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Zero-Carbon Energy for the Asia-Pacific Grand Challenge
Grand Challenge Papers – Non-technical Summaries

Non-technical summary of GCP02-19: *Retrospective and Prospective of the Hydrogen Supply chain: A Longitudinal Techno-historical Analysis*

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Summary by P J Dawson

This paper traces the evolution of research into hydrogen and cross-border collaborations, from tentative beginnings in 1935 to a global acceleration of research and collaboration across the world up to 2018. The more than 58,000 records defy conventional literature review so a social network analysis approach has been used, based on analysis of the co-occurrence of keywords in publications. The aims have been to trace activity by research subject and country and the development of collaboration between countries.

Hydrogen is a great energy vector with the flexibility of conversion and storage in various forms. Nevertheless, access to elemental hydrogen is cumbersome as all pathways to obtain hydrogen involve chemical reactions. The most straightforward pathway is water splitting, which has not been traditionally favoured due to its high energy demand. As such, the dominant industrial approach has been fossil fuel reforming. Recently, however, the sustainability concerns, together with the emergence of abundant and zero-marginal cost renewable energy, has revived interest in water splitting. The possibility of producing hydrogen using 'excess' renewable electricity generated by wind and solar has been enticing for researchers. As well as being a fuel source, hydrogen can be used as an energy storage medium.

Evolution of Hydrogen Research

For the period 1935 to 1970 less than 100 records were identified by the study but the 1970s was a critical decade in the context of energy and by the end of the decade the numb er of records had reached 725. Research clustered around acetate production on the one hand and bacteroids (bacterial production of hydrogen) on the other. There also emerged a 'hydrogen production' cluster.

During the 1980s, hydrogen research evolved and publications increased from 725 at the beginning of 1980 to 2,594 by the end of that decade. The heat map shows the continuation

of the bacteroid/nitrogen fixation cluster but on the left-side dominant keywords 'hydrogen generation', 'metal hydrides', 'coal', and 'fuel cell' refer to the development of the hydrogen supply chain.

The study concludes: 'Therefore, we can confidently associate the emergence of today's hydrogen supply chain research to the energy crisis of the 1970s.'

The decade to 2000 brought the UN Framework Convention on Climate change (UNFCCC) in 1992 and the Kyoto Protocol in 1997 but a low oil price hindered investment in clean energy development. However, following the Kyoto Protocol publications accelerated to 4,822 by the beginning of 2000. Several research problems emerged, notably hydrogen storage alloys. The study concludes: 'It seems that the research community had identified hydrogen storage materials as the key challenge facing hydrogen supply chain development.

In the five years to 2005, publication records doubled to 8,846, the map showed a new cluster 'hydrogen storage material' close to 'hydrogen storage alloy' and the emerging field of nanoscience found applications in hydrogen-related material synthesis. By 2010 publication records had jumped to 22,134 and 'hydrogen production' had become the main research cluster. The key clusters relevant to hydrogen production include hydrogen conversion pathways, fuel cells and distributed renewable energies, catalysis and kinetics and biohydrogen (produced from biomass).

The 2010's were a revolutionary decade in renewable energy with solar PV reaching 500 GW in 2018 from trivial beginnings in the 2000's: similarly with wind energy and hydrogen research. Between 2010 and 2015 the hydrogen research publication record almost doubled to 40,800 (5,008 records in 2017 alone). In the period 2010 to mid-2018 close to 36,000 records were indexed accounting for around 62 per cent of total historical publications on hydrogen. This period saw 'water splitting' emerge as a new cluster while biohydrogen built a stronger cluster and steam reforming attracted more research. From 1980, top keywords moved from 'hydrogen production', 'nitrogen fixation', 'acetylene redu ction' and 'nitrogenase' to, in 2000, 'hydrogen storage alloy', 'hydrogen production', 'hydrogen storage', and 'metal hydride electrode'.

By 2018 attention is drawn to all aspects of the hydrogen supply chain with the top key words: 'hydrogen production, hydrogen storage and hydrogen generation'.

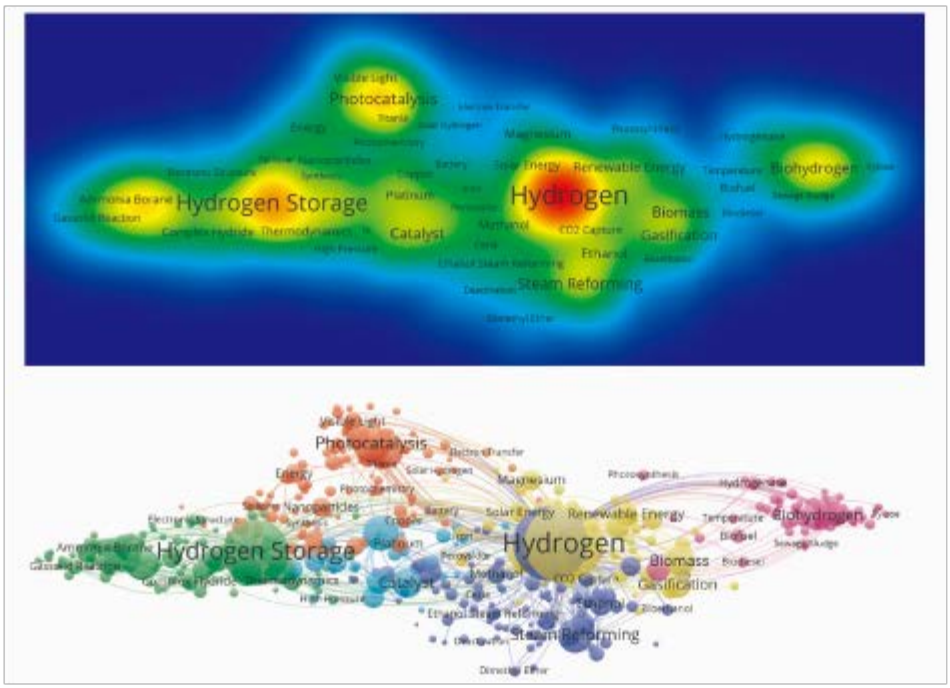


Figure 1: Research network maps for all records until mid-2018 (upper: heat map network; lower: label network)

Evolution of international collaboration on hydrogen

By the 1980's there were only about 725 publications on hydrogen involving 25 countries and collaborations were weak. Two clusters on the left side of the heat map were: one composed of the United States and Germany and the other, Japan and Australia. On the right was a cluster of several European countries with Canada. The top collaborating countries were the United States, Germany and Switzerland. China and South Korea had yet to appear.

By 1990 the number of countries generating publications had almost doubled to 48 but there are islands on the map indicating weak collaboration. The US had emerged as the world's top contributor to hydrogen research coauthoring around a quarter of all publications. The next countries were Japan and Germany. The countries with the top international collaboration ties were the US, Japan and Germany followed by Canada, France and Italy.

By 2000, 59 countries had publications and the growth of collaboration is evident. The US-led collaboration with 129 ties followed by Germany with 61 and Japan with 49. China also emerged as the world's fourth top publishing country although with fewer ties (17). Although Canada and the UK had lower publications than China they had more international ties (37). Notably an Asian research cluster was emerging comprising Japan, China and South Korea.

In 2005 publications numbered 8,846 from 74 countries, and China had become the third

ranked country in hydrogen research after the US and Japan. However, Germany, although the fourth-ranked country in terms of publications output, had the second highest number of collaboration ties after the US. Japan and China had the third and fourth highest collaboration ties.

By 2010 a tightly integrated international collaboration network had developed with 3,664 publications from 84 countries, China had become the second highest research producing country followed by Japan and Germany with South Korea having risen to fifth place. Germany was the second ranked after the US in collaboration ties followed by China and Japan. From 199 ties in 2000, US ties had risen to 1,141 and the top ten publishing countries had at least 150 ties each.

2015 saw the rise of China to top place with the greatest number of publications although still behind the US in terms of collaboration ties. South Korea is in fifth place after Japan and Germany but has the tenth highest collaboration ties. Germany has the third highest collaboration ties.

By mid-2018, there is a tight international network with 108 countries participating and 17,548 collaboration ties. The US leads collaboration with 81 countries on 4,244 publication s closely followed by China with 63 countries and 3,769 publications. Germany has 2,224, France 1,881, the UK 1,769 and Japan 1,757.

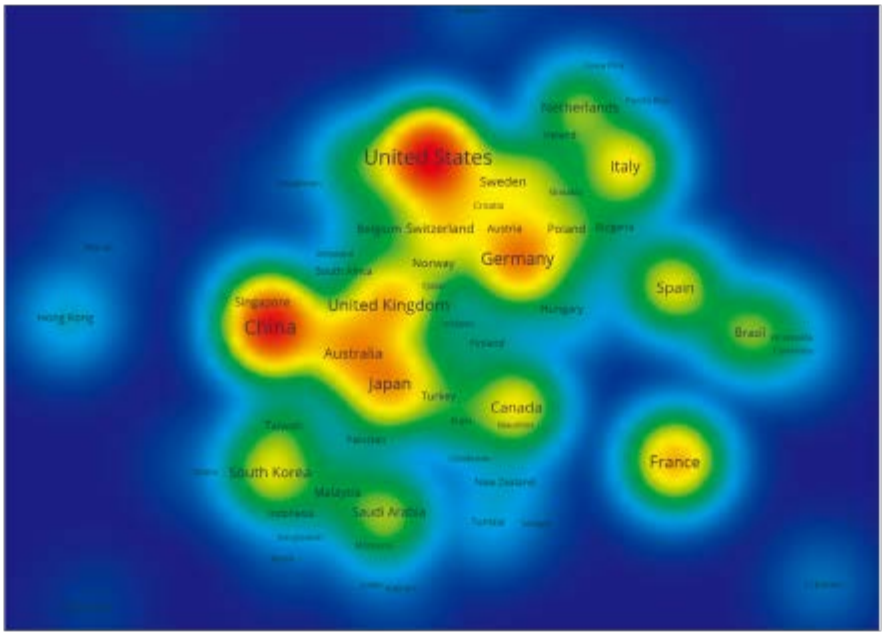
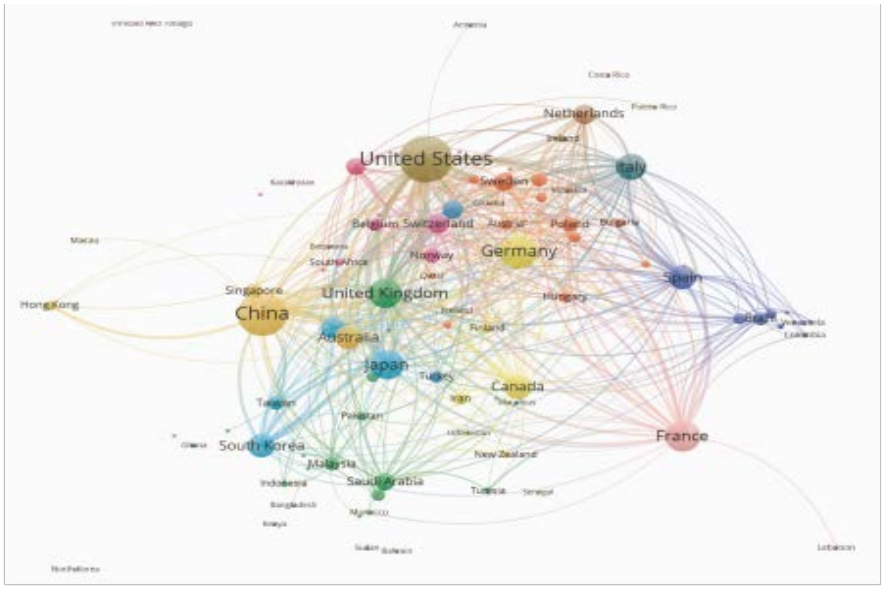


Figure 2: International collaboration network maps for all hydrogen records until mid-2018 (upper: heat map network; lower: label network Evolution of hydrogen research in Australia.



Evolution of hydrogen research in Australia

Australia has historically been one of the leading countries in hydrogen research, ranked 7th in 1980. With the growth of activity after the Kyoto Protocol, Australia fell to 11th place and 12th by 2018, although its output had increased. On a per capita basis, however, Australia ranks in the top five countries. Australia has developed 1,104 international ties with institutions from 535 countries. Australia's main collaborations are with China (398), US (124), Germany (56), Japan (40), India (37) and France.

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