HYDROGEN FUEL: INSIGHTS INTO A GROWING MARKET

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CONTENTS

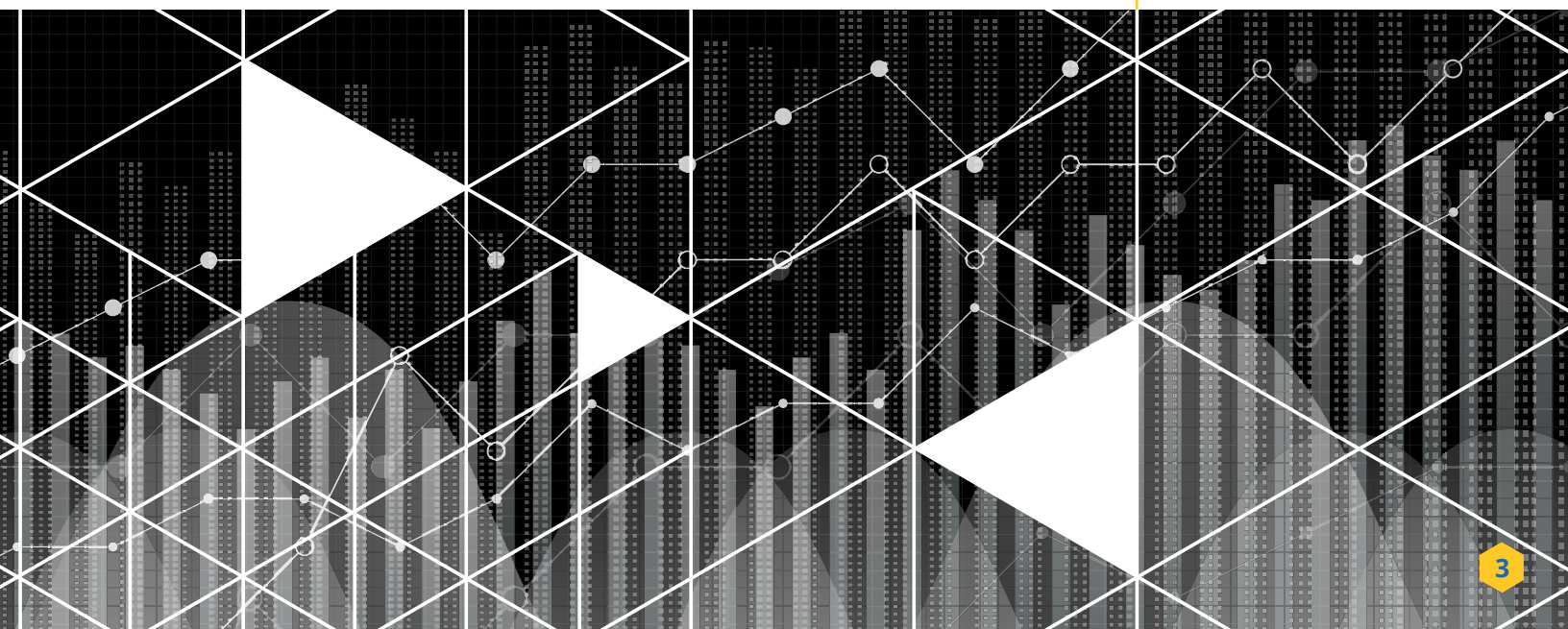
INTRODUCTION

Hydrogen is predicted to transform energy systems worldwide. The current fossil fuel-based model is unsustainable and environmentally damaging. There is a pressing need to move to an alternative approach based on renewable sources, and now it is widely recognized that hydrogen could play a key role in this transition[1].

Given the promise of hydrogen, there is intense and widespread interest across multiple industries including electricity, heating and transportation. With new innovations driving rapid progress, the worldwide hydrogen market is expected to see dramatic growth and is **predicted to exceed $200bn by the end of 2025**[2]. This expanding field raises significant business opportunities.

For companies operating in this space, it is essential to understand the complex landscape in order to identify areas of commercial potential. This analysis uses data provided by the CAS content collection to shed light on the key trends in hydrogen fuel innovation and research. By leveraging this information, companies can gain valuable insights into the growing market.

HYDROGEN IS PREDICTED TO TRANSFORM ENERGY SYSTEMS WORLDWIDE



CHAPTER 1

GLOBAL CONTEXT AND KEY DRIVERS

THE URGENT NEED TO REDUCE DEPENDENCE ON FOSSIL FUELS

While fossil fuels currently account for 90% of the world's energy supply[3], the use of this non-renewable energy source is not sustainable. The depletion of reserves, alongside an increasing global population, means that these resources will soon fail to satisfy worldwide demand. This strain on supply will cause fuel prices to rise, raising significant concerns for governments in terms of energy security. As such, **reducing reliance on fossil fuels is an urgent priority.**

A further driver to move away from fossil fuels is the negative environmental impact of their by-products. Toxins such as mercury can accumulate in certain food chains, ultimately posing a health risk to humans. Furthermore, the combustion of fossil fuels also generates a range of air pollutants. In addition to particulate matter and soot, which can significantly compromise air quality, some emitted gases can cause acid rain and many also contribute to the greenhouse effect[4].

The greenhouse effect is the process by which the atmosphere traps the sun's heat by radiating it back to earth. While this does occur naturally, industrial emissions have enhanced the effect[5]. It is now widely accepted that this has had a significant impact on global temperatures, which have risen by 1.2°C since the Industrial Revolution[6]. The environmental effects of climate change are expected to become more extreme as temperatures continue to rise. For example, melting polar ice caps will cause rising sea levels and increased flooding, and more frequent droughts and heatwaves will result in crop failure and famine[7].

In the context of industrial emissions, the gas primarily responsible for enhancing the greenhouse effect is carbon dioxide (CO_2)[8]. As seen in Figure 1, worldwide CO_2 emissions have been increasing steadily since the mid-20th century, and this gas is produced in huge quantities by the world's largest economies. China has the highest emission levels, followed by the USA and Russia. In general, these countries produce such high levels of CO_2 due to their heavy reliance on fossil fuels to meet substantial domestic energy demands.

Given the significant environmental consequences of these high emission levels, many countries have entered into international agreements to address this problem. As early as 1992, 154 nations signed the United Nations Framework Convention on Climate Change Treaty, committing to reducing atmospheric concentrations of greenhouse gases. Later, in 1997, the Kyoto Protocol set further requirements for cutting down emissions. For countries looking to meet these targets while still satisfying their energy needs, it is essential to leverage alternative sources of energy.

There is a wide range of alternative energy sources, including solar, wind, hydro, wave action, tidal action, ocean thermal, geothermal and biomass. None of these in isolation can provide a reliable, cost-effective and secure energy supply[9], so future models will have to incorporate a range of sources. Developing a diversified renewable energy portfolio raises considerable challenges, and it is increasingly accepted that hydrogen will play a major role in addressing these[1].

The key advantage of hydrogen is its ability to function both as a fuel and an 'energy carrier'. Essentially, it can move and store energy from diverse primary sources, including both fossil fuels and renewable means. With this capacity for storage, it is possible to maximize the potential of renewable technology such as solar and wind. Instead of curtailing renewable electricity production when the grid is saturated, energy can be stored using hydrogen. This can provide valuable reserves to help the system meet periods of high demand. Given the promise of hydrogen, **the 2019 International Energy Agency (IEA) report suggests it is now time to scale up hydrogen fuel technology** and reduce costs to realize its full potential[10].

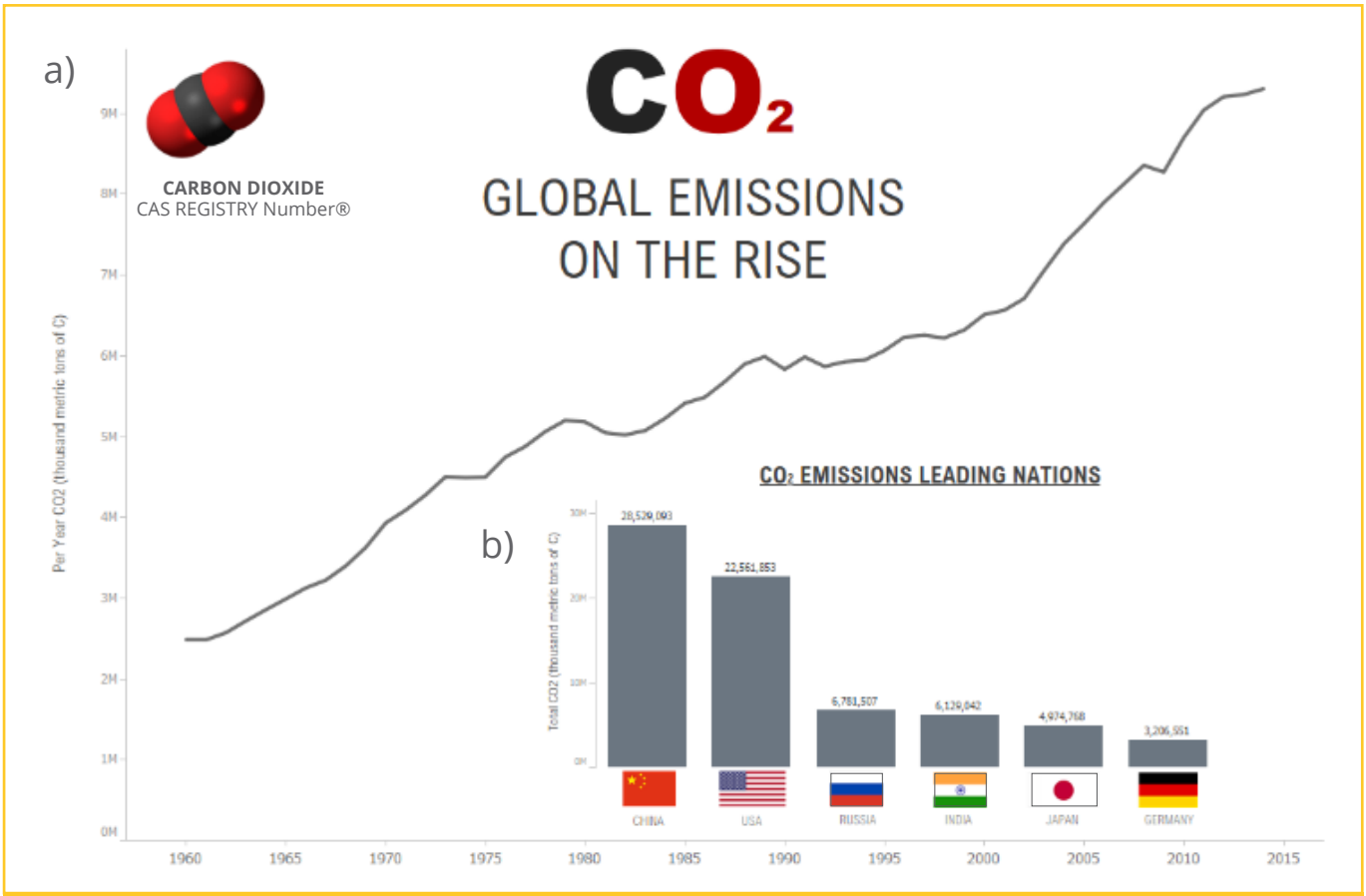


Figure 1. a) The continued rise of global CO_2 emissions over time. b) CO_2 emissions from the six nations generating the highest levels of this gas worldwide. Source: https://cdiac.ess-dive.lbl.gov/

THE 2019 INTERNATIONAL ENERGY AGENCY (IEA) REPORT SUGGESTS IT IS NOW TIME TO SCALE UP HYDROGEN FUEL TECHNOLOGY

HYDROGEN PRODUCTION

Currently, hydrogen gas is most commonly generated from natural gas by the process of steam reforming. However, the disadvantage of this method is that it produces carbon monoxide (CO), an atmospheric pollutant. It is possible to react CO with water to produce additional hydrogen, but this comes at the cost of producing CO_2, a powerful greenhouse gas as previously discussed. To address this issue, a range of technologies has been developed. One is "Carbon Capture and Storage" (CCS)[11], in which CO_2 is captured, stored and used by other industries. For example, the food industry can use it to extend the shelf-life of packaged goods and to carbonate soft drinks. Additionally, oil and gas companies can use the CO_2 to enhance the recovery of crude oil. However, despite the many uses of CCS, its adoption has been relatively low on a global scale. This is primarily due to the high set-up and operating costs.

There is a range of alternative ways to generate hydrogen that do not require fossil fuels. Of these, the most common is to use electricity to split water into hydrogen and oxygen. If this electricity is generated by renewable means, hydrogen production can be fully decarbonized. The disadvantage of electrolysis is the considerable expense of the process, but **improvements in the membranes and catalysts used are expected to reduce the costs of producing hydrogen in the near future**[2].

While electrolysis systems are relatively well-established, there are other methods in the earlier stages of development. For example, solar water splitting uses light energy to convert water into hydrogen and oxygen, and microbes can produce hydrogen using either sunlight or biomass. These options are not yet applicable to large-scale hydrogen production, but may well be used more widely as technology develops.

GENERATING POWER FROM HYDROGEN GAS

Power can be produced from hydrogen via a fuel cell, a system originally developed in the 1970s. Much like a battery, a fuel cell consists of a cathode, anode, and electrolyte. Electrical power is produced through the chemical reaction of hydrogen and oxygen within the cell. Since this reaction generates only water, electricity and heat, **hydrogen use does not contribute to the greenhouse effect.**

The chemical reaction within a fuel cell requires an efficient catalyst that can withstand the harsh acidic environment. Platinum group metals are excellent candidates for such catalysts and have been used in existing fuel cells to date. However, the rarity and high cost of platinum currently inhibit the wide-scale application of fuel cell technology. Given the expense involved, the scientific community is exploring how to make the process more cost-effective. These developments are likely to lead to significant market growth and raise a range of new commercial possibilities in this sector.

IMPROVEMENTS IN THE MEMBRANES AND CATALYSTS USED ARE EXPECTED TO REDUCE THE COSTS OF PRODUCING HYDROGEN IN THE NEAR FUTURE

MARKET OVERVIEW

A general overview of the hydrogen market can prove very valuable for companies planning to enter this space. With an understanding of the global market size and the key areas and geographies involved, businesses will be better-placed to identify promising areas of opportunity.

Across the globe in 2018, over $14.7 billion was invested in developing the hydrogen economy, and this figure is expected to increase to an incredible $26.8 billion by 2024[12]. Hydrogen supply technologies accounted for 63.9% of total investments in 2018, whereas technologies for converting hydrogen to energy made up 30.3% of the market. Over the next five years, it is predicted that the relative market share of these two sectors will begin to equalise, with investments in supply falling and conversion increasing over time[12].

In terms of hydrogen production, the dominant technologies are steam methane reforming, coal gasification, partial oxidation and the electrolysis of water. Of these, steam methane reforming commands the greatest market share, as it is a well-established process for which the raw materials are widely available and easy to source[13]. However, as the technologies used for water electrolysis continue to evolve, it is likely that new commercial opportunities will arise in this area.

Considering the technologies used for converting hydrogen to energy, the market is dominated by a range of fuel cells. Those with the best commercial prospects include polymer electrolyte membrane fuel cells, direct methanol fuel cells and alkaline fuel cells. Companies looking to enter the market may benefit from exploring these sectors.

Geographically speaking, America holds the biggest share of the hydrogen and fuel cells market. Asia Pacific is also a key area of investment, expected to see marked growth over the next five years due to an increasing population, rising energy demands and rapid economic development. Indeed, according to recent estimates, the Asia Pacific market is projected to grow at a CAGR of 27.09% to 2025, as compared to 24.72% for America[14]. For those planning to invest in hydrogen fuel, it is worth keeping an eye on these rapidly expanding areas.

CHAPTER 2

THE EVOLVING RESEARCH LANDSCAPE

INTRODUCTION

As countries strive to reduce greenhouse gas emissions, hydrogen fuel is attracting a wealth of research and innovation. In particular, scientists are seeking to overcome the challenges associated with hydrogen transportation and storage, so the fuel can be used on a larger scale. In this chapter, we describe the overall innovation trends in this field and identify emerging areas of interest that could raise new business opportunities.

TIMELINE OF INNOVATION

Exploring innovation trends in the hydrogen fuel space can shed valuable light on this sector, revealing continuing and emerging areas of interest and opportunity. As such, the timeline of patent publication is shown in Figure 2.

The volume of patents initially began to rise after the Kyoto Protocol was adopted in 1997, due to the increased pressure on participating countries to reduce their contribution to the greenhouse effect.

HYDROGEN FUEL
PATENTS PUBLICATION TIMELINE

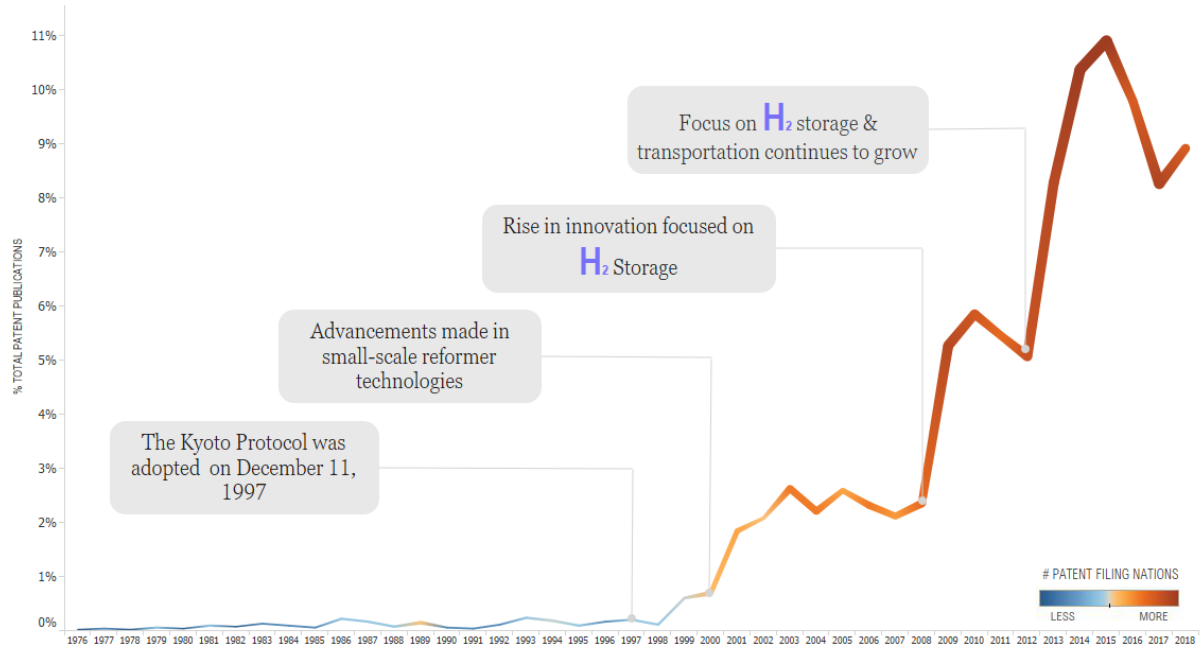


Figure 2: The timeline of patent publication in the hydrogen fuel space. The number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

As scientists began to explore potential avenues for producing reduced or zero-emissions energy, hydrogen gas production via reforming was identified as a promising process that could be employed on an industrial scale.

In 2000, the volume of patent publications in the hydrogen fuel space reached its first peak. At this time, hydrogen use in the residential and transportation sectors was limited because storage tanks were under-developed. Issues such as leakage were a significant concern, and using existing large and heavy tanks in vehicles was impractical. In an effort to address these issues, advancements were made in "plate-type" steam methane reformers for fuel cell systems. These are much more compact than industrial reformers, and it was thought that they could provide a way around using large tanks for storing pressurized hydrogen gas in the residential and transportation sectors. However, this approach was deemed impractical by the industry.

Although "plate-type" reformers are still under investigation, the general focus of research shifted towards solving the challenges associated with the weight of storage tanks and the leakage of hydrogen gas. In 2008, researchers achieved a breakthrough by developing a clay-plastic composite material which is light, durable, and achieved 0.01% gas leakage per year out of a 50-atm hydrogen tank[15]. Following this significant advance, a steep rise in the volume of publications was seen from 2008 to 2009.

In 2008, hydrogen storage materials formed the leading hydrogen-related concept indexed by CAS analysts, but fuel gas reforming and fuel gas steam reforming came a close second and third respectively. A year later, as shown in Figure 3, the volume of publications on hydrogen storage materials had grown by 4.4%. This remains the leading topic of innovation by a wide margin, while publications on steam and gas reforming have dropped.

As the interest in hydrogen storage has grown in the decade since 2008, the number of patent filing nations has increased alongside the volume of publications, as shown in Figure 2. While the number of documents published witnessed a steep drop in 2017, it has recovered a little since. The general upward trend indicates that more companies are competing in this space on a global scale, since successful solutions for improving hydrogen storage could prove very lucrative.

H_2 STORAGE
INNOVATION GROWTH

2008	% OF TOTAL PUBS	2009	% OF TOTAL PUBS
Hydrogen storage materials	4.9%	Hydrogen storage materials	9.3%
Fuel gas reforming	4.0%	Fuel gas steam reforming	2.6%
Fuel gas steam reforming	3.6%	Fuel gas reforming	2.4%
Steam reforming catalysts	2.0%	Ball milling	1.4%
Reforming catalysts	1.9%	Desorption	1.3%
Fuel cells	1.8%	Hydrogenation	1.1%
Reforming apparatus	1.1%	Microstructure	1.1%
Microstructure	1.0%	Absorption	1.1%
Desorption	0.9%	Fuel cells	1.0%
Hydrocarbons	0.8%	Phase composition	0.9%

Figure 3: Comparison of the main areas of hydrogen fuel innovation in 2008 and 2009.
Source: CAS Content Collection.

EMERGING AREAS OF INTEREST

Figure 4 shows that hydrogen storage has remained the leading topic of interest over the last decade. This is followed by dehydrogenation, which has been established as the second leading area of innovation since 2012. With dehydrogenation methods, it is possible to extract hydrogen gas from ammonia or organic hydrides using metal catalysts. Alternatively, hydrogen can be created through the aromatization reaction of organic compounds such as methylcyclohexane.

Although dehydrogenation is a relatively slow process, the strategy has a major advantage in that the storage and transportation infrastructure for both ammonia and methylcyclohexane is well-established. Leveraging existing distribution systems could offer cost advantages compared to handling pure hydrogen, for which the infrastructure remains in the early stages of development despite continuing research efforts.

LEVERAGING EXISTING DISTRIBUTION SYSTEMS COULD OFFER COST ADVANTAGES

RESEARCH FOCUS SHIFT: JOURNALS & PATENTS

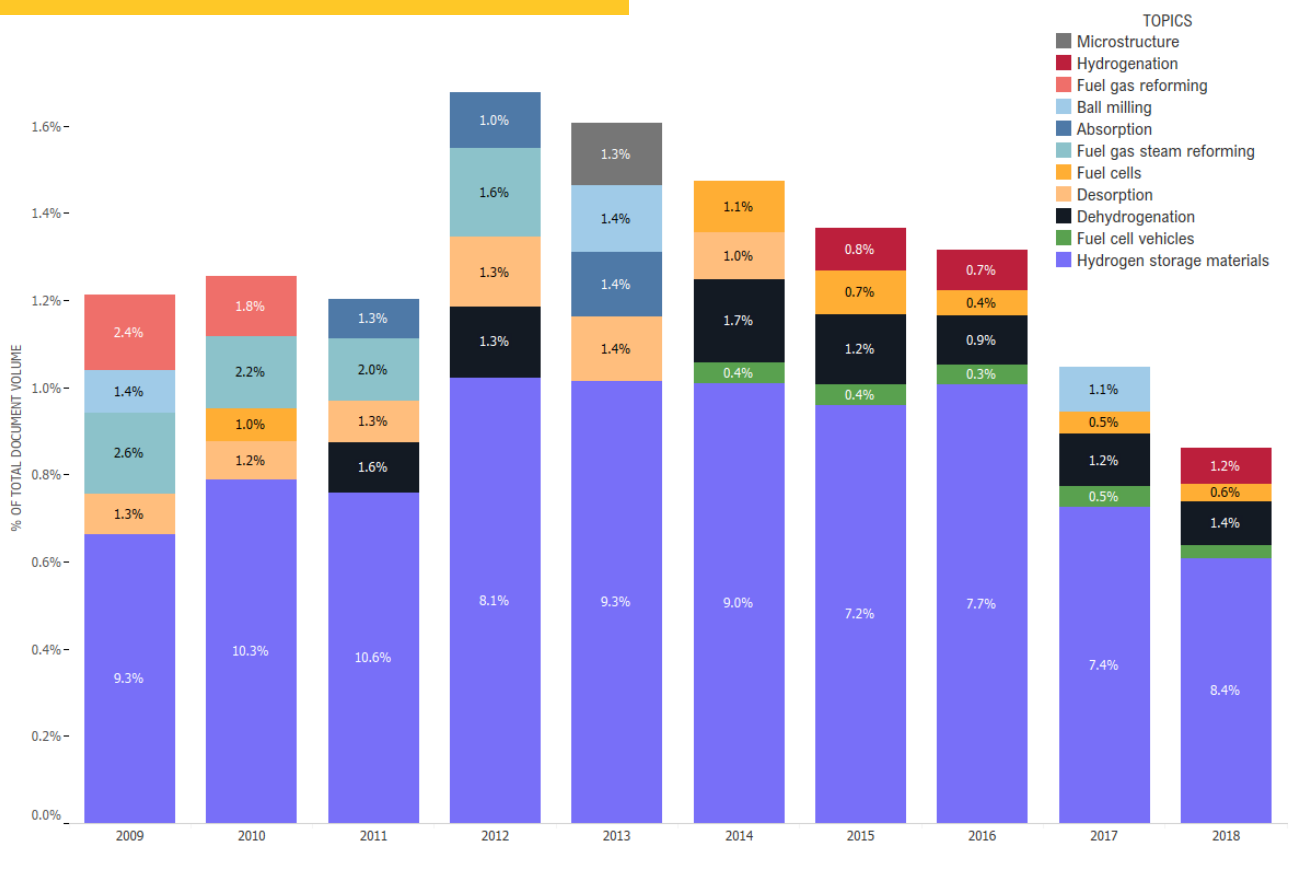


Figure 4: Trends in the focus of journal articles and patents within the hydrogen fuel space. Source: CAS Content Collection.

CONCLUSION

Since the adoption of the Kyoto Protocol in 1997, there has been a marked increase in hydrogen fuel innovation. While initial advancements were centered around small-scale reformer technologies, the focus has now moved to hydrogen storage and transportation. The difficulties encountered in storing hydrogen, coupled with the lack of distribution infrastructure, currently form the biggest barriers to the more widespread use of the fuel. These challenges have stimulated a more recent interest in dehydrogenation methods, which could provide a way to circumvent the main difficulties. For those looking to invest in this sector, it is worth exploring the field of dehydrogenation for commercial opportunities, as well as keeping abreast of the latest developments in hydrogen transportation and storage technology.

CHAPTER 3

GLOBAL TRENDS IN HYDROGEN FUEL RESEARCH

INTRODUCTION

An awareness of the global market can prove immensely valuable for those looking to move into the hydrogen fuel space. For example, analyzing worldwide patterns of innovation can help companies find potential collaborators, discover key areas of expanding potential and make more informed investment decisions. In this chapter, we present the trends in hydrogen research in major global markets and describe the filing patterns in the main patent offices. This information can provide a useful resource to guide business decisions.

HYDROGEN FUEL PATENT PUBLICATIONS
GLOBAL VIEW 1976 -2018

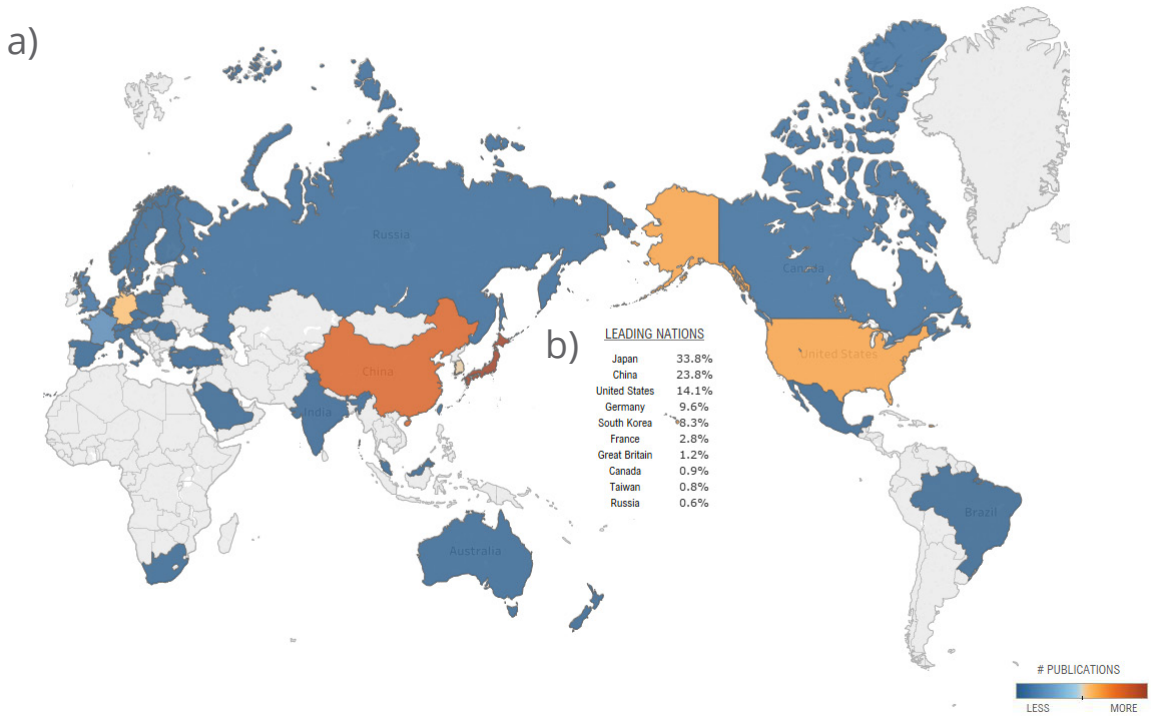


Figure 5: a) Global view of patent filing in the hydrogen fuel space. b) The top ten leading nations in terms of hydrogen fuel patent publications. Source: CAS Content Collection.

GLOBAL PATTERNS IN HYDROGEN FUEL

Figure 5 shows the worldwide distribution of patent filing in the hydrogen fuel space. It shows the Asia-Pacific Region (APAC) produces 66.7% of all hydrogen-related patents, with four of its nations within the top ten. Of these, **Japan is the global leader in hydrogen fuel research**, producing a third of all inventions. The second highest output comes from China, which published almost a quarter of the worldwide total. Overall, APAC continues to be a dominant force in this market, as the region stands to gain the most from adopting hydrogen fuel technology to reduce emissions across various industry sectors.

The top ten list also contains four European countries: Germany, France, Great Britain and Russia. The leading nation here is Germany, which publishes 9.7% of hydrogen fuel documents, whereas Russia is the lowest of the ten, producing only 0.6%. The North American publications are mostly from the USA (14%), with Canada generating a smaller volume (0.9%).

Analysis indicates that the leading nations primarily file patents at home, as shown in Figure 6. Some of the reasons why countries are less likely to file patents abroad include budget and time constraints, concerns about the relevance of inventions in overseas markets, and limitations in the ability to enforce patents abroad.

WHO IS FILLING WHERE?
HYDROGEN FUEL INNOVATION

Figure 6: The patent filing behavior of the leading nations in hydrogen fuel innovation.
Source: CAS Content Collection.

EUROPE

PATENT PUBLICATIONS
2000 - 2018

a)

TOP 10 SUBSTANCES	
Carbon monoxide	1.5%
Carbon dioxide	1.3%
Water	1.2%
Methane	1.1%
Nickel	1.1%
Oxygen	1.0%
Platinum	0.9%
Palladium	0.9%
Alumina	0.7%
Methanol	0.6%

TOP 10 TOPICS	
Hydrogen storage materials	4.3%
Fuel cells	2.3%
Hydrides	1.8%
Fuel gas reforming	1.3%
Hydrocarbons	1.0%
Fuel gas steam reforming	0.9%
Heat exchangers	0.9%
Heat transfer	0.6%
Reforming apparatus	0.5%
Fuel cell vehicles	0.5%

b)

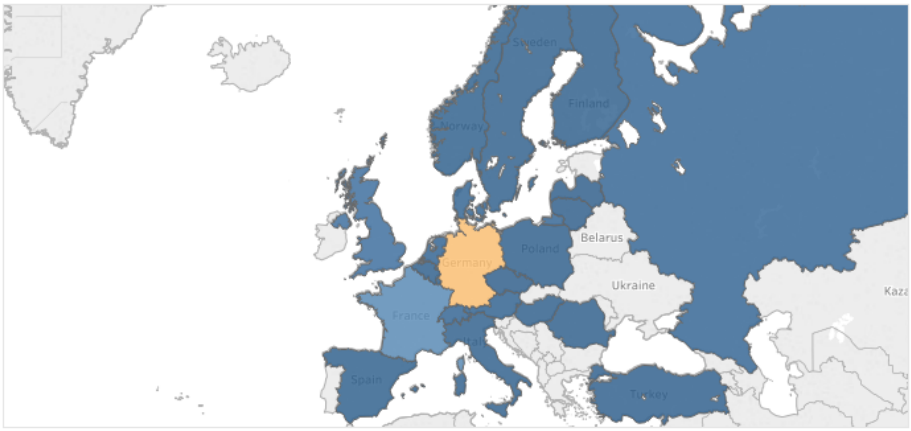


Figure 7: a) Top ten research topics and substances included in hydrogen fuel patents within Europe. b) Regional view of hydrogen fuel patent publications. Source: CAS Content Collection.

For companies looking to invest in hydrogen fuel, examining the current trends in innovation can reveal hotspots of interest and potentially highlight underserved research areas that could provide new opportunities. Figure 7a shows the top subjects of European patent filings and the substances most often indexed by CAS. Examining the data reveals that the leading topics and chemical substances correspond to two main areas of research. For example, subjects such as “Heat exchangers”, “Reforming apparatus” and “Fuel gas steam reforming”, along with methane, carbon monoxide and alumina, are related to the industrial sector. Innovations in these areas will focus on challenges such as the decarbonized production of steel and various chemicals.

The emergence of trending topics such as “Fuel Cells” and “Fuel Cell Vehicles” is driven by the application of hydrogen fuel technology in transportation, as well as commercial and residential heating and electricity. These highly studied areas may generate increasing business potential as progress advances.

Figure 7b shows the geographical distribution of innovation patterns across Europe. As shown, the leading nations in the hydrogen fuel space are France and Germany.

GERMANY

Germany, Europe's largest economy, produces the most chemical research and innovation patent publications focused on hydrogen fuel technology. The interest in this space has intensified as the country strives to reduce the production of greenhouse gases. Indeed, in 2015, Germany reiterated its goal of reducing CO_2 emissions in 2030 to 50% of the level in 1990. The country has made significant strides in approaching this target, successfully cutting emissions by 25%. However, challenges in technology and infrastructure remain, which have resulted in an overall delay of greenhouse gas reduction[16].

Currently, the energy sector in Germany relies heavily on coal-fired power stations, with 42% of energy produced by this route in 2016[17]. Furthermore, about a quarter of Germany's energy demand is met by liquefied natural gas, supplied primarily by Russia. **By increasing its use of hydrogen power, Germany would be able to reduce its heavy dependence on foreign fossil fuel imports.** This could be achieved at a relatively low cost, as its superb existing gas infrastructure could be leveraged for the transportation and storage of hydrogen gas[18].

So far, Germany has made some progress in introducing hydrogen fuel technology. In fact, two hydrogen-powered trains developed by Alstom SA, a French multinational company specializing in rail transportation, entered service in Northern Germany last year. This illustrates how the country is beginning to reduce CO_2 emissions from diesel-powered platforms.

PATENT PUBLICATION TRENDS

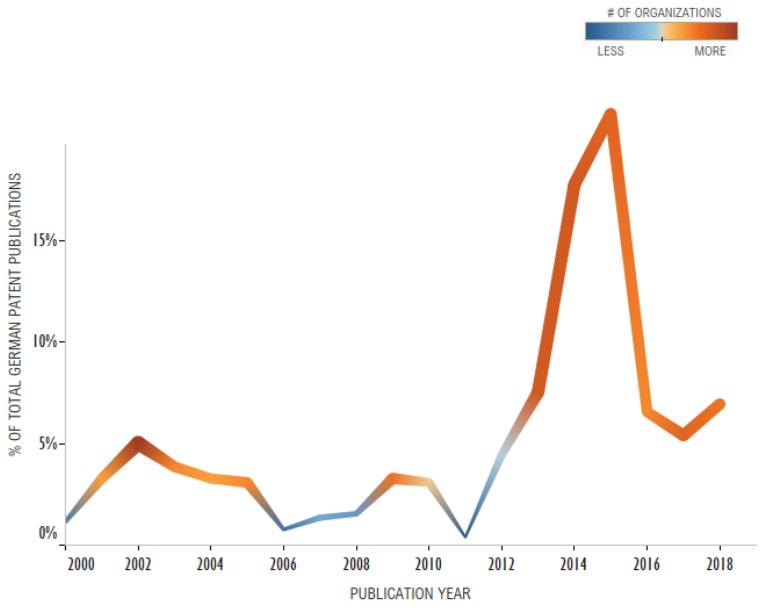


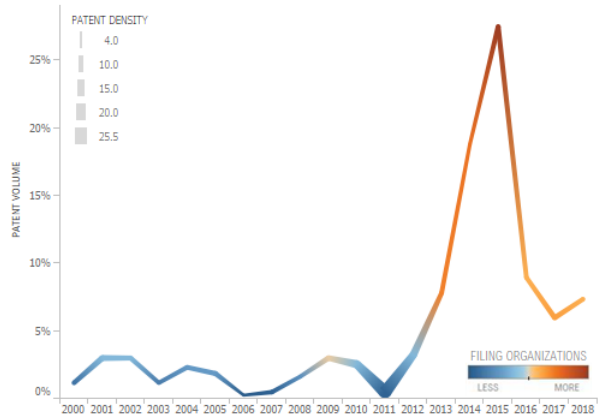
Figure 8: Trends in chemistry-focused hydrogen fuel patent publications in Germany.The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

Examining the trends in patent publications over time can shed light on historical patterns and help predict the future direction of innovation in each geographical market. Looking at Germany's timeline chart in Figure 8, the intensity of the red color represents the number of different organizations filing for patents. After this peaked in 2002, both the number of organizations and the overall volume of patents decreased until the lowest point in 2011. However, towards the end of 2011, the National Organization for Hydrogen and Fuel Cell Technologies issued US $520 million in subsidies supporting research and innovation into hydrogen fuel infrastructure and technology[19]. The funding spurred the volume of publications to increase until 2015. For companies operating in this market, it is crucial to be aware of how changes in available subsidies affect the market landscape.

FOR COMPANIES OPERATING IN THIS MARKET, IT IS CRUCIAL TO BE AWARE OF HOW CHANGES IN AVAILABLE SUBSIDIES AFFECT THE MARKET LANDSCAPE

GERMAN PATENT OFFICE TRENDS

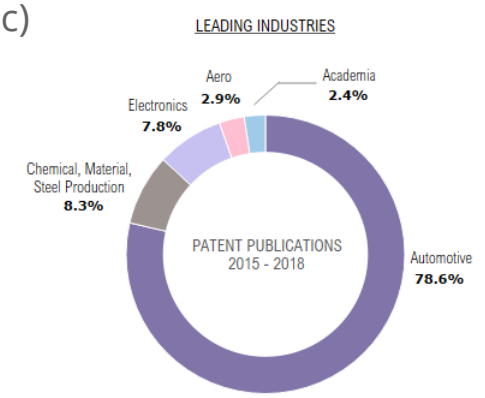
a)



b)

INNOVATION TOPICS 2015 - 2018		TOP 10 SUBSTANCES 2015 - 2018	
Fuel cell vehicles	11.0%	Water	8.5%
Fuel cells	7.0%	Oxygen	5.0%
Air	4.5%	Carbon	2.4%
Traction fuel cells	1.9%	Platinum	1.9%
Process control	1.3%	Carbon dioxide	1.5%
Fuel cell cathodes	1.0%	Aluminum	1.3%
Fuel cell anodes	1.0%	Carbon monoxide	1.0%
Polymer electrolyte fuel ce..	1.0%	Polypropylene	0.5%
Safety	0.6%	Methanol	0.3%
Humidification	0.6%	Graphite	0.3%

c)



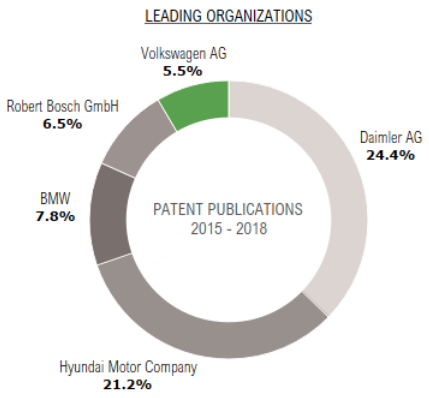


Figure 9: Filing trends in the German patent office (DMPA). a) Temporal changes in patent volume (y axis), number of filing organizations (line color) and patent density (line thickness). b) Top ten substances and topics of innovation in chemistry-focused hydrogen fuel patents from 2015-2018. c) Leading organizations and industries in the patents published by the DMPA between 2015 and 2018. Source: CAS Content Collection.

As shown earlier in Figure 6, the German patent office (Deutsches Patent- und Markenamt, DMPA) receives a comparatively high proportion of the worldwide total of chemistry-based hydrogen fuel filings. Figure 9 provides a more detailed overview of the trends in patents filed here. It can be seen that the volume of patents remained low until reaching a trough in 2011. Subsequently, a steep increase from 2011–2015 reflected a rise in innovation focused on fuel cell technology for automotive applications. It is likely that this trend was partially due to the increase in government subsidies during this time. As the volume of patents rose after 2011, the density of indexing decreased, suggesting that publications were focusing on a more specific area of application. Over the next few years, the volume of patents as well as the number of distinct organizations filing continued to rise, eventually peaking in 2015. However, a subsequent decrease was seen as the funding available declined.

The automotive industry files the majority of hydrogen-related innovations at the DPMA, producing 78.6% of patent publications between 2015 and 2018. Furthermore, four out of the five leading filing organizations during this time were from this industry. Interestingly, Hyundai, a non-German organization based in South Korea, has filed the second most patents at DMPA. This company has been conducting research in Germany since 1994 and released the hydrogen-powered vehicle Hyundai ix35 in Germany in 2009. Now, the company is looking to introduce a fuel cell-powered semi-truck for the European commercial vehicles sector[20].

THE AUTOMOTIVE INDUSTRY FILES THE MAJORITY OF INNOVATIONS

Unfortunately, the adoption of passenger vehicles has so far been low, due to poorly developed hydrogen supply chain infrastructure. This issue has proved a similar barrier to hydrogen-based energy across the globe. As innovations emerge to overcome this challenge, the commercial potential of this sector will likely see rapid growth.

FRANCE

France, which has the third-largest economy in Europe, produced the second-highest volume of chemistry-based hydrogen fuel patent filings in 2018. There are several reasons for this ongoing innovation in alternative energy. First, as France is the world's 9th biggest oil-importing nation, transitioning away from fossil fuels would have a significant impact on the French economy. Second, France has set ambitious goals to reduce CO_2 production – during the 2015 Climate Change Conference, France committed to cut emission levels from 310 metric tons (Mt) to just 90 Mt by 2050.

In France, the transportation sector is a major consumer of fossil fuels and produces a large portion of CO_2 emissions. Currently, approximately 70% of cars in France are powered by diesel[21]. However, Paris is set to ban diesel-powered cars by 2023 and gasoline-based platforms by 2030, to meet its emissions goals and reduce local air pollution in this densely populated city.

Given its need to move away from fossil fuels, France is investing heavily in developing strategies to meet energy demands through renewable means. Hydrogen power could play a key role here, and there has been some progress in developing this approach, with the country set to launch hydrogen-powered locomotives developed by Alstom in the southern region of Occitanie.

PATENT PUBLICATION TRENDS

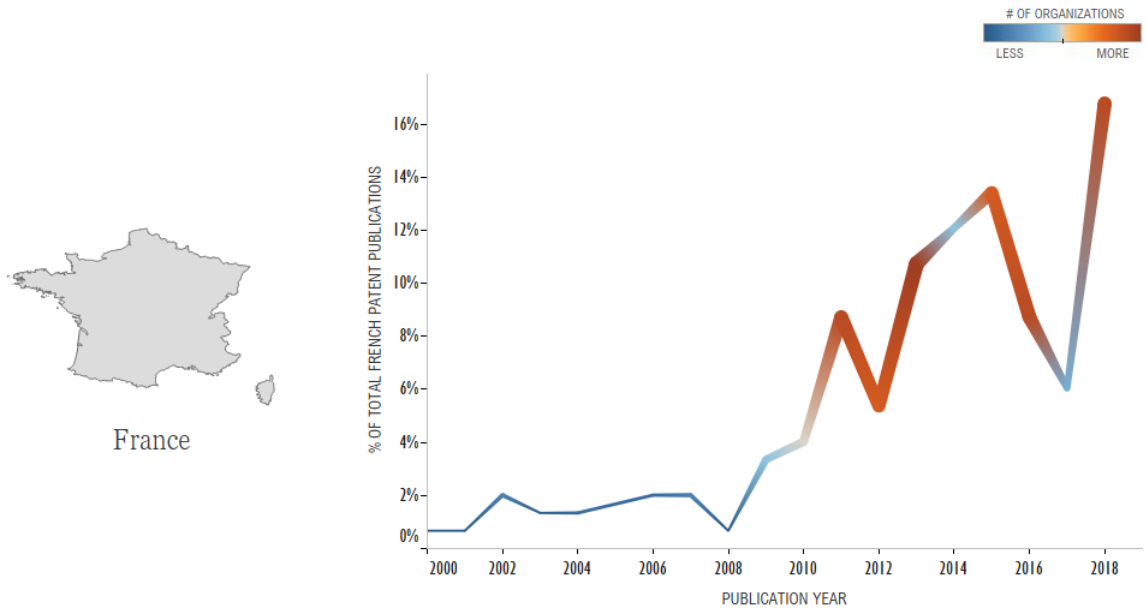


Figure 10: Trends in chemistry-focused hydrogen fuel patent publications in France. The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

Before 2011, the number of chemistry-based patent publications for hydrogen fuel technology filed by French organizations remained relatively low. At this time, research primarily concentrated on the production of hydrogen gas via steam reforming of methane with CCS. However, the landscape changed after 2008, when Honda, one of the world's biggest automotive companies, mass-produced the first hydrogen-powered vehicles. After that, the feasibility of producing these cars on a commercial scale was no longer in question, and the research conducted in French organizations shifted towards developing fuel cells and refining the vehicle support infrastructure. In particular, **challenges around refueling vehicles, replenishing hydrogen refueling stations, and storing and transporting hydrogen gas became key areas of study**. This shift in research focus is reflected in Figure 10 by the gradual rise in chemistry-based publications.

APAC

PATENT PUBLICATIONS
2000 - 2018

a)

TOP 10 SUBSTANCES	
Nickel	2.3%
Alumina	1.7%
Carbon monoxide	1.5%
Platinum	1.5%
Carbon	1.3%
Palladium	1.2%
Oxygen	1.2%
Methane	1.1%
Copper	1.0%
Water	0.9%

TOP 10 TOPICS	
Hydrogen storage materials	8.6%
Fuel cells	2.0%
Fuel gas reforming	1.6%
Secondary batteries	1.6%
Ball milling	1.5%
Fuel gas steam reforming	1.1%
Hydrocarbons	0.9%
Fuel cell vehicles	0.7%
Reforming apparatus	0.6%
Control apparatus	0.3%

b)

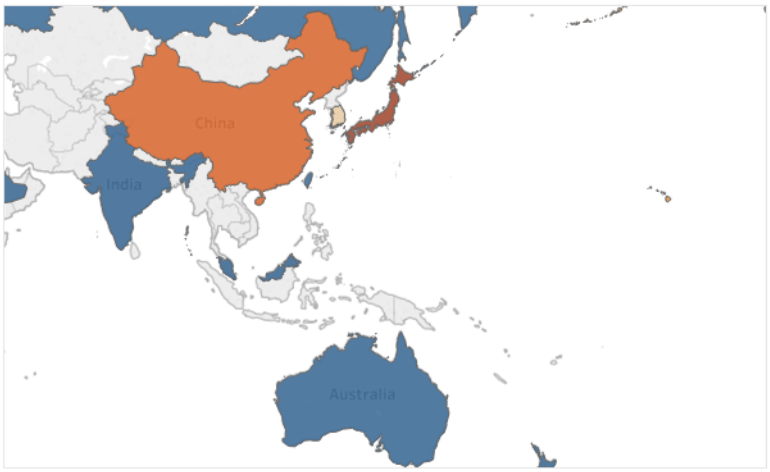


Figure 11: a) Top ten research topics and substances included in hydrogen fuel patents in APAC. b) Regional view of hydrogen fuel patent publications. Source: CAS Content Collection.

Figure 11a shows that research in the APAC region is heavily focused on hydrogen storage materials, much like in Europe. Other highly studied topics and trending chemical substances are related to fuel cell chemistry and development. Nickel, for example, offers a cheaper alternative to platinum, which has historically been the primary catalyst in fuel cell chemistry and has provided a significant cost barrier for hydrogen power. As innovations develop to address this challenge, **the commercial potential of this field is likely to increase**.

Geographically speaking, Japan has historically led the way in hydrogen fuel technology. However, in recent years, China has filed more documents in this area. The third leading country is South Korea, although this country is currently witnessing a decline in hydrogen fuel-related patents.

JAPAN

PATENT PUBLICATION TRENDS

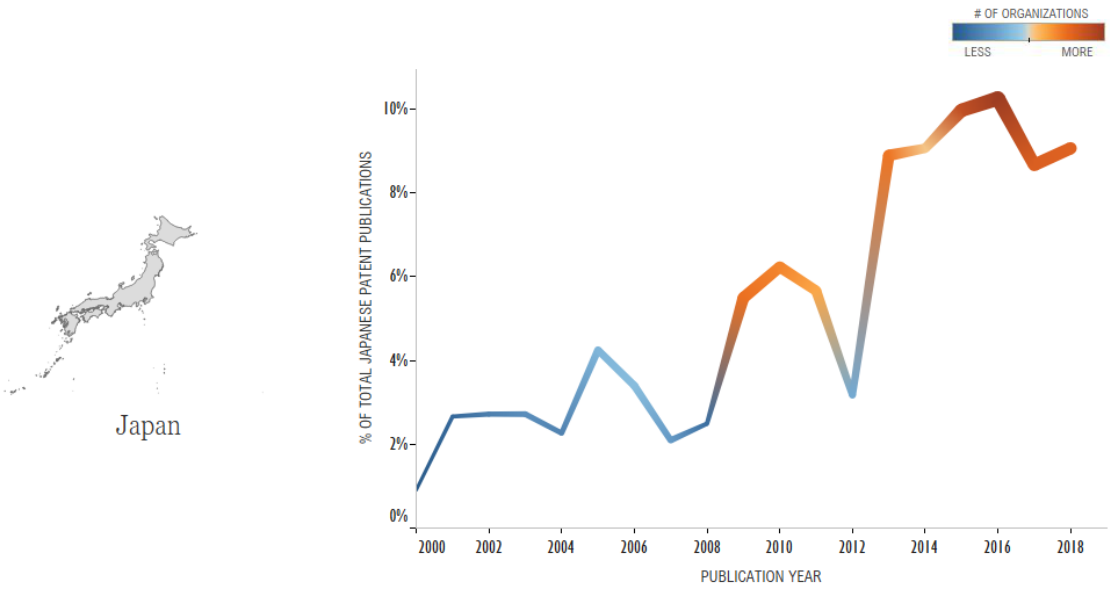
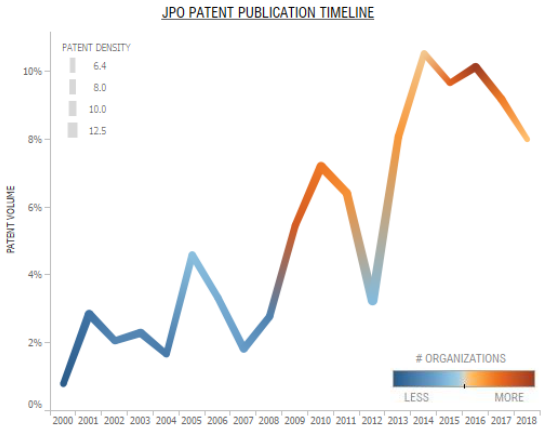


Figure 12: Trends in chemistry-focused hydrogen fuel patent publications in Japan. The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

Figure 12 shows the volume of chemistry-focused hydrogen fuel patents filed in Japan has increased as a general trend, although there was a recent decline in 2016. Since then, filing has rebounded, but the number of organizations filing patents on this topic has dropped. This could be due to the significant chemical challenges of fuel cell technology coupled with the difficulties in applying solutions to Japan's infrastructure. Indeed, when Toyota recalled its entire fleet of fuel cell vehicles in February 2017, this reinforced the existing skepticism about establishing an effective hydrogen economy. Furthermore, Japan's strict regulations around safety add an additional layer of constraint when it comes to building a hydrogen fuel infrastructure[22]. Despite these challenges, Japan is continuing to pursue a vision of hydrogen power. Indeed, **during the upcoming 2020 Summer Olympics, athletes will be transported via hydrogen-powered buses and other commercial vehicles.**

JPO FILING TRENDS

a)



b)

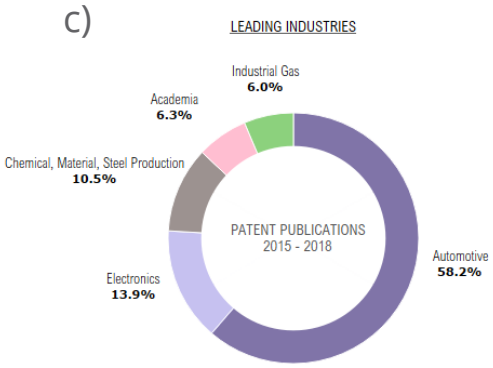
INNOVATION TOPICS
2015 - 2018

Fuel cell vehicles	11.1%
Hydrogen storage materials	7.8%
Fuel cells	4.6%
Nickel-metal hydride secondary ba..	4.2%
Secondary batteries	3.6%
Control apparatus	1.7%
Computerized control apparatus	1.2%
Fuel gases	0.9%
Feeding apparatus	0.8%
Temperature sensors	0.6%

TOP 10 SUBSTANCES
2015 - 2018

Nickel	6.7%
Water	4.6%
Nickel dihydroxide	4.1%
Oxygen	3.4%
Nickel hydroxide	3.1%
Cobalt	2.7%
Potassium hydroxide	2.6%
Poly(vinyl alcohol)	2.0%
Sodium carboxymethyl cellulose	1.9%
Hydrazine	1.5%

c)



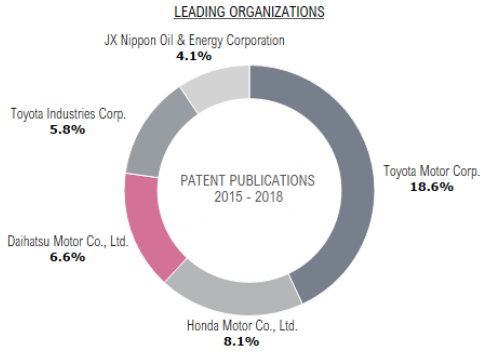


Figure 13: Filing trends in the Japanese patent office (JPO). a) Temporal changes in patent volume (y axis), number of filing organizations (line color) and patent density (line thickness). b) Top ten substances and topics of innovation in chemistry-focused hydrogen fuel patents from 2015-2018. c) Leading organizations and industries in the patents published by the JPO between 2015 and 2018. Source: CAS Content Collection.

Taking a more in-depth look into the filing trends in Japan, Figure 13a shows that the volume of chemistry-based hydrogen fuel patents filed by the Japanese patent office (JPO) has been cyclical. In general, as more organizations enter the space, the publication volume increases, and as the number of organizations drops, the volume decreases also. This pattern has been repeated with peaks observed every four to five years since 2004.

In the troughs, the number of filing organizations tends to be relatively low, indicating that "ground-breaking" discoveries are being made by a small number of leading organizations. These initial claims are typically made for a wide range of applications, resulting in denser indexing as shown by the higher line thickness. As the patent becomes public knowledge, more publications tend to follow, with other organizations developing modifications to the prior art in order to claim novelty.

The automotive industry filed the largest share of patents at JPO over the last four years (58.2%). This industry is a pillar of the domestic economy and provides one of the country's most profitable global exports. However, **as the world moves towards renewable energy sources, the automotive sector has the most to lose.** Therefore, continued research and innovation in this field is a key priority for Japan. This intensely researched industry sector could provide a valuable source of commercial opportunities.

CHINA

PATENT PUBLICATION TRENDS

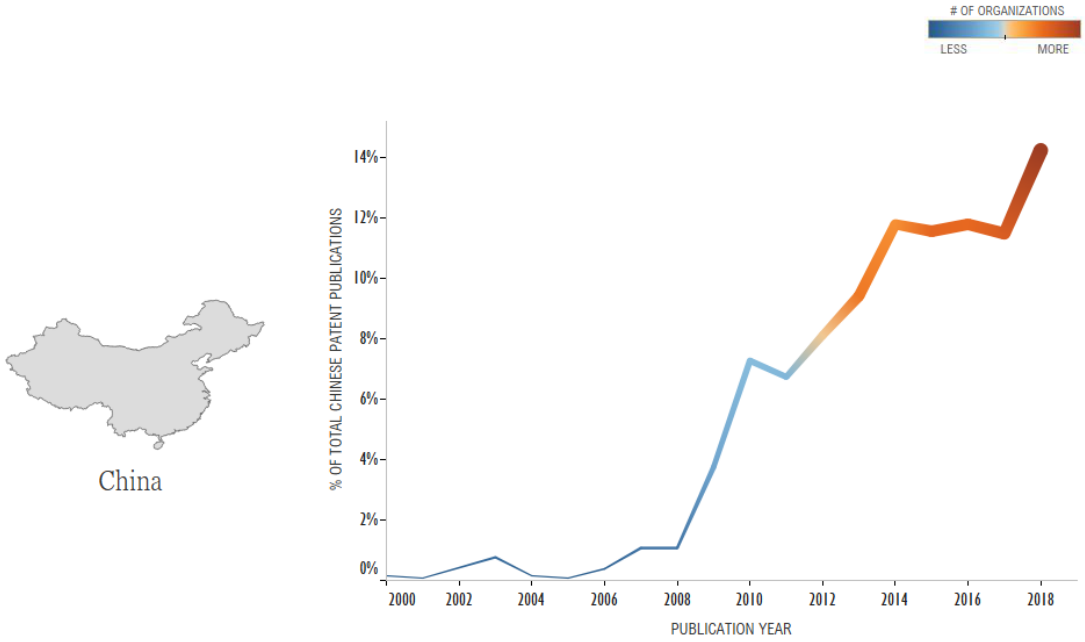


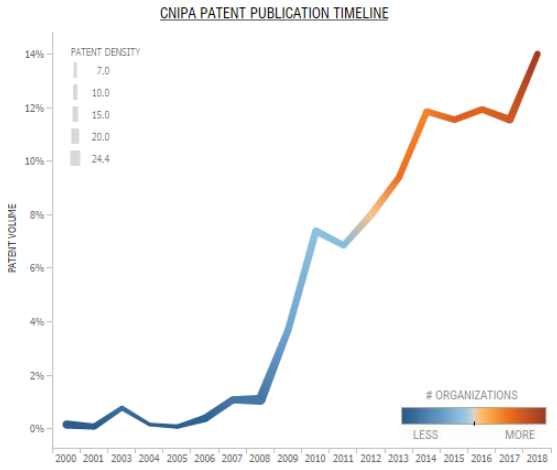
Figure 14: Trends in chemistry-focused hydrogen fuel patent publications in China. The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

In China, recent years have seen a significant increase in the volume of patent publications, the number of organizations filing and the density of patent indexing, as shown in Figure 14. In part, this is due to the Chinese government's decision in 2010 to subsidize new-energy vehicles. As China has the world's largest car market and has committed to reducing CO_2 emissions, the country is encouraging research into solutions to create a clean and efficient energy system. In particular, electric vehicles (EV) have dominated the new-energy vehicles market, with 1.3 million cars sold in 2018[23]. However, the Chinese government is now seeking diversity in the clean-energy transportation space. In 2016, the government reduced EV manufacturer subsidies for vehicles unable to meet the required minimum 150-mile range.

Hydrogen-powered vehicles offer several advantages over EVs, such as longer travel distances and quicker refueling capabilities. The main barriers faced by hydrogen-powered vehicles are the high costs required to manufacture fuel cells and hydrogen gas itself, and the challenge of refueling due to inadequate supply chain infrastructure. As scientists develop strategies to overcome these issues, the volume of patent publications and the number of organizations filing is growing, as shown in Figure 14. **For companies interested in entering the Chinese market, the developing field of hydrogen-powered vehicles is an active area to explore for business potential.**

CNIPA FILING TRENDS

a)



b)

INNOVATION TOPICS 2015 - 2018	
Hydrogen storage materials	8.6%
Ball milling	1.7%
Calcination	1.7%
Smelting	1.1%
Composites	1.1%
Catalysts	1.0%
Secondary batteries	1.0%
Melting	0.7%
Fuel cells	0.7%
Hydrogen fuel cells	0.7%

TOP 10 SUBSTANCES 2015 - 2018	
Nickel	1.8%
Carbon	1.7%
Platinum	1.4%
Graphene	1.0%
Argon	1.0%
Cobalt	1.0%
Nitrogen	0.9%
Potassium hydroxide	0.8%
Magnesium	0.7%
Sodium hydroxide	0.6%

c)

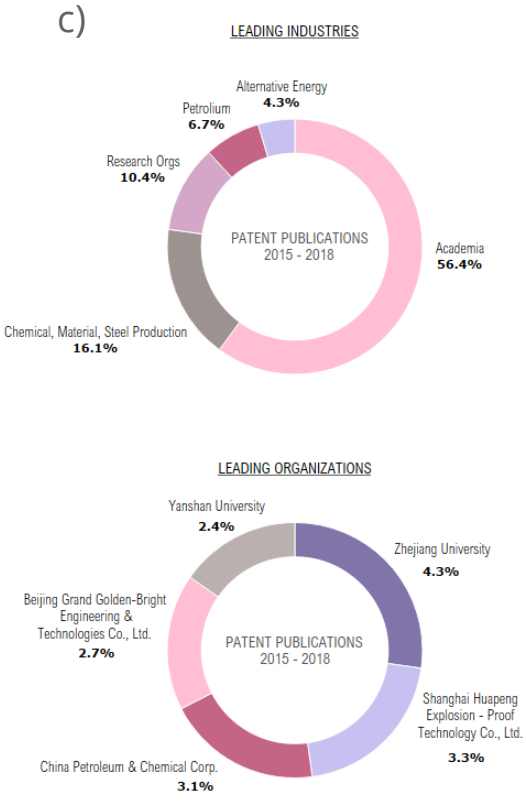


Figure 15: Filing trends in the Chinese patent office (CNIPA). a) Temporal changes in patent volume (y axis), number of filing organizations (line color) and patent density (line thickness). b) Top ten substances and topics of innovation in chemistry-focused hydrogen fuel patents from 2015-2018. c) Leading organizations and industries in the patents published by CNIPA between 2015 and 2018. Source: CAS Content Collection.

As shown previously in Figure 6, China has primarily filed patents at home, much like most of the leading nations in this space. Figure 15 shows that the volume of filings at the Chinese National Intellectual Property Administration (CNIPA) has increased steadily since the turn of the millennium. Patent density peaked in 2008, and the innovations developed at this time triggered a subsequent sharp rise in filing through to 2010. Later, in 2017, the second-highest density of patents was seen as the country continued to invest heavily in hydrogen fuel[24]. This state support is encouraging more organizations to enter the space.

The largest share of filing at CNIPA (56.4%) comes from the academic sector since research and innovation are heavily funded by the Chinese government. The leading filing organization from 2015-2018 was Zhejiang University, one of the top institutions of higher education in China.

After the academic sector, materials engineering is the second leading industry in this space, filing 16.1% of patents between 2015 and 2018. The interest in this area reflects the need to improve the materials used to manufacture hydrogen storage tanks. Overall, China is seeking to become the dominant global force in hydrogen fuel technology, and there are significant business opportunities in this rapidly growing market.

SOUTH KOREA

PATENT PUBLICATION TRENDS

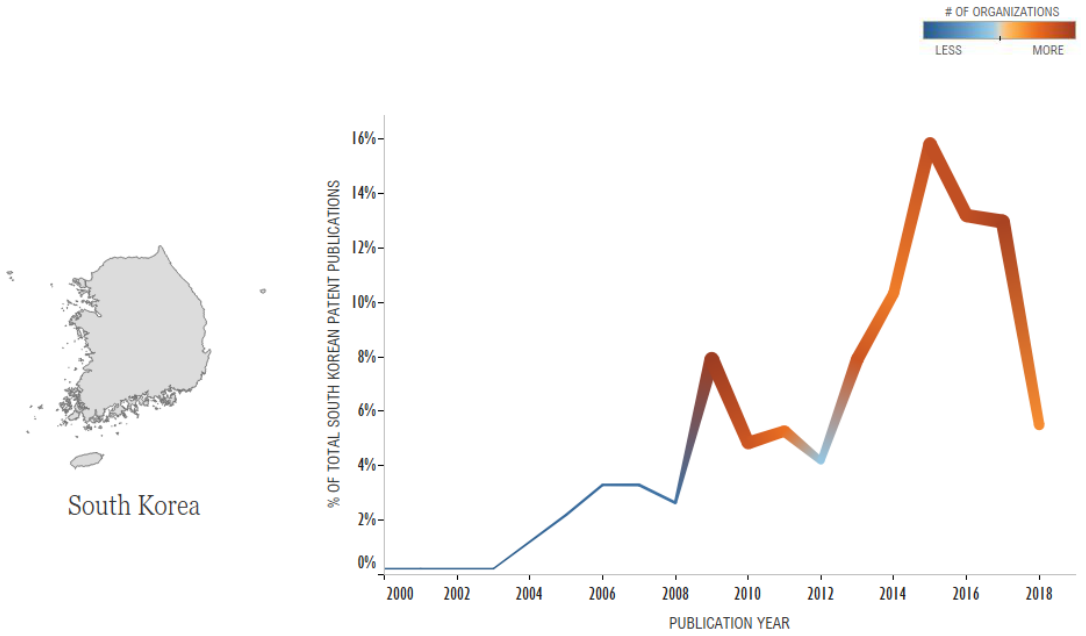


Figure 16: Trends in chemistry-focused hydrogen fuel patent publications in South Korea. The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline. Source: CAS Content Collection.

Based on CAS patent data, South Korean filings have been steadily declining since 2015, with only a small number of organizations active in the chemistry space of hydrogen fuel technology. This is partly because South Korea continues to rebound from the previous administration's policy on nuclear power, which reduced support for the development of a hydrogen infrastructure. Without the government's aid, only large corporations could afford to invest in hydrogen technology research and innovation, while smaller organizations were driven out of business.

NORTH AMERICA

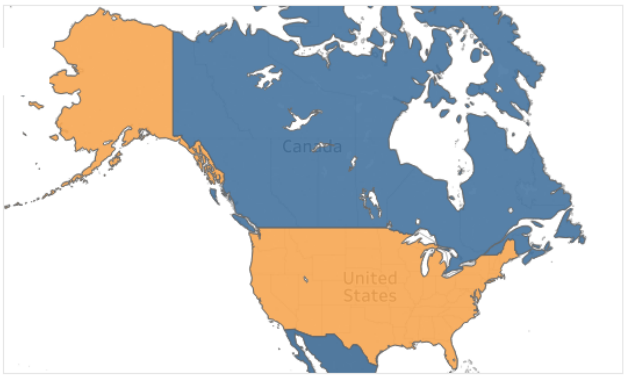
PATENT PUBLICATIONS
2000 - 2018

a)

TOP 10 SUBSTANCES	
Carbon monoxide	1.8%
Methane	1.6%
Carbon dioxide	1.5%
Alumina	1.3%
Platinum	1.2%
Nickel	1.1%
Palladium	1.0%
Oxygen	1.0%
Methanol	0.8%
Carbon	0.8%

TOP 10 TOPICS	
Hydrogen storage materials	4.0%
Fuel gas reforming	2.1%
Hydrocarbons	1.4%
Fuel cells	1.2%
Hydrides	1.1%
Reforming catalysts	1.1%
Fuel gas steam reforming	1.0%
Water gas shift reaction	0.7%
Natural gas	0.7%
Reforming apparatus	0.6%

b)



c)

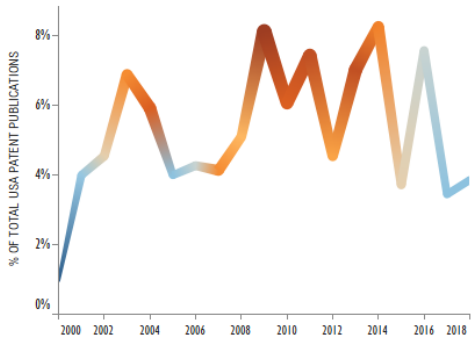


Figure 17: a) Top ten research topics and substances included in hydrogen fuel patents within North America. b) Regional view of hydrogen fuel patent publications. c) Trends in chemistry-focused hydrogen fuel patent publications in the USA. The y-axis shows the volume of publications, while the number of filing organizations is represented by the color and thickness of the sparkline.
Source: CAS Content Collection.

USA

Patent filing in the North American region is heavily dominated by the USA, as seen in Figure 17b. As the world's largest nominal economy, the USA must meet massive domestic energy requirements across the areas of transportation, industry, heating in buildings, and power generation. To meet these demands, the USA has developed a strong fossil fuel industry, drawing on its extensive oil reserves. This industry offers very low costs to consumers, which creates a challenging competitive landscape for renewable energy sources.

INNOVATION TRENDS

Government support plays an important role in the development of alternative energy systems in the USA. During the early 2000s, the George W. Bush administration provided funding to diversify energy resources, which accelerated the development of hydrogen fuel cell technology. Initially, research focused on applying reforming technology to small-scale fuel cell development. This is reflected in Figure 17c by the rise in publications until 2003, coupled with the increased number of filing organizations. However, as research revealed problems with managing the high temperatures associated with the process, it was recognized that applying this technology on a small scale was not commercially feasible. Subsequently, the volume of publications and the number of filing organizations declined and remained stable through to 2009. At this point, the focus of research shifted towards solving the challenges of hydrogen storage. Advances in this area stimulated a subsequent growth in patent filings.

The current administration is a strong supporter of fossil fuels. As such, the USA currently lags behind China and Europe in terms of energy generated from renewable sources, and it is projected to fall further behind by 2050[25]. However, there is widespread enthusiasm for renewable energy amongst the general US population, and popular support for developing infrastructure for fuel cell-powered vehicles is rising[26].

California has made the most progress in this area, investing $900 million in building 200 hydrogen refueling stations, as well as EV charging infrastructure[27]. In fact, given the popularity of its hydrogen-powered Mirai model in California, Toyota has joined forces with Shell Oil to further develop the existing hydrogen fueling infrastructure in this state and expand the availability of refueling stations across the North East region of the USA. The current distribution of stations here is shown in Figure 18.

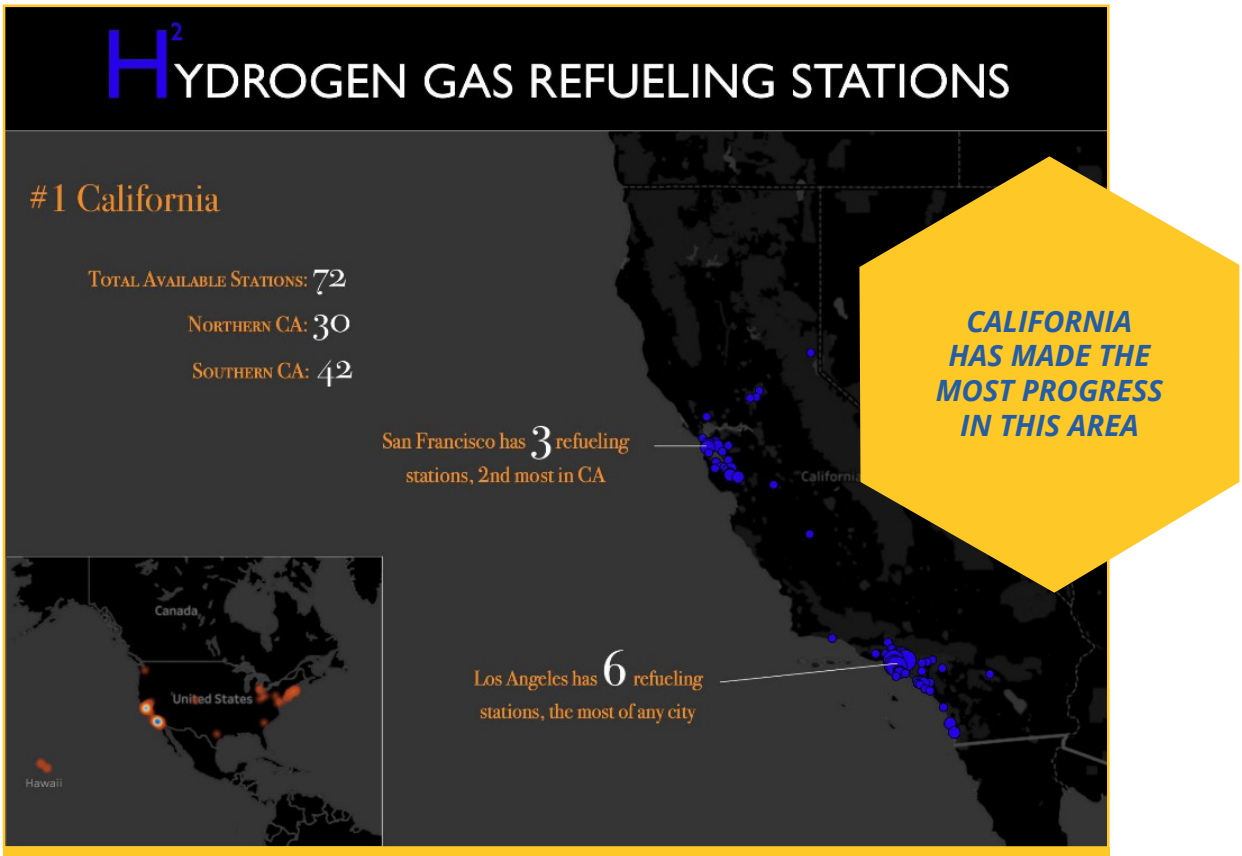


Figure 18: The availability of hydrogen gas refueling stations in the USA. Source: https://developer.nrel.gov/docs/transportation/alt-fuel-stations-v1/all/

Toyota predicts that the economies of scale will significantly reduce the cost of hydrogen fuel. Currently, fuel prices stand at $13.99 per kg of hydrogen, which is equivalent to a gasoline price of $5.60 per gallon, far exceeding the average US price for regular unleaded gasoline of $2.65 in September 2019 [28, 29]. For those planning to invest in this sector, it is important to monitor developments in the cost of hydrogen fuel and the extension of the refueling infrastructure.

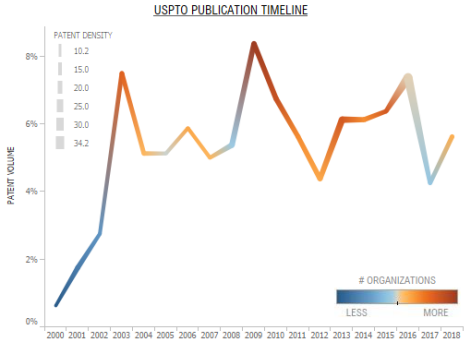
As well as cars, **a range of other hydrogen-powered vehicles has been introduced in the USA.** For example, subsidizing programs in some states have supported the use of fuel cell-powered transit buses. Additionally, hydrogen-powered forklifts have been adopted in many warehouses, since the need to operate within enclosed spaces restricts the use of combustion engines. Compared to their electric counterparts, hydrogen-powered forklifts can run for longer hours with significantly lower refueling times, reducing operating costs and increasing efficiency.

The United States Patent and Trade Office (USPTO) files the fourth largest volume of chemistry-based hydrogen fuel patents worldwide. Figure 19 shows the cyclical pattern in filing volume at this office. This reflects the overall trend in hydrogen fuel innovation, with a peak in the early 2000s when the focus was on reformer technologies, before research moved to concentrate on improving storage capabilities. The volume of publications and the number of organizations filing dropped as the new administration took office in 2016-2017, reflecting the lack of support for renewable energy.

Studying the top substances and topics recently mentioned in patent filings can shed light on current developments for those exploring the commercial potential of this field. Analysis indicates that USPTO filing currently focuses on improving electrolyte components and storing energy produced from hydrogen gas. **Much like other patent offices, the majority of filings are from the automotive industry.**

USPTO FILING TRENDS

a)



b)

TOP 10 SUBSTANCES 2015 - 2018		INNOVATION TOPICS 2015 - 2018	
Nickel dihydroxide	0.5%	Hydrogen storage materials	4.6%
Polyethylene glycol	0.5%	Secondary batteries	4.2%
Potassium hydroxide	0.4%	Alkaline fuel cells	0.4%
1,3-Dimethyl-2-imidazolidinone	0.4%	Hydrides	0.4%
Phenoxyethanol	0.4%	Laves phases	0.3%
Trimethylene carbonate	0.4%	Nickel-metal hydride secondary ba..	0.3%
Triethylammonium methanesulfon..	0.4%	Fuel cell vehicles	0.2%
Dimethoxymethane	0.4%	Fuel cells	0.1%
Hexamethylphosphoramide	0.4%	Process control	0.0%
Ethylene carbonate	0.4%	Control apparatus	0.0%

c)

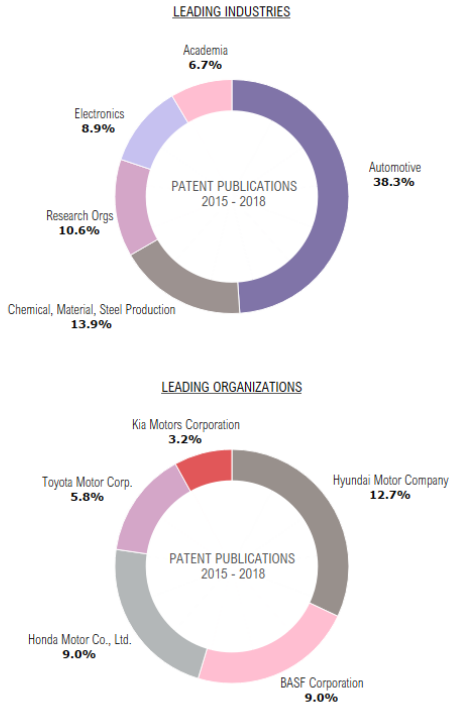


Figure 19: Filing trends in the US Patent and Trade Office (USPTO). a) Temporal changes in patent volume (y-axis), number of filing organizations (line color) and patent density (line thickness). b) Top ten substances and topics of innovation in chemistry-focused hydrogen fuel patents from 2015-2018. c) Leading organizations and industries in the patents published by USPTO between 2015 and 2018. Source: CAS Content Collection.

CONCLUSION

APAC is the clear leader in innovation within the hydrogen fuel space, with Japan producing the highest volume of patents and China coming second. Within Europe, Germany shows the highest levels of research activity, while the US dominates the scene in North America. In general, all of these countries tend to file patents at home.

The automotive industry makes the largest contribution to filings in the main patent offices since it currently stands to lose the most from the shift to renewable energy sources. To apply hydrogen power to this industry on a large scale, it is essential to optimize hydrogen storage materials and fuel cells for onboard use. Indeed, these topics are the top areas of innovation worldwide. While such hotspots of research are likely to generate significant commercial potential, there is also value in exploring less studied areas to identify opportunities where the competition may not be so intense. Studying the top ten substances and topics of innovation in each country and patent office can be beneficial for organizations intending to invest in particular geographical markets.

CHAPTER 4

INDUSTRIAL SECTORS

INTRODUCTION

Hydrogen fuel has developed applications across a range of industrial sectors. The focus of innovation across these different areas is shown in Figure 20.

Across the hydrogen fuel space as a whole, hydrogen storage is the main focus of research. Safe and effective storage solutions are necessary for home and commercial buildings, transport at scale, refueling stations, and on-board applications. As discussed, the development of a hydrogen economy is highly dependent on the ability to store and transport the gas, since it is not feasible to establish a supply chain without this capability.

While storage solutions attract interest across a wide range of industrial sectors, other topics of study have particular relevance for specific fields. For example,

HYDROGEN FUEL INNOVATION FOCUS

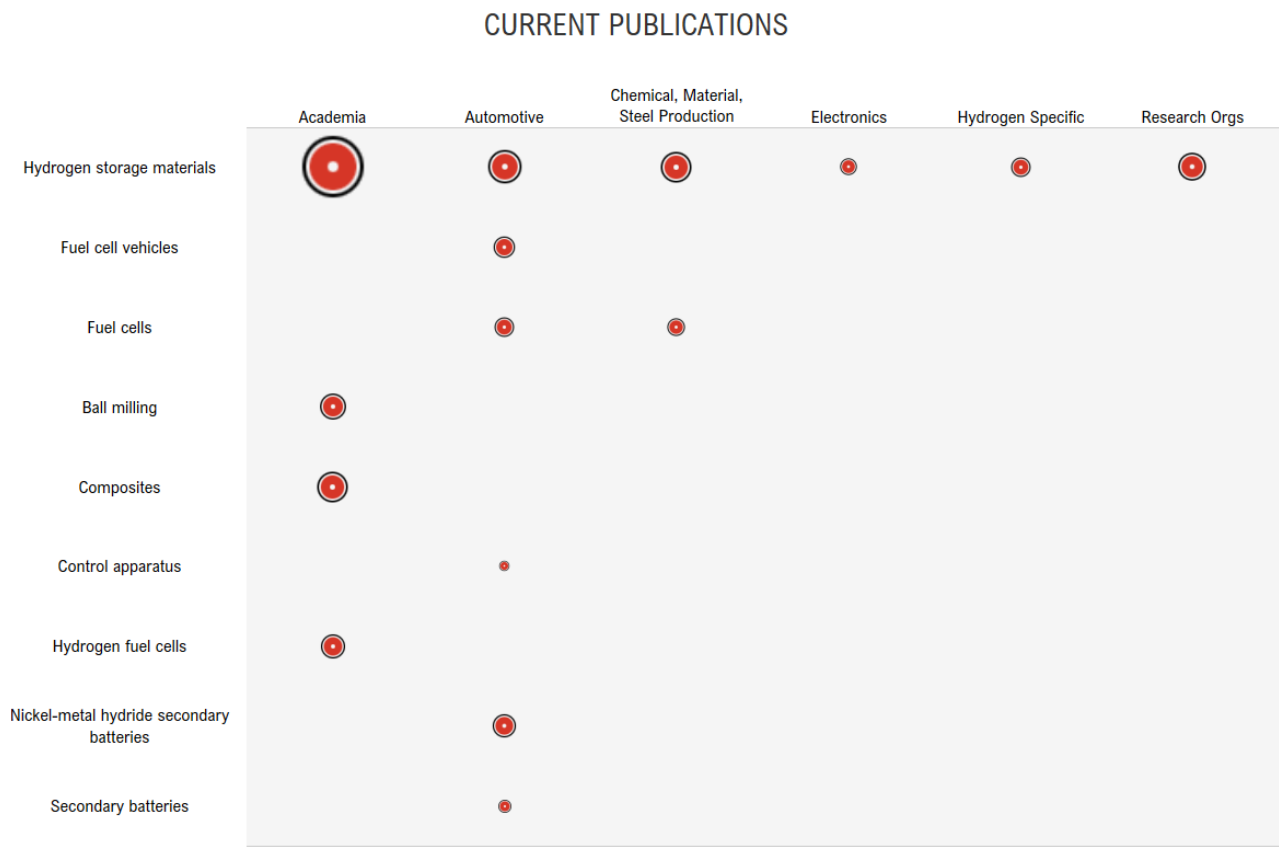


Figure 20: The main areas of innovation in the hydrogen fuel space across a range of industrial sectors. Source: CAS Content Collection.

given the multitude of established transportation infrastructures associated with the petroleum industry, this sector is exploring how to employ aromatic hydrocarbons to address the challenges of hydrogen delivery. In contrast, developing more efficient and cleaner methods for fuel gas reforming is a key area of innovation in the academic and materials sectors. Additionally, academic research is also developing novel catalysis methods by leveraging the properties of long-chain alkenes.

These examples illustrate the range of research avenues across different industrial sectors. To identify promising business opportunities in each area, it is crucial to understand the main priorities in the industry. In particular, an awareness of the trending topics of research and the top chemical substances in the intellectual property (IP) space can be very valuable. Active areas of innovation can indicate rapidly developing fields with high business potential, while some of the lesser-studied topics may prove to be promising areas where the competition is less intense. In this chapter, we present this information for a range of industrial sectors, and also identify which companies are the major players to shed more light on the competitive landscape.

FUEL CELL INDUSTRY

HYDROGEN FUEL IP SPACE

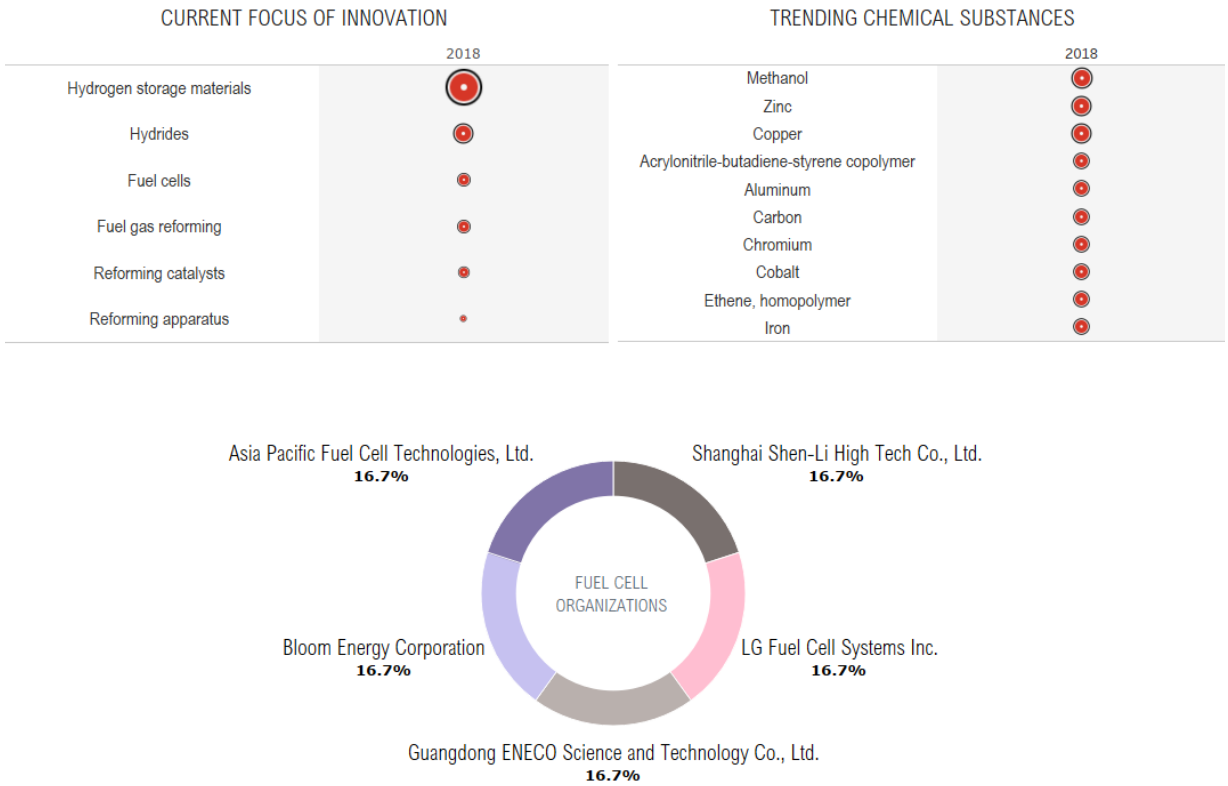


Figure 21: The top topics of innovation, trending chemical substances and active organizations within the hydrogen fuel cell IP space. Source: CAS Content Collection.

Across the fuel cell industry as a whole, the primary focus of innovation in 2018 was hydrogen storage materials. As discussed, the development of storage solutions is essential to enable the more widespread use of hydrogen fuel, so this is a key area of research. The second topic of interest was metal hydrides, which are also relevant to hydrogen storage. Metal hydrides are powders which absorb hydrogen and can, therefore, store it in a solid form under moderate temperature and pressure. While they provide a relatively safe solution and require little energy to operate, their weight is a disadvantage, so research is currently exploring how to design light and reliable metal hydride beds that can be produced economically.

Of the top five organizations filing patents on the topic of fuel cells, two (Asia Pacific Fuel Cell Technology and Shanghai Shen-Li Technology) manufacture proton exchange membrane (PEM) fuel cells for vehicles. PEM fuel cells are currently a major area of interest in transportation and power generation. According to a recent report by Grand View Research, the global market in PEM fuel cells currently stands at $4 billion, and this is expected to see 20% compound annual growth until 2025[30]. As this field expands, it is likely that significant business opportunities will arise.

The top trending chemical substance in 2018 was methanol, which has recently been used alongside PEM fuel cells to extend the range of hydrogen-powered vehicles. These vehicles take on methanol as fuel, convert it to hydrogen with an onboard reformer, then use a high-temperature PEM fuel cell to convert this to electricity. Again, this developing field shows great promise. For those looking to invest in the fuel cell industry, it is worth monitoring the latest developments in storage solutions and onboard technology to identify areas of commercial potential.

THE PRIMARY FOCUS OF INNOVATION IN 2018 WAS HYDROGEN STORAGE MATERIALS

ELECTRONICS INDUSTRY

HYDROGEN FUEL IP SPACE

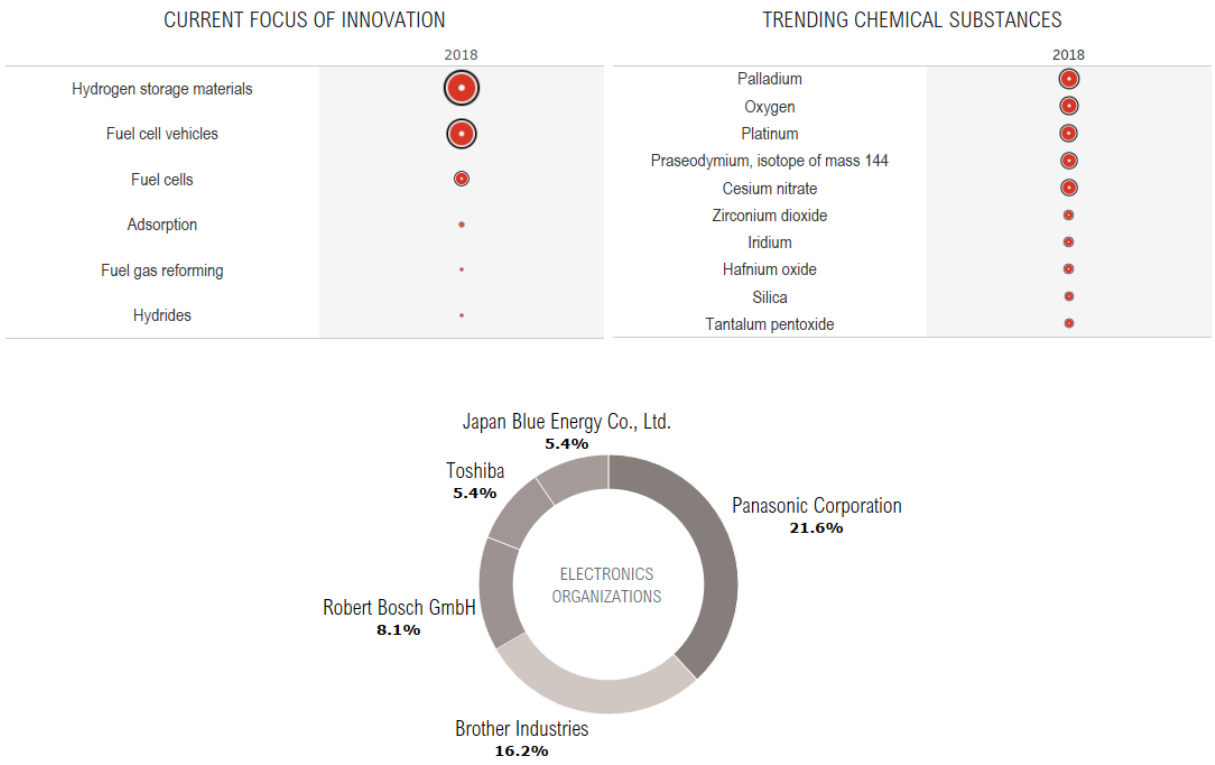


Figure 22: The top topics of innovation, trending chemical substances and active organizations within the electronics industry IP space. Source: CAS Content Collection.

Within the electronics industry, hydrogen storage materials are again the main focus of innovation, followed by fuel cell vehicles and fuel cells. Indeed, the three electronics organizations with the largest share in the hydrogen fuel IP space (Panasonic Corporation, Brother Industries and Robert Bosch GmbH) have all entered the market in fuel cells. Panasonic, the biggest player in this field, is also studying other aspects of hydrogen technology. For example, the company is working on a photocatalyst for solar water splitting. Photocatalytic hydrogen generation is a promising field, though its wide-scale commercialization requires further research. It is likely that the business potential of this field will increase as research develops.

The top trending chemical substances in the electronics industry are palladium, oxygen, and platinum. Palladium is the best-known hydrogen absorber, able to store large quantities of hydrogen at room temperature and pressure as palladium hydride. Recent innovations have improved its hydrogen-absorbing capabilities by alloying with gold[31].

As discussed earlier, platinum is a catalyst used to convert hydrogen and oxygen into water and electricity. While effective, its cost limits its widespread use. However, a new catalyst has recently been developed that maximizes the effectiveness of platinum such that it only uses about a quarter as much of this material as current technology[32]. As platinum-based catalysts become more cost-effective, it is likely that future opportunities will arise.

ELECTRICITY AND POWER INDUSTRY

HYDROGEN FUEL IP SPACE

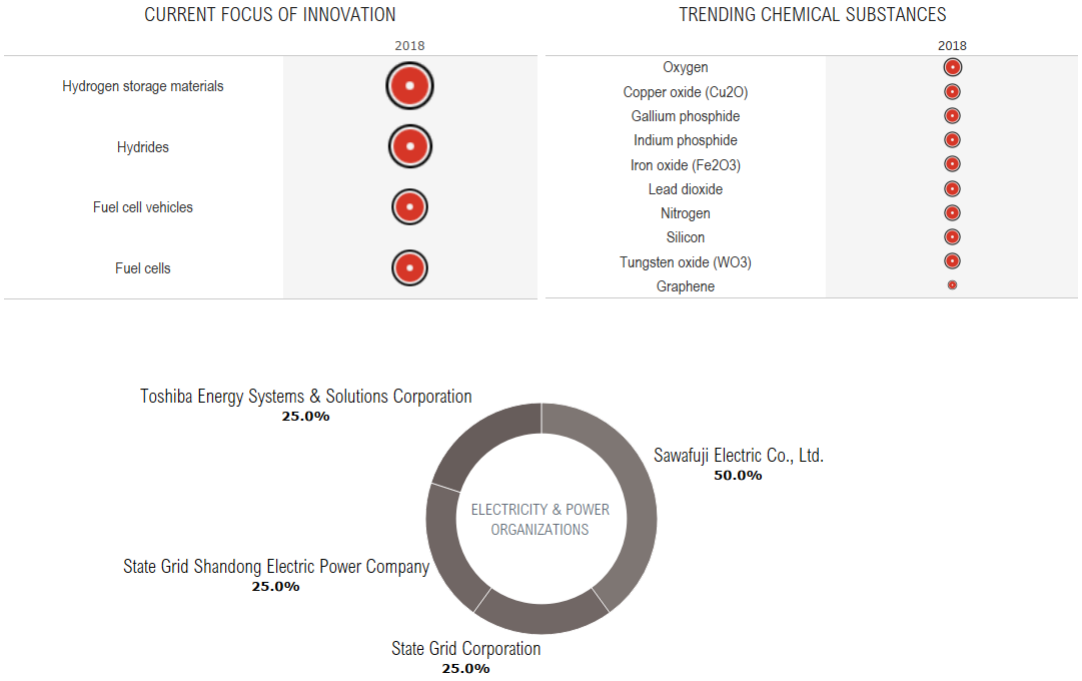


Figure 23: The top topics of innovation, trending chemical substances and active organizations within the electricity and power IP space. Source: CAS Content Collection.

Fossil fuels currently produce two-thirds of electricity globally. Given the pressing need to decarbonize, there is considerable interest in hydrogen fuel within the electricity and power industry. Indeed, it has been proposed that fuel cells can provide a flexible and controllable solution to apply to the electricity system[33].

As seen in other sectors, hydrogen storage materials are the main focus of innovation, but in this case, they are more closely followed by hydrides and fuel cell vehicles. In terms of trending substances, oxygen ranks the highest, followed by copper oxide and gallium phosphate. Interestingly, both copper oxide and gallium phosphate have been the subject of recent advances in generating hydrogen from solar water splitting. While expense has previously been a barrier in this field, such developments are making the process more cost-effective, potentially opening up new opportunities.

The company with the largest share of intellectual property in this space, Sawafuji Electric, recently announced advances in dehydrogenation technology for converting ammonia to hydrogen. As mentioned, there is significant interest in this area given the difficulties in storing and managing hydrogen gas.

FUEL CELLS CAN PROVIDE A FLEXIBLE AND CONTROLLABLE SOLUTION TO APPLY TO THE ELECTRICITY SYSTEM

COOLING AND HEATING INDUSTRY

HYDROGEN FUEL IP SPACE

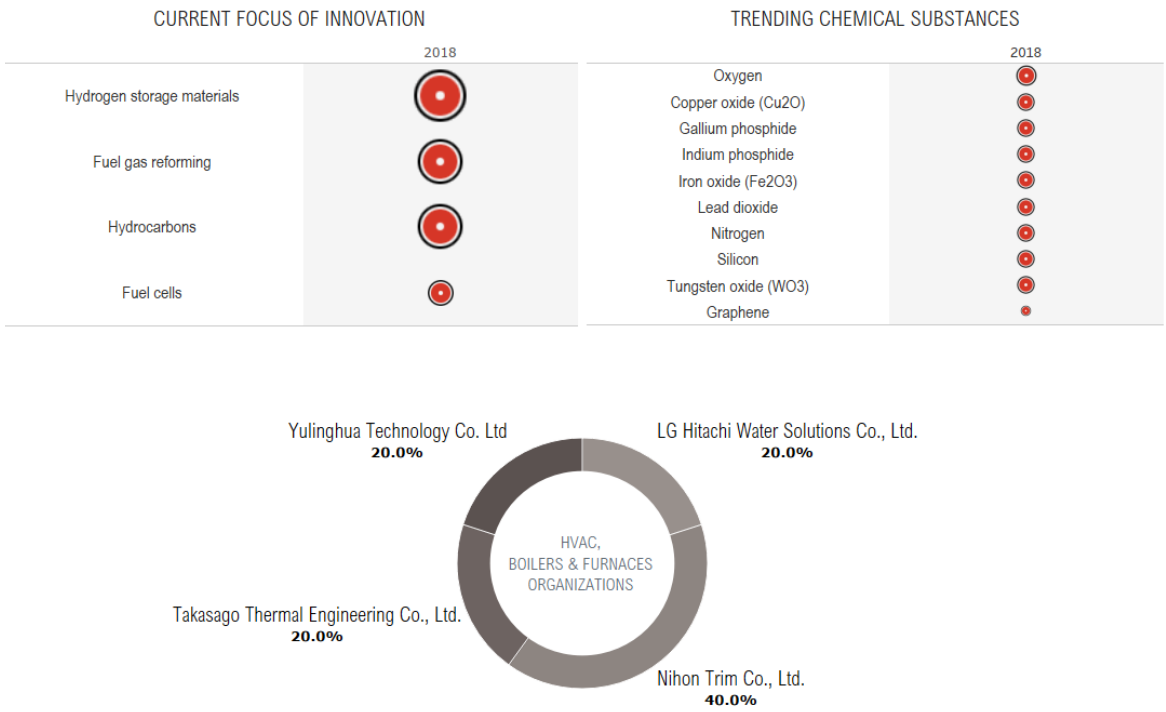


Figure 24: The top topics of innovation, trending chemical substances and active organizations within the cooling and heating IP space. Source: CAS Content Collection.

Heat generation is responsible for over half of energy consumption worldwide and approximately a third of energy-related CO_2 emissions[34]. While the need to decarbonize this sector is well-recognized, the scale of the problem and the variability in heating demands raise considerable challenges. Recent studies have suggested that hydrogen power could play a major role here[33].

As for the electricity and power industry, the main trending substances are oxygen, copper oxide and gallium, and most innovation concentrates on hydrogen storage materials. However, the second topic of interest in this sector is fuel gas reforming. The UK Committee on Climate Change's 2018 report proposes that hydrogen from gas reforming, in combination with heat pumps, could almost completely replace the use of fossil fuels in heating buildings[35]. The strategy described is to fit 'hybrid heat pumps' around existing heating systems, rather than replacing the boiler, in order to make the change more acceptable to the public. For those looking to enter the market, it is worth monitoring the latest developments in this area.

INDUSTRIAL GAS

HYDROGEN FUEL IP SPACE

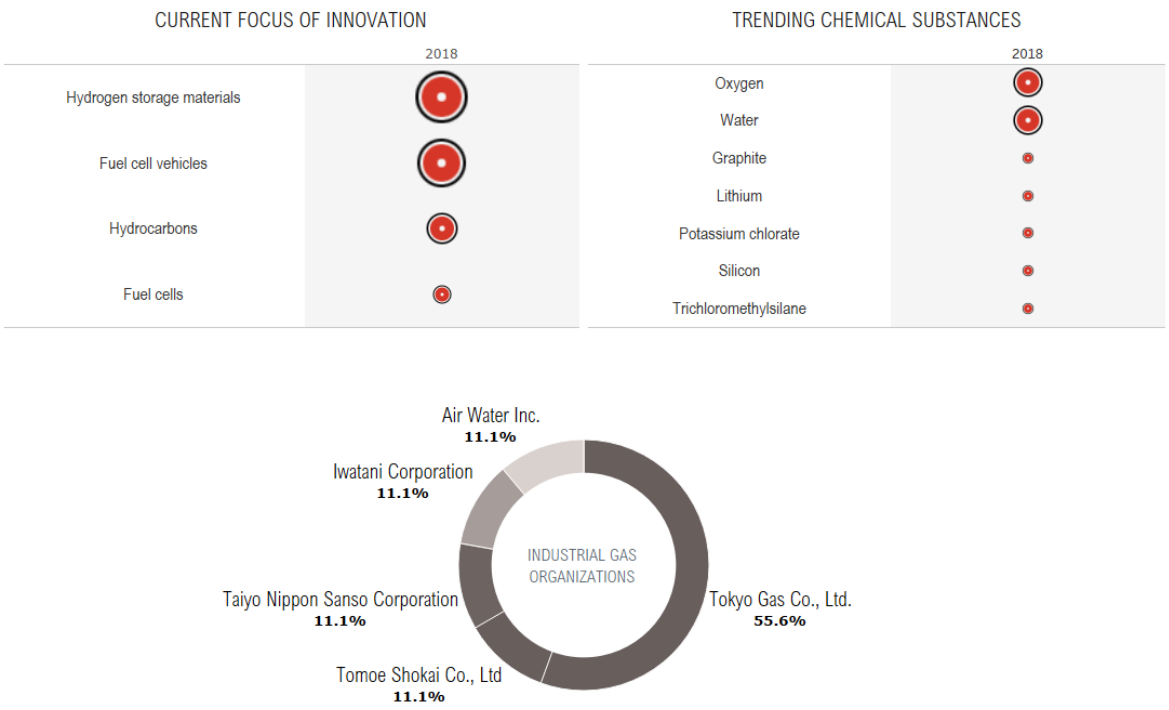


Figure 25: The top topics of innovation, trending chemical substances and active organizations within the industrial gas IP space. Source: CAS Content Collection.

Given the increasing importance of hydrogen as a transportation fuel, major industrial gas companies are now entering the field of hydrogen production. The main areas of innovation in this sector are fuel cells, which are used to power vehicles, and hydrocarbons, which provide a source of hydrogen fuel – either by dehydrogenation or reforming. As previously mentioned, dehydrogenation is an emerging area of interest within the hydrogen fuel space, as there is already a well-developed infrastructure for the storage and transportation of liquid fuels.

Reforming currently remains the main method used to generate hydrogen fuel for vehicles. Generally, the hydrogen is produced in centralized steam methane reformers and then distributed as liquid hydrogen or pressurized gas. Indeed, Tokyo Gas, the organization with most patents in this area, is using its gas system to build a network of hydrogen refueling stations. These will be either 'mother' stations that produce hydrogen by reforming city gas, or 'daughter' stations that are supplied with hydrogen from nearby mother stations.

Due to the importance of reforming in this sector, the main trending chemical substances are CO_2 and CO, the by-products generated from this process. As these can both have a negative environmental impact, there has been recent interest in developing solar water splitting as a decarbonized alternative to reforming. However, only a very small proportion of hydrogen fuel is currently produced in this way. This may prove an interesting area to monitor as future innovations make this process more cost-effective and scalable.

PETROLEUM INDUSTRY

HYDROGEN FUEL IP SPACE

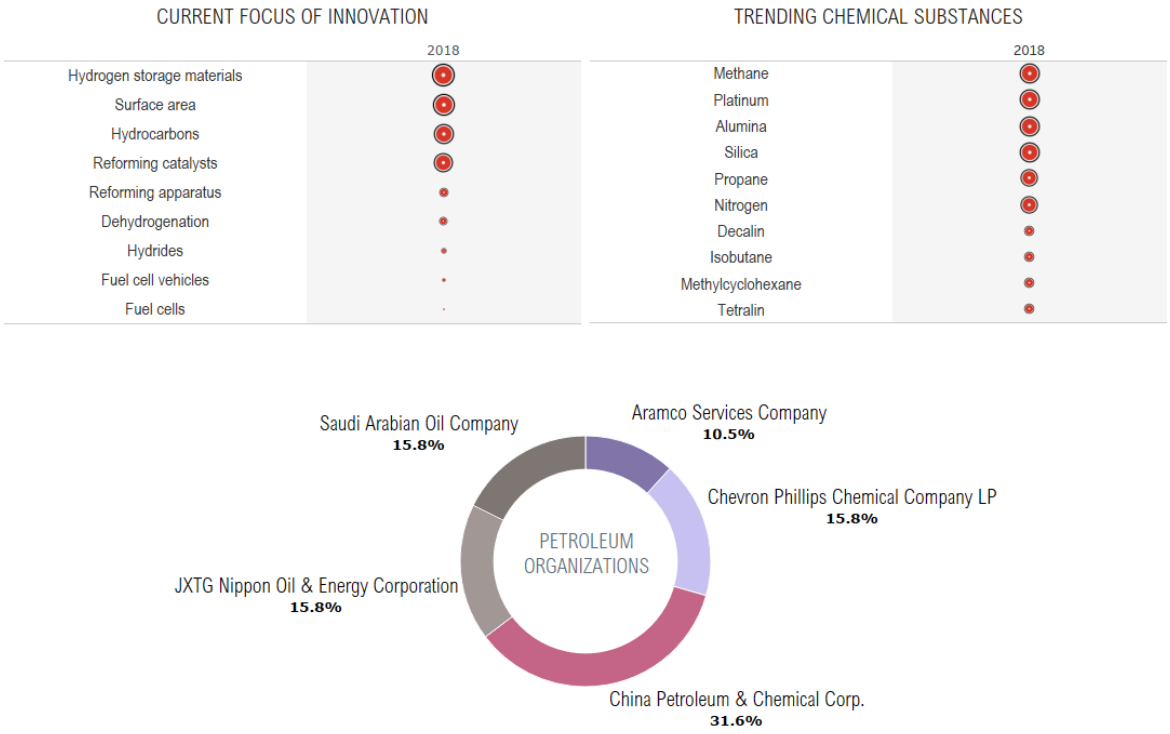


Figure 26: The top topics of innovation, trending chemical substances and active organizations within the petroleum industry IP space. Source: CAS Content Collection.

The promise of hydrogen as a transportation fuel is also driving increased interest within the petroleum industry. Again, the main focus of innovation here is on hydrogen storage materials, and there is considerable interest in areas related to reforming, with hydrocarbons and reforming catalysts attracting significant attention and methane ranking as the top trending substance.

As discussed, hydrocarbons can also be used to produce hydrogen via dehydrogenation. This is a significant area of interest in the petroleum industry, given the well-developed transportation infrastructure already available for liquid fuels.

Many other innovations in this sector focus on increasing the surface area of catalysts used to produce hydrogen. With more of the catalyst surface in contact with the reagents, the reaction can proceed more efficiently. Developments in this field will therefore help this technology become more cost-effective in the long term and boost its commercial potential.

RESEARCH INDUSTRY

HYDROGEN FUEL IP SPACE

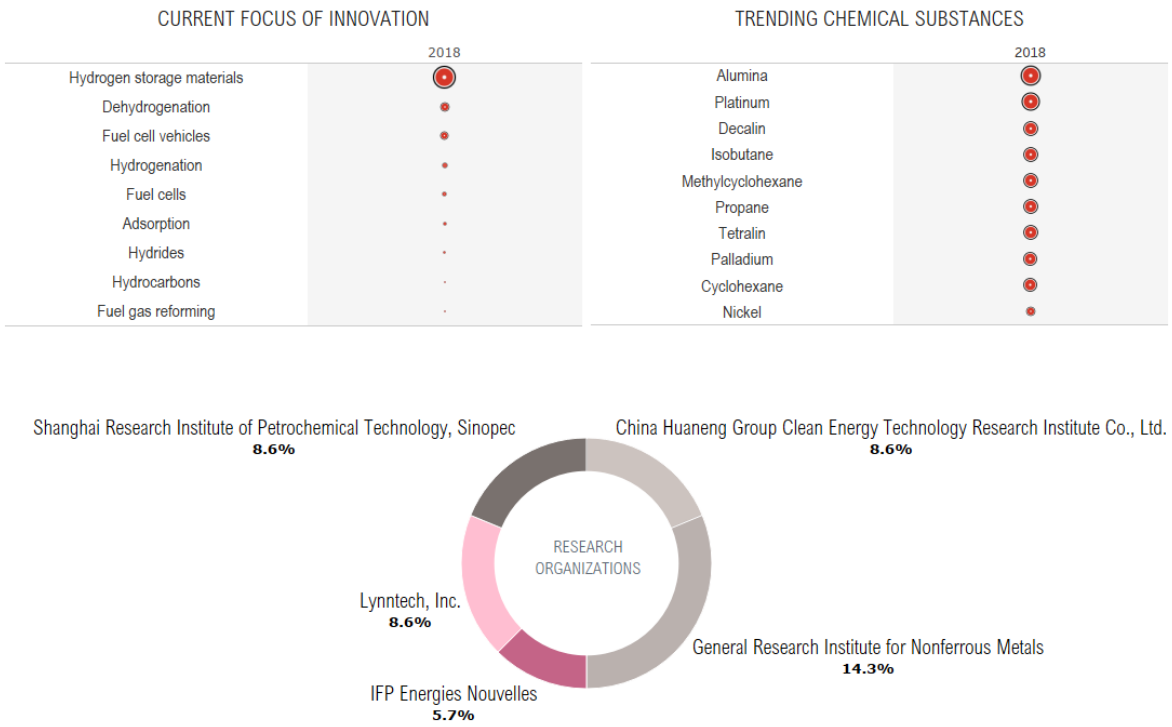


Figure 27: The top topics of innovation, trending chemical substances and active organizations within the research industry IP space. Source: CAS Content Collection.

Within the research sector, the strongest focus of innovation is hydrogen storage materials, since this is the major challenge in the field. The second area of interest is dehydrogenation. As discussed previously, this is an emerging field of research as it provides a potential means to circumvent the problems of storing and transporting hydrogen gas. Instead, hydrogen can be stored using liquid organic hydrogen carriers such as decalin and methylcyclohexane, two of the main trending substances in this area. **Liquid storage opens up the possibility to leverage the transport infrastructure currently used for fossil fuels.** Indeed, as research into dehydrogenation progresses, it is likely that a range of promising business opportunities will arise around the transportation and storage of liquid fuel and its conversion into hydrogen gas.

The top two trending chemicals in hydrogen fuel research are alumina and platinum. As mentioned, platinum is widely used as a catalyst, though it is expensive and researchers are developing ways to minimize its use. Alumina has long been recognized as a means of hydrogen production via the aluminum-water reaction, but the aluminum oxide layer on the metal surface traditionally means that the reaction requires high temperatures or catalysis. However, recent advances in the development of new alloys and the use of plasma immersion technologies[36] have extended the scope of this field.

ACADEMIA

HYDROGEN FUEL IP SPACE

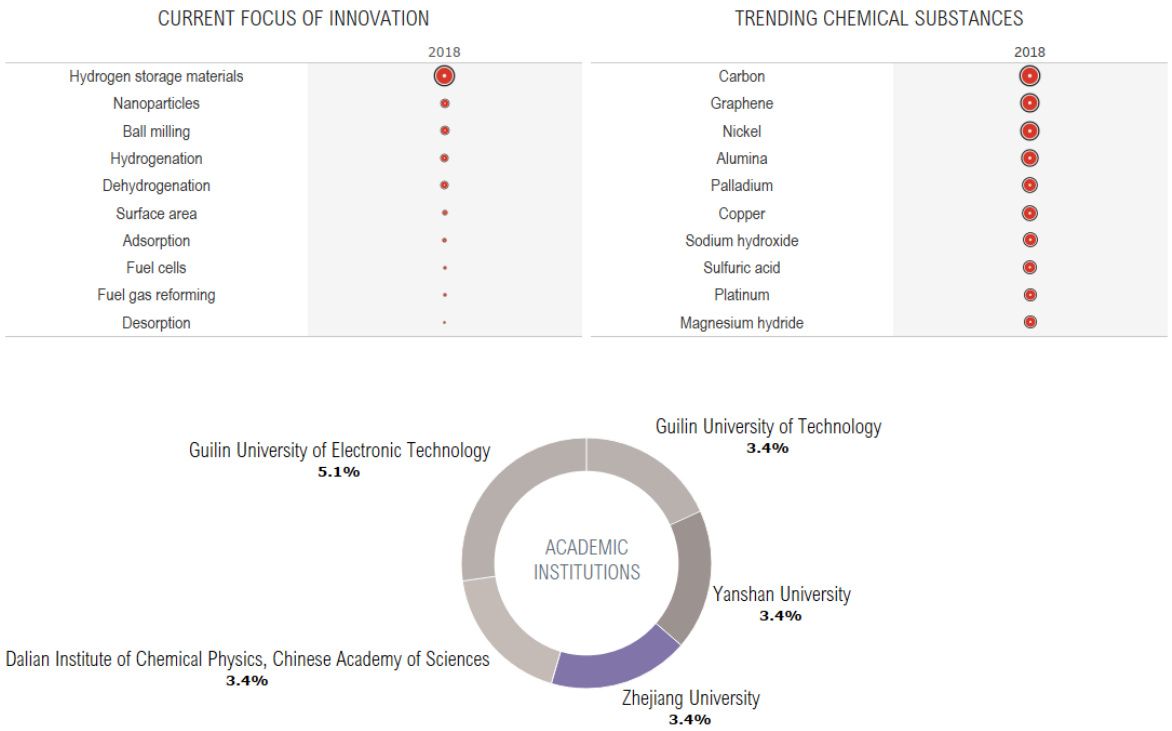


Figure 28: The top topics of innovation, trending chemical substances and active organizations within the academia IP landscape. Source: CAS Content Collection.

In academia, as in the research sector, the main areas of innovation are hydrogen storage materials and dehydrogenation. However, the main trending substances here are ethanol, methanol and cobalt.

Methanol and ethanol can be used to produce hydrogen through the process of steam reforming. A major advantage of these substances from a decarbonization perspective is that they can be produced from biomass without generating greenhouse gases. The recent interest in methanol and ethanol has in part been stimulated by the development of vehicles with on-board reformer technology. In these vehicles, ethanol or methanol is supplied as a fuel, which is converted into hydrogen to generate electricity. An example of this developing technology is NISSAN's new eBio SOFC system. While not yet commercially available, the company estimates that these vehicles could have a range of 500 miles and refueling will be as quick as for gasoline.

Cobalt has recently been employed in a novel way of producing hydrogen, which simply requires water, carbon dioxide and cobalt particles[37]. This has generated particular interest in the field of transportation, as vehicles developed with this technology would not require refueling at filling stations. Consumers would instead replace cobalt canisters as required. While this approach is in the relatively early stages, new opportunities within this field may arise as the technology develops.

AUTOMOTIVE INDUSTRY

HYDROGEN FUEL IP SPACE

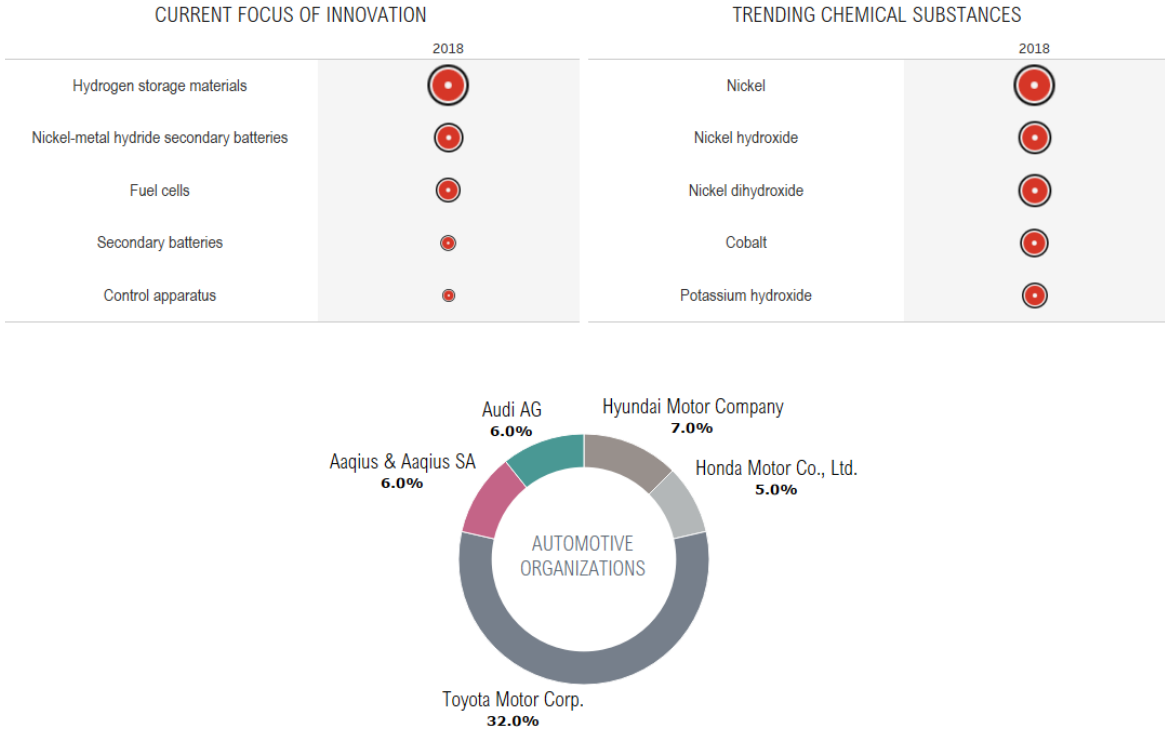


Figure 29: The top topics of innovation, trending chemical substances and active organizations within the automotive industry IP space. Source: CAS Content Collection.

Given its heavy dependence on fossil fuels, the automotive industry currently stands to lose a lot from their depletion and the requirement to reduce emissions. Therefore, intense research interest is devoted to developing hydrogen-powered vehicles.

In this industry, **innovation is primarily focused around refining the chemistry of fuel cells.** Interestingly, the way in which these fuel cells are supplied with hydrogen differs between models. For example, cars commercially available from Toyota and Hyundai employ hydrogen tanks which require refueling at a filling station. However, storage in the vehicle is a key challenge and so companies such as Nissan have recently worked on developing onboard reforming technology to avoid the issue of storage. Daimler AG, on the other hand, has just launched the first vehicle which incorporates both fuel cell and plug-in hybrid technology. This company is the clear innovation leader in this industry, having produced 40% of patents in 2019.

Combining electric and fuel cell technology is an important emerging area, as shown by the innovation focus around flow technology. Flow batteries are hybrid electric-hydrogen devices that can act like a conventional battery or a fuel cell. The main advantages of these systems are their flexibility and the fact that batteries can be recharged quickly, in times comparable to filling a tank of gasoline[38]. As this area continues to advance, it is likely that significant commercial opportunities will arise for companies manufacturing such batteries and integrating them into onboard systems.

CONCLUSION

Solving the challenges associated with storing hydrogen gas is the main focus of innovation across the landscape as a whole. This topic is so highly studied as effective storage solutions are a pressing need across multiple areas of industry.

Beyond hydrogen storage, different industrial sectors have distinct priorities and challenges in the application of hydrogen fuel technology. For example, fuel cells form the main focus of innovation in the automotive industry given the need to refine their chemistry for onboard applications, whereas reforming is of more interest in the academic sphere.

Examining the trending topics and substances in each industrial sector can shed valuable light on established and emerging areas of interest. Companies looking to invest in a particular market can gain useful insights from studying this information.

CHAPTER 5

REALIZING THE POTENTIAL OF HYDROGEN FUEL

The depletion of fossil fuel reserves, coupled with the negative environmental impact of their combustion, has raised an urgent global need to move to a decarbonized energy model. Hydrogen could play a vital role here, as it has the versatility to store energy from multiple renewable sources, and its use does not produce pollutant gases.

The promise of this fuel has led to a surge of research and innovation, with many companies investing heavily in developing hydrogen technology. Globally speaking, the APAC region is a clear leader in this space, with Japan producing the highest number of patents. In Europe, Germany is the most active in hydrogen fuel innovation, while the USA is dominant in North America.

With regard to topics of innovation, research has moved away from reformer technologies to concentrate on hydrogen storage and transportation, since these challenges constitute the main barriers to the widespread use of this fuel. Much research is therefore devoted to refining hydrogen storage materials, and there is emerging interest in the process of dehydrogenation, which may provide an opportunity to circumvent some of the main difficulties.

More recently, there has been increasing interest in on-board storage solutions and fuel cell chemistry and development. These areas are of key importance to the automotive industry, which is heavily dependent on fossil fuels and is therefore highly motivated to reduce reliance on these resources. Indeed, the largest source of filings at the main patent offices in recent years has been the automotive industry.

Overall, the active research and innovation within the hydrogen fuel space reflect the growing potential of this field. Given the rapid pace of developments, it is likely that the global hydrogen market will continue to witness robust expansion, raising a wealth of commercial opportunities for those investing in 'the fuel of the future'.

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