Retrospective and Prospective of the Hydrogen Supply Chain: A Longitudinal Techno-historical Analysis

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Abstract

The objective of this study was to investigate the evolution of hydrogen research and its international scientific collaboration network. From the Scopus database, 58,006 relevant articles, published from 1935 until mid-2018, were retrieved. To review this massive volume of publication records, we took a scientometric network analysis approach and investigated the social network of the publication contents based on keywords co-occurrence as well as international collaboration ties.

An interesting observation is that despite publications on hydrogen occurring since 1935, the growth of this research field ignited with the Kyoto Protocol of 1997. The publication profile reveals that more than 93% of the existing records have been published over the last two decades. More recently, the accelerated growth of renewables has further motivated hydrogen research with almost 36000 academic records having been indexed from 2010 till mid-2018. This accounts for ~62% of the total historical publications on hydrogen. The conventional hydrogen production pathway is fossil fuel-based, involving fossil fuel reforming for synthesis gas generation. The keyword analysis also shows a paradigm shift in hydrogen generation to renewables. While all components of hydrogen supply chain research are now growing, the topic areas of biohydrogen and photocatalysis seem to be growing the fastest.

Analysis of international collaboration networks also reveals a strong correlation between the increase of collaboration ties on hydrogen research and the publications. Until the 1970s, only 25 countries had collaborated, while this has reached 108 countries as of 2018, with over 17,500 collaboration ties. The collaborations have also evolved into a substantially more integrated network, with a few strong clusters involving China, the United States, Germany, and Japan. The longitudinal network evolution maps also reveal a shift, over the last two decades, from US-Europe centred technology development-interaction to a world in which Asian economies play substantial roles.

Keywords: Hydrogen economy; hydrogen supply chain; renewable hydrogen; meta-analysis; social network analysis; international collaboration ties.

1. Background on hydrogen

Hydrogen discovery goes back to 1671 when Robert Boyle (1627–1691) produced the gas while experimenting with iron and acids. He described the reaction and called this gas “inflammable solution of iron” [1]. It took almost a century until in 1766 Henry Cavendish (1731–1810) produced this gas over mercury and recognized it as a distinct element. He explained its properties accurately but failed in naming it correctly by describing it as "inflammable air from metals" as he thought the gas originated from the metal rather than the acid [2]. Finally, it was Antoine Lavoisier (1743–1794) who recognized the nature of the gas (1783) and proposed its current name “hydrogen”, composed of two Greek words "*hydro*" and *"genes*" meaning "*water*" and "*born of*".

Hydrogen is the most abundant element in the universe [3] and accounts for around 90% of the visible universe. In fact, the source of the so-called renewable energy that we receive from the sun or stars is the hydrogen fusion to helium. It is estimated that the sun's supply of hydrogen is enough for another 5 billion years [4].

Despite hydrogen abundance, access to elemental hydrogen is cumbersome. It is not a constituent of air and the only pathways to obtain hydrogen involve chemical reactions. Even the early discovery of hydrogen was through a chemical reaction when Robert Boyle was experimenting with iron exposed acid ($Fe + H_2SO_4 \rightarrow Fe^{2+} + SO_4^{2-} + H_2$) [1].

The industrial hydrogen supply chain includes production/generation, storage/carrier and conversion. Hydrogen is a great energy vector with the flexibility of conversion and storage in various forms. The key advantage of hydrogen over other energy storage alternatives such as batteries is its potential for long-term, seasonal, storage at massive capacities. The lower heating value (LHV) of hydrogen is 120 MJ/kg, compared to about 50 MJ/kg for methane and even less for petroleum products [5]. Although the LHV of hydrogen is extremely favourable, it suffers from low volumetric density (e.g., 0.0823 kg/m^3 at the ambient condition) [6]. Therefore, improving the volumetric density of hydrogen is a necessary step in facilitating optimal hydrogen storage. This is achievable with several options including compression, liquefaction, physisorption, and chemisorption [7].

Figure **1** illustrates various pathways for hydrogen production. The most straightforward pathway is water splitting, but this approach has not been traditionally favoured due to its high energy demand. As such, the widely used approach has been fossil fuel reforming for syngas (CO/H_2) generation, followed by water-gas shift (WGS) reactions ($CO + H_2O \rightleftharpoons CO_2 + H_2$) [8], and CO_2 removal. Although coal, biomass, and oil gasification are also possible approaches for syngas generation, natural gas is the preferred feed due to its high hydrogen/carbon (H/C) ratio.

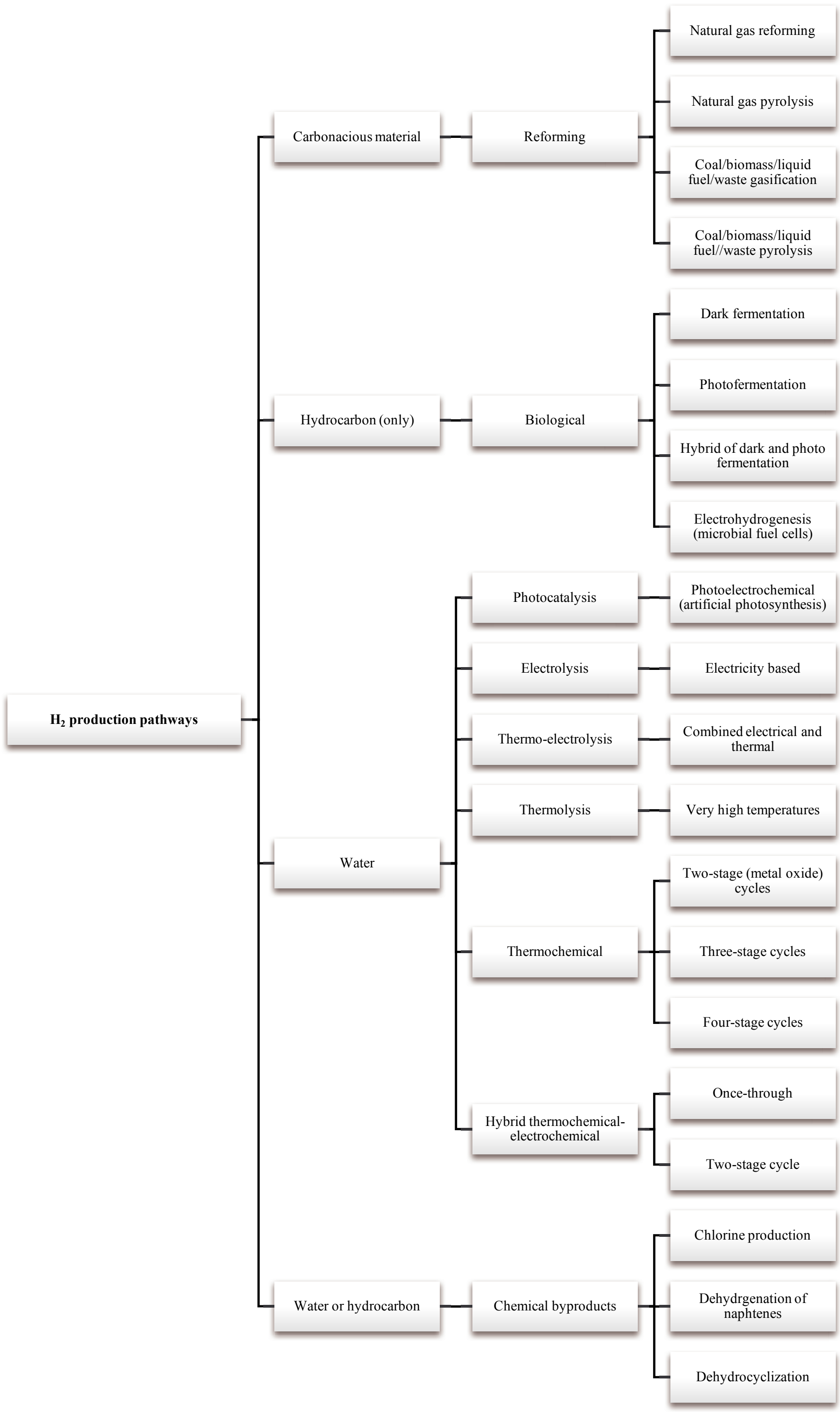


Figure 1: List of some key H_2 production pathways

While hydrogen itself is clean and sustainable, its dependence on fossil fuels has been the key challenge hindering its consideration as an alternative energy source. From the 2010s, however, a new industrial and academic interest is observed in the hydrogen vector [9, 10]. The tipping point in some renewable technologies especially photovoltaic (PV) has revolutionised the energy industry including hydrogen [11, 12]. The increase in production scale together with several other reasons such as reductions in silicon price and the shift of global production to China resulted in a dramatic drop in PV costs to the extent that its market price has dropped far below $1/W - beyond most optimistic imaginations in the 2000s [13]. With this price, PV has passed the parity price of fossil fuels in several jurisdictions.

The projection of a possible renewable energy over-supply has created a new story for the hydrogen economy, which is based mainly on water splitting, using renewably sourced energy [14, 15]. This approach reduces the long-lasting reliance of hydrogen on fossil fuels and underlies the new spike in hydrogen economy publications. It is projected that this current increasing trend may continue over time, as other renewable energy sources, such as solar-thermal, generate more opportunities for hydrogen production through water splitting [16]. Moreover, hydrogen can be used as an energy storage medium for electricity generated from intermittent, renewable sources and also as an energy vector for areas requiring an off-grid power supply [7].

The aim of this study is to assess the existing literature on the hydrogen supply chain to identify 1) the evolution of the international scientific collaborations, and 2) the retrospective and prospective components of this growing research field. Given the massive volume of publication records on this topic (>58000), a conventional literature review on this amount of publication is impracticable. An alternative option is meta-analysis, i.e. statistical analysis of the relevant studies [17]. Consequently, we take a scientometric analysis approach and investigate the social network of the publication contents based on keywords co-occurrence as well as international collaboration ties.

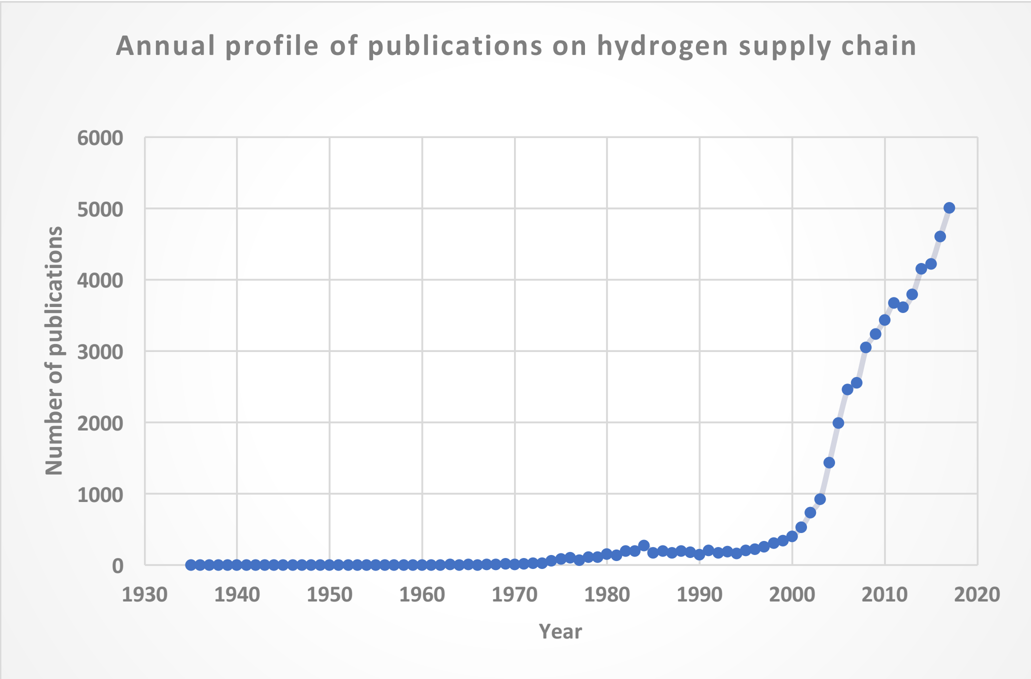
2. Data and methods

The publication dataset used in this study is derived from publication records extracted from Scopus. This bibliometric website was searched for publications which included in their titles, abstracts, or keywords the terms "hydrogen production", "hydrogen generation", "hydrogen storage", "hydrogen carrier", "hydrogen vector", "hydrogen supply chain", "hydrogen value chain", and "hydrogen economy". These data-retrieval keywords are selected based on some expert inputs as the most common and overarching terms of the field. The search, conducted in mid-2018, captured 58,006 publication records in English (see Figure 2). Here we explore the longitudinal dynamics of hydrogen research over the last 84 years, since the first record in 1935 [18].

The analysis of overall publication trends presented above sought to capture all publications containing a particular term and therefore included paper abstracts and titles. However, the main analysis in this paper focuses only on the co-occurrence of “keywords” and “affiliation countries”. The keywords of scientific papers are carefully selected by their authors to describe the main topic and the research focus of the article. Exploring these keywords and identifying the frequency and structure of their co-occurrence in scientific articles can reveal the knowledge structure of discipline [19, 20]. Word co-occurrence analysis is a technique that allows researchers to establish similarity relations between different keywords. Using these relations, a network of concepts and ideas in a corpus may be constructed. Several studies have used this approach in fields such as renewable energy [19, 21], service innovation [22], ecology [23], climate change [24], polymer chemistry [25], zoonotic disease propagation [26], and information retrieval [27].

Similarly, a network of the countries contributing and collaborating on research publications in a discipline can be drawn. This network and its evolution over time can be used to identify major countries conducting collaborative research and how such collaborations formed and evolved across the discipline growth over time. Prior research on countries collaboration networks has been applied to different fields such as simulation-optimization of supply chains [28], library and information science [29], coronary heart disease [30], e-government [31], polymer chemistry [25], carbon capture and storage [24], and renewables [21, 32].

This study examines two networks namely countries collaboration network and keywords co-occurrence network (countries network and keywords network for short). Assuming that two terms are more related if they appear together more frequently in scientific papers [19, 33], we can construct valued networks. Each network consists of a set of nodes and ties connecting certain nodes together. In the former network, each node represents a country. In the latter network, nodes are keywords. A tie between two country nodes means they co-published a scientific paper, while a tie between two keyword nodes is an indication of the two keywords appearing in the list of keywords in a paper.



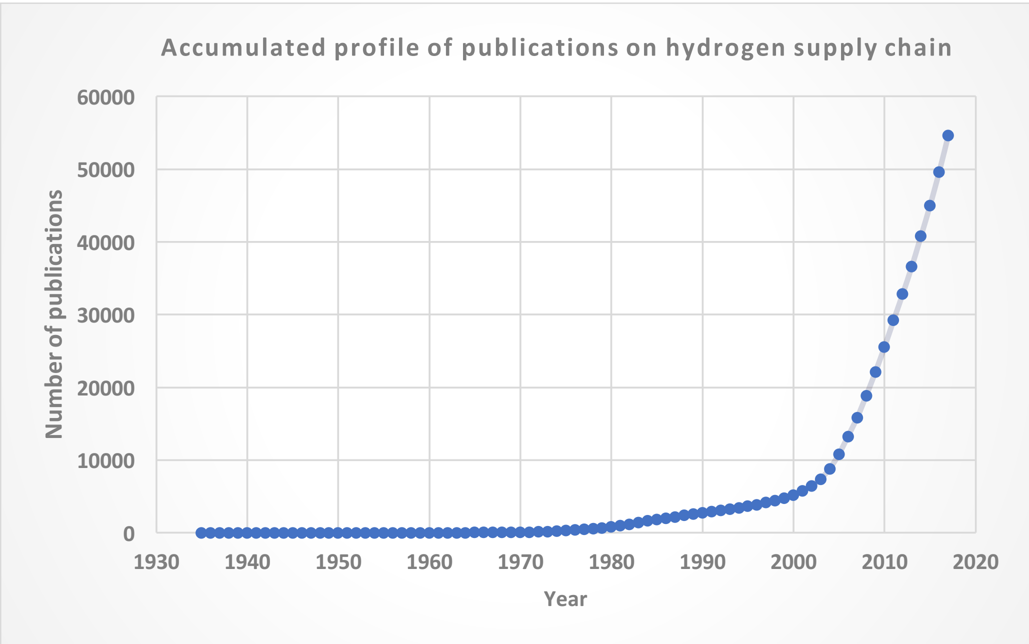


Figure 2: The keywords of study including: "hydrogen production", "hydrogen generation", "hydrogen storage", "hydrogen carrier", "hydrogen vector", "hydrogen supply chain", "hydrogen value chain", and "hydrogen economy" (upper: annual profile, lower: accumulate profile)

We use two different modes of viewing networks. In the label view, each node is represented by a circle and its corresponding label. The sizes of the circles and labels vary, based on the weight of the nodes. The weight of a node is assigned as the total strength of all the links to the node. To avoid overlapping, not all labels are shown. In the density view (heat map), the background of the labels is displayed in colours ranging from red to blue. Background colours close to red represent a higher density of nodes, while colours close to blue demonstrate lower density. Density is defined based on the number of nodes in the area and their weights. This view can be used to identify important areas of a network [34, 35].

In the next section, we present the analysis results and the pattern of keyword network evolution over time.

3. Evolution of hydrogen research

3.1. Hydrogen research map until 1980

As seen from the annual publication profile (see Figure 2), there was only a small number of publications (less than 100 records) from the first instance in 1935 [18] until 1970. The 1970s was a critical decade in the context of energy, in which the international energy crisis caused a spike in attention towards renewable energy sources, including hydrogen [11]. By the end of this decade, the total number of publication records reached 725. The keywords interactivity network for the publications until 1980 are illustrated in Figure 3 which shows two main clusters around acetate production and Bacteroids. Both of these clusters are related to nitrogen fixation and bacterial production of hydrogen. The biological nitrogen fixation (BNF) involves the conversion of atmospheric nitrogen to ammonia by the nitrogenase enzyme. In this process, 16 equivalents of ATP (Adenosine triphosphate) are hydrolysed and further to ammonia one molecule of hydrogen is produced $(N_2 + 16\,ATP + 8\,e^- + 8\,H^+ \rightarrow 2\,NH_3 + H_2 + 16\,ADP16P_i)$[36].

Along with these two clusters, a new cluster "hydrogen production" is also observed in the centre of Figure 3 which could potentially be the emerging field of the hydrogen supply chain. This hypothesis can be investigated in the network maps of the following decades.

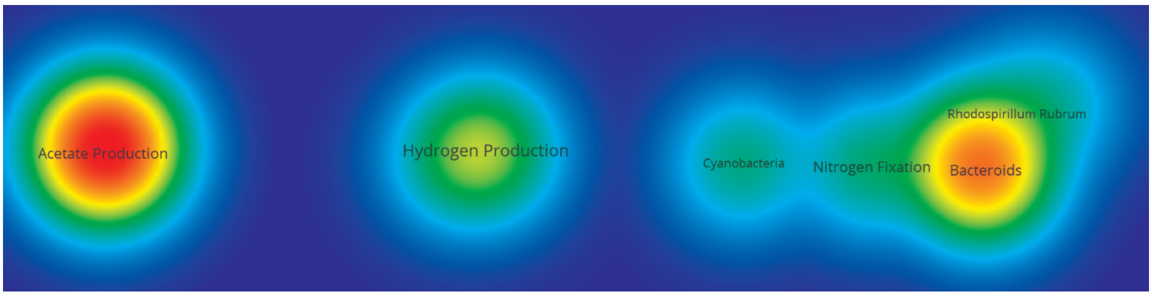


Figure 3: Research network map (heat map) for all records until 1980. Background colours close to red represent a higher density of nodes, while colours close to blue demonstrate lower density.

3.2. Hydrogen research map until 1990

During the 1980s, research on hydrogen evolved and publication records increased more than three-fold, from 725 at the beginning of 1980 to 2594 by the end of 1980s. A small bump in the publication profile is also observable in Figure 2 for this period. The keyword interactivity network for the publications until 1990 is shown in Figure 4 which depicts the creation of two zones. The first zone on the right-side represents the continuation of the bacterial hydrogen research which appeared in the previous period (see Figure 3). However, the zone on the left side with dominant keywords of "hydrogen generation", "metal hydrides", "coal" and "fuel cell" refers to the development of today's hydrogen supply chain. This cluster is, in fact, the developed form of the cluster which appeared in the centre of the map for the 1970s (see Figure 3). Therefore, we can confidently associate the emergence of today's hydrogen supply chain research to the energy crisis of the 1970s [11].

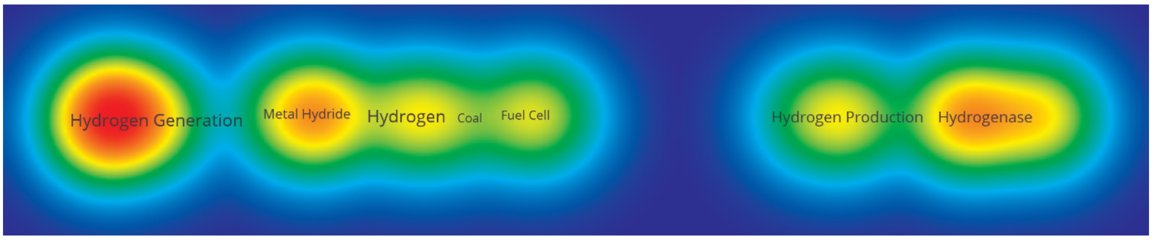


Figure 4: Research network map (heat map) for all records until 1990

3.3. Hydrogen research map until 2000

Hydrogen research confronted a paradoxical situation in the 1990s. This decade witnessed some international movements on climate change mitigation, including the United Nations Framework Convention on Climate Change (UNFCCC) development in 1992 [37] and consequential Kyoto Protocol of 1997 [38]. At the same time, the low oil price during this decade [39] hindered R&D and speed of investment for clean energy development. As a result, the hydrogen publication trend, during most of this decade, shows a similar trend to the previous decade. But, from the year after the Kyoto Protocol, the publication trend shows an acceleration, and by the beginning of the year 2000, the publication records reach 4822 (close to double of that a decade ago). As evident from Figure 2, the Kyoto Protocol of 1997 should be considered as the "burst point" of hydrogen research.

The keywords interactivity network for publications until 2000 is shown in Figure 5. It is evident from the figure that compared to the two earlier decades (Figure 3 and Figure 4), the field is developed and more integrated. It is also evident that several research topics have emerged, the highlight being the "hydrogen storage alloys". As evident in Figure 5, by the year 2000, the research community had identified hydrogen storage materials as the key challenge facing hydrogen supply chain development.

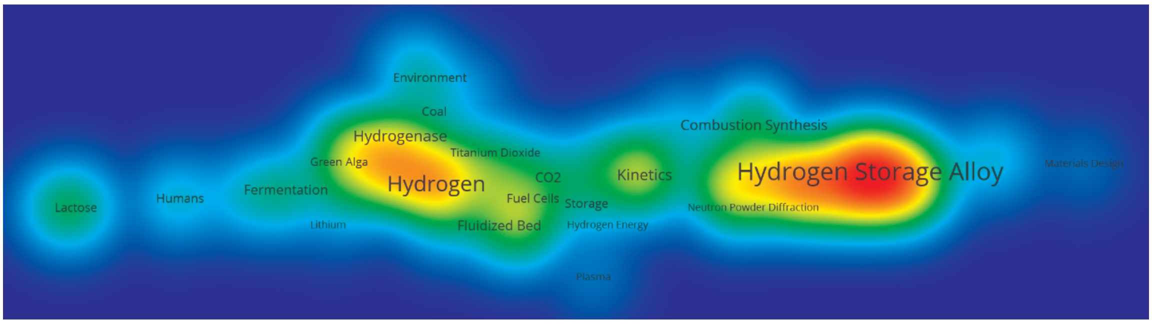


Figure 5: Research network map (heat map) for all records until 2000

3.4. Hydrogen research map until 2005

During the first five years of the 2000s, the publication records almost doubled, reaching 8846 (Figure 2). The updated network map of the keywords (Figure 6), including this period, shows the emergence of a new cluster "hydrogen storage material" close to "hydrogen storage alloy". It is noteworthy that this is the time at which the fields of nanoscience and nanotechnology were emerging [40, 41], and these found several applications in hydrogen-related material synthesis [42].

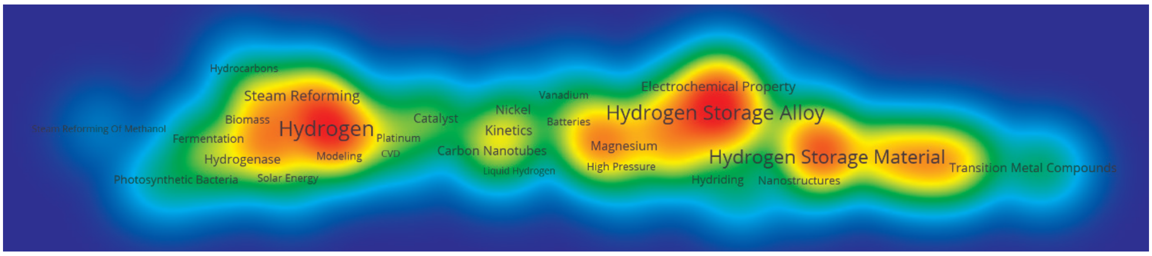


Figure 6: Research network map (heat map) for all records until 2005

3.5. Hydrogen research map until 2010

By the year 2010, the publication records jumped substantially and reached 22134 (Figure 2). Figure 7 shows the updated network map of the keywords until 2010. One interesting observation from a comparison of Figure 6 and Figure 7, is that during the second half of the 2000s, hydrogen production became the main research cluster (see the left side of Figure 7). Figure 8 shows the zoomed image of the hydrogen production cluster and its co-occurrence links. The key clusters relevant to hydrogen production include hydrogen conversion pathways (pink-colour cluster,-top right-side), fuel cells and distributed renewable energies (purple cluster, middle right-side), catalysis and kinetics (green cluster, button right-side), and biohydrogen (khaki cluster, button left-side) (see Figure 8 lower). Biohydrogen refers to the hydrogen produced by microorganisms through four key mechanisms including biophotolysis, indirect biophotolysis, photofermentation, and dark fermentation [43].

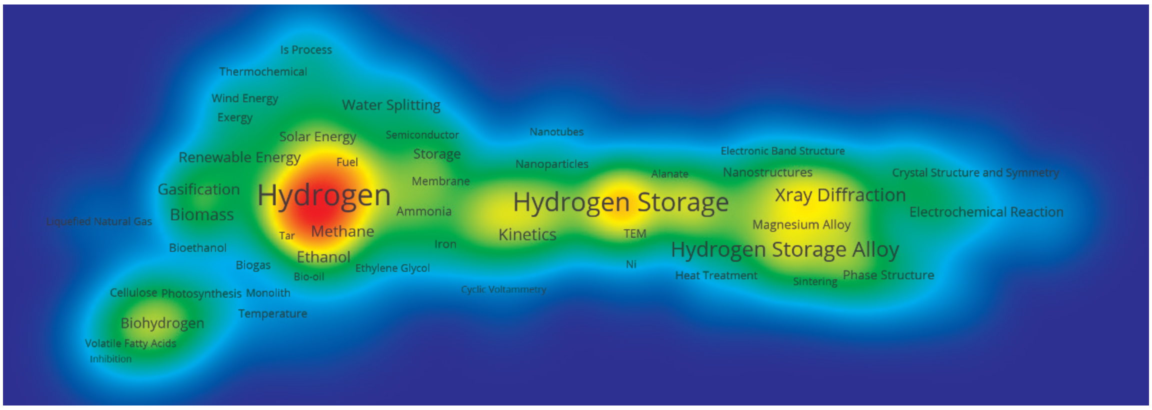
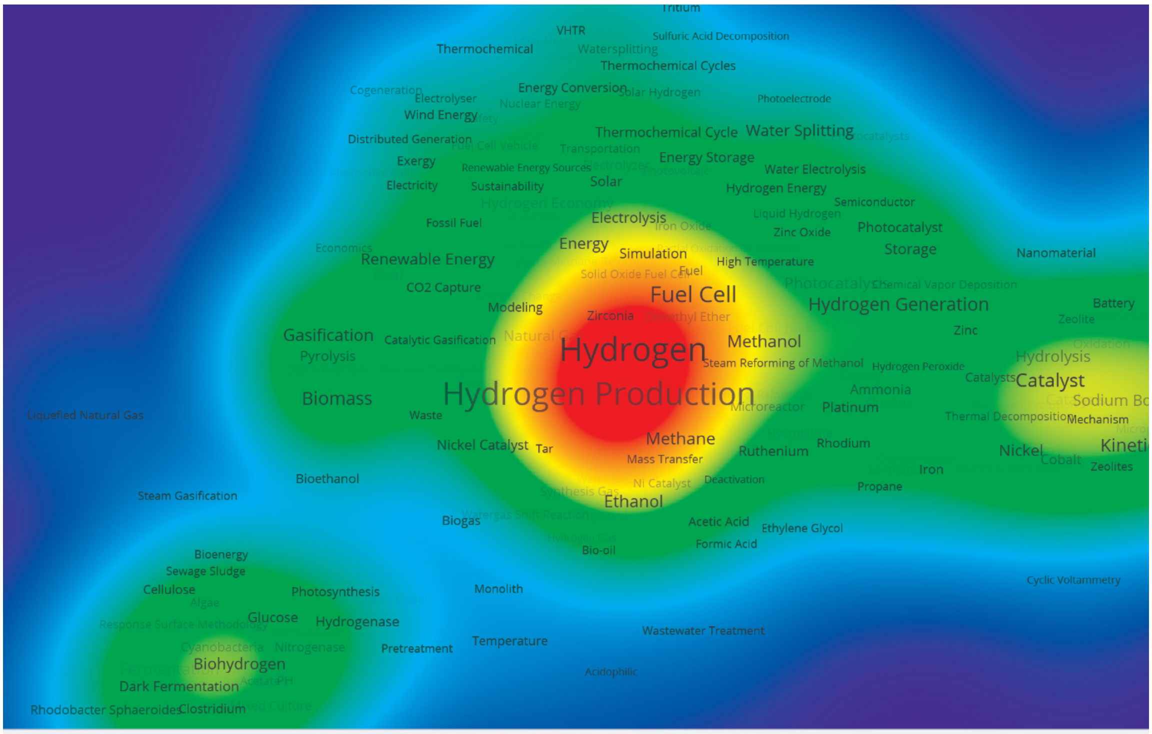


Figure 7: Research network map (heat map) for all records until 2010



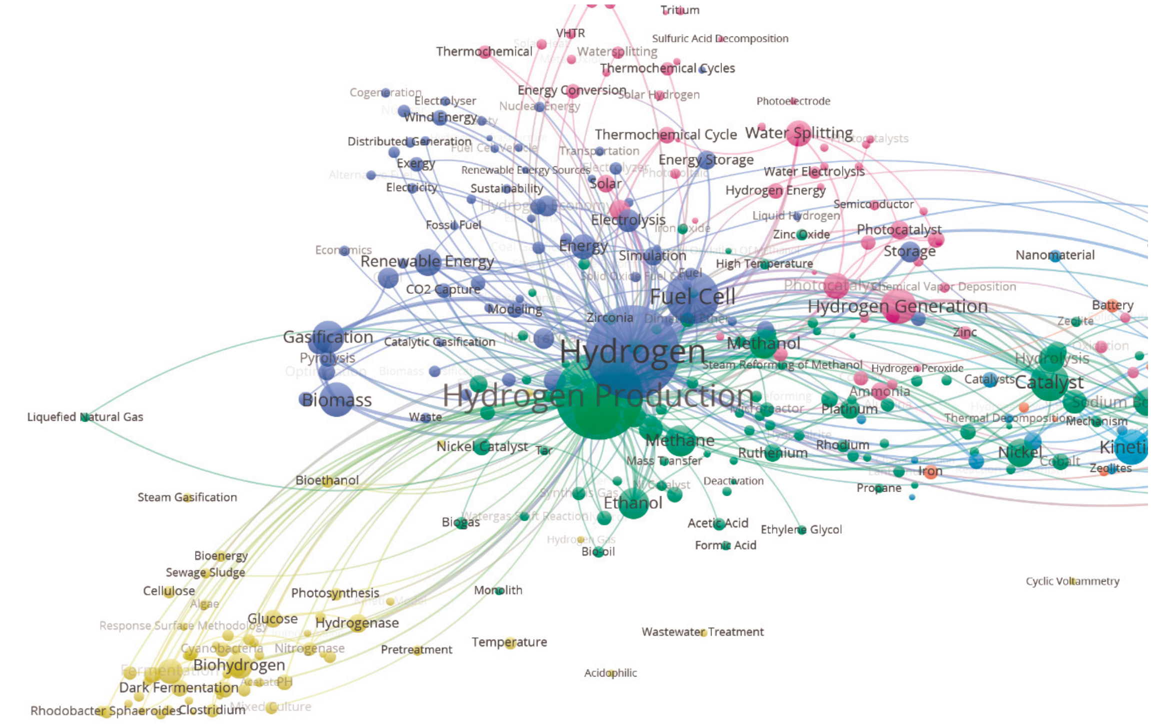


Figure 8: Research network maps for all records until 2010: focus on the hydrogen production cluster (i.e. left side) of Figure 7 (upper: heat map network; lower: label network)

3.6. Hydrogen research map until 2015

The 2010s have indeed been a revolutionary decade in renewable energy uptake especially involving photovoltaics (PV) and wind power. The global PV cell installations reached from a trivial value in the 2000s to 500 GW in 2018, and there are almost identical records for wind turbines [44]. This global trend is also observable in hydrogen research. Over the five years from 2010 until 2015, the publication record totals grew substantially, almost doubling to 40,800 records (Figure 2). Figure 9 shows the updated network map of the keywords until 2015. The observable difference in Figure 9 compared to the previous period, is the emergence of “water splitting” as a new cluster. Biohydrogen also starts to build a stronger cluster, somewhat in isolation from other clusters. The other growing research is “steam reforming” (a fossil fuel-based hydrogen production pathway [10, 45] shown in Figure 1).

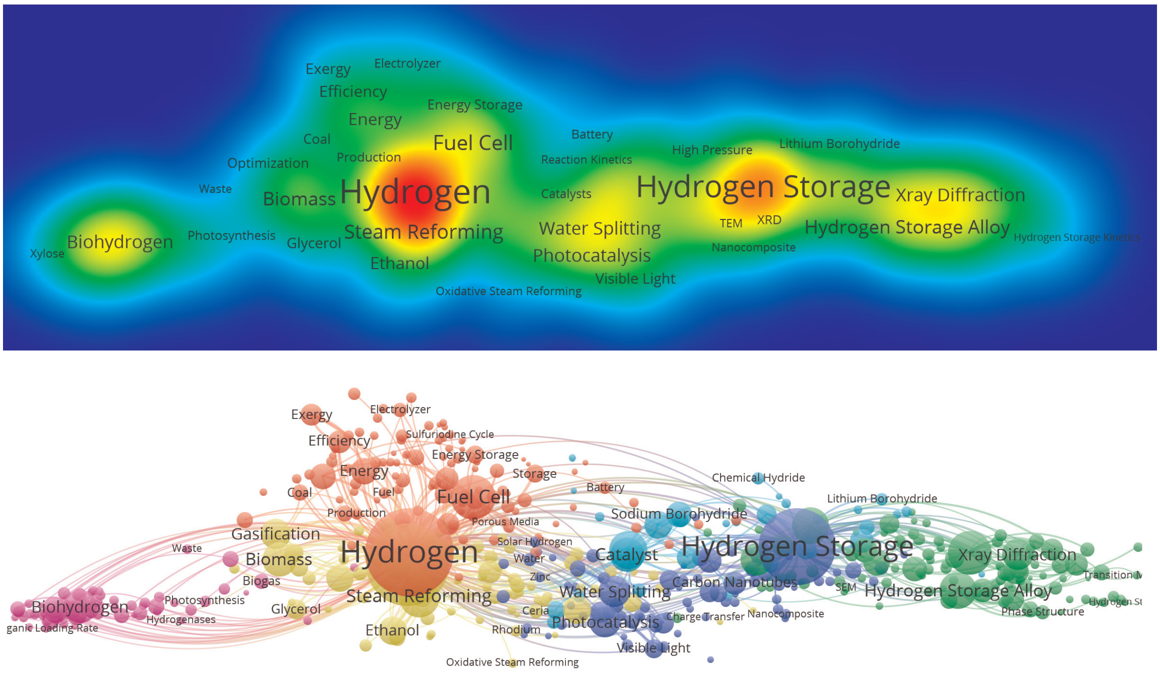


Figure 9: Research network maps for all records until 2015 (upper: heat map network; lower: label network)

3.7. Hydrogen research map until mid-2018

There are some research fields with total publications records in the order of a few thousand (e.g. [26]). The hydrogen field, however, has seen publication records of over 3000, annually, from the beginning of the year 2010, reaching 5008 records in the year 2017. During this decade (2010-mid-2018), close to 36000 academic records have been indexed, accounting for ~62% of the total historical publications on hydrogen. All these data may imply a very strong international determination for the realisation of the hydrogen supply chain.

Furthermore, the total publication records on hydrogen research as of mid-2018 include 58006 items. This accounts for about 0.1% of total publication records on the Scopus database. This value by itself implies that as of today, hydrogen is one of the most highly-researched fields across all academic disciplines.

Following on the longitudinal development of the research fields, the comparison of Figure 10 (for mid-2018) with Figure 9 (for 2015) shows the emergence of two new clusters over the last few years i.e. biohydrogen [43] and photocatalysis [46]. Photocatalysis refers to the methodologies for chemical reactions using the energy delivered by photons (e.g. solar energy) instead of heat or electricity [47]. Generally, there is an overlap between biohydrogen and photocatalysis methodologies. Nevertheless, the slightly isolated biohydrogen cluster, in

Figure 10, may imply that biohydrogen research is carried out in different academic disciplines (i.e. Biology and its associates). Photocatalysis research, however, has a tight connection with both hydrogen production and hydrogen storage research fields. Therefore, it can be concluded that while all components of hydrogen supply chain research are in acceleration pace, the topics of biohydrogen and photocatalysis are growing faster.

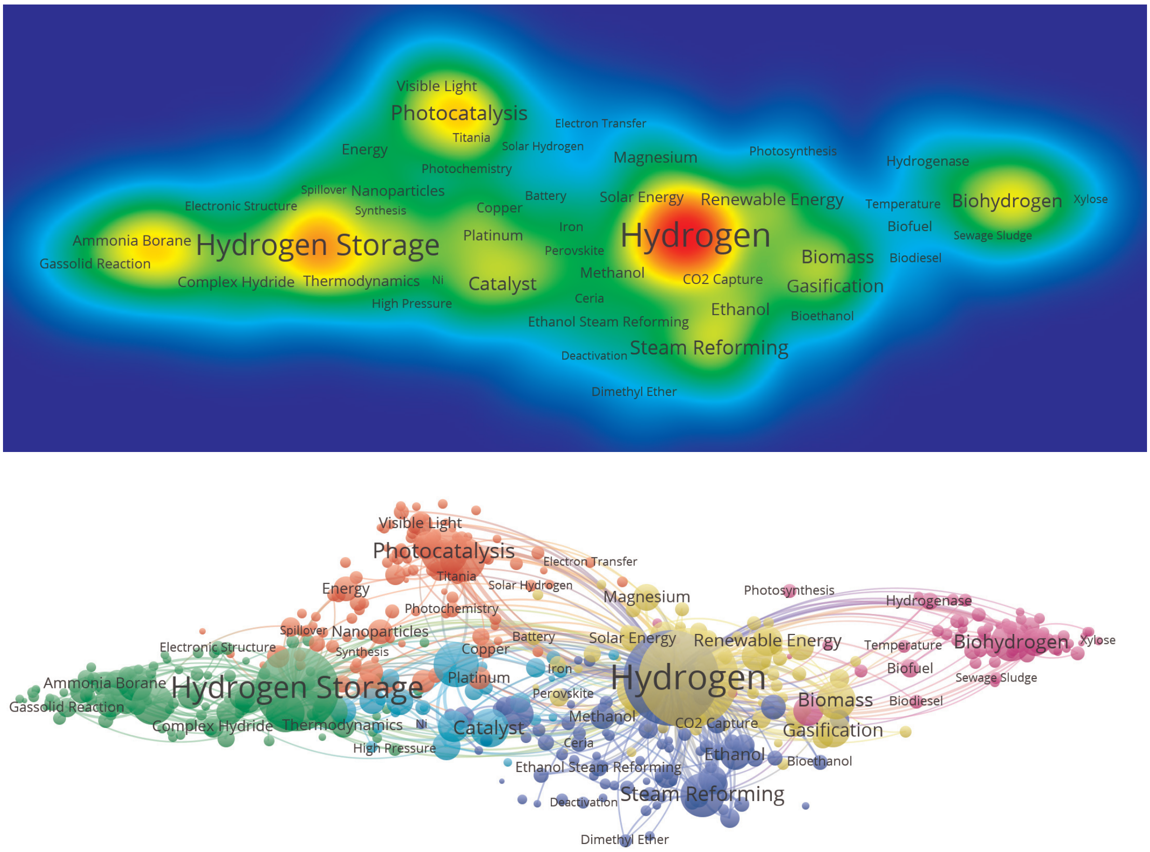


Figure 10: Research network maps for all records until mid-2018 (upper: heat map network; lower: label network)

3.8. Statistics of co-occurring keywords and co-occurrence ties

In the previous section, the historical evolution of hydrogen research (keywords) was illustrated and discussed over seven time periods, between 1935 [18] and 2018. Here, we investigate the statistics of the co-occurring keywords and their co-occurrence ties. We evaluate the strength of co-occurrences with two indicators; the number of occurring keywords (NOK) and the number of co-occurrence ties (NOT). Table 1 shows the top 30 keywords that appeared most often with other keywords in the author keywords list of publications, together with the number of times such co-occurrences happened, at three time intervals (from 1935 [18]) until 1980, 2000, and 2018. As of 1980, "hydrogen production" was the top keyword followed by “nitrogen fixation”, “acetylene reduction”, and “nitrogenase”. By 2000, the data reveal that hydrogen storage, particularly in metal hydrides, became the key focus. The top keywords of this period include “hydrogen storage alloy”, “hydrogen production”, “hydrogen storage”, “metal hydride”, and “metal hydride electrode.” As of 2018, the keywords reveal that research attention is drawn to all aspects of the hydrogen supply chain, the top keywords being “hydrogen production”, “hydrogen storage”, and “hydrogen generation”. Two keywords, *vis.* “photocatalysis” and “biohydrogen”, appear to have received increasing attention in recent years (5th and 6th of top keywords list in Table 1).

Table 1: Top 30 co-occurring keywords and co-occurrence ties on hydrogen research by the years 1980, 2000, and 2018

1980				2000				2018			
No.	**Keyword**	**NOK***	**NOT****	**No.**	**Keyword**	**NOK***	**NOT****	**No.**	**Keyword**	**NOK***	**NOT****
1	Hydrogen Production	5	24	**1**	Hydrogen Storage Alloy	122	75	**1**	Hydrogen Production	6926	432
2	Hydrogen	5	25	**2**	Hydrogen Production	119	51	**2**	Hydrogen	5629	451
3	Nitrogen Fixation	2	13	**3**	Hydrogen	96	68	**3**	Hydrogen Storage	5243	340
4	Acetylene Reduction	2	11	**4**	Hydrogen Storage	61	47	**4**	Hydrogen Generation	1456	298
5	Nitrogenase	2	11	**5**	Metal Hydride	34	35	**5**	Photocatalysis	1270	219
6	Gas Chromatography	2	8	**6**	Metal Hydride Electrode	28	24	**6**	Biohydrogen	1206	162
7	Fuel	2	7	**7**	Hydrogenase	26	22	**7**	Hydrogen Storage Material	1202	182
8	Storage	2	7	**8**	Hydride	24	33	**8**	Water Splitting	1125	226
9	Hydrogen Generation	2	9	**9**	Mechanical Alloying	19	19	**9**	Fuel Cell	1121	299
10	Cyanobacteria	1	4	**10**	Kinetics	19	32	**10**	Hydrogen Storage Alloy	1105	149
11	Enrichment Cultures	1	4	**11**	Hydrogen Generation	18	17	**11**	Steam Reforming	882	191
12	Photosynthesis	1	4	**12**	Nickel-metal Hydride Battery	16	17	**12**	Metal Hydride	853	211
13	Rhodospirillum Rubrum	1	3	**13**	Fuel Cell	15	12	**13**	Catalyst	632	265
14	Determination of CO_2 In Hydrogen Chloride	1	3	**14**	Hydrogen Absorption	13	12	**14**	Biomass	627	209
15	Enrichment	1	3	**15**	Electrochemical Property	13	10	**15**	Kinetics	603	239
16	Headspace Technique	1	3	**16**	Discharge Capacity	12	14	**16**	Gasification	498	131
17	Ppm Level	1	3	**17**	Microstructure	12	18	**17**	Hydrogen Evolution	471	144
18	Hydrogen Carrier Gas	1	3	**18**	Nitrogenase	12	11	**18**	Renewable Energy	470	186
19	Laboratory Safety	1	3	**19**	Catalysis	12	15	**19**	Methane	459	182
20	Leakage Detection with A Gas Monitor	1	3	**20**	Electrode	12	17	**20**	Dark Fermentation	455	114
21	FeTiH and $LaNi_5H_6$	1	2	**21**	Cyanobacteria	11	15	**21**	Xray Diffraction	443	119
22	Proton Diffusion	1	2	**22**	$LaNi_5$	11	14	**22**	Biohydrogen Production	440	95
23	Ti_2NiH_2	1	2	**23**	Mg_2Ni	11	16	**23**	Hydrolysis	433	149
24	Metal Hydride	1	3	**24**	Methane	11	12	**24**	Photocatalyst	430	138
25	Ammine Coordinate Compound	1	7	**25**	Nickel	11	14	**25**	Nickel	422	214
26	Ammonium	1	7	**26**	Nitrogen Fixation	11	12	**26**	Ethanol	409	144
27	Complex Hydroxide	1	7	**27**	Laves Phase	10	11	**27**	Sodium Borohydride	406	113
28	Double Precatalytic Decomposition	1	7	**28**	Fermentation	10	13	**28**	Microstructure	397	123
29	Environmental	1	7	**29**	Electrochemical Properties	10	13	**29**	Electrolysis	381	169
30	Precatalytic Process	1	7	**30**	Hydrogen Diffusion	10	10	**30**	Adsorption	380	136

NOK*: number of keyword occurrence; NOT**: number of co-occurrence ties

4. Evolution of international collaboration on hydrogen

4.1. Collaboration network as of 1980

Given that by the 1980s, only about 725 publications on hydrogen had appeared, it would not be expected to observe a strong pattern of international collaboration up till that time. The publication record shows that only 25 countries were by then involved in hydrogen research. The collaboration network map (Figure 11) of this period displays clearly the weakness of international collaborations. The figure shows two islands. The left island has two clusters, the main one composed of the United States and Germany, and the other of Japan and Australia. The right island includes a few European countries with Canada. But, as the label map shows, the ties between the countries are weak. The top three publishing countries, as of this time, are the United States, Japan and Germany. However, the top collaborating countries (with highest ties) are the United States, Germany, and Switzerland.

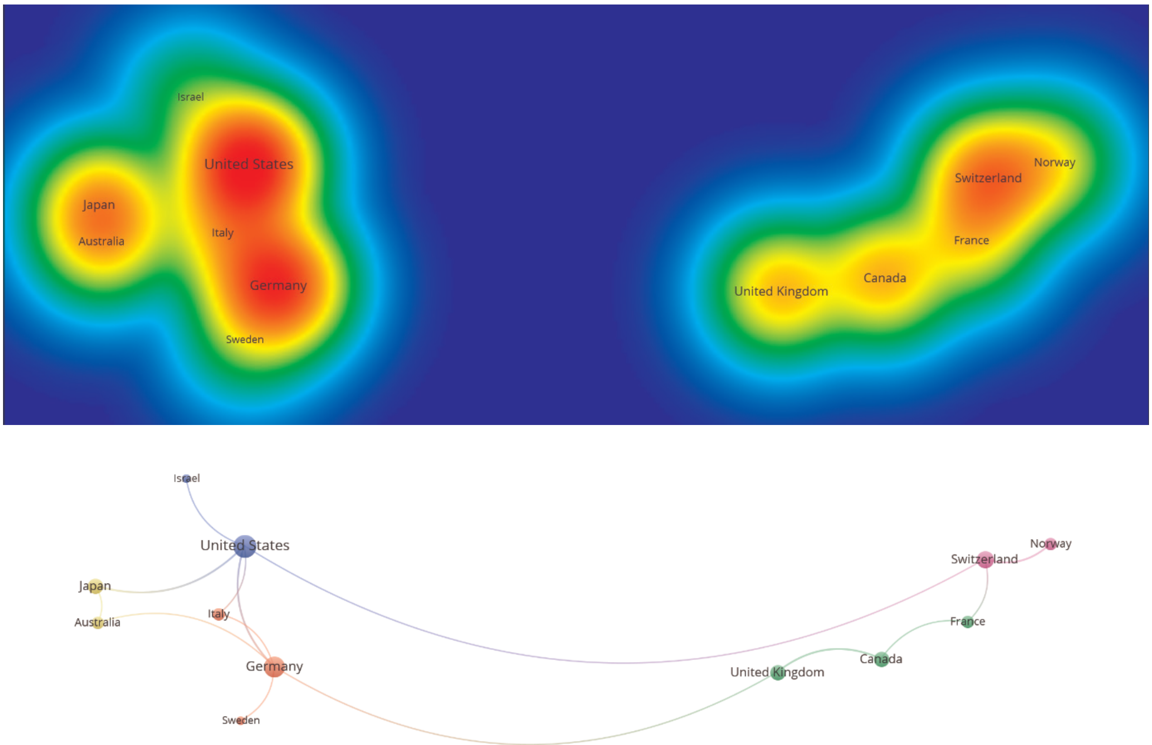


Figure 11: International collaboration network maps for all hydrogen records until 1980 (upper: heat map network; lower: label network)

4.2. Collaboration network as of 1990

By 1990, the number of countries generating publications on hydrogen had almost doubled, compared to the previous decade (48 vs. 25). Figure 12 shows the collaboration network maps as of 1990. Comparison of this figure with the previous decade (Figure 11) clearly shows the emergence of more countries and more collaborations. However, the figure also shows the presence of various islands, implying weak global inter-connection. By this time, the US had emerged as the world's top contributor to hydrogen research. US researchers had co-authored almost a quarter of the publications recorded. The next two top publishing countries were Japan and Germany. These three countries also had the top international collaboration ties, the values being 59, 20, and 16 for the US, Japan, and Germany, respectively. Canada, France, and Italy were the other top collaborators.

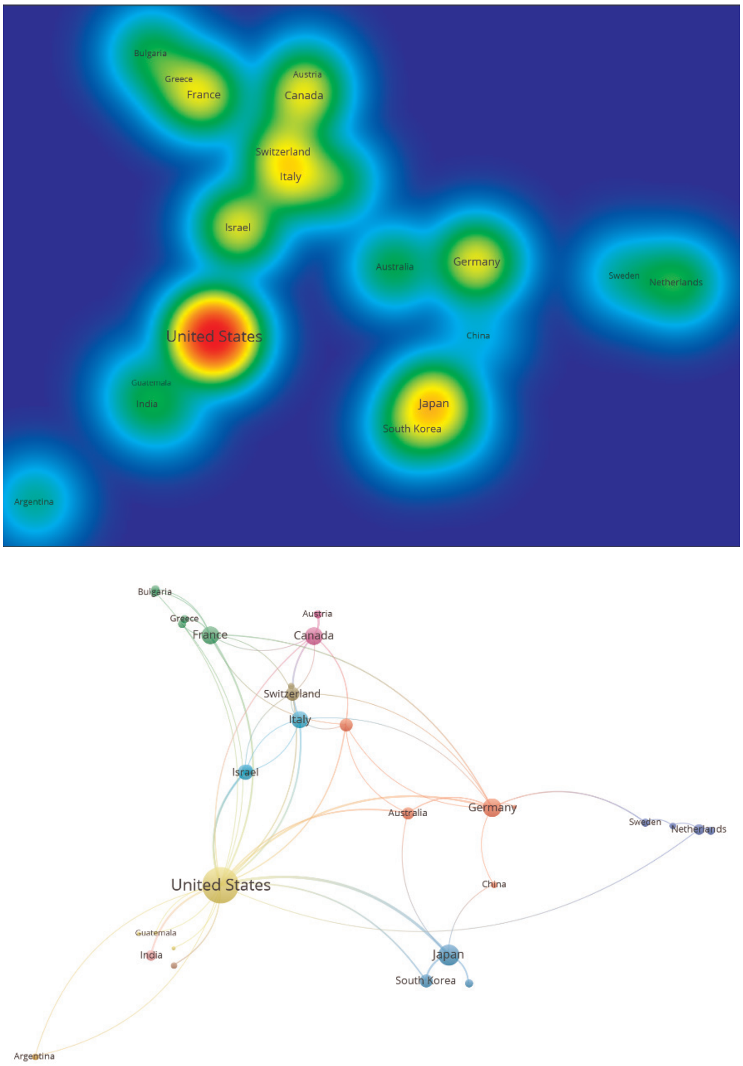


Figure 12: International collaboration network maps for all hydrogen records until 1990 (upper: heat map network; lower: label network)

4.3. Collaboration network as of 2000

By the year 2000, the number of countries with publication on hydrogen increased to 59 countries. Figure 13 shows the collaboration network maps as of 2000. The growth of international collaboration is evident. In this period, the top publishing countries were the US, Japan and Germany, respectively. However, during this period, following the US with 129 international collaboration ties, Germany had the second-highest number of ties, 61, with Japan being the third, with 49 ties. China also emerged as the world's fourth top publishing country, although it had a relatively lower number of international ties, totalling 17. Despite Canada and the United Kingdom having lower publications than China, they both had higher numbers of international ties, at 37. Figure 13 also shows the emergence of an Asian research cluster at the top right of the figure, in which China, Japan, and South Korea have developing ties.

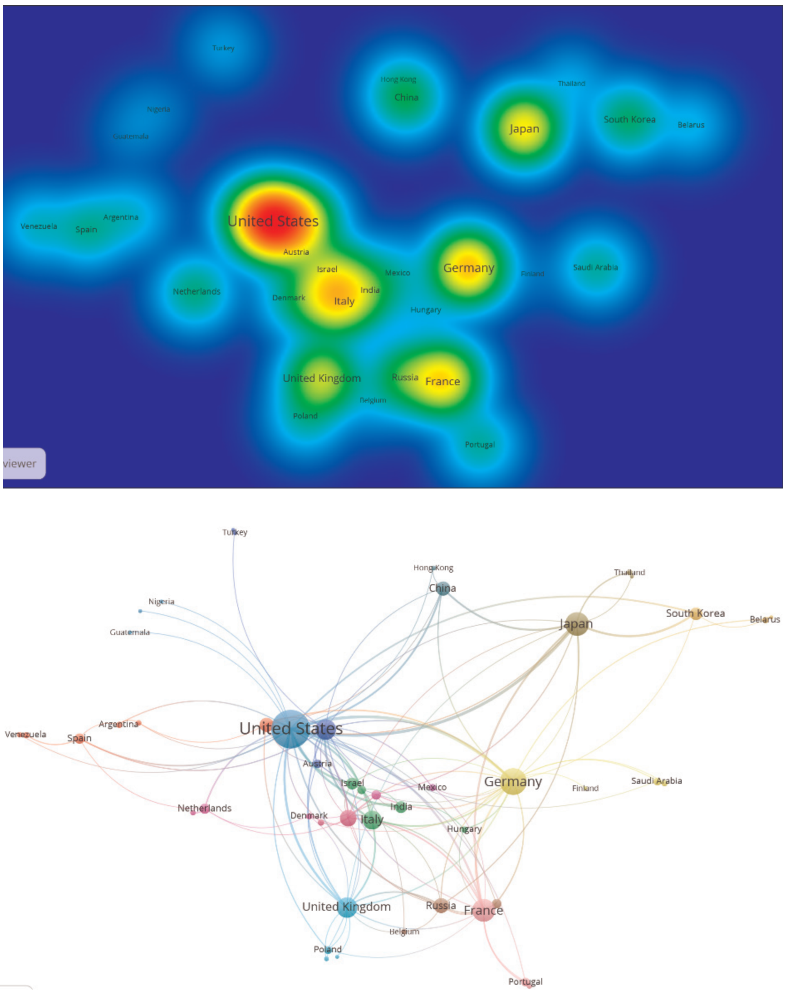


Figure 13: International collaboration network maps for all hydrogen records until 2000 (upper: heat map network; lower: label network)

4.4. Collaboration network as of 2005

Figure 14 shows the collaboration network map as of 2005. By this time, the publication outputs had reached 8846, from 74 countries. China had become the world's third-ranked country in hydrogen research, after the US and Japan. However, Germany as the fourth-ranked country in terms of publications output, had the second-highest number of international collaboration ties, after the US. Japan and China were the third and fourth in terms of collaboration ties.

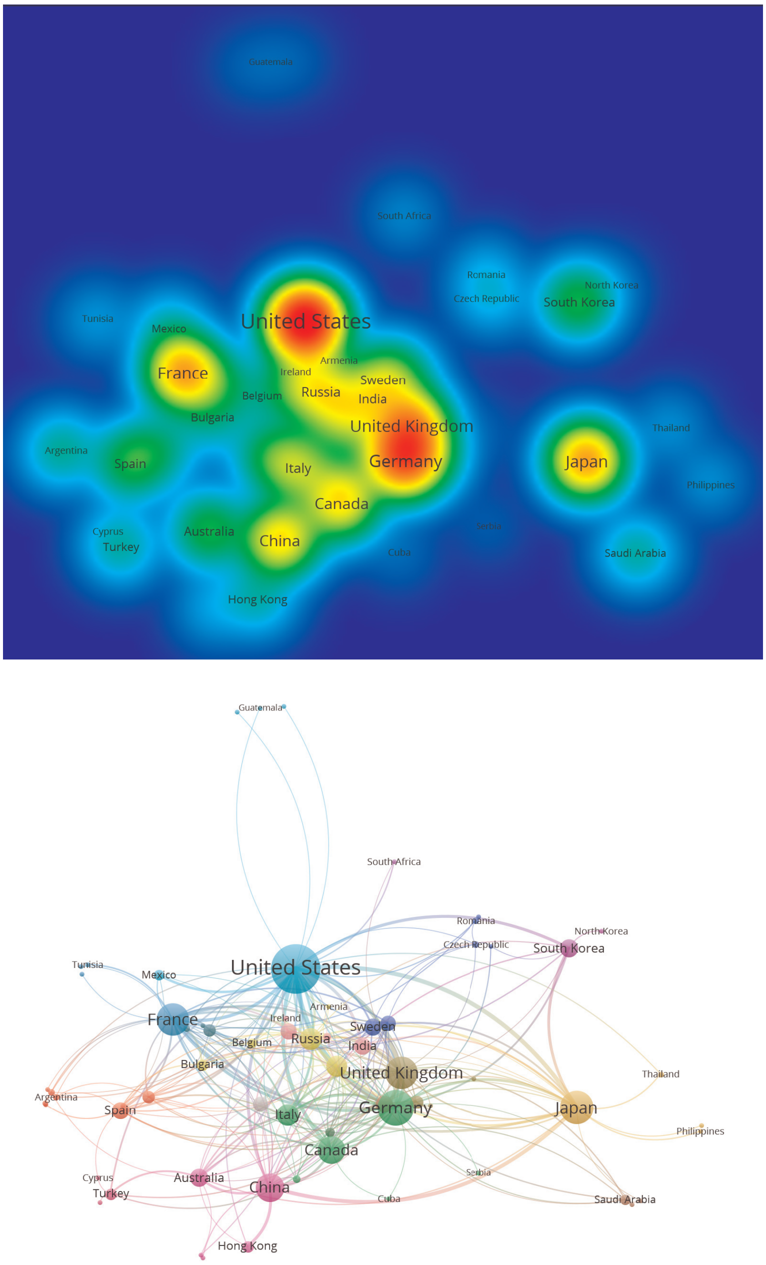


Figure 14: International collaboration network maps for all hydrogen records until 2005 (upper: heat map network; lower: label network)

4.5. Collaboration network as of 2010

Figure 15 shows the collaboration network map as of 2010. In this period, we first observe the development of a tightly integrated international collaboration network. Within this time, the publication output was 3664, from 84 countries. China had become the world's second-highest research producing country in hydrogen, after the US. While Japan and Germany were the third and fourth publishing counties, South Korea had rapidly advanced to the fifth top publishing position. In terms of international collaboration ties, Germany was still the second-ranked country after the US, followed by China and Japan. The total scale of collaboration ties was also notable. For instance, in the 2000 period, the US as the world's top collaborating country, had 119 international ties, while by 2010 this had reached 1141, with all top 10 publishing countries having at least 150 international collaboration ties each.

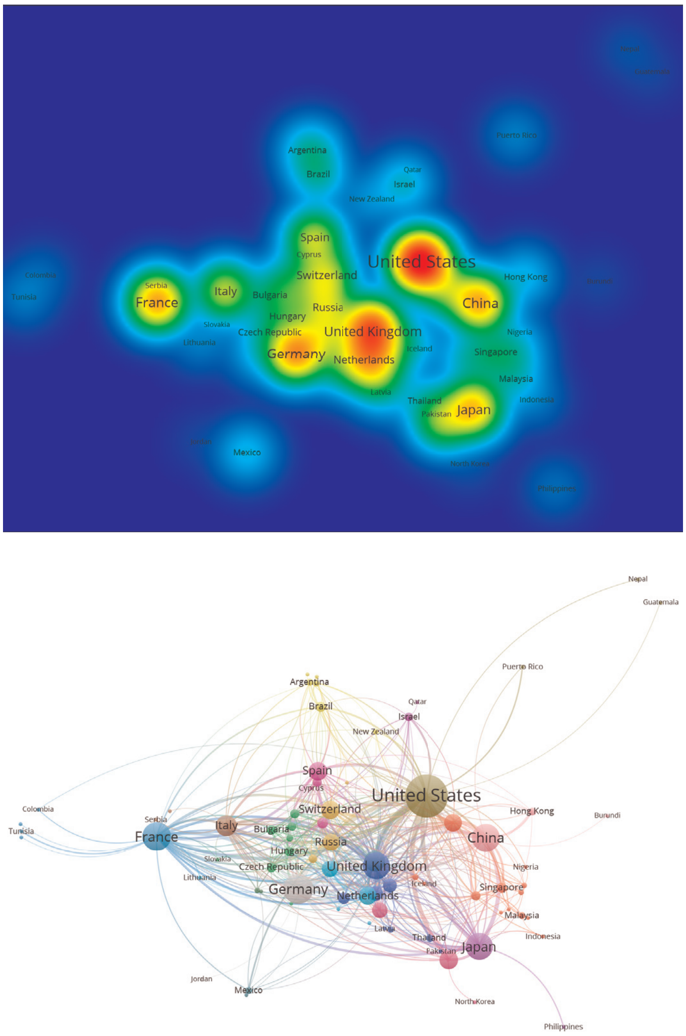


Figure 15: International collaboration network maps for all hydrogen records until 2010 (upper: heat map network; lower: label network)

4.6. Collaboration network as of 2015

By the year 2015, China became the first country in terms of publication quantity, with the US becoming the second, though with almost close quantities (8807 vs 8745). However, in terms of collaboration ties, the US had much stronger collaboration than China (2542 vs 1564). Figure 16 shows the international collaboration network as of 2015 and the strong cluster around the US. The two countries also show the strongest collaborations with 405 co-publications. During this period, Japan, Germany, South Korea, and France are the 3rd to 6th top publishing countries, respectively. Germany, however, has the third top international collaboration ties (1285) followed by France (1211). South Korea, despite being the fifth publishing countries is the 10th in terms of collaboration ties.

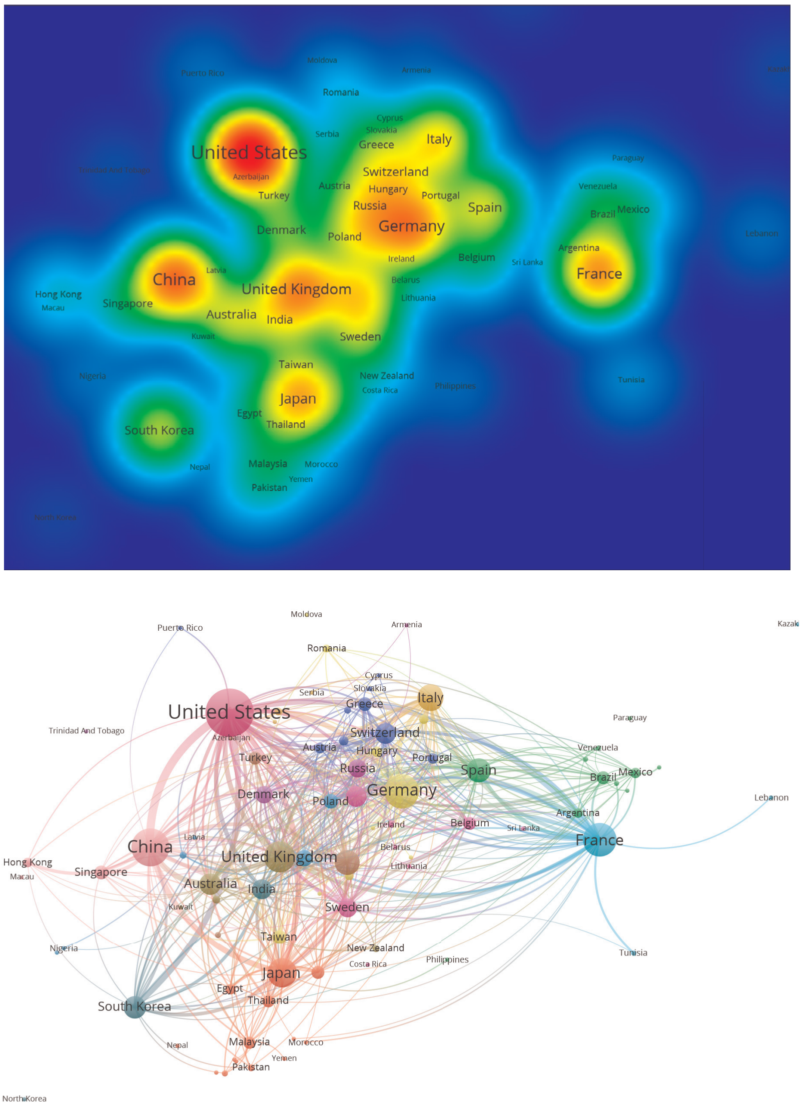


Figure 16: International collaboration network maps for all hydrogen records until 2015 (upper: heat map network; lower: label network)

4.7. Collaboration network as of 2018

Figure 17 shows the international collaboration network on hydrogen supply chain research as of mid-2018, which is based on 58,006 publications. Compared to two decades earlier (Figure 17 vs. Figure 11 to Figure 16), there is indeed a tight international collaboration network, with 108 countries participating and 17,548 total collaboration ties. China, the US, Japan, Germany, and South Korea are the top countries in terms of research. But the top five collaborating countries and their tie totals are; the US (4244), China (3769), Germany (2224), France (1881), the UK (1769), and Japan (1757).

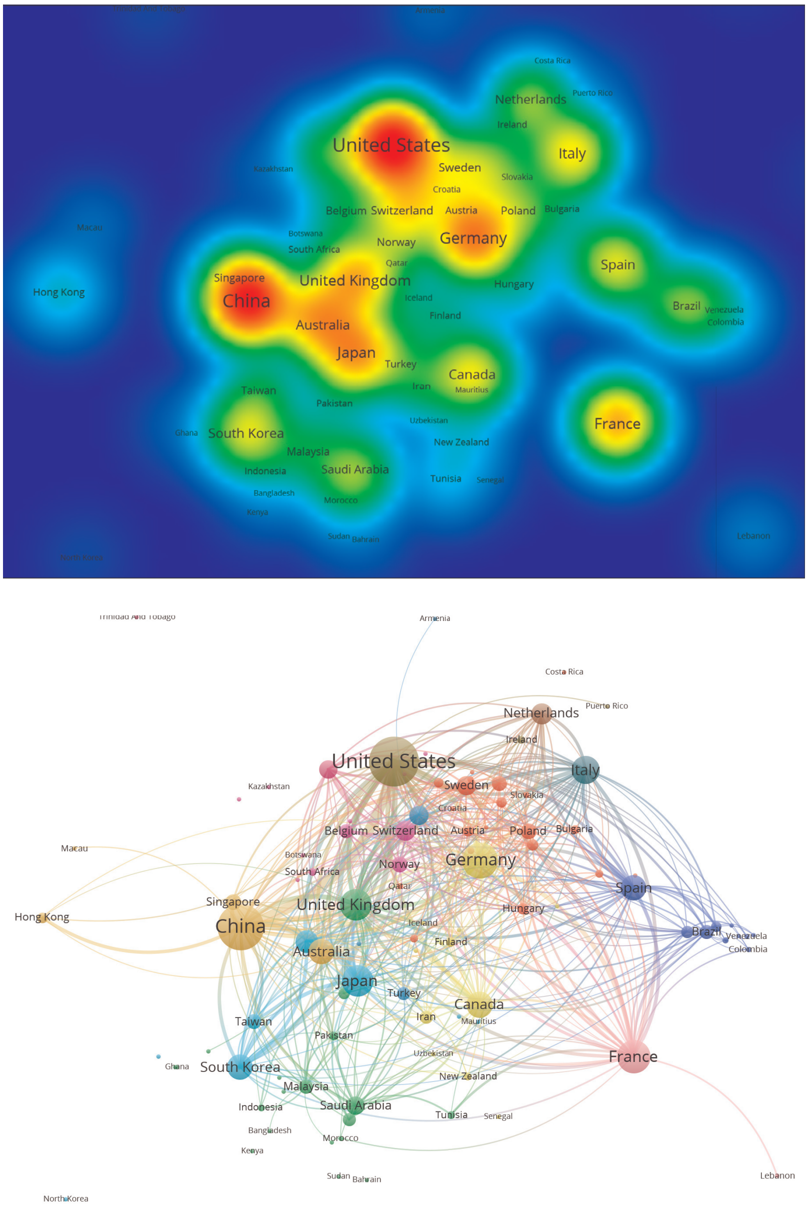


Figure 17: International collaboration network maps for all hydrogen records until mid-2018 (upper: heat map network; lower: label network)

4.8. Statistics of international collaborators and collaboration ties on hydrogen

In the previous section, the historical evolution of collaborations between individual counties was discussed, over seven different time periods. Here, we summarise the longitudinal evolution of those networks by exploring the statistics of the collaborating countries and their collaboration ties. We assess the strength of collaboration with three indicators, the number of publications (NOP), the number of countries in the collaboration (NOC), and the number of co-occurrence ties (NOT). Table 2 shows the top 30 countries, noting that as of 1980 only 25 countries were conducting research on hydrogen. The historical top three countries with influence in this field are the United States, Japan, and Germany, respectively. China is not seen in the list of countries conducting hydrogen research, up to 1980. By 1990, that country becomes 13th among the other countries. By the year 2000, it has become the 4th. By 2010, its publication output became the second in the world, after the United States, while by 2015 it became the leading country in hydrogen research output. It is noteworthy, however, that although China's publication record exceeds that of the United States, the United States still has the strongest collaboration ties (NOC and NOT). As of 2018, the United States has collaborated with 81 countries on 4244 publications, while China's international collaboration list includes 63 countries on 3769 publications.

Table 2: Top 30 countries in terms of publications and international collaborations (ties) on hydrogen research as of 1980, 2000, and 2018

1980					2000					2018				
No.	**Country**	**NOP***	**NOC****	**NOT*****	**No.**	**Country**	**NOP***	**NOC****	**NOT*****	**No.**	**Country**	**NOP***	**NOC****	**NOT*****
1	United States	181	5	7	**1**	United States	1153	29	129	**1**	China	15158	63	3769
2	Japan	51	2	3	**2**	Japan	767	13	49	**2**	United States	11008	81	4244
3	Germany	28	5	6	**3**	Germany	295	22	61	**3**	Japan	5285	58	1757
4	United Kingdom	25	2	3	**4**	China	276	6	17	**4**	Germany	3038	72	2224
5	Switzerland	17	3	4	**5**	Canada	218	15	37	**5**	South Korea	2865	59	1091
6	France	12	2	2	**6**	United Kingdom	177	15	37	**6**	India	2640	58	892
7	Australia	10	2	2	**7**	India	169	5	13	**7**	France	2347	71	1881
8	Canada	8	2	3	**8**	France	163	14	45	**8**	Canada	2325	62	1223
9	Italy	6	2	2	**9**	Switzerland	92	14	24	**9**	United Kingdom	2310	70	1769
10	Russia	6	0	0	**10**	Russia	86	9	20	**10**	Italy	2131	62	1366
11	Netherlands	5	1	1	**11**	Australia	84	8	17	**11**	Spain	1659	65	1136
12	Israel	4	1	1	**12**	Italy	82	9	31	**12**	Australia	1379	53	1104
13	Norway	3	1	2	**13**	South Korea	67	4	15	**13**	Taiwan	1291	38	394
14	Austria	3	0	0	**14**	Netherlands	59	5	10	**14**	Turkey	1038	40	323
15	Hungary	3	0	0	**15**	Israel	35	5	13	**15**	Russia	929	53	635
16	Sweden	2	1	1	**16**	Austria	35	5	7	**16**	Iran	889	42	312
17	Belgium	2	0	0	**17**	Sweden	34	5	8	**17**	Netherlands	886	49	778
18	Guatemala	1	0	0	**18**	Spain	31	5	10	**18**	Brazil	798	49	355
19	South Africa	1	0	0	**19**	Egypt	24	2	4	**19**	Switzerland	702	51	738
20	Ireland	1	1	1	**20**	Brazil	23	4	7	**20**	Malaysia	680	41	369
21	Iraq	1	0	0	**21**	Saudi Arabia	23	3	6	**21**	Poland	670	45	422
22	Czech Republic	1	0	0	**22**	Denmark	20	4	4	**22**	Sweden	620	54	662
23	India	1	0	0	**23**	Belgium	20	3	3	**23**	Saudi Arabia	572	46	589
24	Argentina	1	0	0	**24**	Taiwan	19	1	1	**24**	Mexico	562	39	262
25	Poland	1	0	0	**25**	Bulgaria	19	4	8	**25**	Singapore	519	39	436
26					**26**	Argentina	15	3	4	**26**	Greece	503	40	377
27					**27**	Hungary	14	3	4	**27**	Thailand	473	31	227
28					**28**	Finland	13	1	1	**28**	Denmark	459	47	583
29					**29**	Poland	12	5	6	**29**	Norway	452	38	447
30					**30**	Mexico	11	4	5	**30**	Argentina	407	30	200

NOP**: number of publications; NOC***: number of collaborating countries ties; NOT***: number of co-occurrence ties (international collaborations)

Figure 18 profiles the historical development of international hydrogen research in terms of the number of publishing countries and the total number of collaboration ties (NOT). While by 1980, there were only 25 countries involved in hydrogen-related research, by 2018, this number had increased, almost linearly, finally reaching 108 countries. However, the international collaboration ties have increased near exponentially since 2000. The total number of international ties by 1980 was only 19, becoming 321 by 2000. Within a decade, by 2010, this value increased by more than ten-fold to 3664. As of mid-2018, there were 17,548 international collaboration ties, an astonishing expansion over a relatively short period of time.

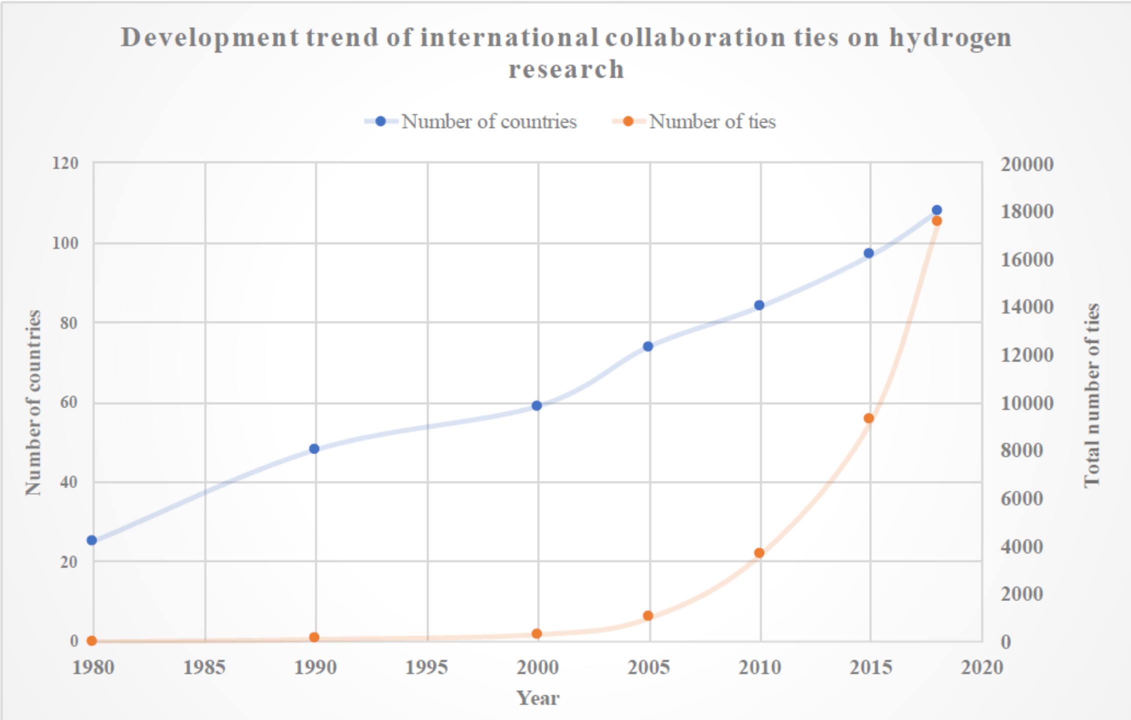


Figure 18: Historical development of international hydrogen research: Number of publishing countries, and the total collaboration ties

5. Implications and conclusion

The objective of this study was to investigate the research community of the hydrogen supply chain and assess the longitudinal evolution of this research field from an international scientific perspective. This can enable us to identify the key directions in both research and international collaboration ties. Given the mass of publication records on this topic (>58,000), a conventional literature analysis on this amount of publications was totally impracticable. Consequently, we followed a scientometric analysis approach and developed a ‘social network’ of publication records retrieved from Scopus database. Two types of networks were created, based on keyword co-occurrence and the establishment of international collaboration ties. The methodology enabled us to analyse and visualise the longitudinal development of this field and explore the emerging research focus.

An interesting observation was that despite publications on hydrogen occurring since 1935 [18], the growth of this research field ignited with the Kyoto Protocol of 1997 [38]. The publication profile reveals that more than 93% of the existing records have been published over the last two decades.

The first decade of this millennium witnessed dramatic uptake of some renewable energy types. The installations of photovoltaic cells and wind turbines have made a tipping point over the recent decade [44]. The accelerated growth of renewables has further motivated hydrogen research with almost 36000 academic records having been indexed from 2010 till mid-2018. This accounts for ~62% of the total historical publications on hydrogen. All these data imply a very strong international determination in hydrogen community for crossing the chasm.

Past research focus and future directions: Keyword network analysis reveals that until the 1970s, biological hydrogen generation was the most significant research area. In the 1980s, another strong cluster was formed with "hydrogen generation", in connection with coal and fuel cells. By the 1990s, hydrogen storage was identified as a critical challenge and a strong research cluster encompassing "hydrogen storage alloys" is observed. With the emergence of nanotechnology [42], hydrogen storage alloys and materials accounted for a significant portion of the research in this area, along with hydrogen generation research (from both renewable and non-renewable resources). Towards the late 2000s, hydrogen generation research became the main research cluster, with biohydrogen production also starting to form a small cluster. This trend has continued in the 2010s and the network maps show that over the last few years "water splitting" and "photocatalysis" from visible light [48] are emerging as new strong research clusters. In summary, while all components of hydrogen supply chain research are now growing, the topic areas of biohydrogen, photocatalysis, and water-splitting (all three related to the use of renewable energies) seem to be growing the fastest and more innovative technological solutions should be expected from these areas in near future.

International collaboration networks: The network maps not only show the research directions which can help organisations in setting up their H_2 research plans, but also provide an overview of countries collaboration. The analysis of international collaboration networks reveals a notable evolution of collaboration on hydrogen research with a near 'exponential' growth of inter-country involvements evidenced in Figure 18. Until the 1970s, only 25 countries had collaborated, while this has reached 108 countries as of 2018. While the total number of collaboration ties was as low as 321 by 2000, within a decade, by 2010, this value increased by more than ten-fold to 3664. As of mid-2018, there were 17,548 international collaboration ties. The collaborations have also evolved into a substantially more integrated network, with a few strong clusters involving China, the United States, Germany, and Japan.

The collaboration network analyses dramatically reveal the changes in the world economic/technological balance over the last several decades. This has seen a shift from US-Europe centred technology development-interaction, to a world in which Asian economies play substantial roles. In hydrogen research, this occurred initially in their local region, but recently, essentially globally amongst industrial countries (Figure 17).

The collaboration network maps could be useful for any country or organisation's research policy development. For instance, the map shows that Australia is collaborating strongly with some research hubs while it has weaker ties with some others. The results of this study can help the Australian (or any other country's) funding organisation in developing some schemes for the promotion of research collaboration with hubs with current weak ties. In summary, the progressive time-series analyses we have used, with both network types, allows a detailed appreciation of not only the paths taken in the historical development of hydrogen research, but crucially, informs sensible expectation of the important directions ahead, for technology and international interactions.

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