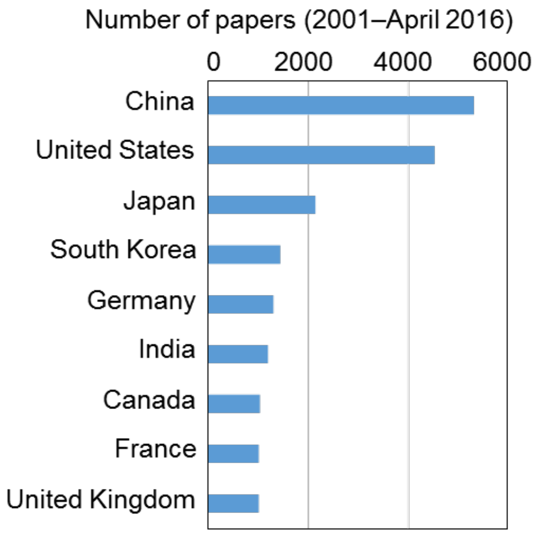

Figure 1 - Key Countries in Hydrogen Production-Related Research Publications

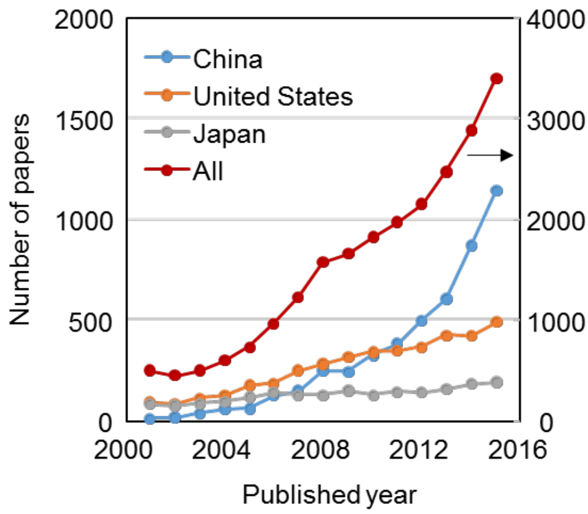

Figure 2 - Number of Articles from the Leading Three Countries and for the Whole

Figure 1 shows the key countries in terms of articles published on hydrogen production, while Figure 2 shows the numbers of articles for the three leading countries and the whole cohort. In Figure 2, the left axis shows the number of articles by country (China, United States, Japan), whereas the right axis shows the amount for total articles (all).

In this technology region, **China and the US have a particularly high number of published articles**, followed by Japan, South Korea, and Germany. When looked at by country, **it is clear that the number of academic citations for the US is growing, but the number of articles coming out of China has been increasing remarkably since 2011**. The number of all hydrogen production-related articles has been surging since around 2010, which can be mostly attributed to the dramatic rise in articles published by China.

Cluster Analysis of Hydrogen Production-related Articles

We performed a cluster analysis of the articles we gathered, in order to get a panoramic view of the complete picture of hydrogen production-related research and development. We used tf–idf values to evaluate the feature quantity of documents gathered for the analysis, which provides a visualization of this data based on the degree of similarity among documents. We used the titles and abstracts of the articles to evaluate their degree of similarity. The results are shown in Figure 3. The dashed lines in the chart distinguish the major technology regions.

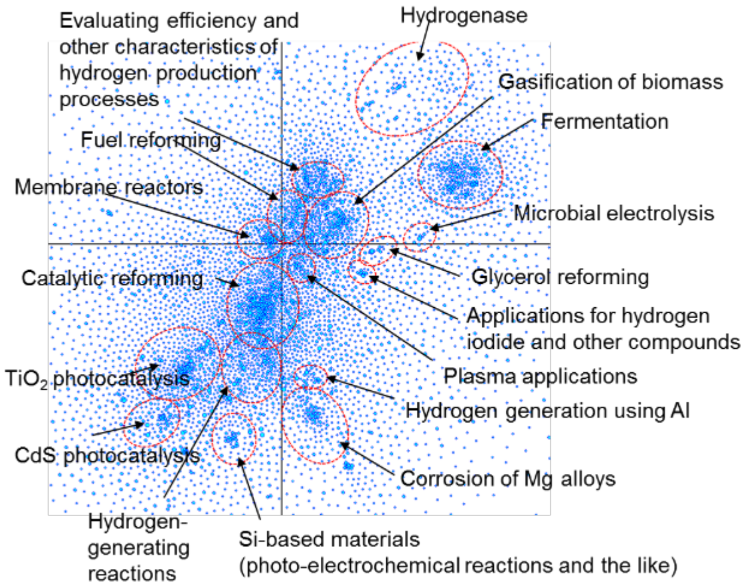

Figure 1 - Cluster Analysis Results of Relevant Articles

Looking at these results, in the upper right quadrant, we find an aggregation of **biological hydrogen production processes, using fermentation and hydrogenase** (an enzyme). To the lower left of this region, there is a group of research related to **evaluating the efficiency of various hydrogen production methods**, which includes renewable energy applications. Further down and to the left, there are collections of **reforming-related research**, such as fuel reforming and catalytic reforming. Continuing down and to the left, we see clusters of **photo catalysis-related research**. Finally, in the bottom center of the chart, there is research related to **hydrogen generation that corresponds to the corrosion of metals and alloys** comprising magnesium and aluminum.

In terms of density in the cluster analysis, among the research related to hydrogen production, **reforming technologies using catalysis have the greatest densities, followed by membrane reactors and biomass gasification, and then photocatalytic applications**.

We created visualizations of how the research regions for hydrogen production have changed over time—found in Figure 4—using our cluster analysis data. These color contour charts show the shifting trends in hydrogen production research, divided among three-year periods of time. The red regions have the highest concentrations of research, with decreasing density, in order, of yellow, green, and blue regions.

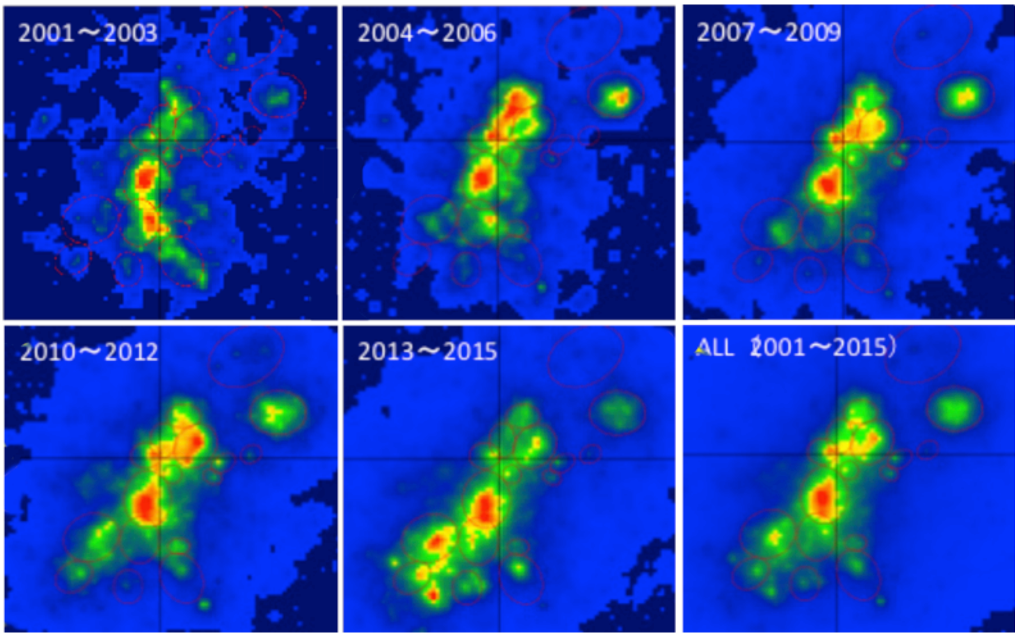

Figure 4 - Shifting Trends in Hydrogen Production-Related Research and Development

During the period of 2001–2003, research was focused on reforming using catalysts and hydrogen-generating chemical reactions. During the next span (2004–2006), the region for hydrogen-generating reactions contracted, while research became active in fuel reforming and conversion efficiency. We also see an increase in research related to fermentation. This trend remains the same during the next span (2007–2009). **Since 2010, research has been actively investigating photo catalysis applications. This trend has become particularly aggressive since 2013.**

Research Fields by Country

The three leading countries in research on hydrogen production—China, the US, and Japan—have different research fields, which are shown in Figures 5a, 5b, and 5c. The figures show research fields over the entire period (since 2001) and specifically since 2013, in order to demonstrate recent trends.

CHINA

China's research fields in hydrogen production are broadly distributed, from biological methods in the upper right quadrant down to photocatalysis.

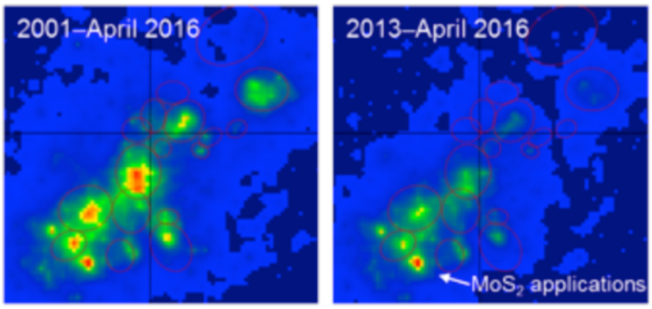

Figure 5a - Research Fields in China; (L) Since 2001, (R) Since 2013

However, **the regions in the lower left of the cluster analysis, which contain catalytic reforming and photocatalysis, have more publications**. Since 2013, this trend is even more marked. In addition, we find a concentration of research in a location that has not been assigned a cluster density region on the chart. This region contains research related to hydrogen production using layered materials, such as MoS2.

THE USA

For the entire period, the US's research on hydrogen production is found close to the center of the chart, mostly in fuel reforming, catalytic reforming, and photocatalytic applications.

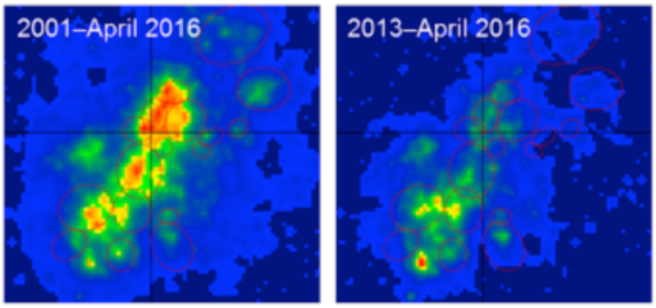

Figure 5b - Research Fields in the USA; (L) Since 2001, (R) Since 2013

Looking to recent years, **the rate of reforming-related research, near the center of the chart, has dropped, while TiO2 photocatalysis and hydrogen-generating reactions are becoming more active.** Additionally, as in China, research using layered materials such as MoS2 is increasing. That said, we could confirm that several of these papers on research using layered materials were co-written with Chinese research institutes.

JAPAN

Throughout the entire period, most of Japan's research on hydrogen production has been related to catalytic reforming, membrane reactors, and photocatalysis.

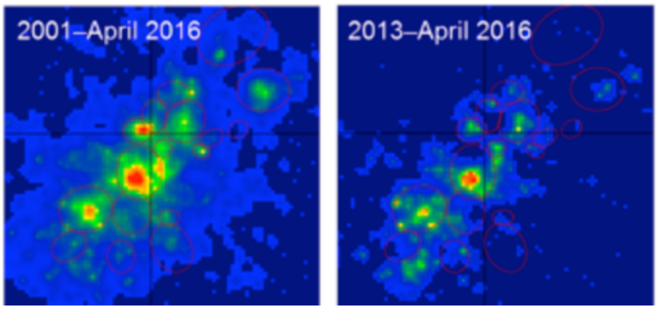

Figure 5c – Research Fields in Japan; (L) Since 2001, (R) Since 2013

This trend has not undergone major changes in recent years; however, membrane reactor-related research has contracted slightly. Moreover, we also find hydrogen production-related research using layered materials such as MoS2. However, the concentration of this research is not seen to the degree that it is in China and the US.

The State of Research Grants in the Leading Countries

Hydrogen energy is a field of research and development that is also receiving attention in the form of government policy. We elucidated the different initiatives for each leading country, using the grant-funding data recorded by Scopus. Figure 6 shows the primary grant-funding institutions, while Figure 7 indicates the research regions with which each institution is concerned.

Looking at the key grant-providing institutions, we can see that the National Natural Science Foundation of China (NSFC) has an especially substantial number of relevant articles (the horizontal axis in Figure 6 uses a logarithmic scale). In addition to the NSFC, the Chinese Academy of Science also appears as a leader in research grant funding.

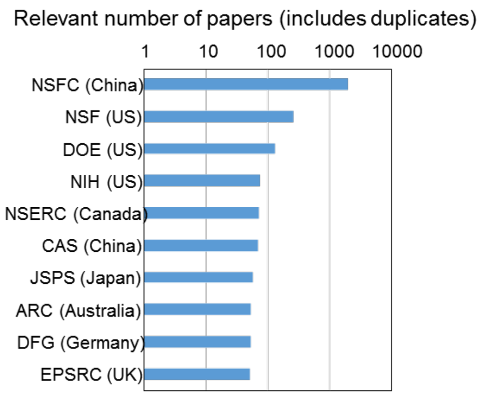

Figure 6 - Key Grant-Providing Institutions for Hydrogen Production-Related Research and Development (according to data found in Scopus)

Following China, the greatest number of papers funded is in the US, led by the National Science Foundation (NSF) and the Department of Energy (DOE). The American National Institutes of Health (NIH) also provide funding in this field. The US is characterized by not being inclined toward any specific institute, with multiple organizations providing research funding.

In Japan's case, the leading grant provider is the Japan Society for the Promotion of Science (JSPS). In addition, we also see funding from the Japan Science and Technology Agency (JST), but this organization does not appear in the top ten.

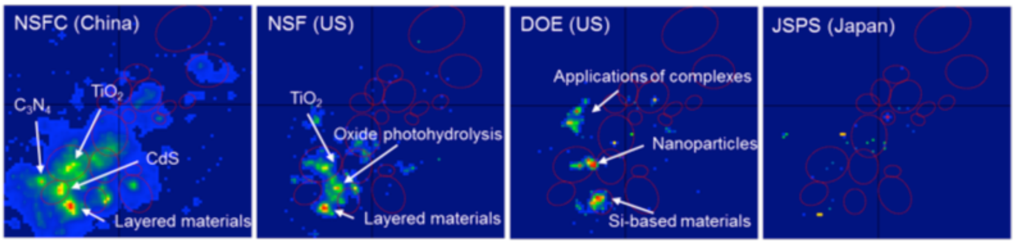

Figure 7 - Research Fields by Grant Funding

NSFC (China)

Relative to all research in China since 2013 (see Fig. 5a), the upper-right region of biological production and the central region of reforming receive fewer grants from the NSFC than expected, based on the research density in these regions. Instead, **research is concentrated in regions for TiO2 or CdS photocatalysis and applications for layered materials such as MoS2**. Applications for C3N4 also have a relatively high concentration.

NSF (US)

Compared to the research fields since 2013 that are shown in Fig. 5b, **there is a much greater concentration of research in photocatalysis-related regions, in terms of research funded by the American NSF.** Funded research is for TiO2 photocatalysis, photo-electrochemical reactions using oxides such as Cu2O or Fe2O3, and applications for layered materials such as MoS2.

DOE (US)

The research fields funded by the DOE can be broadly divided into three regions. One of these regions includes hydrogen production using complexes such as iron pentacarbonyl as catalysts. We also find concentrations of research related to nanoparticle and Si-based material applications. **These research fields are outside the NSF's regions, so we believe that these agencies are compartmentalizing their funding.**

JSPS (Japan)

In terms of grant-funding data on Scopus, the information for Japan is limited, with the agency funding the greatest number of articles—the JSPS—having only around 60 hits. **Looking at the cluster analysis, it is difficult to say that the agency is focused on any specific research field.**

As before, from the perspective of grant funding, **it is clear that China and the US are funding research for chemical reactions using oxides, nitrides, and complexes, rather than technologies related to reforming.** It should be noted, the results of this analysis can only be used as a parameter to evaluate whether funding exists, and for further details, it is necessary to evaluate the extent of this funding.

Conclusions

We performed a panoramic analysis of research and development trends in hydrogen—which holds promise as a clean energy source—and its production methods, using academic citations as a resource.

Hydrogen production-related research and development is becoming an active macro trend, of which China has been the primary driver. In terms of research fields, we see biological applications—fermentation, hydrogenase, and microbial electrolysis—several types of reforming technologies, and applications using photocatalysis and photo-electrochemical reactions. In terms of related research, we see hydrogen generation when metal corrodes. The greatest research trend is seen in photocatalysis and photo-electrochemical reactions. In recent years, hydrogen production using layered substances such as MoS2 has been a particularly active field of research, with China and the US conducting much of this research.

Looking at research funded by public grants, much of these grants are provided for research on hydrogen production using photocatalysis or photo-electrochemical reactions, and applications for layered materials. On the other hand, turning to Japan, we are unable to see concentrated research and development investment, at least as far as what is shown by the data found on Scopus. The question of how to increase conversion efficiency is crucial for hydrogen production, but this does not necessarily require a dependence on new materials or chemical reactions. Thus an evaluation in terms of patent information, not just academic citations, may be more appropriate; however, it could just be that Japan is trailing the US and China in terms of research and development.

For the future realization of the hydrogen society, energy cost is particularly vital. Therefore, it is essential that highly efficient production methods are developed first, and we expect research and development in this field to progress in the future.

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After serving as a researcher at the Research Development Corporation of Japan and as lead researcher at Mitsubishi Research Institute, Inc., he has been in his current position since 2008. Fields of expertise: Analysis of cutting-edge science and technology fields such as nanotechnology and nanomaterials; research on and analysis of international science and technology.