Hydrogen Transport & Storage

Research analysis based on patent literature review

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Executive Summary

Climate change has become one of the main focal points of European and global policies, with increasingly strict targets for greenhouse gas (GHG) emission reduction set in a short timeframe. In this context, the potential of hydrogen as a climate-friendly energy carrier/feedstock in many applications and sectors, has renewed interest in building on its capabilities. Designing a hydrogen-based economy, however, will require efficient hydrogen transport and storage. Any disruption in these processes will pose complex technological challenges during the massive scale-up and widespread use of hydrogen.

Hydrogen can be transported in gaseous as well as liquid forms. For both entities, challenges are associated with the density of hydrogen that may affect economic and physical yield, as well as hamper environmental safety. Hydrogen storage solutions can be classified into three categories. Firstly, physical solutions, offer a closed space to store the hydrogen at high pressure above or below the ground. This storage mean can be combined with transport. The second category is based on bonding hydrogen molecules with metal or chemical hydrides, while the third category concerns adsorption-based solutions.

This report includes an overall analysis of the patent landscape in the field of hydrogen transport and storage, and provides a more targeted analysis of the three main categories of storage. The analysis shows that research activity on hydrogen storage and transport has rapidly increased during the last eight years. Most of the activity in the field of transport is related to liquid hydrogen. In the field of storage, most of the activity was related to physical storage solutions.

The predominant publications in the field of liquid transport and physical storage solutions that represent the two more mature and cost-efficient solutions for transport and storage respectively, tend to emphasize the global determination to upscale and standardize the use of hydrogen in numerous sectors.

The top 10 list of companies active in the field of transport depicts a well-balanced representation, with Japan, China and the US sectors leading the board. On the academic front, China predominates, with academic institutes there leading the top 10 list in the field of storage as well as transport, and significantly monopolizing the top 10 list in the latter field.

Hydrogen transport entails the shipment of gaseous as well as liquid hydrogen. The analysis of patent application over time has shown that both fields have benefited from a renewed interest in recent years, with publication numbers reaching unprecedented levels in 2019, 2020 and 2021. However, the relative activity levels for gaseous hydrogen remain negligible compared to that for liquid hydrogen. The market is predominantly led by Chinese academic entities while European academic and industrial entities lag behind noticeably.

In terms of patent publications on hydrogen storage in recent years, a rising trend is observed, confirming the growing interest for hydrogen around the world. Research efforts are focused on physical storage solutions. Contrary to transport, European industries are leading in the storage field, while China's domination is confined to the academic sector. Chemical storage and adsorption-based solutions appear to be more niche markets mainly led by Japan, followed by Europe and the US on the industrial front, while China remains a central player in the academic ranking.

1. Introduction

Climate change has become one of the main focus points of EU policies, with objectives set to reduce CO_2 emission by 55% by 2030 and achieving climate neutrality by 2050. The European Commission (EC) is gathering public and private initiatives to mitigate the course and impact of climate change. The EC is currently leading the fight to reduce greenhouse gas (GHG) emissions by creating legislative frameworks promoting clean and sustainable energy and related processes. The latest framework for action presented by the EU is the "Fit for 55" package, which focuses on the alignment of the EU climate, energy, and transport related legislation with its climate ambitions.

In order to effectively initiate an in-depth energy revolution, the use of fossil fuels should be massively targeted. While the EU plans to decrease its CO_2 emissions by 55% by 2030, it is a fact that fossil fuels still accounted for 71% of the gross available energy in 2019[1]. The switch to synthetic fuels and the injection of renewable and decarbonised energy in the current system, represent important leverage approaches. In that context, H_2, an efficient energy carrier, is regarded as one of the main actors in this transition and several initiatives are flourishing to foster its large-scale deployment, as it currently only makes up for 1% of Europe's energy supply. As such, the EC published in 2020 its Hydrogen strategy[2], that aims at supporting an upscaled and widespread use of hydrogen by 2050. The strategy underlines the multifaceted nature of hydrogen that can be used as a feedstock, replacing more polluting energy sources; or as a storage option/energy carrier. In both cases, hydrogen needs to be distributed, however, the massive up-scaling of H_2 production and use may involve several technological barriers. One of the main challenges in the transportation and the storage of hydrogen is the density of hydrogen. As the lightest molecule, hydrogen, in its gaseous form, occupies $11m^3$ per kilo at room temperature and atmospheric pressure[3]. This is why the transport and storage of hydrogen have been topics of much interest over the past years.

Accordingly, this report aims to provide an analysis of the innovative activities in the field of hydrogen transport and storage. The analysis is performed through a review of the (published) patent trends in this field. Using the patent database, "Orbit intelligence"[4], various datasets were created as detailed in the next section. For each dataset, multiple analyses were carried out, including activity over time, key players, and text pattern analysis. These enable an insight into the nature of the activity, as well as patent value analysis, in order to indicate key innovations in the respective data sets.

[1] ec.europa.eu/eurostat

[2] A hydrogen strategy for a climate-neutral Europe, COM (2020) 301

[3] J. Andersson, S. Grönkvist, Large-scale storage of hydrogen, International Journal of Hydrogen Energy, 4 (23) (2019), pp. 11901-11919

[4] https://www.orbit.com/

2. State of the art

As previously mentioned, hydrogen is the lightest gas on Earth. This particular status implies non-negligible constraints when it comes to its transport and storage. While hydrogen is regarded as one of the main levers to reduce the GHG emission of the road transport, notably, the storage or transport of 1 kg of hydrogen at atmospheric pressure would require 11 m^3, in other words, the equivalent of the trunk of a large truck. For yield considerations, economical as well as physical, it is thus essential to increase the density of the hydrogen, this can be achieved by increasing the pressure of hydrogen in its gaseous form or by liquefying the gas, for example. However, the latter methods require considerable energy input, either to maintain the liquified hydrogen below its boiling point (-253°C) or to raise its pressure.

Additionally, it is important to note that the application (i.e., the end use of the hydrogen) can also imply important constraints on certain phases of the procedure[5]. For instance, certain applications will require short response time for the release of hydrogen while others work at more controlled rates of filling. In the same way, certain applications have strict demands regarding the purity of the hydrogen. All these demands have a direct impact on the storage and transport options to be considered.

In terms of existing solutions for hydrogen storage, two main categories of storage can be distinguished: physical-based storage and material-based storage.

In physical-based solutions, hydrogen can be stored either in its gaseous or liquid form. When considering consequent amounts of hydrogen (over 10.000 tons), the solutions focus mainly on high-pressure storage underground[6] in natural (e.g., salt cavities) or specifically created cavities, and containers (e.g., gas holders, spherical pressure vessels, pipelines, etc.). High-pressure storage for gaseous hydrogen can also be situated above ground. However, investment costs are significantly higher. For above ground applications, hydrogen is usually stored in its liquid form in cryogenic vessels. Those vessels can be directly integrated onto vehicles, creating an overlap between hydrogen transport and storage. In practice, all hydrogen transport processes also constitute storage processes.

Material-based storage is mainly based either on adsorption (relying on physical van der Waals bonding between molecular hydrogen and a material with a large surface area) or on chemical bonding of hydrogen with hybrids (either chemical or metal).

Lastly, regarding transport, the solutions consist in pipeline transportation or transportation in supertank via either truck or rail, where hydrogen can be transported in gaseous or liquid form, or ship, where hydrogen is usually liquified. The choice of one mean of transportation over another is mainly correlated with the distance to be covered as well as the quantity distributed. It is important to note that hydrogen transportation entails specific safety issues related to the properties of the gas. Hydrogen has a wide flammability range, causes embrittlement of materials, and can easily escape from containment[7].

[5] J.B. Taylor, et al., Technical and economic assessment of methods for the storage of large quantities of hydrogen, International Journal of Hydrogen Energy, 11 (1) (1986), pp. 5-22
[6] F. Crotogino, Larger scale hydrogen storage Storing energy, Elsevier (2016), pp. 411-429
[7] Royle M., Willoughby D. The safety of the future hydrogen economy, Process Safety and Environmental Protection, 89 (6) (2011), pp. 452-462

In conclusion, the main levers for innovation and optimization in the field of hydrogen transport and storage mainly rely on:

- Increased storage density;
- Limited risks (for the environment where the storage takes place as well as for the durability of the components and equipment);
- Optimized energy intake.

3. Search strategy and datasets

To explore the patent landscape of hydrogen transport and storage, separate datasets were created for each topic. Every dataset was parametrized to only consider patents with a priority date after 2002 (20 years timeframe).

For transport, firstly, a large dataset was created by searching for the keywords “hydrogen” or “H_2” appearing within one word of “transport” in the title, abstract or claims, with stemming enabled. The final large dataset contained 1.468 patent families and was used to create a general overview of the patent landscape on hydrogen transport. Thereafter, more focused datasets were created in order to distinguish and analyse more in-depth the transport of liquified hydrogen and gaseous hydrogen. The original dataset was narrowed down by searching for patents that had the terms “liquid*” in the title, abstract or claims. This resulted in a set of 87 patent families. The same methodology was used for gaseous hydrogen transport using the term “gas*” to refine the results of the original large datasets. The resulting set contained 39 patent families.

Regarding the storage of hydrogen - the topic was explored by firstly creating a large dataset with a search for “hydrogen” or “H_2” in the same sentence as “stor*” in the title, abstract or claims, with stemming enabled, resulting in a dataset of 57.595 patent families. The large dataset was further refined by focusing on CPC class Y02E-060/32, which specifically focuses on hydrogen storage technology. The resulting dataset had 5.090 patent families.

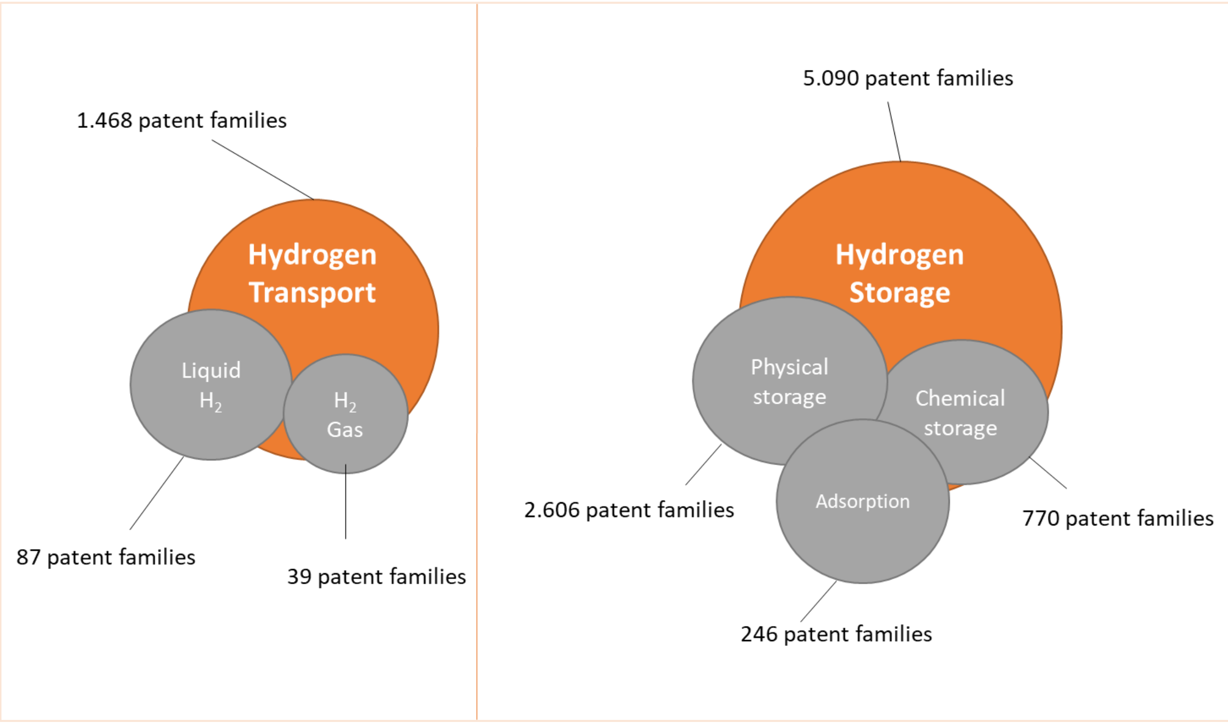
Similar to transport, more focused datasets were created in order to explore the main categories of storage described in section 2, namely, physical storage, adsorption and chemical-based storage.

Physical storage was explored by narrowing the large dataset to patents related to the CPC class F17C, in order to exclude patents related to material-based storage. This translated into a dataset of 2.606 patent families.

Regarding storage based on adsorption, the dataset was created by searching for patents that included the term “adsorpt*” in the same sentence as “stor*” and “hydrogen” or “H_2” in the title, abstract or claims, yielding a data set of 246 patent families.

Lastly, a dataset for chemical-based storage was elaborated. For this, the original large dataset for hydrogen storage was narrowed down to patents including the term “hydrid*” in the title, abstract or claims. The thus resulting set displayed 770 patent families.

It is important to note that, for the large dataset related to hydrogen storage, as well as for each focused datasets of this domain, patents including, and not only related to, adjacent services such as compression, filling, monitoring etc. have been retained. Indeed, as mentioned in section 2, certain applications require specific yield or level of purity which are generally guaranteed through those adjacent services.



4. Overall analysis of patents in the fields of hydrogen transport

Using the large dataset presented in section 3, a general overview and analysis of the field of hydrogen transport was realized. Firstly, the patent activity over time between year 2002 to 2022 was analyzed by plotting the number of patents families against the first year of publication. The results of the analysis are presented in **Figure 1** below.

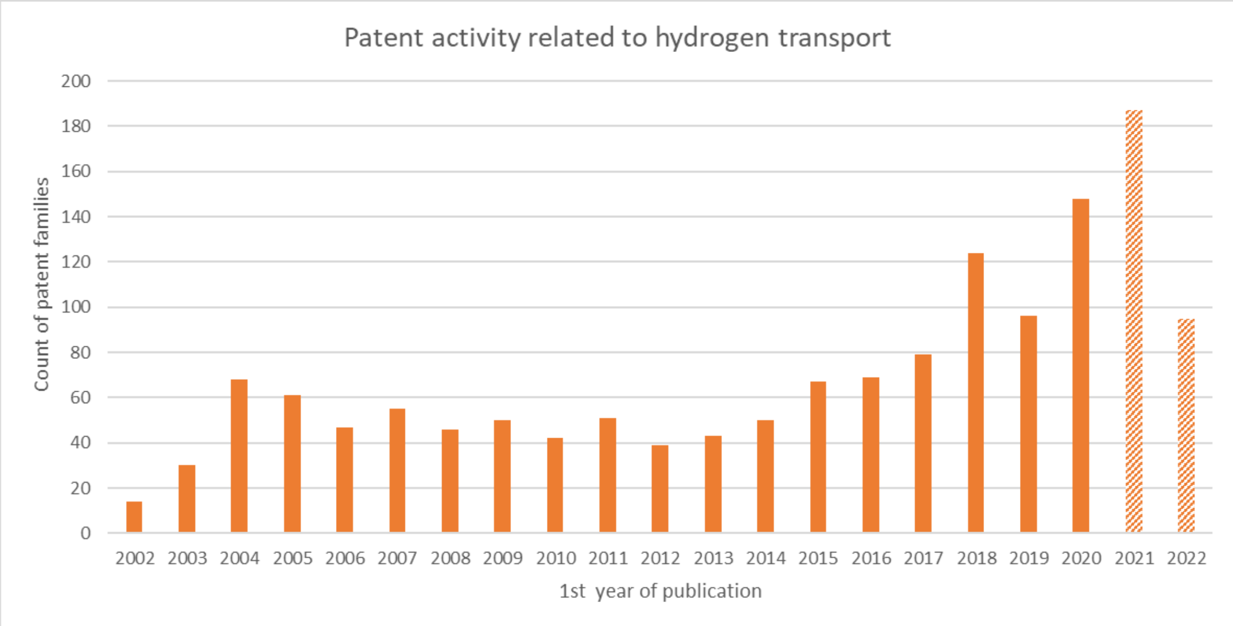


Figure 1: Number of patent families related to hydrogen transport over time (2021-2022 not fully published yet)

Figure 1 shows a clear increasing trend in the number of patent applications over the last twenty years with a noticeable acceleration in the last 5 years with patent activity reaching unprecedented levels. This steep acceleration aligns with the market's growing interest in hydrogen in the recent years for mobility and energy generation and storage.

This global increase is confirmed when analyzing the more specific patent activity of liquid hydrogen and gaseous hydrogen transport. However, when comparing both patent activities, a clear predominance of patents related to the transport of liquid hydrogen appears (c.f. **Figure 2**). This can be explained by the economics of hydrogen transportation. Though the compression and liquefaction processes account for between 80% to 87% of transportation costs[8], over long distances, transporting liquid hydrogen proves to be more economical than transporting gaseous hydrogen on account of the low density of gaseous hydrogen allowing for lesser energy storage in an identical volume.

[8] S&P Global Platts Analytics report, 2019

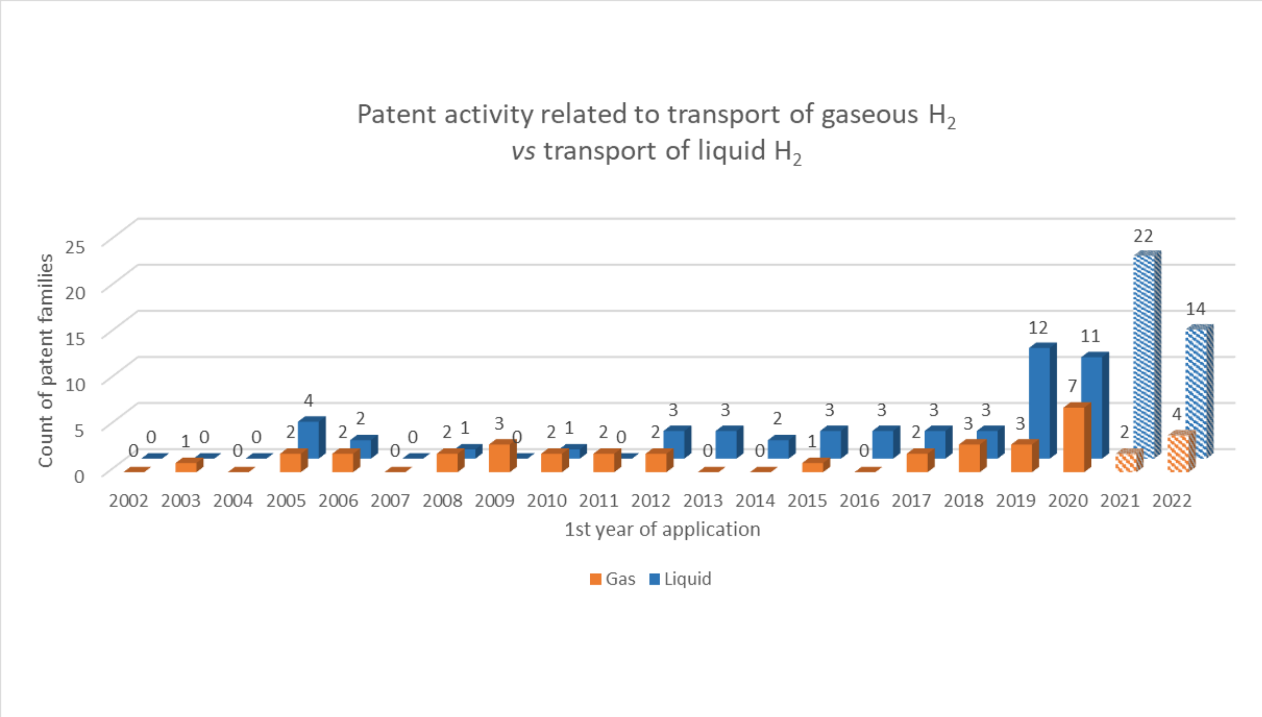


Figure 2: Count of patent families related to transport of liquid hydrogen VS gaseous hydrogen over time (2021-2022 not fully published yet)

Figure 3 shows that China is leading the market in terms of patent publication, registering more than double the number of publications than the US, ranked second. European countries lag significantly behind. Most noticeably, Belgium does not appear in the top 100 of countries where patents related to hydrogen transport were published.

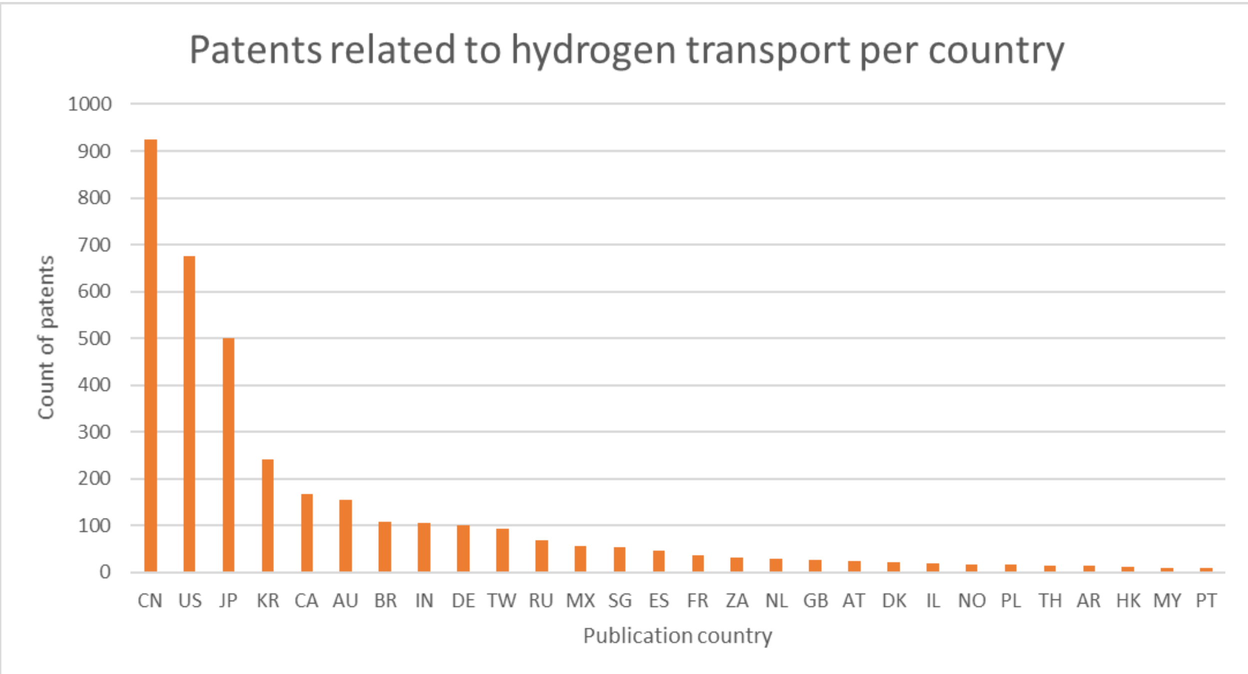


Figure 3: Patent publications related to hydrogen transport per country

Figure 4 provides an overview of the patent activity over the last twenty years for the top 5 countries. There is a clear overall dominance of China in terms of publication. This is mainly due to a gradual increase in the number of publications since 2012. The US ranked second in terms of number of publications and maintained a relatively constant number of publications over the years.

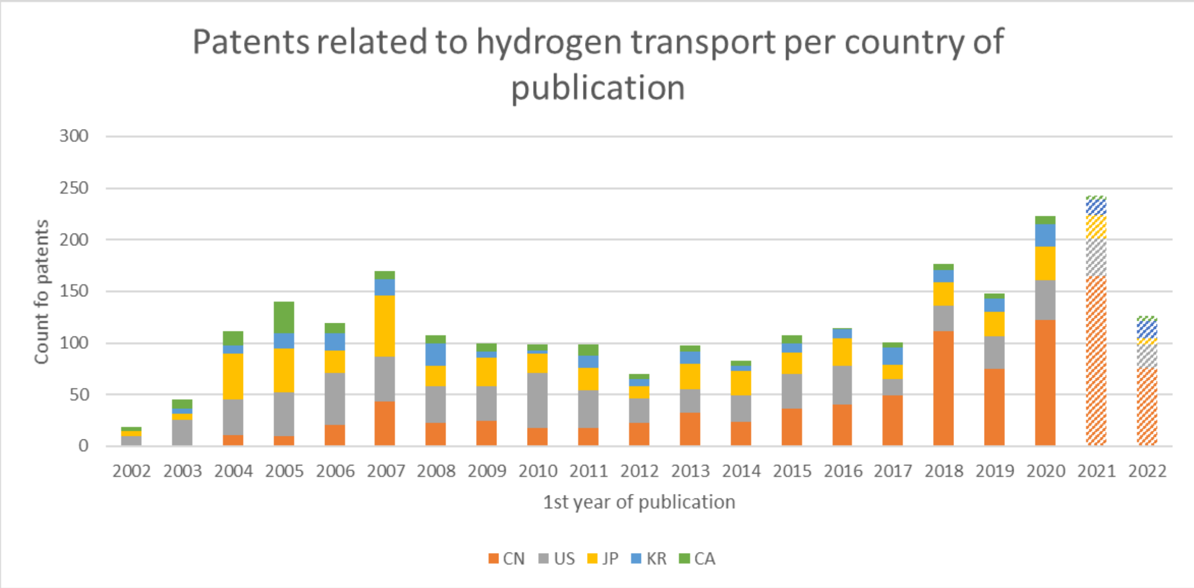


Figure 4: Patent publications related to hydrogen transport per country of publication over the last twenty years (2021 and 2022 not fully published)

Lastly, with regards to the players active in the filling of patents related to hydrogen transport, there is a clear dominance of industrial players which represent 80% of the top 15 players in the field of hydrogen transport. The trend is similar on the more specific fields of liquid and gaseous hydrogen transport.

Tables 1 and 2 show the top 10 of respectively companies and academic institutions in the large data set of hydrogen transport.

Table 1: Top 10 of industrial players in the field of hydrogen transport

Company name	Country	Number of patent families
INTELLIGENT ENERGY	UK	22
KAWASAKI HEAVY INDUSTRIES	JP	14
QINGDAO HAIER	CN	14
TOSHIBA	JP	12
NISSAN MOTOR	JP	11
GM GLOBAL TECHNOLOGY OPERATIONS	US	10
GUANGDONG HYDROGEN ENERGY SCIENCE & TECHNOLOGY	CN	10
HEBEI QIMING HYDROGEN ENERGY DEVELOPMENT	CN	10
PRAXAIR TECHNOLOGY	US	10
HONDA MOTOR	JP	9

Table 2: Top 10 of academic players in the field of hydrogen transport

Name of Academic institute	Country	Number of patent families
TSINGHUA UNIVERSITY	CN	13
NANJING YANCHANG REACTION TECHNOLOGY RESEARCH INSTITUTE	CN	10
ZHEJIANG UNIVERSITY	CN	10
HUANENG CLEAN ENERGY RESEARCH INSTITUTE	CN	6
HUNAN INSTITUTE OF SCIENCE & TECHNOLOGY		6
BEIJING UNIVERSITY OF TECHNOLOGY	CN	5
TONGJI UNIVERSITY		5
BEIJING ZHONGQINGYUAN ENGINEERING TECHNOLOGY	CN	4
CHANGJIANG SURVEY PLANNING DESIGN & RESEARCH	CN	4
NANYANG EXPLOSION PROTECTED ELECTRICAL APPARATUS RESEARCH INSTITUTE	CN	4

The large activity of China shown in **Figures 3 and 4 is** not reflected in the top 10 of industrial players as only 3 of the ranked companies are Chinese. Japan dominates the top 10 of companies and, surprisingly, the USA is only represented by one company in the top 10. However, the Chinese dominance is striking in the academic field, with the top 10 of academic institutes being strictly composed of Chinese institutes.

It can thus be concluded that a significant portion of activity in patent published in China is coming from academic institutions while the industrial field is mainly led by Japan.

5. Overall analysis of patents in the fields of hydrogen storage

Overview on hydrogen storage

Similar to the previous section focusing on hydrogen transport, a general overview and analysis of the field of hydrogen storage was realized using the large dataset presented in Section 3.

Firstly, the patent activity over time between year 2002 to 2022 was analyzed by plotting the number of patent families against the first year of publication. The results of the analysis are presented in **Figure 5** below.

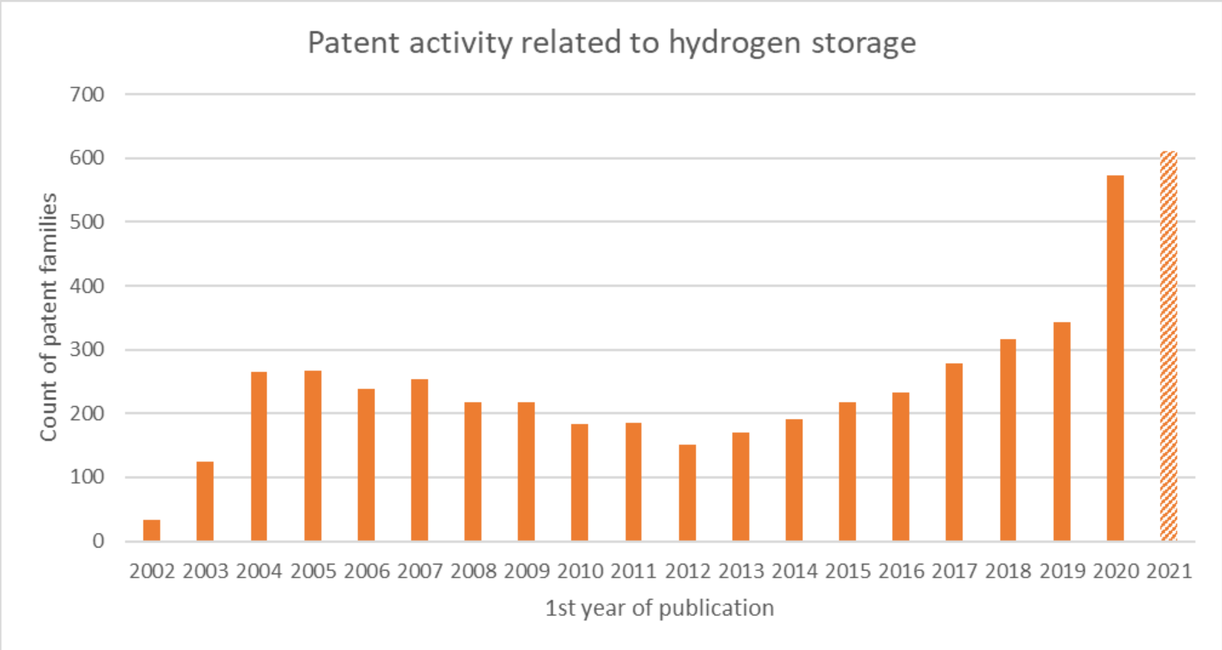


Figure 5: Count of patent families related to hydrogen storage over time (2021 not fully published)

The patent activity was relatively constant between 2002 and 2017. As of 2018, the number of patent publications in the field of hydrogen storage increased to reach a peak in 2021.

Figure 6 sets forth the number of patent families published in the top 10 countries. Similar to hydrogen transport, China is the most active country with over 2.000 patent families published. However, in the field of hydrogen storage, the competition seems to be more active as the second ranked country, Japan, gathers a close total number of patent families. Additionally, European countries are better represented in this field with two countries ranking in the top 10. Belgium ranks 52 with one published patent family assigned to the company Energy for All.

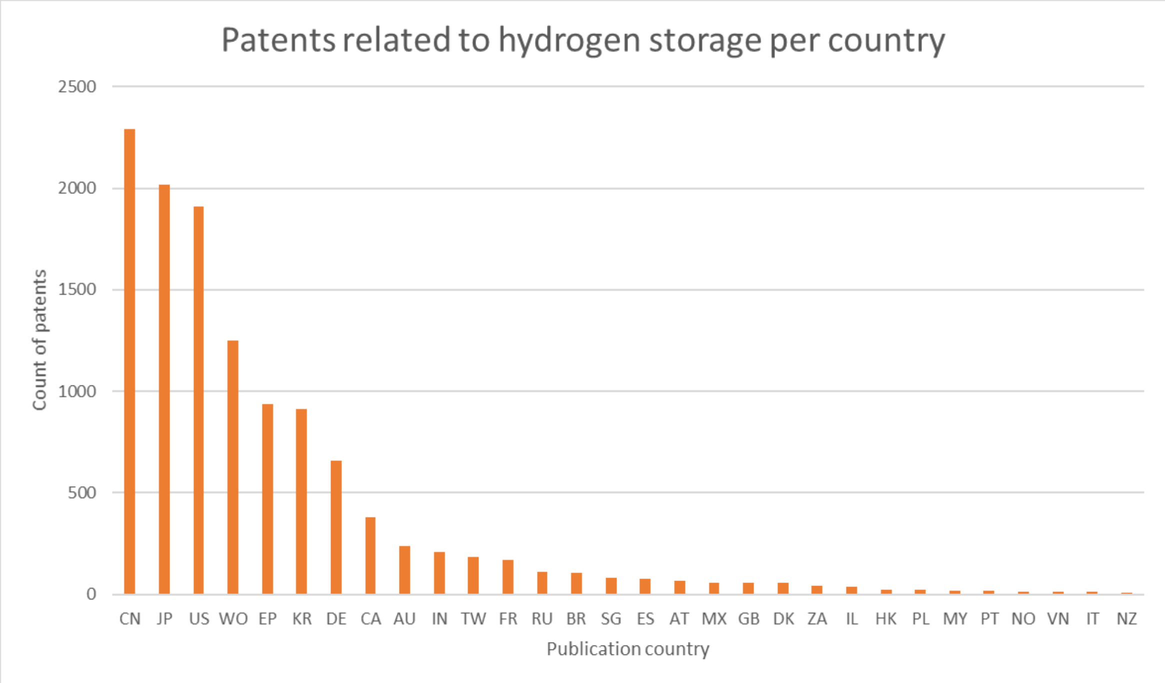


Figure 6: Patent publications related to hydrogen storage per country

More surprisingly, the predominance of China in the publication of patents is only recent in the field of hydrogen storage. **Figure 7** depicts the number of patents of the top 5 countries over the years. Until 2010, Japan was the most active country, closely followed by the US who took the lead between 2010 and 2014. As of 2014, China consequently increased its number of publications and carried on its gradual increase the following years. In 2021, China published almost twice the sum of the number of patent families in the other four countries combined. The activity of Korea is noteworthy as well, they doubled their number of publications in 2017 and later again in 2020.

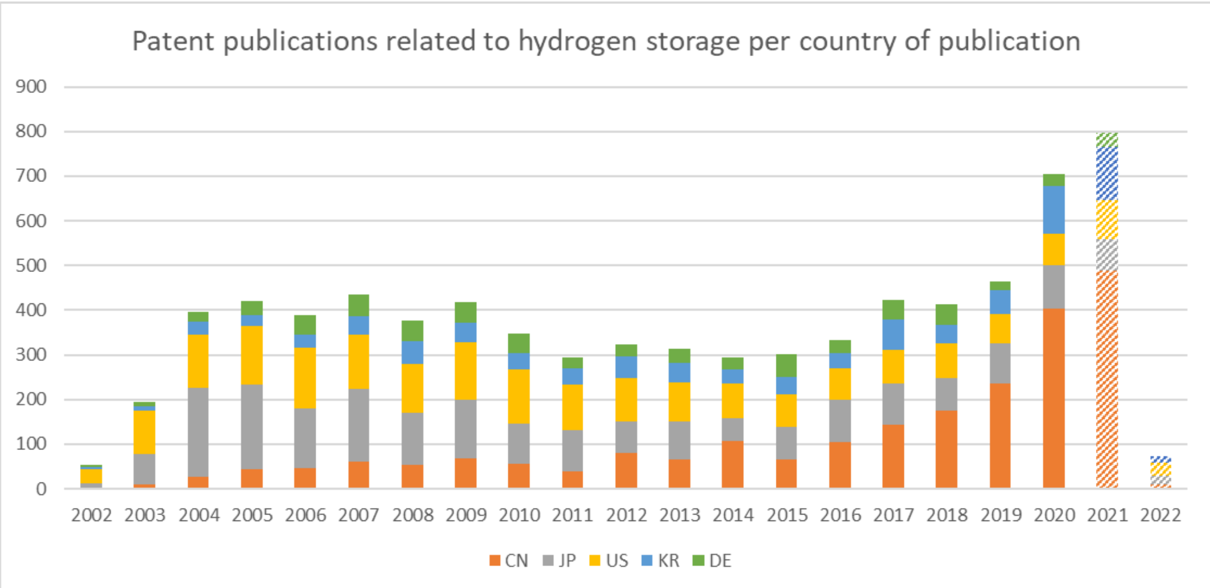


Figure 7: Patent publications related to hydrogen storage per country of publication (2021 and 2022 not fully published)

Lastly, with regards to the actors, the market is led by industrial players who occupy 14 spots of the top 15.

Tables 3 and 4 display the top 10 of respectively companies and academic institutions in the large data set of hydrogen storage.

Table 3: Top 10 of industrial players in the field of hydrogen storage

Company name	Country	Number of patent families
TOYOTA MOTOR	JP	214
HONDA MOTOR	JP	103
GM GLOBAL TECHNOLOGY OPERATIONS	US	88
AIR LIQUIDE	FR	76
LINDE	DE/US	74
BMW - BAYERISCHE MOTOREN WERKE	DE	70
TOYOTA CENTRAL RESEARCH & DEVELOPMENT LABS	JP	63
HYUNDAI MOTOR	KR	55
NISSAN MOTOR	JP	55
TOYOTA INDUSTRIES	JP	55

Table 4: Top 10 of academic players in the field of hydrogen storage

Name of Academic institute	Country	Number of patent families
ZHEJIANG UNIVERSITY	CN	54
TIANJIN NORMAL UNIVERSITY	CN	34
GENERAL RESEARCH INSTITUTE FOR NONFERROUS METALS	CN	30
CEA - COMMISSARIAT A L'ENERGIE ATOMIQUE & AUX ENERGIES ALTERNATIVES	FR	24
ZHANGJIAGANG QINGYUN NEW ENERGY RESEARCH INSTITUTE	CN	21
BEIJING AEROSPACE EXPERIMENTAL TECHNOLOGY INSTITUTE	CN	19
HIROSHIMA UNIVERSITY	JP	19
CNRS - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	FR	18
INHA INDUSTRY PARTNERSHIP INSTITUTE	KR	17
YANGZHOU UNIVERSITY	CN	17

Although the activity of Japan decreased in the previous years, the country is well represented in the top 10 of industries leading the market in terms of publication, with 5 companies ranking in the top 10 and the top 2 companies gathering a number of publications significantly higher. Europe gathers two representatives ranking high in the top 10.

Contrary to hydrogen transport, the overview of academic players in the field of hydrogen storage is more balanced with 2 European entities ranking 4th and 7th. The top remains, however, predominantly led by Chinese entities.

Similar conclusions to Section 4 can be drawn, with Chinese academic entities accounting predominantly for China's patent publication activity, while Japanese industrial actors remain the most represented in the top 10 of industrial players of both fields.

Overview on physical storage

As previously described in section 3, a narrowed dataset of about 2.606 patents was created within the large dataset used in the analysis in the preceding section 5 to specifically examine the patent landscape of physical storage solutions.

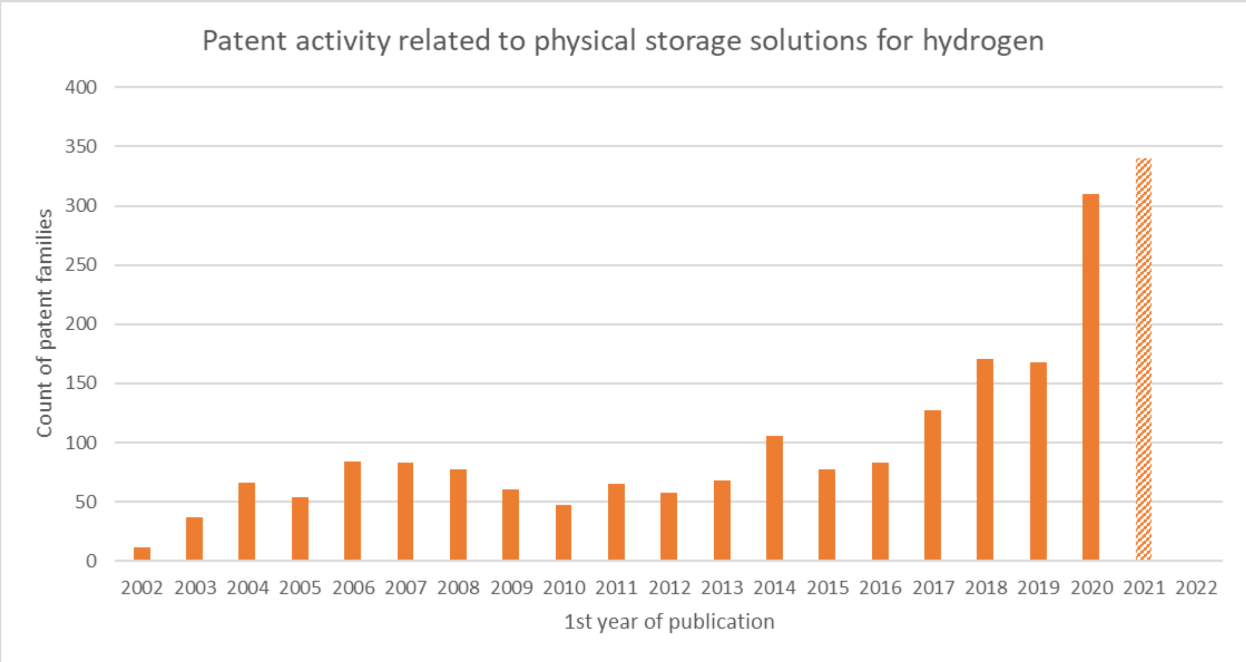


Figure 8: Patent families related to physical storage solutions for hydrogen over time (2021 and 2022 not fully published)

As can be seen from **Figure 8**, the patent publication trend in physical storage is similar to that of the overall hydrogen storage field (cf. **Figure 5**) with an increase starting from 2017 and accelerating in the year 2020.

Based on the CPC classification codes distribution an overview was created on the main activities in the field of physical storage solutions for hydrogen. **Figure 9** below displays the CPC distribution.

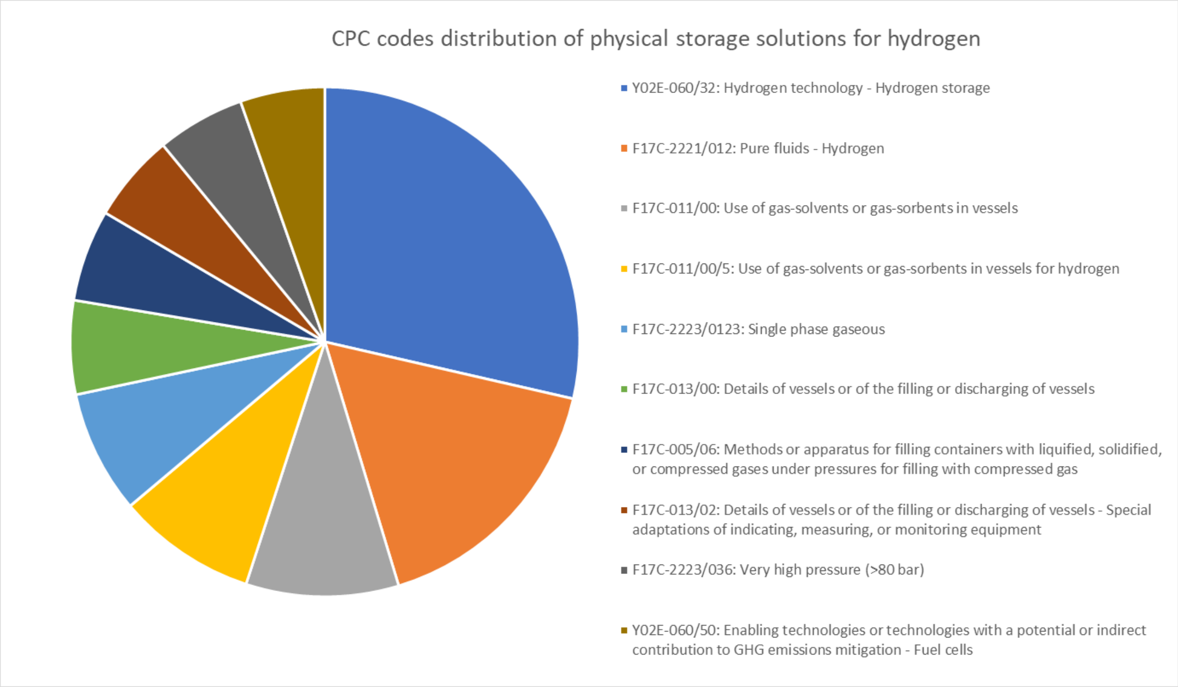


Figure 9: CPC codes distribution of physical storage solutions for hydrogen

It can be seen that vessels (F17C-011/00, F17C-011/00/5, F17C-013/00 and F17C-013/02) are the most explored activities in the field.

Tables 5 and 6 display the top 10 of respectively companies and academic institutions in the specific data set of physical storage solutions for hydrogen.

Table 5: Top 10 of industrial players in the field of physical storage solutions for hydrogen

Company name	Country	Number of patent families
AIR LIQUIDE	FR	74
LINDE	DE/US	70
BMW - BAYERISCHE MOTOREN WERKE	DE	64
GM GLOBAL TECHNOLOGY OPERATIONS	US	56
SHANGHAI HUAPENG EXPLOSION PROOF TECHNOLOGY	CN	45
DAEWOO SHIPBUILDING & MARINE ENGINEERING	KR	44
HYUNDAI MOTOR	KR	44
TOYOTA MOTOR	JP	41
DAIMLER	DE	38
HONDA MOTOR	JP	32

Table 6: Top 10 of academic players in the field of physical storage solutions for hydrogen

Name of Academic institute	Country	Number of patent families
CEA - COMMISSARIAT A L'ENERGIE ATOMIQUE & AUX ENERGIES ALTERNATIVES	FR	19
ZHANGJIAGANG QINGYUN NEW ENERGY RESEARCH INSTITUTE	CN	15
BEIJING AEROSPACE EXPERIMENTAL TECHNOLOGY INSTITUTE	CN	12
ZHEJIANG UNIVERSITY	CN	11
CHINA SINOPEC QINGDAO SAFETY ENGINEERING INSTITUTE	CN	10
GENERAL RESEARCH INSTITUTE FOR NONFERROUS METALS	CN	8
CNRS - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	FR	7
TSINGHUA UNIVERSITY	CN	7
DEUTSCHE ZENTRUM FUER LUFT & RAUMFAHRT	DE	6
KOREA INSTITUTE OF ENERGY RESEARCH	KR	6

With regards to the academic players, a similar trend to the one of the large storage dataset can be observed, with the predominant presence of Chinese institutes. However, a more important number of European academic entities are present in the top 10 and a French institute is leading the ranking in this specific field.

This growing European presence in the ranking is also visible in the top 10 of industrial players that is led by 3 European companies. Noticeably, Japanese companies appear at the bottom of the ranking.

In sum, the publications in this specific field are driven by the same actors as the large dataset with variations in their rankings.

Overview on chemical storage

The specific dataset created within the large dataset to analyze the specific activity in the field of chemical storage solutions for hydrogen gathers 770 patents. **Figure 10** displays the CPC code distribution of this dataset with a majority using the CPC code Y02E-060/32 or C01B-003/00.

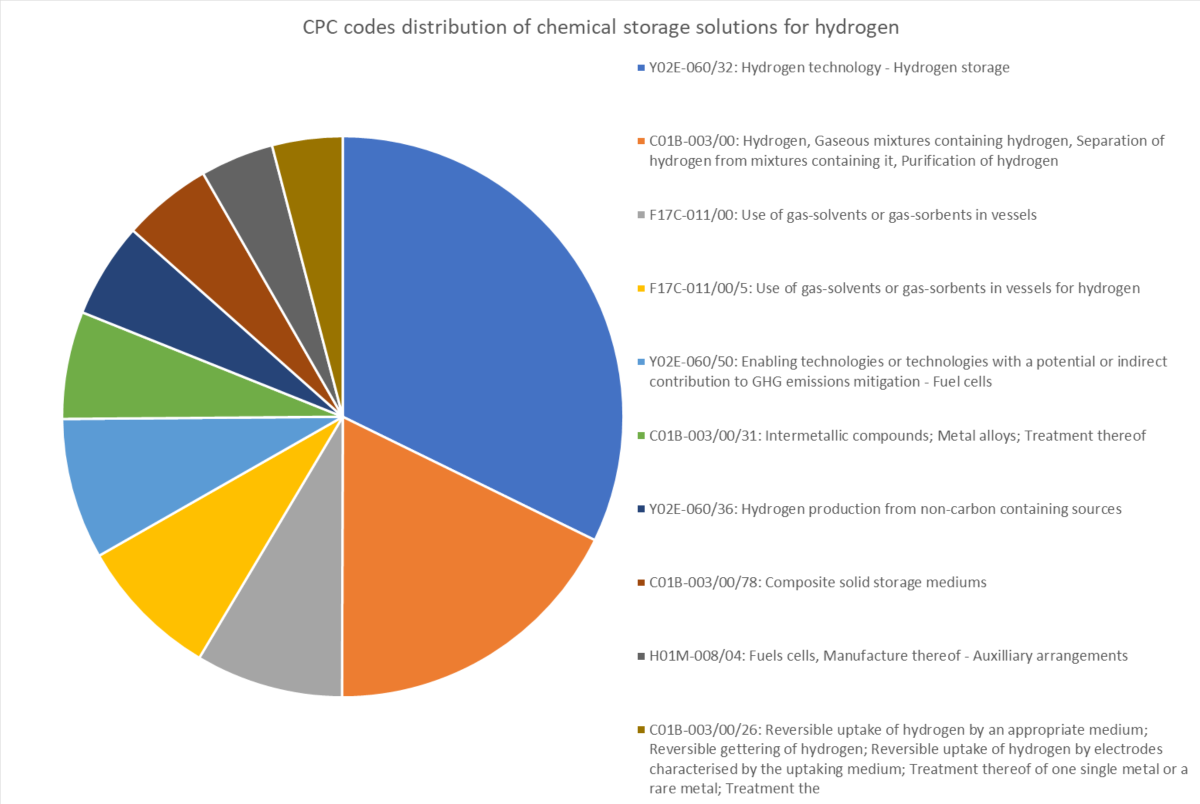


Figure 10: CPC codes distribution of chemical storage solutions for hydrogen

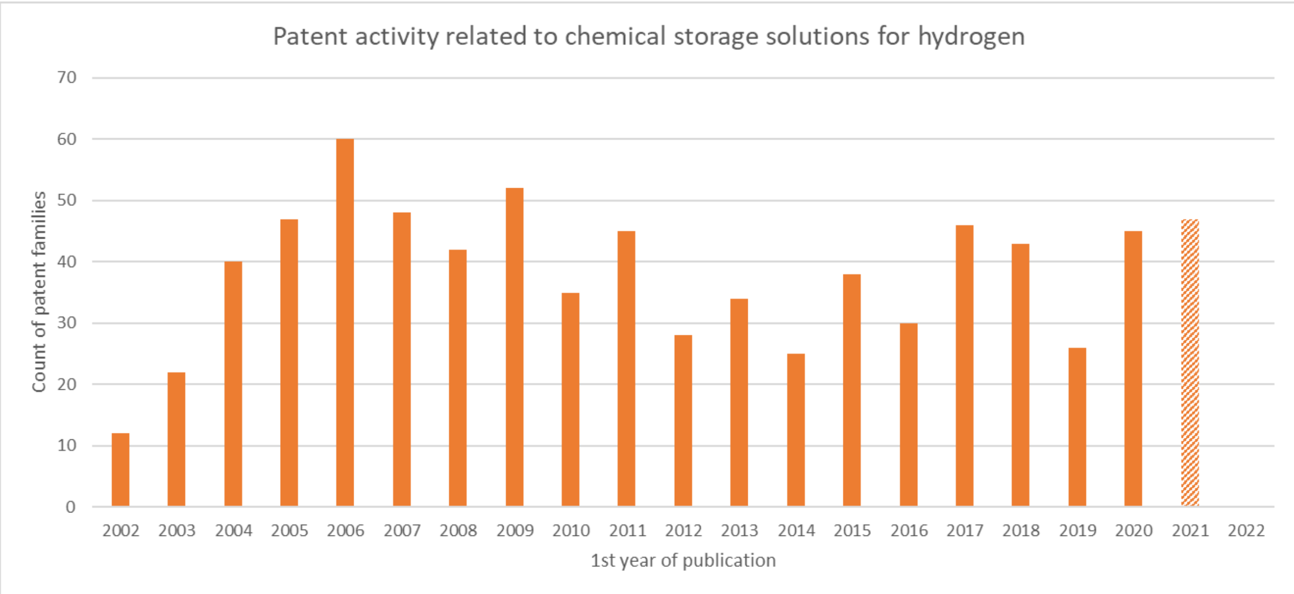


Figure 11: Number of publications of patents related to chemical storage solutions for hydrogen over time (2021 and 2022 not fully published)

Figure 11 displays a relatively unique trend in the number of publication over time in this specific field compared to the trends of the fields previously analyzed. The number of publications reached a peak in 2006 and has been globally decreasing since, with cycles of increase and decrease over 2-3 years periods.

With respect to the industrial players displayed in **Table 7**, a clear dominance of two countries appears as the top 10 is almost exclusively composed of companies from Japan and the US. More surprisingly, no Chinese companies appear in the top 10. This absence of China is also visible, to a lesser extent, in the academic field shown in **Table 8**. The top 10 is composed of a balanced mix of European, Japanese, Korean and Chinese entities

Table 7: Top 10 of industrial players in the field of chemical storage solutions for hydrogen

Company name	Country	Number of patent families
GM GLOBAL TECHNOLOGY OPERATIONS	US	29
TAIHEIYO CEMENT	JP	24
TOYOTA CENTRAL RESEARCH & DEVELOPMENT LABS	JP	19
NISSAN MOTOR	JP	12
SAVANNAH RIVER NUCLEAR SOLUTIONS	US	10
HYUNDAI MOTOR	KR	9
INTELLIGENT ENERGY	UK	9
TOYOTA MOTOR	JP	9
GENERAL ELECTRIC	US	8
VODIK LABS	US	8

Table 8: Top 10 of academic players in the field of chemical storage solutions for hydrogen

Name of Academic institute	Country	Number of patent families
CEA - COMMISSARIAT A L'ENERGIE ATOMIQUE & AUX ENERGIES ALTERNATIVES	FR	21
GENERAL RESEARCH INSTITUTE FOR NONFERROUS METALS	CN	19
HIROSHIMA UNIVERSITY	JP	16
ZHEJIANG UNIVERSITY	CN	14
CNRS - CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE	FR	12
GUILIN UNIVERSITY OF ELECTRONIC TECHNOLOGY	CN	6
KOREA INSTITUTE OF SCIENCE & TECHNOLOGY	KR	6
SHANDONG UNIVERSITY OF TECHNOLOGY	CN	6
HELMHOLTZ ZENTRUM GEESTHACHT	DE	5
KOREA BASIC SCIENCE INSTITUTE	KR	5

Overview on adsorption-based storage

In order to examine the activity in the field on adsorption-based storage solutions in details, a specific dataset of 246 patents was created within the large dataset of hydrogen storage.

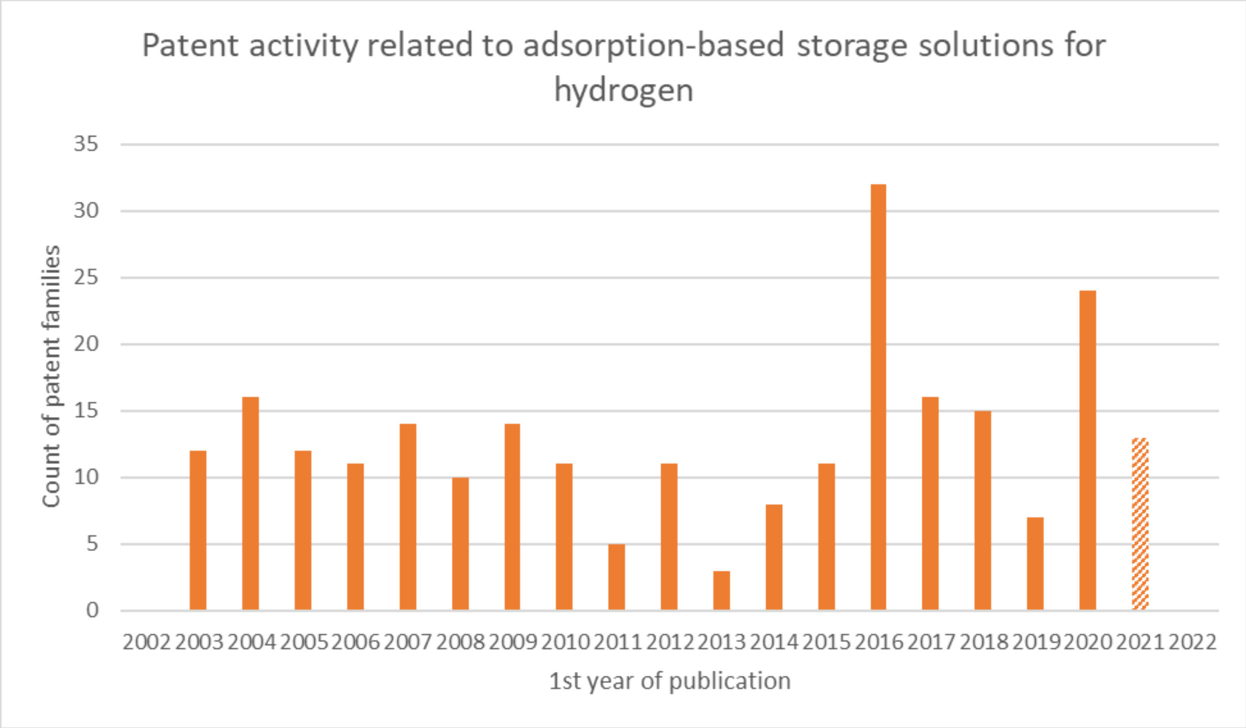


Figure 12: Patent families related to adsorption-based storage solutions for hydrogen over time (2021 and 2022 not fully published)

Similar to chemical storage solution for hydrogen, there is no clear trend in the number of patents publications in the field of adsorption-based storage solution over the years. The number of publications remained relatively stable until 2016 where it reached its peak. It then decreases again before reached another, lower, peak in 2020.

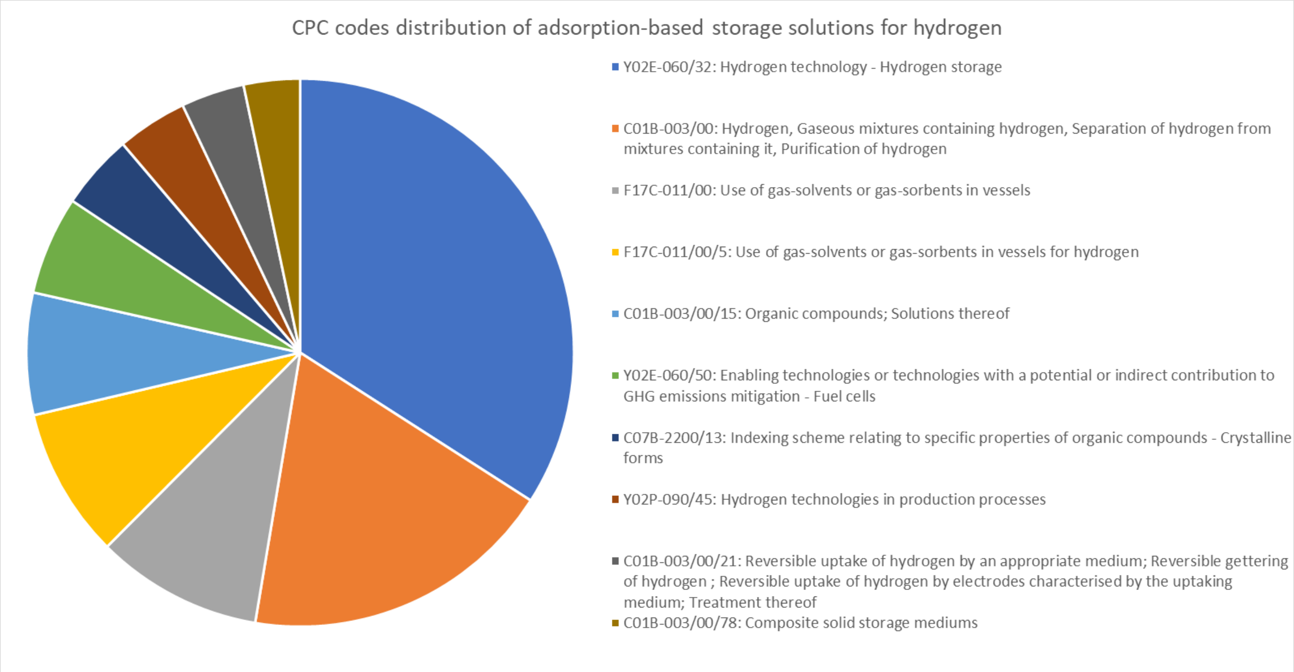


Figure 13: CPC codes distribution of chemical storage solutions for hydrogen

Table 9: Top 10 of industrial players in the field of adsorption-based storage solutions for hydrogen

Company name	Country	Number of patent families
HONDA MOTOR	JP	6
TOYOTA MOTOR	JP	6
CHINA PETROLEUM & CHEMICAL	CN	5
TOYOTA CENTRAL RESEARCH & DEVELOPMENT LABS	JP	5
TECHNO BANK	JP	4
AAQIUS & AAQIUS	CH	3
AIR LIQUIDE	FR	3
AIR PRODUCTS & CHEMICALS	US	3
BLUCHER	DE	3
GM GLOBAL TECHNOLOGY OPERATIONS	US	3

Table 10: Top 10 of academic players in the field of adsorption-based storage solutions for hydrogen

Name of Academic institute	Country	Number of patent families
TIANJIN NORMAL UNIVERSITY	CN	32
INHA INDUSTRY PARTNERSHIP INSTITUTE	KR	7
TSINGHUA UNIVERSITY	CN	5
SHANDONG UNIVERSITY OF TECHNOLOGY	CN	4
WORLD ENERGY HYDROPOWER TECHNOLOGY	CN	4
KONKUK UNIVERSITY INDUSTRIAL COOPERATION	KR	3
KOREA INSTITUTE OF ENERGY RESEARCH	KR	3
CEA - COMMISSARIAT A L'ENERGIE ATOMIQUE & AUX ENERGIES ALTERNATIVES	FR	2
EAST CHINA NORMAL UNIVERSITY	CN	2
GUILIN UNIVERSITY OF ELECTRONIC TECHNOLOGY	CN	2

Comparing the top 10 list of companies with the most patents in the field of absorption-based storage solutions with the previous lists in the field of physical and chemical storage, the most active entity from the US, GM GLOBAL TECHNOLOGY OPERATIONS, leading in the field of chemical storage does not appear in the top 10. Additionally, numerous new actors, mainly European, appeared. The research in this specific field is thus carried out by different players.

Similarly, the ranking of academic players is composed of new players, mainly Chinese. Compared to the previous rankings in the academic field, the predominance of Chinese entities is more acute.

6. Conclusions

As global warming is imposing ambitious GHG emission reduction targets, hydrogen is looked upon as a key component in the energy transition due to its strong potential as a fuel, energy carrier and intermediate storage mean.

Nevertheless, some important technical and technological barriers are hindering the massive scale-up and widespread use of hydrogen in the industry – the two main hindrances being hydrogen storage and transport. Consequently, companies and academic entities have been investigating these fields in order to develop innovative, standardizable and scalable solutions.

With regard to **hydrogen transport**, two main directions are discussed - the transport of gaseous hydrogen and the transport of liquid hydrogen. The analysis of patent applications over time has shown that both fields have benefited from a renewed interest in the last years, with high publication numbers in 2019-2021. Nevertheless, the relative activity levels of gaseous hydrogen remain negligible compared to the activity levels of liquid hydrogen. The market is predominantly led by Chinese academic entities, while European academic and industrial entities take a second place. Although both categories have been separately examined, it is important to note that all hydrogen transport solutions can be considered as hydrogen storage solutions, as the hydrogen is temporarily stored during the time of transportation.

Concerning **hydrogen storage**, similar trends can be observed in patent publications in recent years, confirming the growing interest for hydrogen around the world. The research efforts are mainly focused on physical storage solutions. Contrary to transport, European industries are leading the way in this field while China's domination is confined to the academic scene. Chemical storage and adsorption-based solutions appear to be more niche markets mainly led by Japan, followed by Europe and the US on the industrial front, while China remains a central player in the academic ranking.

The patent activity trends in the field of **hydrogen transport and storage** confirm that globally there is a growing interest in making hydrogen a safe and climate-friendly tool in the context of the energy transition by investing in multiple technologies to safely transport and store this fuel of the future.