SCIENTIFIC REPORT
TECHNOLOGY TREND ANALYSIS

Moving towards a Hydrogen Society: Hydrogen Storage

Distributed August 16, 2016

Hydrogen is garnering attention as a clean energy source, but there are several problems with its practical application. One problem is its production as it rarely occurs independently in nature. We presented an outline of research trends in hydrogen production in our previous report, dated August 16. Another problem is that hydrogen is difficult to handle because it has a wide range of flammability limits, it is highly transparent in its gaseous state, and it causes hydrogen embrittlement in steel. In other words, the problem is how to safely store large volumes of hydrogen. Accordingly, for this report, we focused on hydrogen storage, using academic citation information to create a panoramic overview of research and development trends.

When gathering articles on hydrogen storage, we used Scopus, the publisher Elsevier's bibliographic database. We looked for peer-reviewed articles that have been 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, storag*, and reserv*. There were roughly 11,300 relevant articles.

PANORAMIC VIEW ANALYSIS

Macro Trends in Hydrogen Production

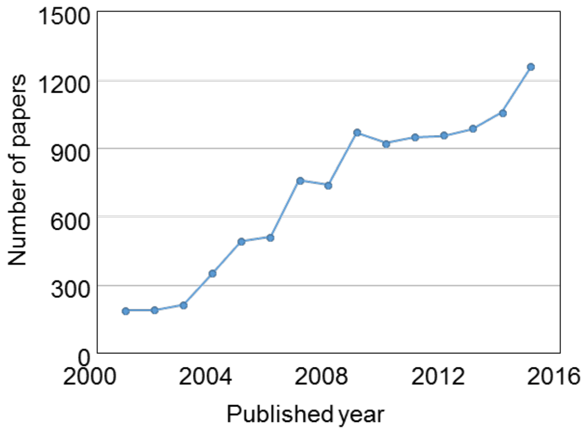

Figure 1 - Number of Hydrogen Storage-Related Articles

Figure 1 shows the number of hydrogen storage-related articles published annually. In 2001, there were around 200 such papers published, but **publications surged beginning around 2004**, and the number reached nearly 1,000 articles published in 2009. Until 2012, the annual number of hydrogen storage-related articles remained steady at just under 1,000. **Since 2013, we have been seeing another trend of rapid growth.**

The top ten countries conducting hydrogen storage research are shown in Figure 2. The number of papers published from 2001 to 2012 is indicated by the blue bars, while the number of papers published since then is indicated in red. Also, the figures in the parentheses are the ratio (%) of papers published since 2013. As seen in the figure, **the ratio of publications in recent years is high in China, at more than 40%.** Additionally, India and Australia have also published a high ratio of papers since 2013. Meanwhile, the US and Japan are just under 30%, indicating a decline in the ratio of papers published in recent years, despite these countries being prominent research nations.

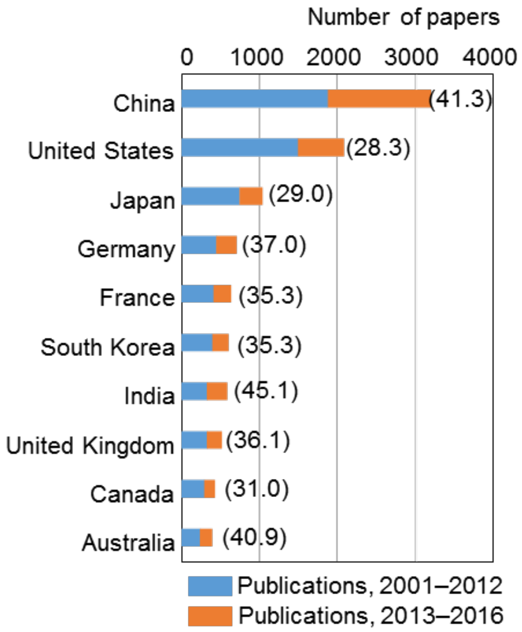

Figure 2 - Key Countries in Hydrogen Storage-Related Research

We have omitted time trends by country due to space limitations, but the US is demonstrating a steady decline in the number of papers published since the peak in 2009. Japan has also published a fixed number of papers annually since 2005. Thus **the growth in the number of papers published since 2013, as seen in Figure 1, is primarily due to the active research environment in China**.

Cluster Analysis of Hydrogen Storage-related Articles

We performed a cluster analysis of the articles we gathered, in order to get a panoramic view of hydrogen storage-related research and development. We evaluated the feature quantity of documents gathered for our cluster 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 of our cluster analysis are shown in Figure 3. In Figure 3, concentrated clusters are circled in red dashed lines, to make it easier to distinguish among the major regions of concentrated research.

The primary regions of concentrated hydrogen storage-related research are broadly divided among hydrogen evolution using alloy-based materials (on the left side of the chart), hydride applications (in the lower left), hydrogen absorption (in the lower right), and hydrogen storage-related applications and associated systems (in the upper right). **The region with the greatest volume of research is related to applications of alloys, as well as magnesium and other metallic hydrides.** Otherwise, materials-related research consists of a core technology region, with research including ammonia borane applications, metal-organic frameworks (MOF), and carbon-based nanomaterials. However, there is not much research related to systems and controls for hydrogen storage.

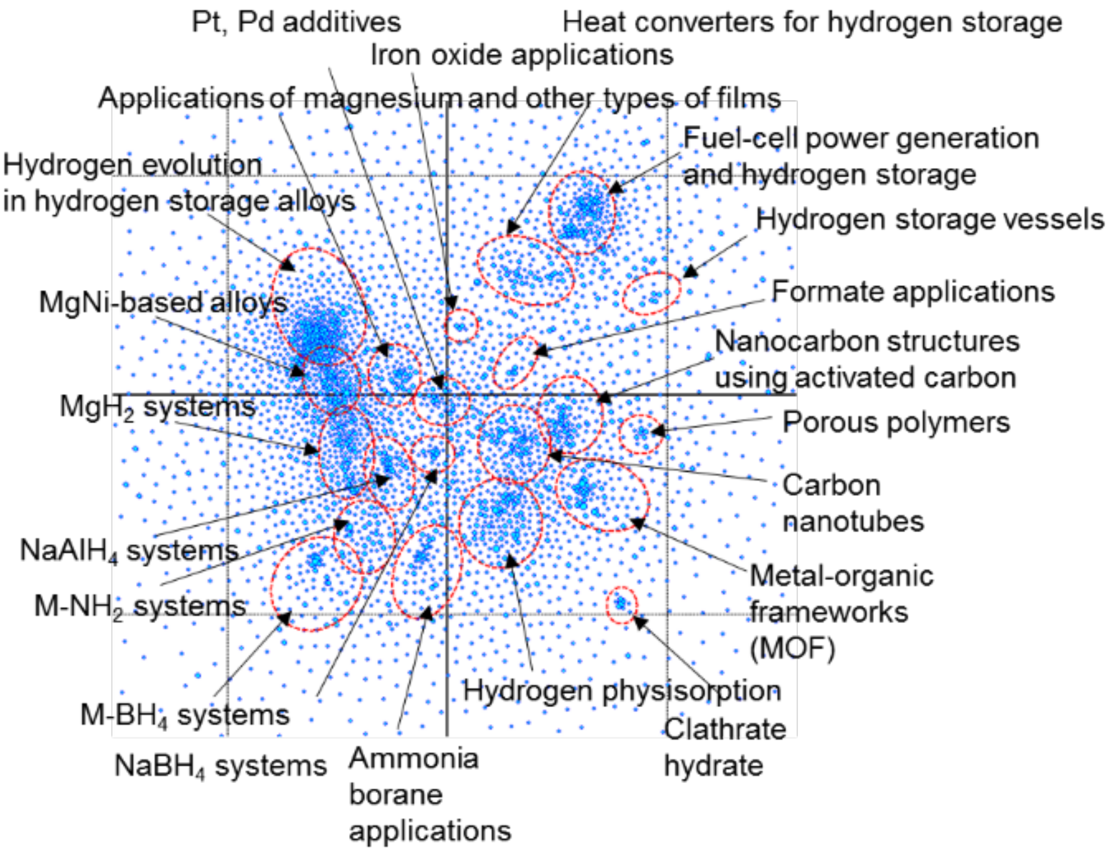

Figure 3 - Cluster Analysis Results for Hydrogen Storage-Related Research

Per figure 1, the trends in hydrogen storage-related research shifted from a rapid increase in publications until 2009, a stagnation in this growth until 2012, and the revitalization of the field since 2013. We created visualizations of how the research trends have changed during this period—found in Figure 4—using our cluster analysis data. The red regions have the highest concentrations of publications, with decreasing density, in order, of yellow, green, and blue regions. Furthermore, in order to facilitate annual comparisons, we standardized the maximum value to 50 papers.

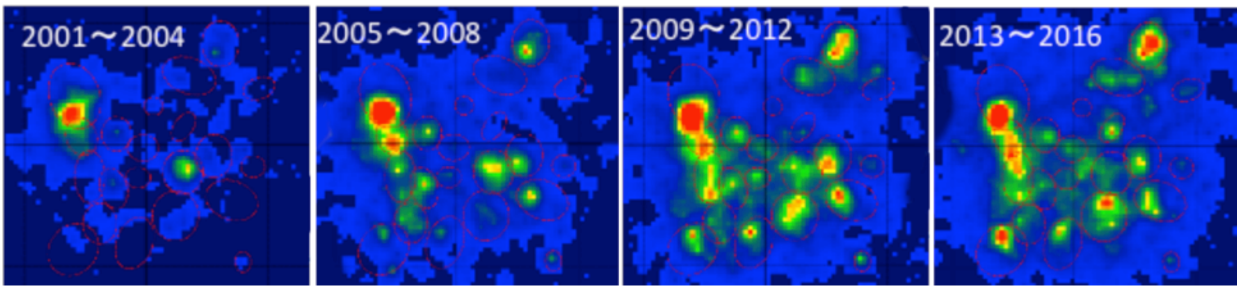

Figure 4 - Visualization of Research Trends Using Cluster Analysis

Looking to the annual trends found in the cluster analysis, for the period from 2001 to 2004, **there was an especially large volume of research related to hydrogen evolution in hydrogen storage alloys**, in addition to the considerable number of papers published on hydrogen storage using carbon nanotubes.

From 2005 to 2008—which saw a rapid increase in the number of published articles—research fields that became active include MgNi-based alloys and film applications, hydride research for complexes such as $NaAlH_4$, and the evolutionary characteristics of storage alloys. In addition to these fields, there was also more research related to nanocarbon structures using activated carbon and porous polymers.

Although the growth in the number of papers published stagnated from 2009 to 2012, the cluster analysis indicates that **this period included many articles on MgH_2-related materials**; hydrides, such as metallic BH_4-related and ammonia borane-related materials; and hydrogen physisorption and MOF. **There was also an increase in associated research**, such as fuel cell applications and heat converters. Since 2013, when research volumes began to increase again, researchers have remained focused on similar structures, albeit with growth in research fields studying fuel cell-based power generation technologies and the increase of formate applications.

Thus we can see the proliferation of inquiries into new hydrogen storage materials during the period of stagnating research publications from 2009 to 2012. **This period can be considered a paradigm shift in hydrogen storage-related research topics**. Nonetheless, the regions with the most research publications during 2015 and 2016 (up to October) have been hydrogen evolution in hydrogen storage alloys, MgH_2 and metallic BH_4 materials, and formate applications. Regions associated with fuel cell-based power generation have also seen research in hydrogen storage systems and combinations of photovoltaics and hydrogen production.

Research Fields by Country

The three leading countries in research on hydrogen storage — China, the US, and Japan — have different research fields, 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. To clarify the differences in research fields, we used red on the color contour chart to show the maximum values during each period. Therefore, readers should bear in mind that the comparisons between periods or among countries are not in terms of absolute numbers.

CHINA

Hydrogen storage-related research in China is mostly specialized in hydrogen storage alloys. This trend has not really changed in recent years, but research related to hydrides and absorption is increasing. There is not much research on systems or applications, such as fuel cell-based power generation or heat converters.

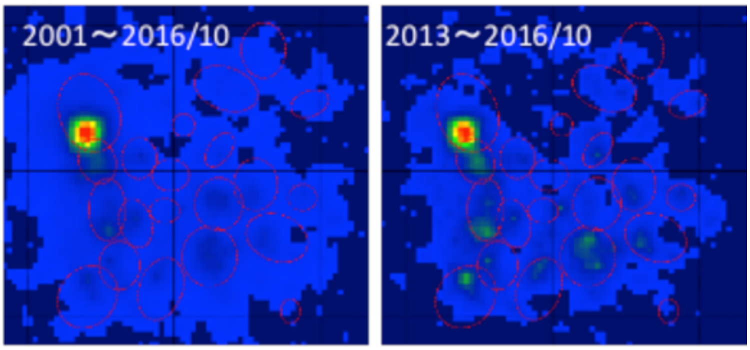

Figure 5a - Research Fields in China; (L) Since 2001, (R) Since 2013

THE USA

The US's initiatives in hydrogen storage research are completely different from those in China. Throughout the entire period, much of the US's research has been in ammonia borane and MOF-related materials, with growing systems-related research, such as fuel cell-related power generation systems and heat conversion.

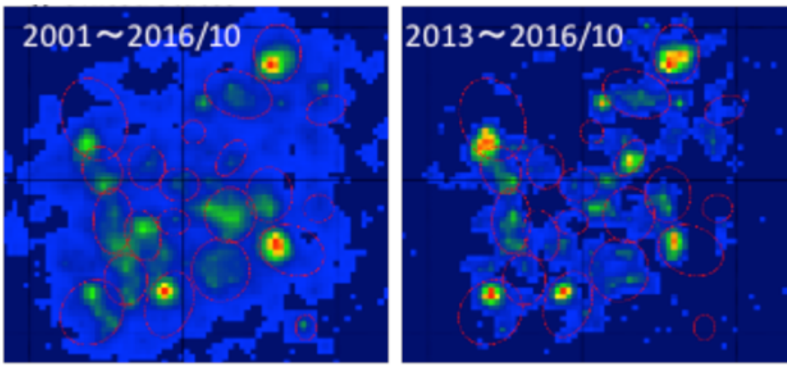

Figure 5b - Research Fields in the USA; (L) Since 2001, (R) Since 2013

Focusing on the period since 2013, there has been a considerable amount of research in the evolutionary characteristics of storage alloys, metallic BH4 materials, and formate applications. In terms of research seen in the cluster analysis, there is a clear shift in the concentration of research since 2013, which likely means that research in the previously mentioned specialized fields will continue to be the focus.

JAPAN

Hydrogen storage research in Japan demonstrates tendencies that differ from those found in China or the US. Throughout the entire period, the prominent region with a high concentration of research is Ti-based alloys (indicated by an arrow on the chart), which is slightly outside the primary concentration regions.Otherwise, there is a considerable amount of research in metallic NH2 materials and metallic BH4 materials. Since 2013, research has been conducted in TiFe-based intermetallic compounds (indicated by an arrow on the chart) and hydrogen storage using Pd nanocrystals. While not to the extent found in the US, there is also research being performed on systems-related topics.

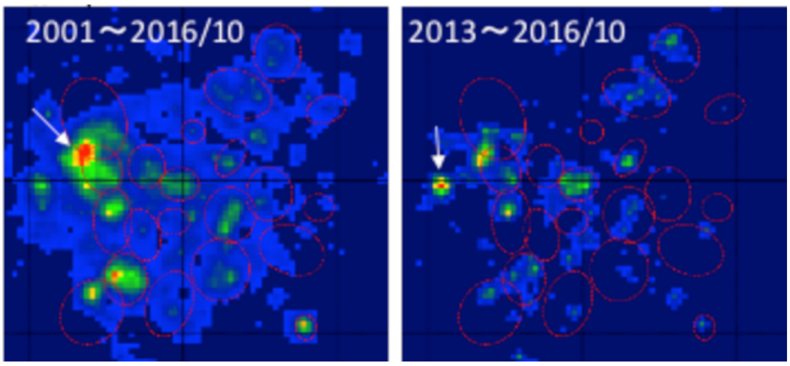

Figure 5c – Research Fields in Japan; (L) Since 2001, (R) Since 2013

The State of Research Grants in the Leading Countries

As we mentioned in the report on hydrogen production, **hydrogen energy is a field of research and development that is also receiving attention in the form of government policy**. We elucidated the different public investments for each leading country, using the grant-funding data recorded by Scopus (thought to span the latest information dating back to around 2013). Figure 6 shows the primary grant-funding institutions, while Figure 7 indicates the research fields that are receiving some sort of grant funding in the three key countries. Additionally, for comparison, Figure 7 shows the research fields that have received funds from representative grant-funding institutions in each country.

Looking at the key grant-providing institutions, we can see that the National Natural Science Foundation of China (NSFC) has a remarkably high number of relevant articles (the horizontal axis in Figure 6 uses a logarithmic scale). This result is similar to that seen in the hydrogen production report.

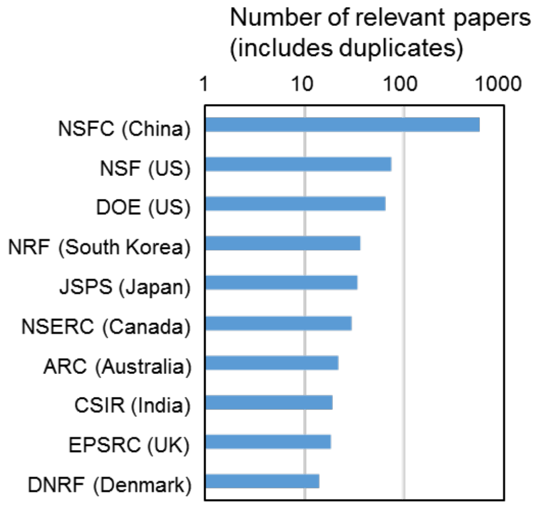

Figure 6 - Key Grant-Providing Institutions for Hydrogen Storage-Related Research and Development (according to data found in Scopus)

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). This is also the same as with hydrogen production. Following these, various organization appear in the top ten, including South Korea's National Research Foundation (NRF), Japan's Japan Society for the Promotion of Science (JSPS), Canada's Natural Sciences and Engineering Research Council (NSERC), and Australia's Australian Research Council (ARC). Many of these grant institutions provide funding focused on basic research, so many of the research fields funded by them can be understood to be basic research.

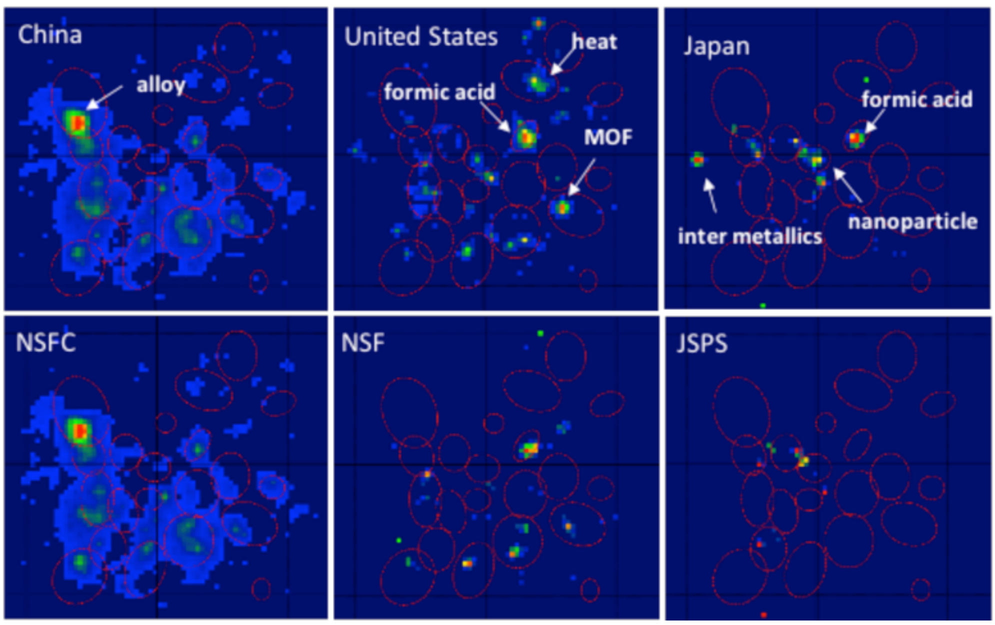

Figure 7 - Research Fields by Grant Funding Focus

CHINA

Looking at the research grant situation in China, **it is clear that funding covers an extremely broad spectrum of research**. Although concentrations are mainly seen in research related to hydrogen storage alloys, other materials-related research also receives a wide range of funding. The overall national research grant situation is nearly identical to that for the NSFC, which indicates that **the NSFC serves a leading role in funding hydrogen storage-related research in China**.

THE USA

Regarding the US, **research receiving grants includes formate applications; heat-related systems, such as heat converters; and MOF**. The NSF funding situation is similar, but it does not appear to provide systems-related funding. The institutions providing funding to this research field are primarily the DOE and NASA.

JAPAN

In Japan, **we find research receiving funding in fields such as intermetallic compounds, formate applications, and nanoparticle applications**. JSPS—the primary fund-granting institution—focuses on nanoparticles, while intermetallic compound research is primary funded by the JSPS and the Ministry of Education, Culture, Sports, Science and Technology. Formate applications research includes joint research with foreign institutions that are receiving foreign grants from institutions such as the DOE or the NSFC.

If we consider hydrogen storage-related research from the perspective of funding, **it appears that, at present, the main research fields receiving funding are those for basic research, such as materials discovery**. That said, if we compare this funding with that for hydrogen production research, the proportion of research receiving funding since 2013 is similar, with hydrogen production receiving 25.2% of funding and hydrogen storage receiving 27.9%.

Conclusions

We performed a panoramic analysis of research and development trends in hydrogen—which is garnering attention as a clean energy source—and its storage methods, using academic citations as a resource.

Much hydrogen storage-related research has been on hydrogen storage alloys, but various material systems—various hydrides, MOF, formate, etc.—have also been considered as research topics. Specifically, in recent years, researchers have been looking at hydrogen physisorption (researching topics such as fullerene-based materials), as well as materials such as metallic BH4 and ammonia borane. This indicates that the phase of material investigations should continue. Meanwhile, more practical research is getting underway, especially in the US, with a focus on hydrogen storage for fuel cells and heat conversion for high-pressure hydrogen storage systems.

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The key countries in hydrogen storage-related research and development are China, the US, and Japan, the same as in hydrogen production. Nonetheless, these three countries are involved in different projects, with China continuing its focus on hydrogen storage alloys and other materials-related research. In contrast, the US has a large volume of research on materials, such as ammonia borane, metallic BH4 and MOF, and associated systems. Japan's research had been focused on Ti-based alloys and metallic BH4 materials, but recently, the country's research has been focused on intermetallic compounds and Pd nanoparticle applications.

The trend in research paper volume shows that Germany, France, South Korea, India, and other nations are increasing their numbers of publications in recent years, which could mean that research and development will become even more vigorous in the future. In such an environment, we will continue to watch how Japan demonstrates its presence in materials research, which has been its strength.

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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.