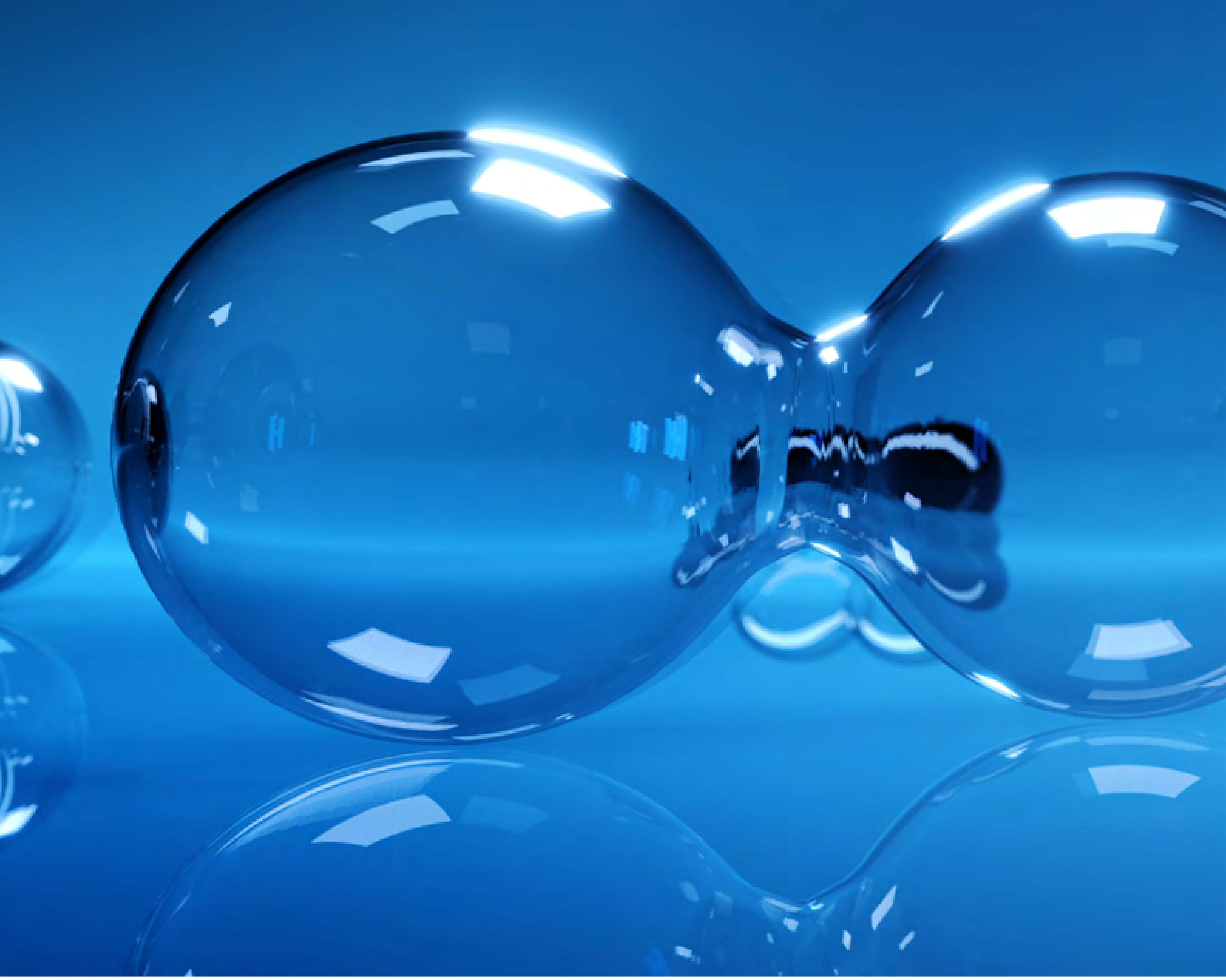
Hydrogen patents for a clean energy future

A global trend analysis of innovation along hydrogen value chains

January 2023



Europäisches Patentamt
European Patent Office
Office européen des brevets

International Energy Agency

Foreword

Faced with a convergence of crises spanning energy, geopolitics and the environment, the future of the European economy now depends more than any time in its history on its capacity for innovation and creativity. The transition away from fossil fuels is a challenge unparalleled in scale and complexity, with a narrowing time window by which to bring solutions to market. In this context, producing reliable intelligence on trends in low-carbon innovation is crucial for supporting robust business and policy decisions. This also forms a vital aspect of EPO's strategic commitment to sustainability.

This study - the third of its kind undertaken in collaboration with the IEA since 2020 - addresses innovation trends related to hydrogen which is a core element to energy transitions in the EU and beyond. Combining the energy expertise of the IEA with the EPO's patent knowledge, it provides the most comprehensive and up-to-date global review of patenting trends in a broad range of technologies – from the production of hydrogen to its storage, distribution and transformation, through to its end-use applications across many different industries. Because patent information is the earliest possible signal of industrial innovation, this report offers a unique source of intelligence on a complex and fast-moving technology landscape that is reaching new heights of strategic importance to decision-makers around the world.

Patent protection is key for innovators to transform hydrogen research into market-ready inventions. Patents enable enterprises and universities to reap the rewards of their creativity and hard work. As the patent office for Europe, the EPO provides high-quality patents to protect innovations in up to 44 countries (including all EU member states). European patents are not only for large multinational companies. They are also key to helping small businesses raise funding, establish collaborations and eventually scale.

The study is designed as a guide for policymakers and decision-makers to assess their comparative advantage at different stages of the value chain, shed light on innovative companies and institutions that may be able to contribute to long-term sustainable growth, and direct resources towards promising technologies. Drawing on the EPO's cutting-edge patent data, it introduces new search strategies to compare incremental innovation related to established fossil fuel processes with emerging technologies motivated by the climate challenge.

The results reveal encouraging transition patterns across countries and industry sectors, including a major contribution of Europe to the emergence of new hydrogen technologies. Importantly, they highlight the contribution of start-ups to hydrogen innovation, and their strong reliance on patents to bring new technology to market. However, this report also flags some blind spots where more innovation is needed to unlock new applications of green hydrogen. By giving decision-makers an unparalleled perspective of patenting trends along hydrogen value chains, these findings can act as a valuable guide in steering the transition to a new hydrogen economy.

António Campinos
President, European Patent Office

Foreword

The global energy crisis sparked by Russia's invasion of Ukraine has highlighted the urgent need to tackle the overlapping challenges of energy security, energy access, climate change and economic recovery. Technology, including hydrogen, is at the heart of any policy package that can successfully address these interrelated issues.

Hydrogen produced from low-emissions sources has the potential to reduce reliance on fossil fuels in applications where few other alternatives exist. In the medium- to long-term, it represents our best chance to limit exposure to volatile fuel prices in critical sectors like long-haul transport and fertilizer production. However, a future of available and affordable low-emissions hydrogen is dependent on near-term policies to develop and improve technologies and to establish value chains for investment, equipment and trade.

Many countries are stepping up. The REPowerEU plan and other European Union programmes will mobilise investment to reduce EU gas demand. In the United States, the Inflation Reduction Act will drive capital towards cleaner sources of hydrogen and, we hope, also facilitate competitive international supply chains. Japan's Green Transformation Programme also contains bold plans for funding advanced technologies. Last September, 16 countries committed to funding a global portfolio of large-scale demonstration projects this decade to bring technologies like hydrogen-based steel production to market in time to achieve net zero emissions by 2050.

This report shows that competition to be the leader in hydrogen innovation is intensifying and has the potential to drive commercialisation. The stakes are high: installations of electrolysers reach 380 gigawatts in 2030 in the International Energy Agency's (IEA) Net Zero Emissions by 2050 Scenario, illustrating the economic opportunity for countries that can translate research excellence into industrial competitiveness. However, activity remains concentrated in a small number of regions, limiting the exchange of ideas. Looking ahead, hydrogen innovation must address specific national challenges, for example by helping Africa tap into some of the lowest-cost clean energy on the planet.

This study, which showcases the growing partnership between the IEA and the European Patent Office (EPO) after our work on batteries (2020) and low-carbon energy (2021), is the most comprehensive comparison of patenting trends across the full hydrogen value chain. Such an integrated approach is essential for hydrogen, which relies on multiple technologies to connect supply and demand.

The development of secure, robust and sustainable supply chains for clean energy is critical to minimise the risk of repeating today's energy crisis. The IEA's *Energy Technology Perspectives 2023*, due to be released in the same week as this report, explores in detail this topic and the important role that innovation has for the development of resilient clean energy systems.

This report's findings give us confidence that innovators are responding to the need for low-emissions hydrogen, and to the economic opportunity it represents. But the report also identifies areas – particularly among end-use applications – where more effort is required. Our continued co-operation with the EPO will allow us to track progress going forward.

Dr Fatih Birol
Executive Director, International Energy Agency

Table of contents

List of tables and figures

Tables

Figures

Figures

List of abbreviations

AEM	Anion exchange membrane
ALK	Alkaline electrolyser
CCUS	Carbon capture, utilisation and storage
CO	Carbon monoxide
DRI	Direct reduced iron
EPO	European Patent Office
eSMR	Electrified steam methane reformer
EU	European Union
FCEV	Fuel cell electric vehicle
FT	Fischer-Tropsch reaction
H_2	Hydrogen
H_2O	Water
HVO	Hydrotreated vegetable oil
ICE	Internal combustion engine
ICT	Information and communication technology
IEA	International Energy Agency
IP	Intellectual property
IPFs	International patent families
LOHC	Liquid organic hydrogen carriers
Mt	Million tonnes
NZE	Net Zero Emissions by 2050 Scenario
OEM	Original equipment manufacturer
PEM	Polymer electrolyte membrane
pH	Potential of hydrogen
PROs	Public research organisations
R&D	Research and development
RTA	Revealed technology advantage
SDGs	Sustainable Development Goals (United Nations)
SE-SMR	Sorption-enhanced steam methane reformer
SOEC	Solid oxide electrolyser cell
SPE	Solid polymer electrolyte
TRL	Technology readiness level
VC	Venture capital

List of countries

CA	Canada
CH	Switzerland
CN	P.R. China
DE	Germany
DK	Denmark
EPC countries	European Patent Convention (member states of the European Patent Organisation)
FR	France
IT	Italy
JP	Japan
KR	R. Korea
LU	Luxembourg
NL	Netherlands
Other Europe (countries)	Member states of the European Patent Organisation that are not part of the EU27, i.e. AL, CH, IS, LI, MC, ME, MK, NO, RS, SM, TR, UK.
RoW	Rest of world
UK	United Kingdom
US	United States

Executive summary

A successful transition to a clean energy future will be supported by rapid changes in the global economy and in people's patterns of energy consumption, all of which have the potential to sustain healthier societies, more equitable outcomes and a more resilient planet. Technology will be at the heart of many of these changes, and nowhere more so than in the scale-up of hydrogen as a clean energy carrier.

While strong policy will be needed to make low-emission hydrogen cost-competitive, it will not be possible without technology improvements across a value chain that touches nearly every part of the energy system. Innovators around the world are ramping up their efforts in areas as diverse as fossil fuel conversion, electrochemical splitting of water, graphene tanks, cryogenic storage, fuel cell motors for aircraft and the reduction of iron ore. If hydrogen is to play a major role in reducing fossil fuel emissions, its future depends on uniting a wide range of advances in different types of hardware and creating new markets for them. Compared with digital technologies such as software, hardware generally takes more time to develop and involves greater investment risk during the prototyping and market entry phases. Through patenting, inventors seek to ensure that they can recoup these investments in innovation.

Coordinating the deployment of the full hydrogen energy value chain is perhaps the most complex of all the technical challenges facing energy engineers and it is sometimes hard to discern the status of all the underpinning technology areas. Patents are strong indicators of innovation activity which can give very detailed insights into the state and direction of the science.

This study, which combines the expertise of the International Energy Agency and the European Patent Office, is the most comprehensive, global and up-to-date investigation of hydrogen-related patenting so far. Uniquely, it covers technologies for the full range of hydrogen supply, storage, distribution, transformation and end-user applications, as well as introducing new search strategies to compare incremental innovation related to established fossil fuel processes with emerging technologies motivated by the climate challenge.

Key findings

1. Global patenting in hydrogen is led by Europe and Japan, with the US losing ground in the period 2011–2020 and hydrogen-related innovation from R. Korea and P.R. China only starting to emerge at the international level.

About half of international patent families (IPFs)[1] in hydrogen technologies in the period 2011–2020 were related to hydrogen production. The other IPFs were split between end-use applications of hydrogen and technologies for the storage, distribution and transformation of hydrogen.

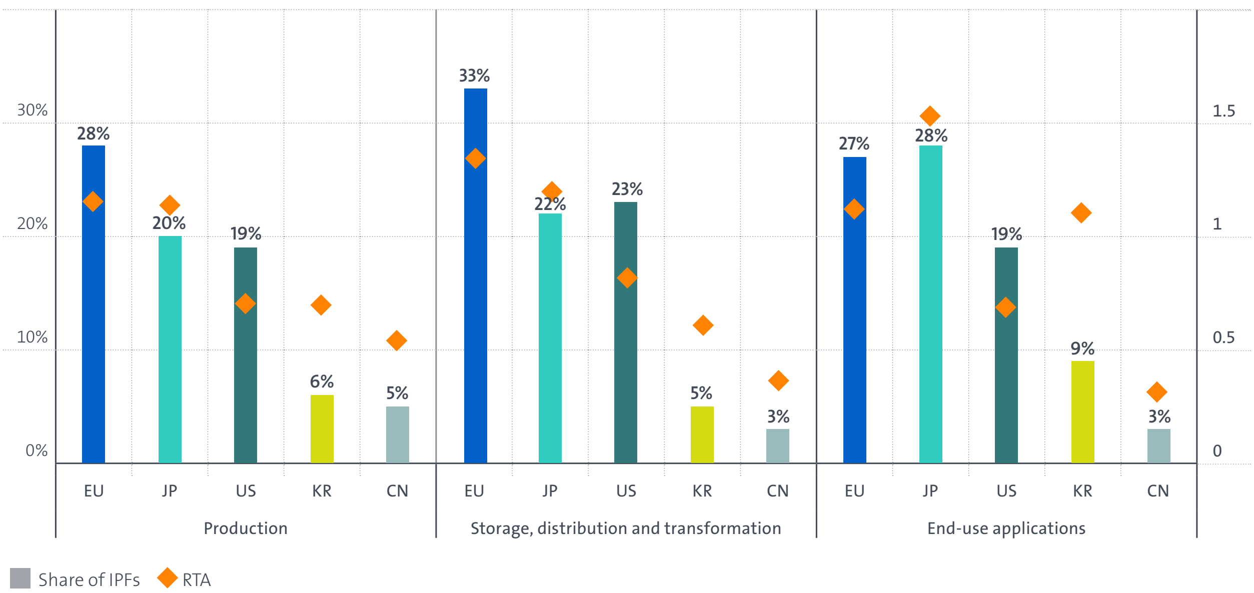
With 28% of all IPFs in the period 2011–2020 and revealed technology advantages (RTA[2]) across the three technology segments of the hydrogen value chain, EU countries are global leaders in hydrogen patenting (including 11% from Germany and 6% from France).

Japan is likewise a strong innovator in hydrogen, with 24% of all IPFs published and a revealed technology advantage in all three categories of technology. Hydrogen patenting grew even faster in Japan than in Europe during the past decade, with compound average growth rates of 6.2% and 4.5% respectively between 2011 and 2020.

The US contributed 20% of all IPF publications related to hydrogen between 2011 and 2020 and is the only major region where the number of IPFs decreased during the past decade. The number of international patent applications originating from R. Korea and P.R. China remains modest in comparison. However, it increased steadily in the period 2011–2020, with average annual growth rates of 12.2% and 15.2% respectively and a strong focus on emerging end-use applications of hydrogen in the case of R. Korea.

Figure E1

Share of international patenting and revealed technology advantage by main world regions and value chain segments (IPFs, 2011–2020)



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

1 Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally. The patent trend data presented in this report refer to numbers of IPFs.

2 The RTA index indicates a country's specialisation in terms of hydrogen innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one reflects a country's specialisation in a given technology.

2. Innovation in established hydrogen technologies is dominated by the European chemical industry, but the new hydrogen patenting heavyweights are companies from the automotive and chemicals sectors focusing on electrolysis and fuel cell technologies.

Within each of the three main technology segments of hydrogen value chains, a distinction can be made between i) incremental improvements to well-established processes in the chemicals and refining sectors and ii) emerging technologies that could help mitigate climate change by making hydrogen a clean energy product for a much wider range of sectors. Hydrogen technologies primarily motivated by climate generated twice as many IPFs in the period 2011–2020 than established technologies. They were particularly focused on end-use applications and production methods, whereas established technologies still generate a majority of IPFs in hydrogen storage, distribution and transformation.

Top applicants in established technologies are dominated by chemical companies with an extensive background in the production and handling of hydrogen from fossil fuels. They are also diversifying into emerging technologies (such as carbon capture, utilisation and storage - CCUS) enabling the supply of low-emission hydrogen. Top applicants in emerging technologies motivated by climate are led by Japanese and Korean companies, typically from the automotive industry. Their patent portfolios are mainly focused on production by electrolysis and applications based on fuel cells but also extend to established technologies for the storage and distribution of liquid or gaseous hydrogen, an area of focus for these countries which plan to import stored hydrogen in the near future.

Universities and public research institutions generated 13% of all hydrogen-related IPFs between 2011 and 2020, with the top ten research institutions alone accounting for about 3% of all IPFs. They are dominated by Korean and European institutions and show a strong focus on climate-motivated hydrogen production methods, such as electrolysis.

Figure E2

Top international applicants in established technologies and technologies motivated by climate (IPFs, 2011–2020)

	Production		Storage, distribution and transformation		End-use applications	
	Established technologies	Motivated by climate	Established technologies	Motivated by climate	Established technologies	Motivated by climate
Top 4 – Established						
Air Liquide (FR)	174	44	94	50	18	21
Linde (DE)	155	48	87	40	9	23
Air Products (US)	61	20	30	13	2	8
BASF (DE)	34	34	23	11	2	13
Top 4 – Motivated by climate						
Toyota (JP)	12	48	114	50	2	528
Hyundai (KR)	1	16	44	14		319
Honda (JP)	7	48	48	16		200
Panasonic (JP)	5	128	2	1		6
Top 3 – Research						
CEA (FR)	10	109	21	11	1	7
IFP (FR)	48	30	4	8	1	30
CNRS (FR)	3	30	4	12	1	7

Note: IPFs have been allocated to the listed entities based on the identification of these entities as an individual or co-applicant of the related patents. Technologies related to CCUS and CO_2 avoidance in fossil fuel-based hydrogen production, as well as technologies for vehicle refuelling, are labelled in this chart as "motivated by climate". Ranking is based on the size of applicant portfolios of IPFs in established and climate-motivated hydrogen technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolio due to some IPFs being counted as relevant to two or three different segments of the value chain.

Source: author's calculations

3. While hydrogen production remains almost entirely fossil fuel-based, patenting has already seen a major shift towards alternative, low-emission methods. This shift anticipates a boom for electrolysers, a field in which Europe has gained an edge in new manufacturing capacity.

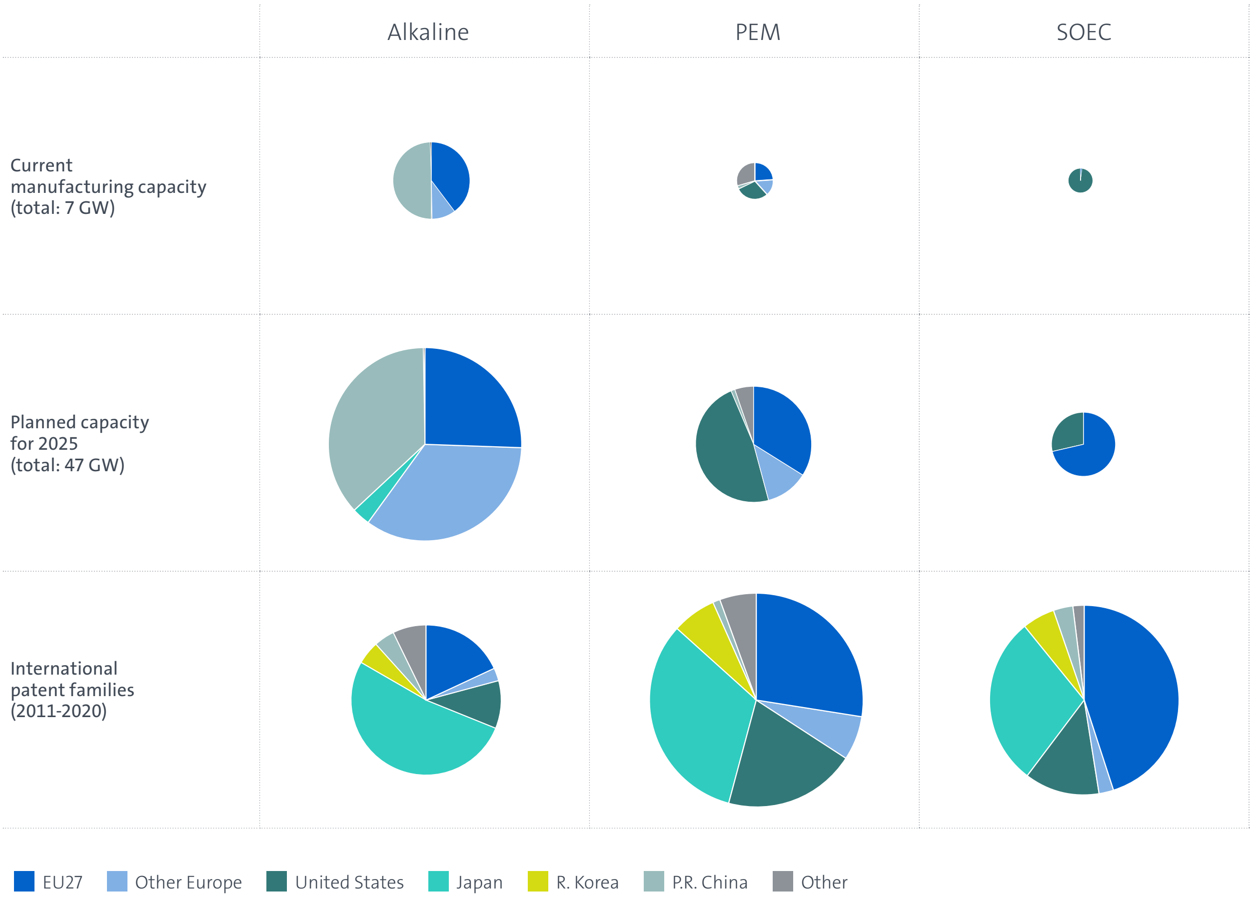
A comparative analysis of patenting trends in hydrogen production technologies over the past twenty years shows a clear shift of innovation from traditional, carbon-intensive methods to new technologies with the potential to decarbonise hydrogen production. Technologies motivated by climate concerns generated nearly 80% of IPFs related to hydrogen production in 2020. Their growth was chiefly driven by a swift rise in innovation in electrolysis.

Several categories of electrolysers are competing for the large expected market, which could rise from 1 GW to over 65 GW per year by 2030 under announced government pledges. Japan led patenting in state-of-the-art alkaline technologies and more cutting-edge PEM technologies between 2011 and 2020. However, investment in manufacturing capacity for these technologies has not yet taken off there. The EU 27 and other European countries are active in both patenting and manufacturing – notably in SOEC technologies – while also making significant contributions in terms of PEM and alkaline technologies. The US is very active in developing PEM manufacturing capacity, but less active in innovation, as indicated by patenting. P.R. China is only a small contributor to international patenting in electrolyser technologies, but is investing heavily in manufacturing capacity, with a nearly exclusive focus on cheaper alkaline technology, which has a much longer history but lower expectations for future improvements.

Published IPFs related to hydrogen production from fossil fuels have been decreasing since 2007, with emerging solutions to decarbonise fossil fuel-based hydrogen generating only limited patenting thus far. Innovation in other hydrogen production technologies motivated by climate likewise appear to lack momentum. Patenting activities in hydrogen production from biomass or waste (via gasification or pyrolysis) rose sharply between 2007 and 2011 but have decreased considerably since then. The number of IPFs related to water splitting via non-electrolytic routes has also decreased slightly since 2010. In 2020, it represented 12% of the total number of IPFs published in the field of electrolysis.

Figure E3

Origins of inventions related to electrolysers and manufacturing capacity



Note: The calculations are based on the country of the investors and IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations (based on announcements by electrolyser manufacturers)

4. Patenting activities targeting improvements in existing technologies for the storage of hydrogen and the production of ammonia and methanol grew steadily from 2001 to 2020. However, innovation in the development of hydrogen-based fuels lost momentum in the past decade.

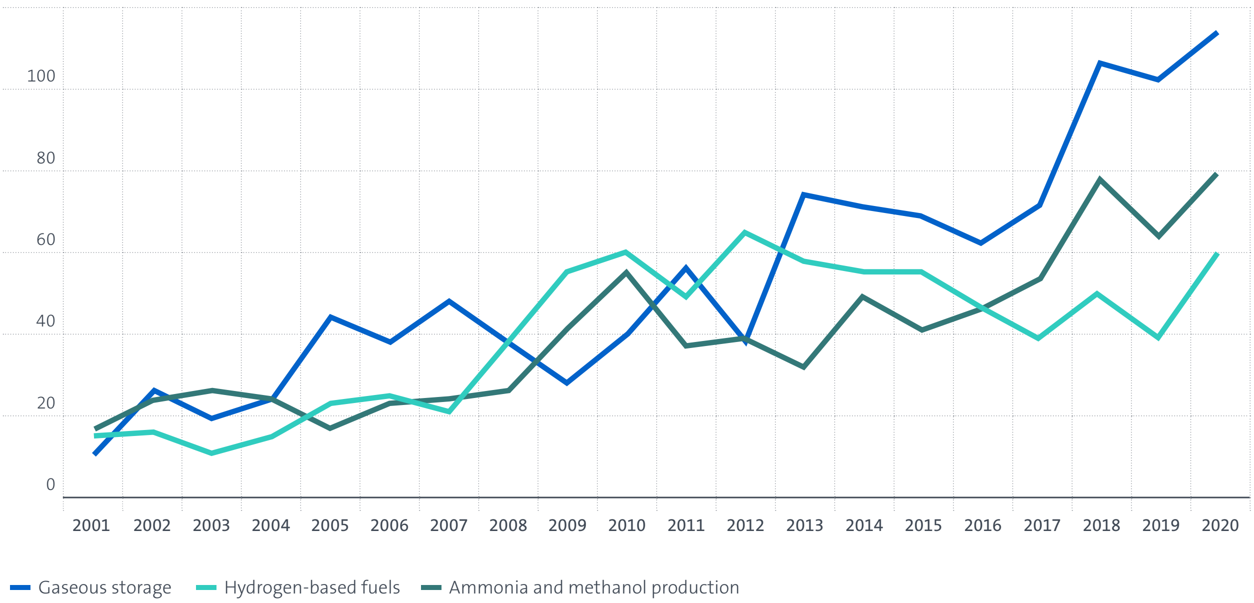
Pure hydrogen is currently transported either in gaseous form by pipelines and tube trailers or in liquefied form in cryogenic tanks. Patenting trends since 2001 show that these established technologies have attracted increasing innovation efforts over the last two decades, signalling the industry's ability to improve and interest in improving the deployment and efficiency of hydrogen distribution systems right through to vehicle refuelling. While long-established actors of the hydrogen industry are active in all technology segments of hydrogen storage and distribution, automotive companies have also become important patent applicants in some of these segments due to the importance of on-board hydrogen storage to the commercialisation of hydrogen-powered vehicles.

The number of published IPFs related to the use of hydrogen for ammonia and methanol production likewise grew between 2001 and 2020, reflecting both the efforts to reduce the significant climate impact of their production processes and the recent interest in these molecules as hydrogen-based fuels for the power and transport sectors. Like pure hydrogen storage technologies, innovation in these fields is chiefly driven by (mostly European) companies that are already specialised in the production and handling of hydrogen from fossil fuels.

Progress in other hydrogen-based fuels – for example synthetic kerosene for aviation or synthetic methane – also relies on improvements to efficiency and cost reductions, but patent data suggest that innovation in these technologies lost momentum during the past decade. US- and Europe-led efforts to develop synthetic fuels have stalled since 2011. Patenting for the competing technologies for long-distance transportation of hydrogen energy increased rapidly from 2011 to 2020, with compound average growth rates of 12.5% for liquid organic hydrocarbons (LOHC) and 7.8% for ammonia cracking. However they only represent a small number of patent families, half of which still originate from science-oriented research institutions.

Figure E4

International patenting trends in gaseous hydrogen storage, ammonia production, methanol production and alternative hydrogen-based fuels (IPFs, 2001–2020)



Source: author's calculations

5. Patenting activities for hydrogen use in the automotive sector continue to expand at much higher rates than for other end-use applications, despite some recent progress towards the use of hydrogen for steel production. However, innovation has yet to take off significantly in other industrial applications, including long-distance transportation using hydrogen-based fuels.

The strong growth of IPFs in transportation was driven by innovation in fuel cell propulsion in the automotive sector and, to a lesser extent, short-distance aviation (particularly drones). Patenting activities in these fields are largely dominated by Japanese and Korean automotive companies, and appear to generate synergies with innovation in PEM electrolysis. By contrast, innovation in internal combustion engines (ICE) and turbines using hydrogen, ammonia or methanol as a fuel has not yet been boosted by the recent policy momentum behind hydrogen, though these technologies are likely to be needed for long-distance transportation, particularly for shipping and medium-haul aviation.

IPF publications related to the use of hydrogen for iron and steel production rebounded in 2017 following several years of decrease since 2014. Nearly 40% of patenting activities in the period 2011–2020 were concentrated among a small number of steel producers and equipment suppliers. The latter are led by European companies and appear to be in a more advanced position to integrate the most advanced hydrogen technologies (such as direct reduced iron and smelting reduction) into a new generation of production equipment.

The level of patenting in other end-use applications of hydrogen in buildings and electricity generation decreased during the 2010s, denoting a lack of interest in building applications in regions other than Japan and a growing interest in batteries as an alternative solution for stationary electricity storage.

Figure E5

International patenting trends in hydrogen-based propulsion technologies, 2011–2020

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Automotive										
Fuel cells	64	72	105	98	107	187	170	171	182	234
Internal combustion engines	80	67	51	69	58	47	54	60	79	61
Aviation										
Fuel cells	16	19	34	18	22	25	30	25	23	71
Gas turbines	6	12	10	17	14	15	16	12	15	16
Shipping										
Fuel cells	3	5	15	12	8	14	10	8	16	19
Internal combustion engines	5	10	16	11	11	15	14	12	16	24

Source: author's calculations

6. Patenting underpins fundraising by start-ups developing hydrogen businesses, with more than 80% of later-stage investment in hydrogen start-ups going to companies which had already filed a patent application, indicating the importance of patenting for young firms in this area.

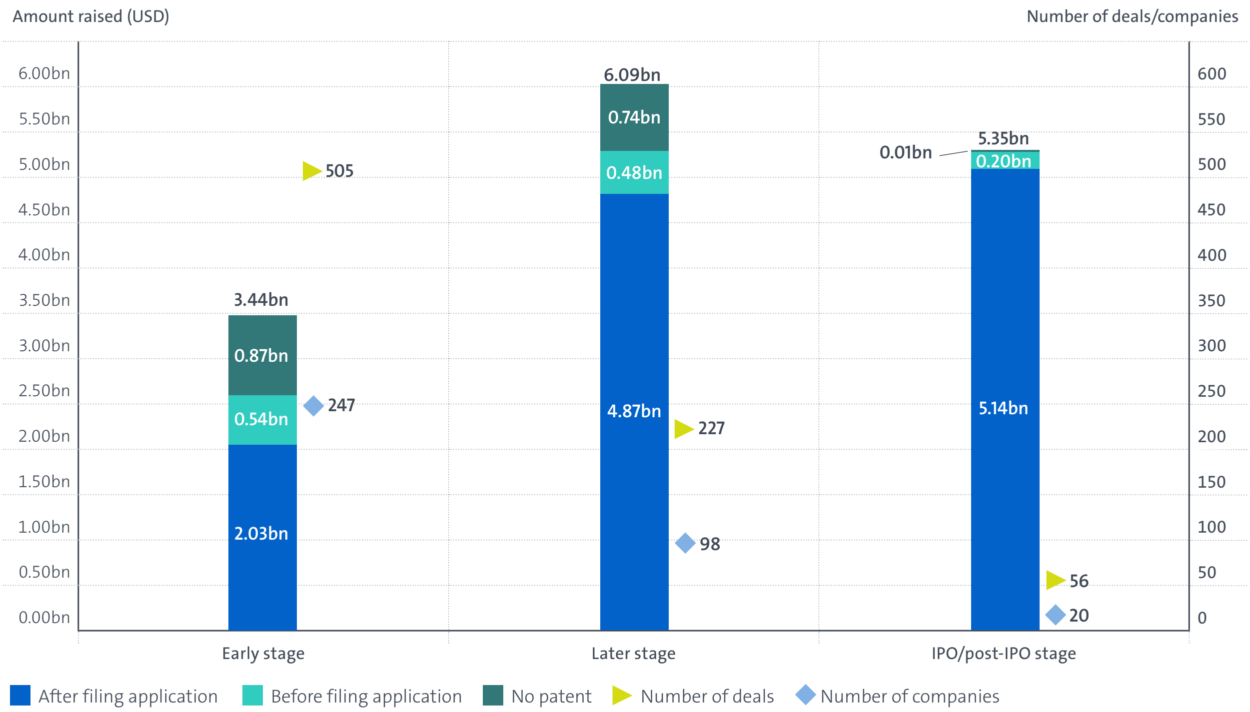
Almost 70% of the 391 start-ups which have activities related to hydrogen hold at least one patent application. Indeed, the majority of start-ups in the hydrogen sector start their journey in the laboratory and rely either on the recombination of existing technologies or on leveraging emerging technologies to address fundamental technical problems. These types of ventures require significant investments in R&D and engineering, and typically rely on patents to secure those investments.

Only 117 of the 391 start-ups filed IPFs in the scope of this study during the period 2011–2020, mostly in the EU (34%) and the US (33%), but they attracted 55% of the venture capital funding provided for early, late and IPO/post-IPO stages. A broader analysis of venture capital deals involving hydrogen start-ups with or without patent applications shows that the share of the total amount of funding raised by companies with patent applications grows consistently when moving to later funding rounds (Figure E6). More than 80% of the later-stage investment in hydrogen start-ups is received by companies which had already filed their first patent application. This percentage increases to 95% when funding acquired in the IPO/post-IPO stage is taken into consideration.

The IPFs of hydrogen start-ups mainly target technologies primarily motivated by climate, such as electrolysis and fuel cells. However, about a third of them also show patenting activities in established technologies, usually in combination with IPFs in climate-motivated technologies. This is the case in particular in hydrogen production, thus signalling attempts to reduce the carbon impact of hydrogen from gas and other fossil fuels.

Figure E6

Share of funding accruing to start-ups, by funding stage, 2000-2020



Note: Funding deals are only included for companies that were founded between 2000 and 2020. The reference date with respect to the patent filing is the earliest priority date calculated for the set of patent families assigned to the specific company. Cleantech Group, Crunchbase and Dealroom have been used as data sources for funding rounds. Early-stage funding contains the following investment types: Seed, Series A, Series B. Later-stage funding contains the following investment types: Series C-F. IPO/post-IPO stage: non-equity type transactions are not included in this stage. Reported funding at the post-IPO stage is limited to private investments in public equity types of investments, thus excluding additional public shares issues.

Source: author's calculations

7. The uneven trends in hydrogen-related patenting across technologies and regions indicate opportunities for policy action to help realise a net zero emissions future.

Despite overall positive signals from the growth of patenting activity in hydrogen technologies, there are several areas of concern. The reliance of hydrogen technologies on a complex technical value chain means that the widespread use of low-emission hydrogen will only proceed as quickly as the weakest link in the chain. The emphasis of innovators on hydrogen production is very welcome, and will lead to cost reductions over time, but cost and performance improvements are also needed in areas such as hydrogen-based fuels synthesis and end-use applications. While cost reductions in these areas are widely anticipated in analysts' economic models of the future energy system, patent data suggest that inventors are not yet incentivised to make them a reality.

The risk of a mismatch in supply and demand technologies should be taken seriously by governments. The variety of electrolyser solutions being developed in laboratories and, more recently, in commercial-scale factories has created a momentum for innovation that is supported by economic competition between companies and regions. There is a good case for governments to steer innovation towards novel manufacturing techniques, reduced reliance on some critical minerals or the use of desirable inputs such as brine or contaminated water, and the general direction is already very encouraging. However, investments into the deployment of these technologies depends on there being willing purchasers of low-emission hydrogen, which in turn depends on the existence of appropriate and competitive transformation and end-use technologies. Unless so-called "drop-in" hydrogen-based fuels are available on the market, or the technologies to switch from fossil fuel-based hydrogen are widely accessible to consumers and businesses around the globe, investment will be limited.

Governments play a key role in setting the research agenda and adopting policies that incentivise the private sector to invest in innovation. The patent data clearly shows that established players are heavyweights in hydrogen patenting and are capable of expanding into new market segments. Automotive companies and chemical companies that are active in fuel cells and electrolysis are a clear example. Sending signals about the need to transition to cleaner fuels to companies in the iron and steel, aviation and shipping sectors will stimulate technology efforts among incumbents and also catalyse new start-ups. Such signals can be based on regulation, market incentives or financial transfers, coupled with support for innovative projects. Similarly, patenting trends for the use of hydrogen to upgrade biofuels and for stationary power generation need a new impetus.

Another area to be monitored in future studies of hydrogen patenting for a clean energy future is the production of hydrogen from fossil fuels. To reduce emissions significantly, this established sector of the economy cannot continue with incremental innovations to improve efficiency. All fossil fuel-based technologies should be aligned with climate motivations if these technologies aim to have a role in a net zero energy system.

1. Introduction

Today, there is a near universal consensus that hydrogen is one of the means by which a fully decarbonised future can be realised. Expectations for the scale-up of hydrogen to meet clean energy goals have continued to grow in 2022, and it is widely understood that this outcome hinges on reductions in costs of hydrogen-related equipment.

However, the full scope and dynamics of this transition remain difficult to grasp. There is often little awareness of which elements of the value chain need to come together to connect hydrogen supply to a wider range of hydrogen applications, where novel solutions are required to supplement tried and tested technologies, and which industry actors will drive these transformations. The purpose of this study is to address these questions by providing a comprehensive overview of the evolving hydrogen technology landscape using patent data as a measure of innovation.

1.1 Why hydrogen?

The rapid change in fortune for hydrogen as a potential widely-used energy carrier relates largely to three new considerations for energy planners that are unrelated to hydrogen's underlying technologies:

- Countries and companies have set their sights on eliminating – not just reducing – the impacts of fossil fuel emissions from their energy systems. This target, often referred to as "net zero emissions", has focused attention on how to avoid fossil fuel emissions in all sectors, including sectors where fossil fuels have the largest comparative advantage, such as heavy industry and long-distance transportation (IEA, 2021) . Among the few alternatives for these sectors, hydrogen and other combustible fuels that can be made from it have the most attractive characteristics in terms of energy density, storability and chemical properties.
- Most of these net zero pledges by countries and companies set 2050 as the target year, in line with climate science. Having less than three decades to radically overhaul the energy system, transport system, building stock and industrial processes in tandem requires large sums of capital to be mobilised quickly, including for infrastructure. The tightness of the timeline gives hydrogen an advantage because it can link new assets with existing infrastructure, such as for the transport and storage of natural gas and oil.
- Finally, the pace of improvements to the costs and performance of wind and solar electricity, as well as batteries, has forced a shift in consensus among energy planners. In 2021, investment in wind, solar and batteries represented 40% of the global electricity sector investment, more than three times the size of the investment in fossil fuel power generation (IEA, 2022a). There is now a broad expectation that the most secure and competitive energy system of the future will be oriented around variable renewable electricity, raising the challenge of how to deliver it affordably to as many energy uses as possible. Producing hydrogen from water using electricity is among the most effective ways to store this electricity over long periods and thereby use it in places that are hard to reach with electricity or for purposes that do not match the time profile of renewable power generation.

Hydrogen is not an energy source but an energy carrier, which means that its potential role has similarities to that of electricity. The IEA report "The Future of Hydrogen" presents the various ways in which different energy sources can be transformed into hydrogen, the different ways in which hydrogen can be stored and distributed, and the different applications in which it can be used (IEA, 2019). Like electricity, hydrogen's strength lies in its flexibility to perform a variety of energy-related tasks with a diversity of energy inputs and no carbon dioxide emissions at the point of use. This flexibility has the potential to bolster the overall security of energy networks if the interconnections between electricity and hydrogen value chains are well planned.

1.2 The need to ramp up supply and demand for low-emission hydrogen

While it is possible to produce hydrogen from a range of energy inputs, not all routes will lead to an emissions reduction. In 2021, around 94 Mt of hydrogen were produced worldwide, with an energy content equivalent to 2.5% of global final energy consumption. Less than 1% was produced using low-emission production technologies (IEA, 2022b). This hydrogen was produced for two main sectors: oil refining and chemicals production (including ammonia for fertilisers). To make a valuable contribution to energy transitions, changes are needed on both the supply and demand sides.

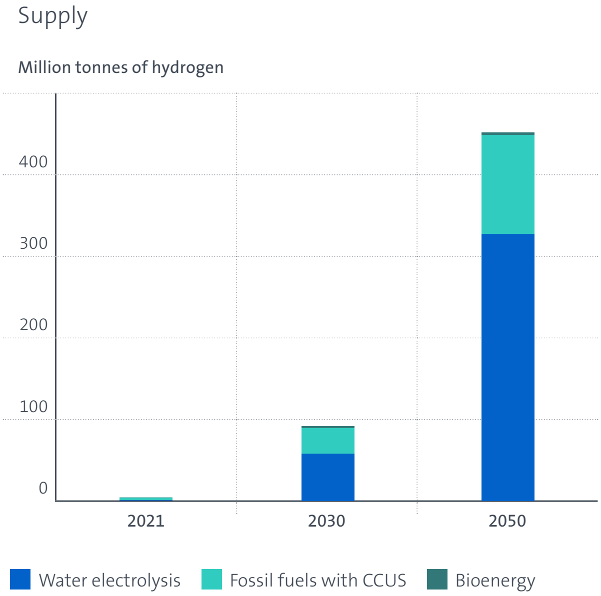
— On the supply side, only low-emission hydrogen is compatible with the decarbonisation of the energy system. Low-emission hydrogen is produced from water using electricity generated by renewables or nuclear, from fossil fuels processed in facilities equipped to avoid CO_2 emissions (e.g. via CCUS with a high capture rate) and with minimal associated methane emissions, or derived from bioenergy. While some of these solutions are already being deployed, others are still at an early development stage, and all of them require further development and scaling up to ensure full cost-competitiveness.

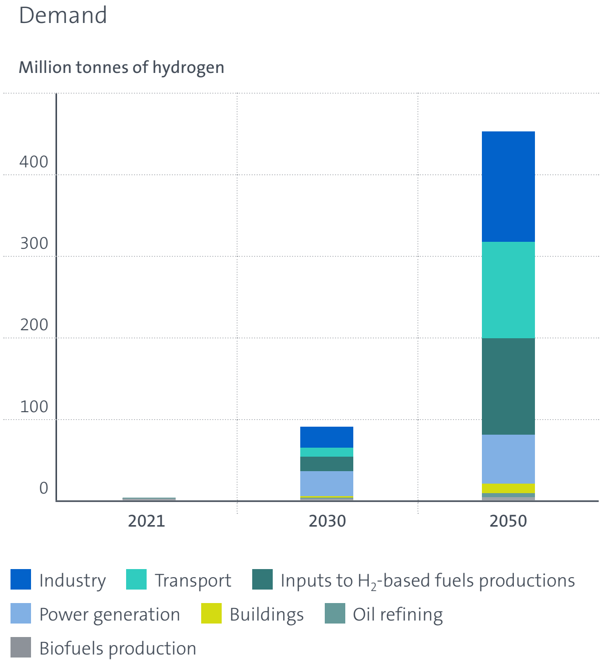
— On the demand side, hydrogen needs to penetrate more sectors in addition to chemicals and refining. These new applications are mostly "energy" applications, such as transport, high- temperature heating and as the energy input for making replacement fuels for shipping and aviation (so-called low-emission hydrogen-based fuels such as ammonia or synthetic kerosene). New non-energy applications include replacing coal and natural gas as a reducing agent for steel manufacture. As with hydrogen supply, these applications typically involve the implementation of new technologies, many of which have yet to be demonstrated on a large scale. Demand in each sector will depend on the advantages of these hydrogen-based options compared with other decarbonisation solutions.

Government action on both the supply and demand sides is growing. A total of 26 governments have adopted national hydrogen strategies, including nine adopted since September 2021 (IEA, 2022b). In Europe, where Russia's invasion of Ukraine has disrupted natural gas supplies, the EU's resolve to quickly scale-up hydrogen from renewable electricity has strengthened. In May 2022, the European Commission proposed that EU demand could rise to 20 million tonnes in 2030, which could replace 27 billion cubic metres of natural gas demand and four million tonnes of oil demand. Given the EU's domestic resources for making hydrogen from renewable electricity and the challenges of such a rapid scale-up, the proposal suggested that half of this total would need to be imported from outside the EU. At present, facilities for international trade in hydrogen do not exist commercially, but considerable attention is being given to the exploration of how existing infrastructure – such as that for trading ammonia or natural gas – could be used for this purpose.

Figure 1.1

Supply and demand for low-emission hydrogen in the IEA net zero emissions scenario





Note: One Mt H_2 contains the energy equivalent of the annual energy consumption of two million average EU households. Norway's natural gas production in 2021 was equivalent to 35 Mt H_2.

Source: author's calculations

Box 1: Investors are placing bets on a variety of hydrogen technologies

In response to government action and raised expectations for the competitiveness of clean energy, more capital is flowing to key hydrogen technologies. More electrolyser capacity that can produce hydrogen from water came online in 2021 than in any previous year – almost 210 megawatts (MW). In total, close to 900 MW of electrolyser capacity is planned for operation in 2022, which would produce roughly 0.1 million tonnes of hydrogen per year. More than USD 1.5 billion was spent on projects at advanced stages in 2021 (IEA, 2022b).

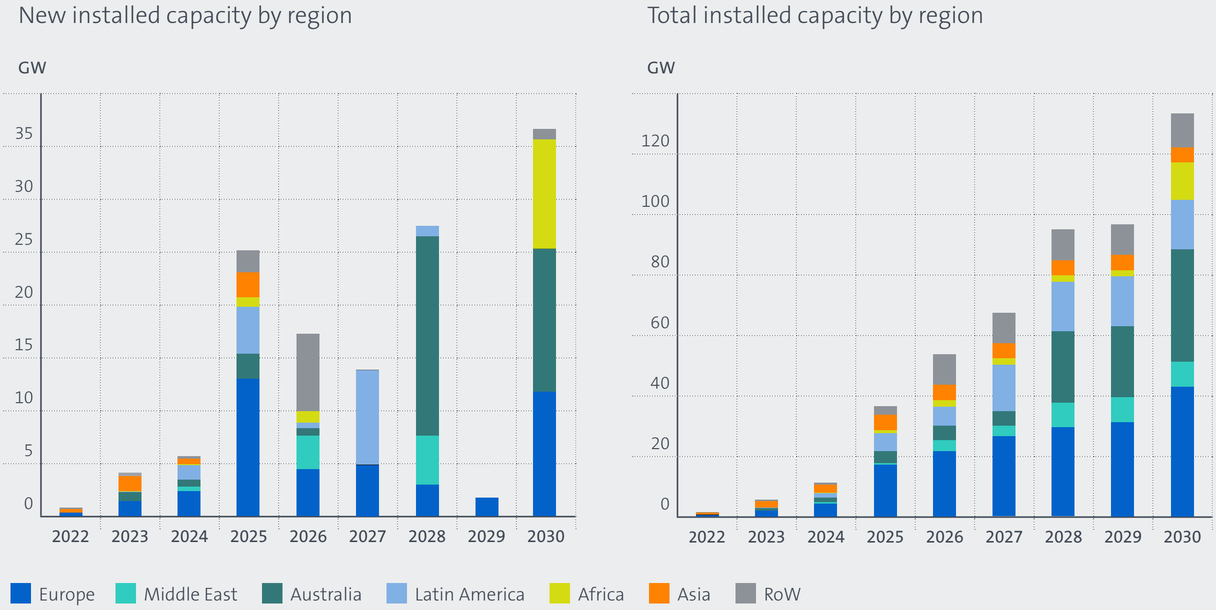
These projects are now reaching the commercial scales of industries like refining and fertilisers that they supply. A 150 MW project came online in P.R. China in 2022, and 200 MW and 260 MW projects have entered construction in the Netherlands and P.R. China. Before 2020, no project worldwide had reached 10 MW using these technologies.[3] If all projects currently at an advanced stage of planning were to be realised, by 2030 the production of low-emission hydrogen could reach 16 million tonnes per year, with 9 million tonnes based on electrolysis and 7 million tonnes based on fossil fuels with CCUS.

To supply these projects, investment is also needed from the companies developing and integrating the technologies. These companies have been very successful in raising funding in recent years despite the economic impacts of the pandemic and, more recently, inflation. For example, the installed capacity of electrolyser factories has rapidly increased, reaching 8 GW in 2022. Based on company announcements, global manufacturing capacities could reach 65 GW per year by 2030 and include gigawatt production lines for three of the four competing electrolyser types: alkaline, polymer electrolyte membrane, and solid oxide electrolyser cell (announcements related to anion exchange membrane electrolysers are still limited due to its lower technological development). Companies have not had difficulty increasing their capitalisation significantly to fund these expansions, as well as growth in other related technologies. A portfolio of publicly traded companies tracked by the IEA, whose success depends on the increasing demand for low-emission hydrogen, is worth around ten times more today than it was five years ago, at USD 33 billion, and four times more than at the end of 2019.

At an earlier stage of technology development, venture capital (VC) investments in hydrogen technologies boomed in 2021, as investors embraced a wide range of technology opportunities that could help drive more low-emission energy into all sectors and applications. Early-stage deals that back higher risk, innovative ideas – Seed, Series A and B rounds – reached over USD 1 billion, nearly six times the equivalent value in 2020. Overall, hydrogen accounted for about 10% of all early-stage VC investments in clean energy start-ups, compared with 5% in 2020.

Figure 1.2

Electrolyser capacity by region based on project pipelines to 2030



Notes: Only projects with a disclosed start year for operation are included. Projects at very early stages of development, such as those in which only a co-operation agreement among stakeholders has been announced, are not included.

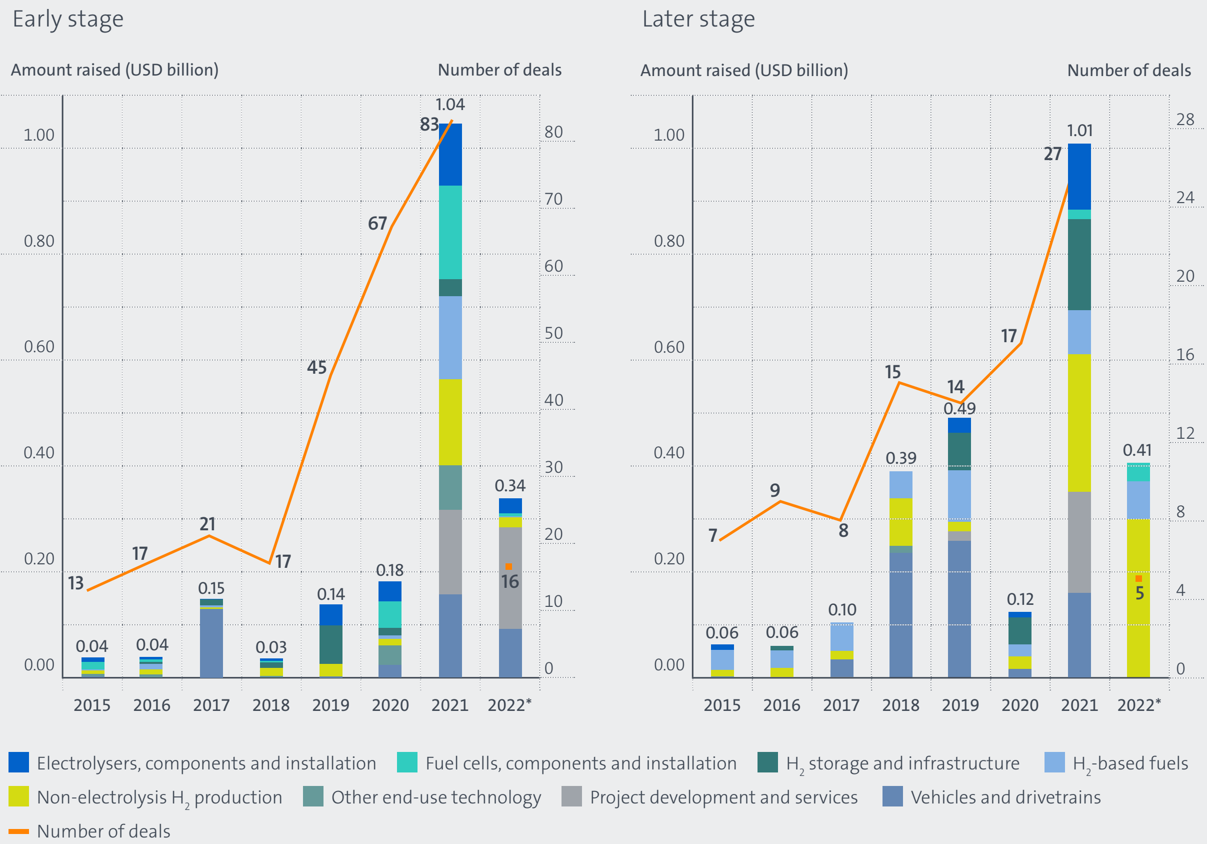
Source: IEA, 2022 "Global Hydrogen Review"

3 There are some exceptions. Some large projects were developed in the 20th century in Africa, Europe and Latin America, but these were not developed with a view to reducing emissions, and most were decommissioned many decades ago as natural gas became the preferred hydrogen source.

There were three major trends in early-stage deals in 2021: the emergence and fundraising success of start-ups offering project development services; the strong performance of firms with technologies for potential (non-automotive) hydrogen users; and more interest in non-electrolysis routes to low-emission hydrogen. In line with the broad understanding that hydrogen's key position in the transport sector might be in longer-distance modes, notable investments in 2021 were led by aviation companies rather than road vehicle firms and went to start-ups developing hydrogen-powered aircraft.

Figure 1.3

Venture capital investment in clean energy start-ups related to hydrogen, 2015–2022



Source: IEA-EPO calculations based on Cleantech Group database (2022), Crunchbase and Dealroom data

* 2022 data are only for H1 2022

1.3 Why this report?

Innovation in a wide range of technologies will be indispensable for reducing the costs of producing and using hydrogen and unlocking more applications of hydrogen in hard-to-abate industries. Lower costs narrow the finance gap that governments have to bridge through regulation or funding in order to make hydrogen an attractive product for users. By increasing hydrogen demand in this way, investment in the value chain will rise, further stimulating innovation and achieving cost reductions through economies of scale. In the near-term, researchers and business developers need the right conditions to find and test new approaches that have the potential to make low-emission hydrogen more competitive. Alongside investment in first-of-a-kind projects that demonstrate safe, commercial operation, sustained technology improvements through innovation provide the best chance of entering a virtuous cycle of cost reduction and deployment.

Many governments and companies around the world are therefore asking whether innovation for hydrogen technologies is adequate, which parts of the value chain are making progress or lagging the most, and in which direction they should focus their innovation efforts. Understanding the bigger picture also requires not only identifying the countries and industry players that are leading ongoing progress in hydrogen technologies, but also asking whether innovation for low-emission hydrogen is now outpacing that for fossil fuel-based and legacy hydrogen production methods. Incremental innovation in traditional, polluting routes makes cost-competitiveness a moving target and low-emission technologies will have to run faster to compete.

The sheer breadth of hydrogen-related technologies significantly complicates how these questions can be reliably answered.

— On the supply side, it is important to include inventions that seek to improve the performance and costs of extracting hydrogen sustainably from water, but also those that look for other ways to produce low-emission hydrogen from biomass, inorganic materials or fossil fuels, including potential future approaches like methane pyrolysis as well as comprehensive CO_2 capture. The latter category poses a particular challenge. Distinguishing inventions that seek to sustain unabated fossil fuel use from those that enable the application of CCUS is generally not feasible. For example, any improvement to the efficiency of steam reforming of natural gas to hydrogen could improve the economics of production with or without CCUS.

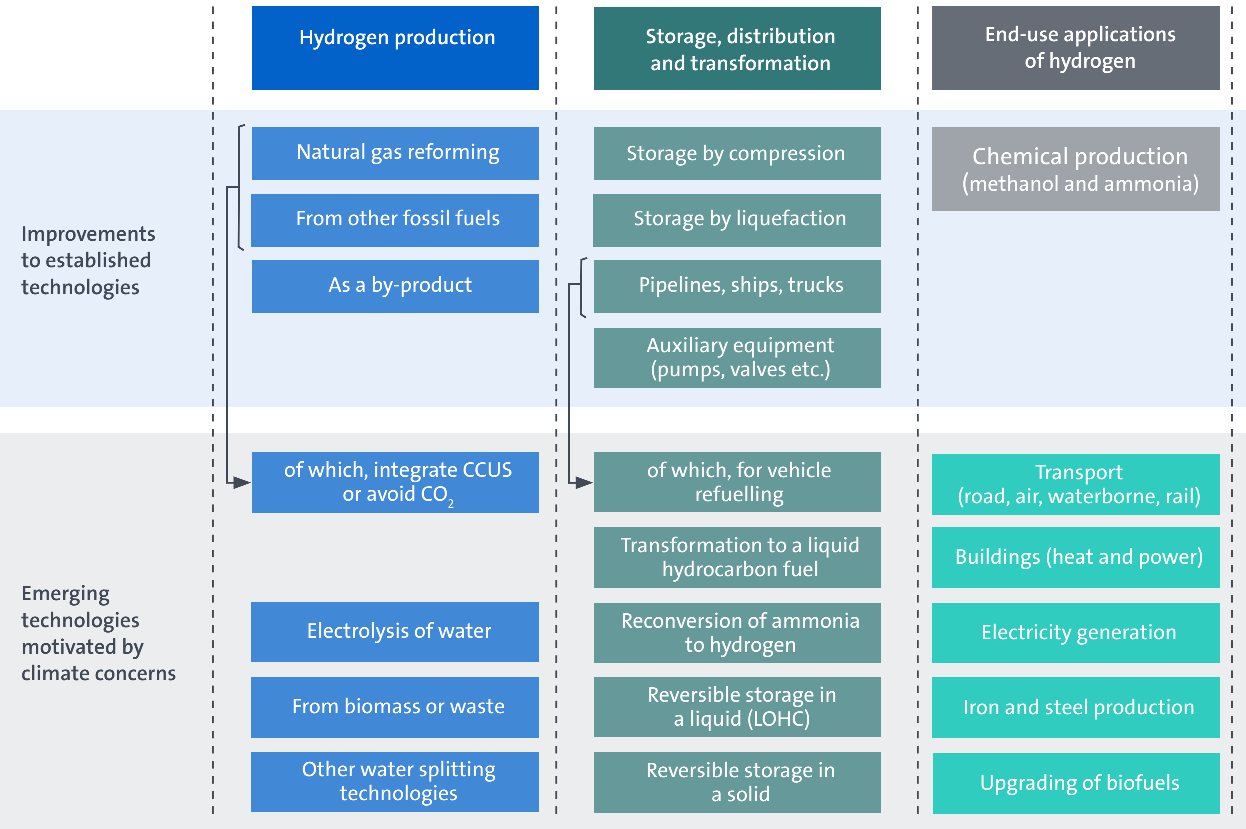
— On the demand side, many pertinent patent applications do not specify hydrogen in their titles and search strategies must be devised to identify inventions that could reduce the barriers to adopting hydrogen in the transport, industrial and buildings sectors. In addition, many such inventions are not specific to a single sector and could be applied to different end-uses. Fuel cells are prime examples of this situation.

— In between supply and demand, the different means of storage, distribution and transformation often overlap. For example it may not be possible to allocate an invention for containing liquefied hydrogen to either stationary hydrogen storage or seaborne transport of hydrogen. There is a suite of technologies being developed for transforming hydrogen into derivative products that can be more easily stored and used in turbines and engines with minimal modifications. While these technologies could increase demand for hydrogen, the final sectoral "demand" is not for hydrogen itself but for a fuel such as ammonia or synthetic kerosene. In the case of ammonia manufacture, it is generally not possible to distinguish inventions for low-emission ammonia fuel from those for traditional fertiliser applications. In the case of synthetic kerosene, the aviation sector does not need to innovate to accommodate this "drop-in" fuel, leading to an underrepresentation of aviation when looking at end-use applications separately from transformation.

This study uses patent information to track technical progress in hydrogen-related technologies and assesses their alignment with the needs of energy transitions. The data presented in this report show trends in high-value inventions for which patent protection has been sought in more than one country (IPFs). While some long-term trends are examined in the report, most of the analysis is focused on the last decade (2011–2020) in order to provide an up-to-date picture of the current state of play by highlighting technology fields that are gathering momentum and the cross-fertilisation taking place. Therefore, the study is designed as a guide for policymakers and decision-makers to assess their comparative advantage at different stages of the value chain, shed light on innovative companies and institutions that may be in a position to contribute to long-term sustainable growth, and direct resources towards promising technologies.

Figure 1.4

Cartography of hydrogen-related technologies



Notes: Refining is not analysed in the report due to the difficulty of reliably assessing the relevance of hydrogen in inventions for which a patent application has been filed in this field. Due to indistinguishability of technologies, methods for the production of ammonia from hydrogen are included only under chemical production applications and are omitted from hydrogen transformation, despite recent inventive effort to find new means of integrating ammonia and low-emission hydrogen production. Other end-use applications may be directly based on hydrogen, as well as on ammonia and methanol derived from hydrogen.

With the combined expertise of both the EPO and IEA, the report has been able to map hydrogen-related technologies to patent data with both relevance and precision. The analysis aims to be inclusive of all the technologies tracked by the IEA as potential contributors to a net zero emissions future. While existing patent classification systems and the EPO's Y02 tagging scheme for climate change mitigation technologies already contain dedicated classes for some hydrogen-related technologies (such as fuel cells), they are not systematically aligned with the IEA approach to analysing energy systems in all their complexity. The expertise of the EPO was therefore used to identify all relevant technologies within the universe of patent applications and design search strategies that fairly present the relevant trends.

The resulting scope covers the whole value chain as comprehensively as possible, split into three categories:

1. Hydrogen production. These are technologies that seek to improve the performance or reduce the costs of processes to isolate hydrogen from any feedstock through the application of energy.

2. Storage, distribution and transformation. These are technologies that facilitate the use of supplied hydrogen at a different geographical location and/or a different point in time from its production. In the case of hydrogen transformed to hydrogen-based fuels (ammonia, methanol, synthetic hydrocarbons), the product that is ultimately used is not in the form of hydrogen.[4]

3. End-use applications. These are technologies that seek to make it more attractive or cheaper to use hydrogen to make products or supply energy services, including transportation, heat and power.[5]

For each category, the patent analysis has been further split into two groupings to reveal the trends for established hydrogen technologies that are already employed in the industry and for newly-emerging hydrogen technologies motivated by climate that can contribute to achieving net zero fossil fuel emissions. In the case of storage, distribution and transformation, this split helps to show whether inventions are diversifying away from established approaches and towards greater competition between options. This design allows for a fine-grained comparative analysis of patenting trends at different stages of the value chain, also by specifically assessing the uptake and impact of innovation based on new technology paradigms supporting the energy transition.

1.4 Structure of the report

Chapter 2 provides a high-level overview of patenting trends in hydrogen technologies over the past two decades. It benchmarks the emergence of new technology paradigms at different stages of the hydrogen value chain against incremental progress achieved in established technologies during that period, and offers a geographic perspective on hydrogen innovation ecosystems at global and regional levels.

The following three chapters specifically address the dynamics of innovation at the different levels of hydrogen value chains. Chapter 3 focuses on the production of hydrogen and analyses trends in both established fossil fuel-based production routes and emerging low-emission alternatives such as water electrolysis. Technologies enabling the storage, distribution and transformation of hydrogen are addressed in Chapter 4. Finally, Chapter 5 examines patenting trends related to established and emerging industrial applications from hydrogen, ranging from the production of ammonia and methanol to the use of hydrogen to decarbonise transport industries or iron and steel production.

4 There is a technical argument, based on formal energy accounting standards, to allocate hydrogen use in biofuels upgrading and electricity generation to the "transformation" category. However, for the purposes of this report, we have placed them among the "applications" because they do not directly tackle the same set of challenges as the other items under "storage, distribution and transformation"; namely, the containment or conversion of hydrogen so that its energy can be used at a later time or in a different location.

5 End-use applications often involve the use of fuel cells in vehicles, buildings or electricity production. International patent families related to hydrogen-based fuel cells have therefore been identified in the context of this study. This corresponds to a specific and relatively narrow definition of fuel cells patents. In comparison, the dedicated section of the EPO's Y02 tagging scheme for climate change mitigation technologies is broader, as it refers to all possible types of fuel cells.

2. Hydrogen patents: an overview

2.1 Geography of hydrogen innovation

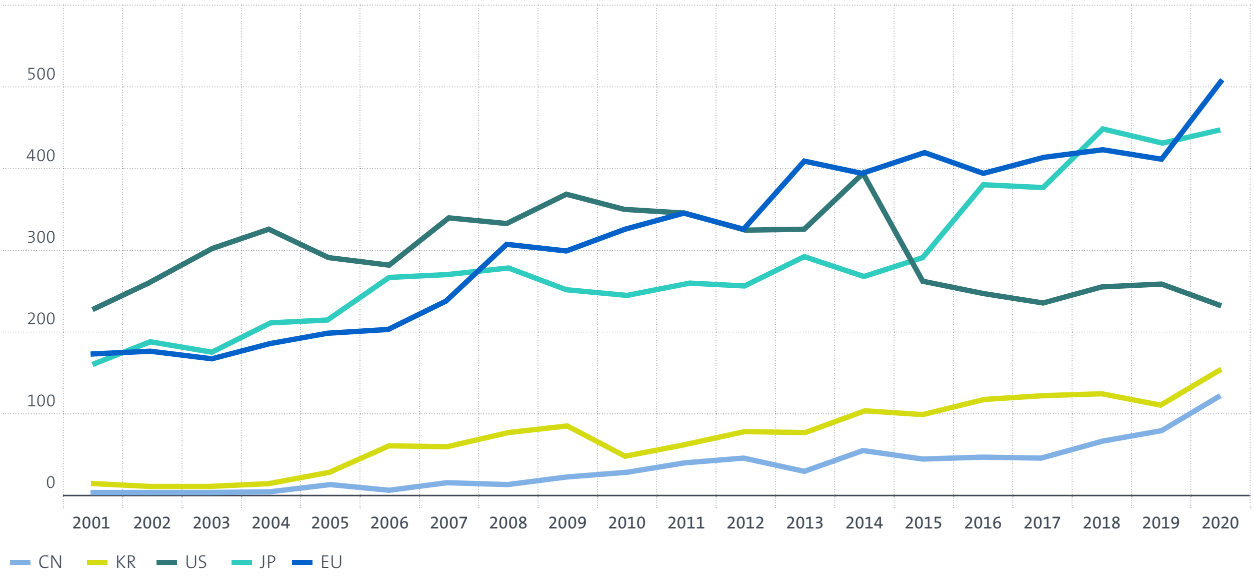
Published international patent families (IPFs) are used in the study as a uniform metric to measure patenting activities in the different categories of hydrogen-related technologies. This section reports on the global geography of hydrogen innovation, as identified by the locations of the applicants and inventors[6] of IPFs for hydrogen-related technologies. The distribution of inventive activities between the main global innovation centres is analysed as a first step. A second part of the section focuses on the main hydrogen innovation clusters in Asia, Europe and North America.

Figure 2.1 provides a trend analysis of hydrogen-related IPFs originating from the world's five largest innovative regions – the EU countries being considered as a block – since 2001. It shows a clear lead on the part of the EU, Japan and the US, but also different trends in each of these countries. Both the EU and Japan show a sustained growth of hydrogen patenting, with a steady increase in Europe in the period from 2001 to 2020 and a stagnation in Japan in the period from 2006 to 2015 followed by a rapid growth in more recent years. As a result, hydrogen patenting grew even faster in Japan than in Europe during the past decade, with compound average growth rates of 6.2% and 4.5% respectively between 2011 and 2020.

By contrast, hydrogen patenting decreased significantly in the US after 2015, and the US was a distant third to the EU and Japan in 2020, despite being the main innovator in hydrogen in 2011 in terms of volume of international patent families. The number of international patent applications originating from R. Korea and P.R. China still remains modest in comparison. However, it took off in the period 2011–2020, with average annual growth rates of 12.2% and 15.2% respectively.

Figure 2.1

Patenting trends by main world regions (IPFs, 2001–2020)



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

6 The country of the applicant is used in the study to identify the country of origin of the IPFs. The country of the inventor(s) is used specifically to track inventive activities at the more local level when analysing hydrogen innovation clusters.

Table 2.1 shows these regions' shares of IPFs in the main segments of hydrogen value chains during the last decade (2011–2020). It also provides insights into their respective specialisation profiles, as measured by the revealed technology advantage (RTA) index. An RTA indicates a country's specialisation in terms of hydrogen innovation relative to its overall innovation capacity. It is defined as a country's share of IPFs in a particular field of technology divided by the country's share of IPFs in all fields of technology. An RTA above one thus reflects a country's specialisation in a given technology.

These indicators clearly confirm the leadership of Europe and Japan in hydrogen innovation, with clear economies of scope across the value chain segments. With 28% of all IPFs in the period 2011–2020 (including 11% from Germany, 6% from France and 3% from the Netherlands) and an RTA in all three main segments of hydrogen technologies, EU countries rank first in hydrogen patenting. Japan is a close second with 24% of all IPFs and likewise has an RTA in all three categories of technologies. It has in particular a strong specialisation in end-use applications of hydrogen. R. Korea is the only other major innovation centre that shows a revealed technology advantage, also in the domain of end-use applications of hydrogen. Apart from these five main innovation centres, the United Kingdom, Switzerland and Canada also stand out, with a strong RTA in most segments of hydrogen technologies.

Table 2.1

Revealed technology advantages in hydrogen technologies by value chain segments, 2011–2020

		Hydrogen production		**Storage, distribution and transformation**		**Industrial applications**	
	Share of all hydrogen-related IPFs	Share of IPFs	RTA	Share of IPFs	RTA	Share of IPFs	RTA
EU	28%	28%	**1.2**	33%	**1.3**	27%	**1.1**
JP	24%	20%	**1.1**	22%	**1.2**	28%	**1.5**
US	20%	19%	0.7	23%	0.8	19%	0.7
KR	7%	6%	0.7	5%	0.6	9%	**1.1**
CN	4%	5%	0.5	3%	0.4	3%	0.3
DE	11%	10%	0.9	14%	**1.3**	12%	**1.1**
FR	6%	7%	**1.4**	9%	**1.8**	4%	0.8
NL	3%	4%	**2.5**	2%	**1.2**	3%	**1.8**
UK	3%	3%	**1.1**	2%	0.9	2%	0.9
CH	2%	2%	**1.5**	1%	**1.2**	2%	**1.4**
CA	2%	2%	**1.3**	2%	**1.3**	1%	1.0

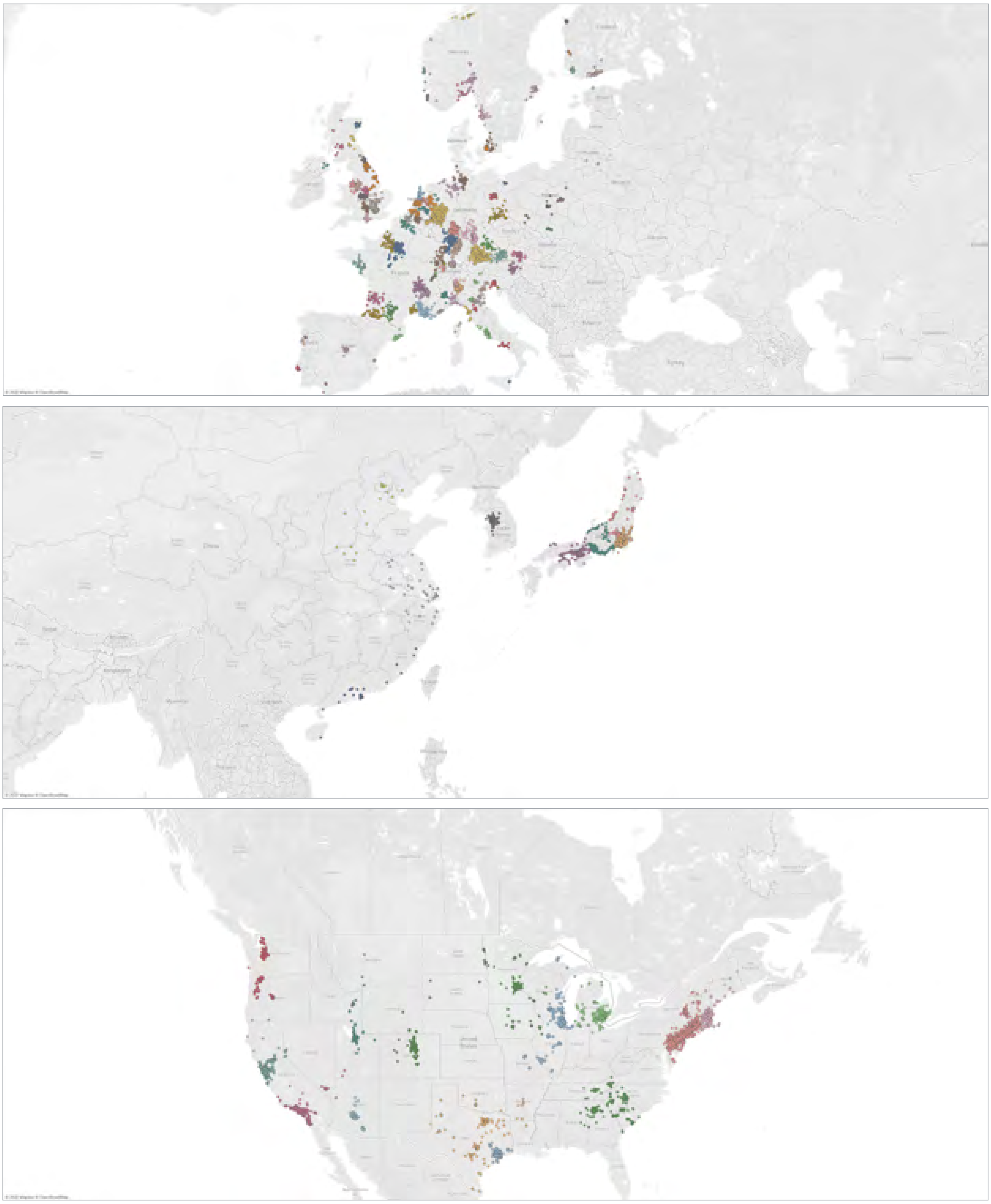
Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

The maps in Figure 2.2 provide a more detailed overview of the geographic distribution of hydrogen innovation clusters (each of which is identified by a different colour) based on the geolocation of the inventors listed in the published IPF in the period 2011–2020. A total of 120 clusters have been identified, the large majority (98) of which are located across Europe.

Most of these European clusters are of a relatively modest size. However, three regions in Germany (Munich and the Ruhr area) and France (Paris) feature among the top ten global hydrogen innovation clusters, with a large and rapidly growing number of IPFs in the period 2011–2020 (Table 2.2). The Munich and Paris clusters are led by well-established players in the hydrogen industry (Linde and Air Liquide), with important patent activities also stemming from universities and public research organisations (PROs) in the case of Paris. The Ruhr area features Thyssenkrupp, a steel production company, as its top applicant.

Figure 2.2

Global distribution of hydrogen innovation clusters (IPFs, 2011–2020)



Note: Hydrogen innovation clusters are identified by applying a hierarchical clustering procedure to the geocoded inventor locations for all relevant IPFs published in the period 2011–2020. Each cluster is identified by a different colour.

Source: author's calculations

Table 2.2

World's top ten hydrogen innovation clusters, 2011–2020

City	Country	% of world's IPFs*	Average of IPFs**	Specialisation*** (technologies motivated by climate in bold)	Top three applicants* (% of IPFs in cluster)	Universities and PROs**** (% of IPFs in cluster)
Tokyo	JP	7.5%	-1.1%	**Domestic applications of H_2; H_2 applications for rail**	Mitsubishi (10%) Toshiba (8%) JX Nippon OGE (6%)	6.9%
Osaka	JP	3.9%	+5%	**Domestic applications of H_2**	Panasonic (21%) Kawasaki (9%) Hitachi (5%)	5.8%
New York	US	3.5%	-1%	H_2 production as a by-product; **H_2 applications for aviation and electricity generation**	ExxonMobil (10%) Air Products (8%) Hamilton Sundstrand (6%)	6.1%
Nagoya	JP	3.0%	+7%	**H_2 applications in the automotive sector**	Toyota (55%) Suzuki (8%) Panasonic (4%)	4.9%
Houston	US	2.9%	+2%	H_2 production as a by-product; from gas, other fossil fuels, **biomass/waste;** distribution tasks; H_2 use for methanol and **synthetic fuels production**	ExxonMobil (13%) Air Liquide (10%) SABIC (9%)	4.4%
Paris	FR	2.8%	+9%	Separation/purification; liquid storage	Air Liquide (36%) IFP (12%) CNRS (6%)	27.6%
Munich	DE	2.5%	+10%	Separation/purification; liquid storage; **H_2 applications in aviation**	Linde (38%) BMW (22%) Airbus (9%)	2.8%
Ruhr area	DE	2.2%	+10%	Ammonia production; **H_2 applications in steel production and rail; solid storage**	Thyssenkrupp (24%) BASF (8%) Kautex Textron (7%)	6.5%
Sendai	JP	2.1%	+3%	**H_2 carriers; H_2 applications in rail; domestic applications of H_2**	Toyota (18%) Mitsubishi (8%) Kobe Steel (7%)	6.3%
Seoul	KR	2.1%	+19%	**Domestic applications of H_2; H_2 applications in shipping**	KIER (6%) Daewoo SME (5%) Hyundai (5%)	20.9%

Notes: * The allocation of IPFs to local clusters is based on the address of the inventors listed in the patents. The share of IPFs from universities and PROs is calculated using IPFs listing at least one university or PRO among the applicants.
** The average growth rate of the IPFs is computed over the period 2011–2018 to ensure availability of inventor data.
*** Specialisation in a given field is determined using the RTA as an indicator. The RTA in a field is calculated as the share of the cluster's IPFs in that field, divided by the share of the same cluster's IPFs in all hydrogen technologies. An RTA threshold of 3.5 has been set to identify fields of specialisation.
**** The share of IPFs from universities and PROs is calculated using IPFs listing at least one university or PRO among the applicants. As such, the figures cannot be interpreted as measures of the share of universities and PROs in IPFs.

In contrast to the US and European countries, hydrogen innovation is more concentrated geographically in Japan, R. Korea and P.R. China, with a small number of very large regional clusters. Four Japanese regions feature among the top ten global clusters, including Tokyo and Osaka at the top of the list. Apart from Tokyo, patenting activities related to hydrogen have increased rapidly in these regions, typically with a strong focus on end-use applications of hydrogen. Seoul is the only cluster identified in R. Korea, with a similar focus on end-use applications. It stands out with a very rapid growth of patenting activities in the period 2011–2020 and an important contribution by public research institutions to these activities.

Another fourteen clusters have been identified in the US, of which two (New York and Houston) feature in the global top ten. These two clusters show a specialisation in established hydrogen production technologies. Unlike other major clusters in Europe and Asia, they did not experience a significant growth of patenting activities during the past decade.

2.2 General patenting trends in established and emerging technologies

IPF publications related to hydrogen date back to the 1970s, but really took off in the late 1990s. As reported in the top left-hand corner of Figure 2.3, patenting is relatively evenly spread across the different technology segments of the hydrogen value chain, with technologies motivated by climate generating more than twice the number of IPFs than established technologies in the period 2001–2020.

The largest number of IPFs is observed in technologies supporting the production of hydrogen. About two-thirds of the corresponding inventions are focused on technologies motivated by climate, such as electrolysis or the production of hydrogen from biomass or inorganic compounds. Overall, patent data show that innovation in these technologies increased rapidly between 2001 and 2020, whereas the annual flows of IPF publications targeting established (fossil fuel-based) hydrogen production technologies stagnated during the same period (see also Chapter 3).

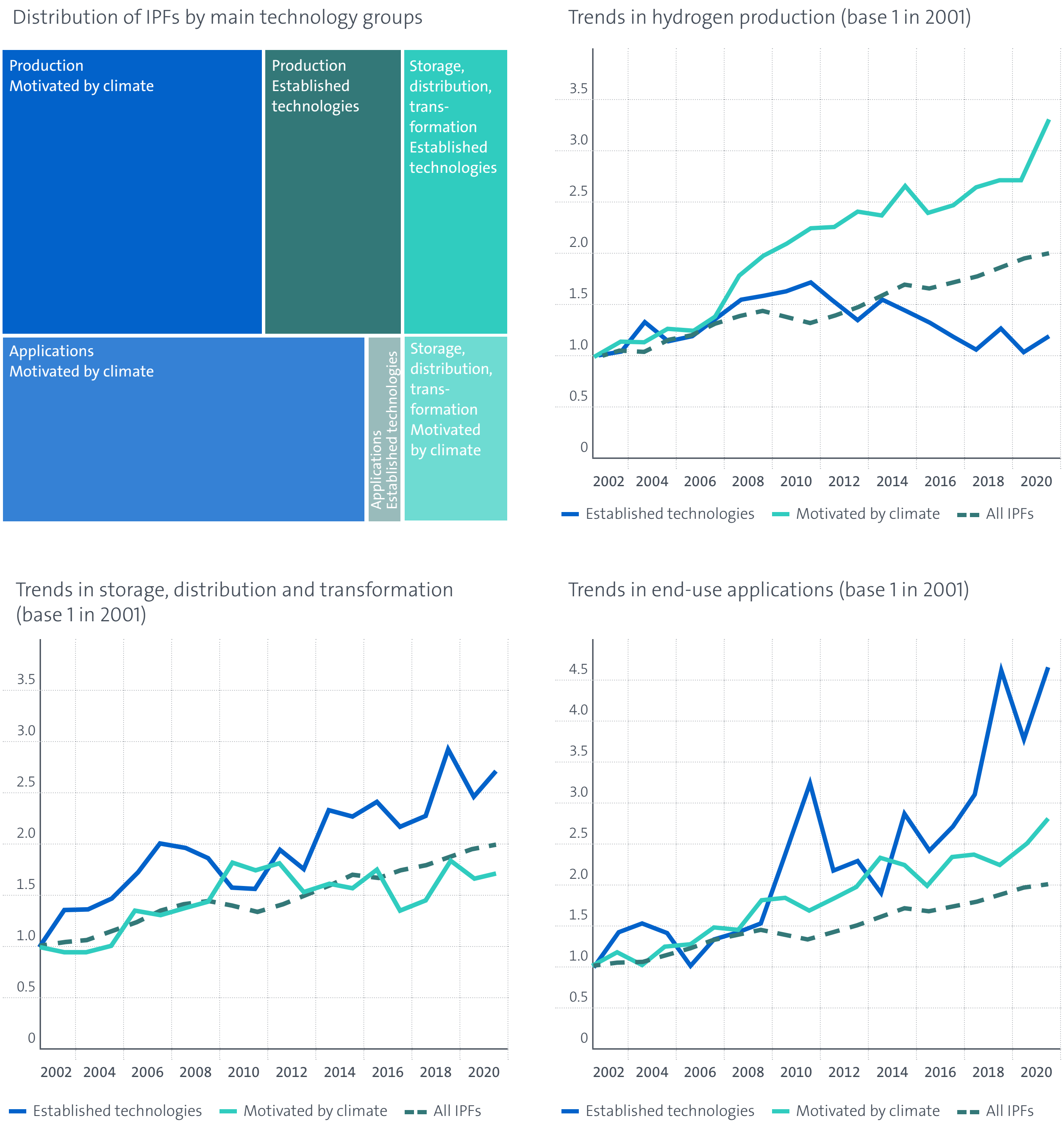
Innovation in end-use applications of hydrogen is likewise chiefly driven by new applications motivated by climate concerns, with more than 90% of IPFs targeting such applications in transport, iron and steel manufacturing, buildings or electricity generation. Existing applications of hydrogen in the chemical industry for the production of ammonia and methanol represent only a modest volume of IPFs in comparison. However, there has been a significant increase since 2008, which may be related to the pursuit of ammonia as a clean energy carrier rather than a fertiliser (see also section 5.1).

The storage, distribution and transformation of energy using hydrogen is a critical challenge for the large-scale deployment of hydrogen value chains. The relatively lower number of IPFs in this field compared with hydrogen production and applications hides different dynamics at a more granular technology level. Established technologies such as the storage and transportation of pure gaseous or liquid hydrogen generated two-thirds of patenting activities between 2001 and 2020, with strong growth of the number of published IPFs during this period, denoting the high potential for linking the assets of new hydrogen production and applications with existing infrastructure.

By contrast, the publication of IPFs related to emerging storage, distribution and transformation technologies that are motivated by climate (such as low-emission hydrogen-based fuels, solid carriers or the use of hydrogen in biofuel production) peaked in 2012 after a strong growth period but then fell dramatically, suggesting a loss of momentum for innovation in these technologies. As shown in Chapter 5, this trend is mostly due to patenting activities in low-emission hydrogen-based synthetic fuels, whereas innovation in other hydrogen carriers has been gaining momentum during the same period.

Figure 2.3

Overview of patenting trends in hydrogen technologies, (IPFs, 2001–2020)



Note: Technologies related to CCUS and CO_2 avoidance in fossil-based hydrogen production, as well as technologies for vehicle refuelling, are labelled in this chart as "motivated by climate" to indicate that they would mostly not be pursued without the climate imperative.

Source: author's calculations

The identification of the leading global applicants in established technologies and emerging technologies motivated by climate in the period 2011–2020 provides further insights into the industry dynamics underpinning those trends. For starters, Figure 2.4 features the top ten global applicants in established technologies (accounting together for around a fifth of all IPFs in that field) as well as the distribution of their IPFs between the main subcategories of established and emerging climate-motivated technologies. This list is dominated by chemical companies, such as Air Liquide, Linde and Air Products, which are building on an extensive background in the production and handling of hydrogen from fossil fuels to expand their businesses into the supply of low-emission hydrogen. Unsurprisingly, their specialisation is concentrated in improving established technologies for hydrogen production, storage and industrial applications. However, they are also diversifying into inventions relating to technologies motivated by climate in order to stay competitive, with a focus on the use of CCUS and biomass for hydrogen production.

Two Japanese companies – Toyota and Honda – as well as R. Korea's Hyundai stand out. All three feature in this list thanks to patent portfolios in established technologies for the storage, distribution and transformation of gaseous or liquid hydrogen. However, their investments in innovation appear to focus mainly on emerging, climate-motivated production technologies and applications such as electrolysis (see Chapter 3) and fuel cells (see Chapter 5) respectively. In this respect, their profile is closer to that of new entrants to the business of low-emission hydrogen.

Figure 2.4

Profile of the top ten corporate applicants in established hydrogen technologies (IPFs, 2011–2020)

	Production		Storage, distribution and transformation		End-use applications	
	Established technologies	Motivated by climate	Established technologies	Motivated by climate	Established technologies	Motivated by climate
Air Liquide (FR)	174	44	94	50	18	21
Linde (DE)	155	48	87	40	9	23
Toyota (JP)	12	48	114	50	2	528
Air Products (US)	61	20	30	13	2	8
BASF (DE)	34	34	23	11	2	13
Shell (UK)	52	33	18	14	1	82
Mitsubishi (JP)	37	46	10	7	20	75
Honda (JP)	7	48	48	16		200
Hyundai (KR)	1	17	44	14		319

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents. Technologies related to CCUS and CO_2 avoidance in fossil-based hydrogen production, as well as technologies for vehicle refuelling, are labelled in this chart as "motivated by climate" to indicate that they would mostly not be pursued without the climate imperative. Ranking is based on the size of applicant portfolios of IPFs in established hydrogen technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolios due to some IPFs being relevant to two or more segments of the value chain.

Source: author's calculations

The list of the top ten applicants in emerging technologies motivated by climate (Figure 2.5) confirms this observation, with Toyota, Honda and Hyundai featuring at the top of the list. Most of the applicants in this list have similar specialisation profiles, with a strong focus on new production technologies and applications, as well as significant patenting activities in established technologies for the storage, distribution and transformation of gaseous or liquid hydrogen. Most of them show an overlap of 15%–20% between their portfolios of IPFs in fuels cells and electrolysis (typically focused on PEM technology), thus signalling significant synergies in research between these two fields. In the period 2011–2020, these ten applicants generated a slightly higher share (18.5%) of all hydrogen-related IPFs than the top ten applicants in established hydrogen technologies (16.6%).

While the top applicants in established technologies feature mainly chemical companies, the leading applicants in emerging technologies motivated by climate are mainly automotive companies and equipment suppliers. They are dominated by Japanese and Korean applicants, which occupy the first five places in the list. Together these top ten applicants generated up to 20% of IPF publications related to hydrogen technologies motivated by climate in the period 2011–2020.

Figure 2.5

Profile of the top ten corporate applicants in hydrogen technologies motivated by climate (IPFs, 2011–2020)

	Production		Storage, distribution and transformation		End-use applications	
	Established technologies	Motivated by climate	Established technologies	Motivated by climate	Established technologies	Motivated by climate
Toyota (JP)	12	48	114	50	2	528
Hyundai (KR)	1	16	42	14		319
Honda (JP)	7	48	48	16		200
Panasonic (JP)	24	128	14	11		70
Kia (KR)	1	11	25	6		171
Siemens (DE)	14	92	11	9	11	75
Shell (UK)	52	33	18	14	1	86
Mitsubishi (JP)	37	46	10	7	20	75
General Electric (US)	43	35	25	10	2	73
Air Liquide (FR)	174	44	94	50	18	21

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents. Technologies related to CCUS and CO_2 avoidance in fossil fuel-based hydrogen production, as well as technologies for vehicle refuelling, are labelled in this chart as “motivated by climate” to indicate that they would mostly not be pursued without the climate imperative. Ranking is based on the size of applicant portfolios of IPFs in established hydrogen technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolios due to some IPFs being relevant to two or more segments of the value chain.

Source: author’s calculations

Universities and public research institutions generated 13.5% of all hydrogen-related IPFs in the period 2011–2020. They were particularly active in hydrogen production technologies with 18% of IPFs in that field, compared with 13.3% for storage, distribution and transformation technologies and only 7.1% for end-use applications. The top ten research institutions (Figure 2.6) together accounted for 3.3% of all IPFs related to hydrogen in the period 2011–2020, with a stronger presence in emerging technologies motivated by climate than in established technologies. They are led by French and Korean institutions, with three French research centres topping the list, and five Korean research centres featuring in the list. Interestingly, there is no Japanese research institution among the top ten, although Japanese companies are well represented in the list for corporate patenting.

The top two applicants, France's Commissariat à l'Energie Atomique (CEA) and Institut Français du Pétrole (IFP), stand out with significant contributions in established technologies for the storage and distribution of liquid or gaseous hydrogen and the production of hydrogen from fossil fuels respectively. However, by far the main focus of the CEA's patenting activities has been on climate-motivated production technologies (particularly electrolysis), whereas the IFP also shows significant levels of activity in climate-motivated production and storage, distribution and transformation technologies.

Figure 2.6

Profile of the top ten research institutions in hydrogen technologies (IPFs, 2011–2020)

	Production		Storage, distribution and transformation		End-use applications	
	Established technologies	Motivated by climate	Established technologies	Motivated by climate	Established technologies	Motivated by climate
CEA (FR)	10	109	21	11	1	7
IFP (FR)	48	30	4	8	1	30
CNRS (FR)	3	33	4	12	1	7
KIER (KR)	20	33		4	1	9
KIST (KR)	6	23	4	5	2	8
University of California (US)	2	18	8	12		2
KAIST (KR)	3	7	1	4	1	5
KRICT (KR)	4	10			2	3
Forschungszentrum Julich (DE)	3	7		1	1	3
RIIST (KR)	2	1		3		2

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents. Technologies related to CCUS and CO_2 avoidance in fossil fuel-based hydrogen production, as well as technologies for vehicle refuelling, are labelled in this chart as "motivated by climate" to indicate that they would mostly not be pursued without the climate imperative. Ranking is based on the size of applicant portfolios of IPFs in established hydrogen technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolios due to some IPFs being relevant to two or more segments of the value chain.

Source: author's calculations

Finally, Figure 2.7 provides an overview of the number and distribution (both in terms of regions and technologies) of start-ups which filed international patents applications related to hydrogen in the period 2011–2020. A total of 117 such hydrogen start-ups have been identified, most of which are located in the US (33%) or Europe (51%), including 34% for EU countries alone. This subset of hydrogen start-ups attracted 55% of the venture capital funding provided for early, late and IPO/post-IPO stages (see Box 2). Unsurprisingly, a majority of their IPFs relate to emerging technologies motivated by climate, such as electrolysis and fuel cells in particular. However, about a third of the start-ups also show patenting activities in established technologies, usually in combination with IPFs in climate-motivated technologies. This is particularly the case in hydrogen production, thus highlighting attempts by companies such as LanzaTech, Monolith Materials (both US) and Velocys (UK) to develop technologies that can reduce the carbon impact of hydrogen from gas and other fossil fuels (see Box 3 for a further discussion of these technologies).

Figure 2.7

Distribution of start-ups with IPFs on hydrogen

	Production		Storage, distribution and transformation		End-use applications	
	Established technologies	Motivated by climate	Established technologies	Motivated by climate	Established technologies	Motivated by climate
US	13	29	9	13	3	11
EU27	9	31	7	10	2	13
Other Europe	2	14	4	1		5
Japan			1	1	1	
Other	2	12	1	6		2

Note: The chart is based on all start-ups listed by Cleantech Group, Crunchbase and Dealroom which are less than 20 years old, have fewer than 500 employees and have filed international patent applications in the period 2011–2020. The patent portfolio of such companies has been derived by performing an automatic name matching procedure using the EPO internal database of patent applications.

Source: author's calculations

Box 2: Hydrogen start-ups and patents

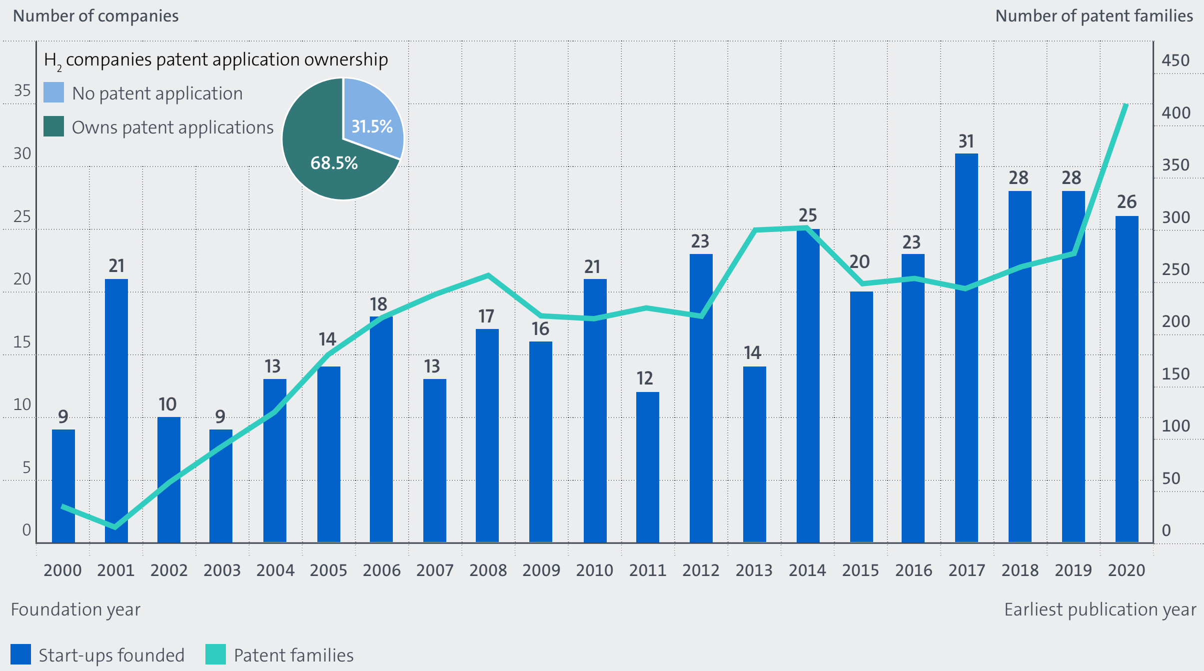
Start-ups are one of the main routes by which hydrogen innovations reach the marketplace. Many of the underlying technologies depend on advanced science coming out of public research organisations and universities, and represent high-risk, disruptive bets for business developers. However, given that many of the technologies also have small unit sizes that lend themselves to standardised manufacturing, they are attractive to venture capital investors hunting for exponential returns as the clean energy transition gathers speed. Since 2000, the number of new, independent companies founded in the hydrogen sector has grown consistently, and many of them owned patents at the time they were incorporated or filed for them shortly afterwards. We estimate that 70% of start-ups active in the hydrogen technology areas covered by this study hold at least one patent application.

Owning intellectual property can provide investors with confidence in the underlying technology and insure against imitation by competitors. These benefits are critically important when there can be long development timescales before early-stage investors are able to see any returns from product sales, acquisitions or stock market flotation. As part of the category of companies often referred to as "deep tech" start-ups, hydrogen entrepreneurs typically require significant R&D and engineering to test their ideas, build prototypes and develop practical market offerings.[7] The technology development cycles are therefore much longer than those in the ICT sector, with the average age of hydrogen start-ups raising later-stage venture capital funding being around ten years. For these entrepreneurs, patents can be used as proof of innovation, a signal of value and even collateral against debt.

An analysis of venture capital deals involving hydrogen start-ups shows that the share of the total amount of funding raised by companies with patent applications grows consistently when moving to later stages of fundraising. More than 80% of the later-stage venture investment in hydrogen start-ups was in companies which had already filed at least one patent application. The share rises to 95% when considering funding acquired in the IPO/post-IPO stage. It thus appears critical for young start-ups in this highly technical field to secure patent protection prior to raising early-stage funding.

Figure 2.8

Number of hydrogen start-ups founded annually and their patent applications (2000–2020)



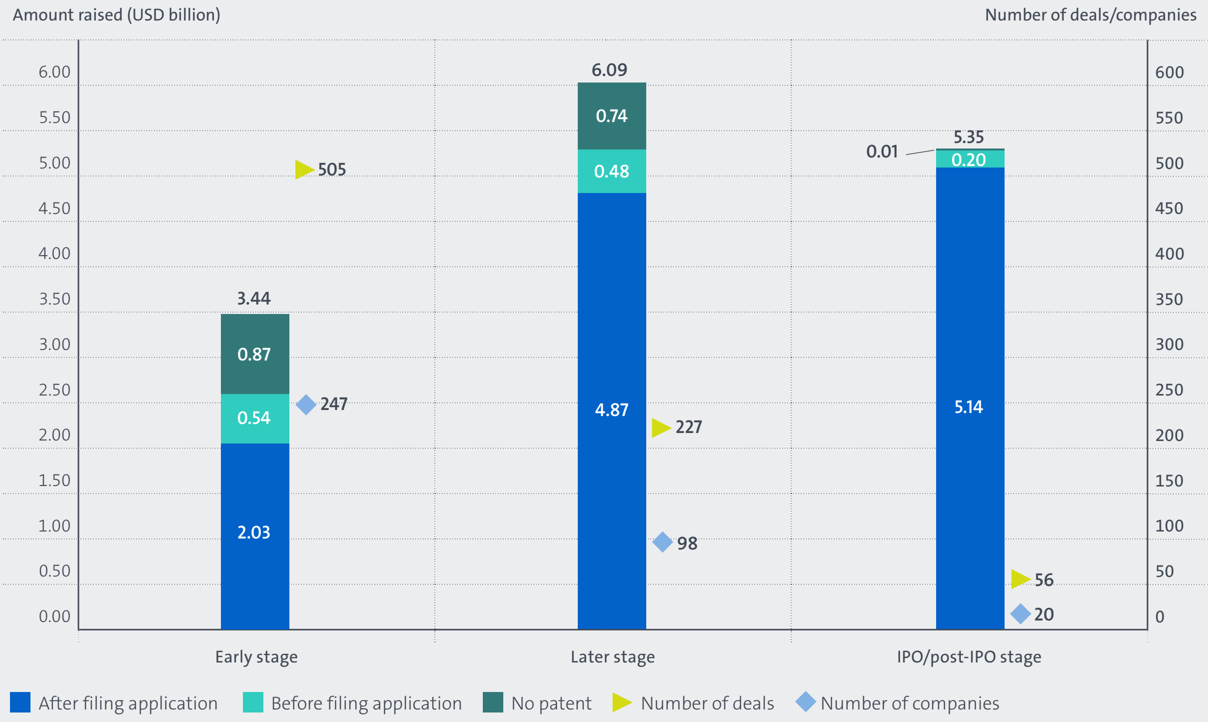
Note: The number of companies is displayed with respect to their foundation year, while the number of patent families is presented with respect to the year of publication. Cleantech Group, Crunchbase and Dealroom have been used as data sources for company identification. The patent portfolio of such companies has been derived by performing an automatic name matching procedure using the EPO internal database of patent applications. The automatic pre-selection has been manually curated and enriched by the EPO and IEA research teams.

Source: author's calculations

7 Deep tech refers to applying advances in basic science areas to engineering and societal challenges to generate new classes of solutions to improve existing technologies, outside the scope of more incremental R&D. Advanced materials, advanced manufacturing, artificial intelligence, biotechnology, blockchain, robotics, photonics and quantum computing are all typically considered deep tech fields.

Figure 2.9

Share of funding accruing to start-ups, by funding stage, 2000-2020



Note: Funding deals are only included for companies that were founded between 2000 and 2020. The reference date with respect to the patent filing is the earliest priority date calculated for the set of patent families assigned to the specific company. Cleantech Group, Crunchbase and Dealroom have been used as data sources for funding rounds. Early-stage funding contains the following investment types: Seed, Series A, Series B. Later-stage funding contains the following investment types: Series C-F. IPO/post-IPO stage: non-equity type transactions are not included in this stage. Reported funding at the post-IPO stage is limited to private investments in public equity types of investments, thus excluding additional public shares issues.

Source: author's calculations

3. Hydrogen production

Global hydrogen demand of 94 Mt in 2021 was met almost entirely by fossil fuel-based hydrogen, 62% of which came from dedicated natural gas reforming plants without CO_2 capture. Unabated coal plants, mostly in P.R. China, supplied 19% of the total, with most of the remainder coming as a by-product from facilities designed primarily for other products, such as refineries that reform naphtha into gasoline and generate hydrogen as an inevitable part of the process. The dominance of fossil fuels made hydrogen production responsible for over 900 Mt of direct CO_2 emissions in 2020 (2.5% of global CO_2 emissions in energy and industry). As the production of hydrogen from coal and natural gas is an established, competitive business, there has been a substantial amount of incremental innovation to improve efficiency and environmental performance.

However, technology development motivated by climate concerns is growing in the area of hydrogen production. These technologies can help produce low-emission hydrogen in various ways: from water and electricity (known as electrolysis), from fossil fuels with minimal CO_2 emissions (using carbon capture, utilisation and storage (CCUS)), and from bioenergy (for example via biomass gasification). The first two of these are already used commercially, but in very limited quantities because they are more expensive than using fossil fuels, given the limited regulatory costs of emitting CO_2. Sixteen natural gas plants with CCUS produced 0.7 Mt of low-emission hydrogen (0.7% of total hydrogen production) in 2021, while water electrolysis was responsible for around 0.04% of total hydrogen production.

In 2022, the economics have shifted in favour of low-emission hydrogen from electrolysis, due to high natural gas prices. At the same time, governments around the world have sought to bridge the remaining cost gap and manage future natural gas price risks for hydrogen producers. New tax credits from the US Inflation Reduction Act and funding from EU member states under the Important Projects of Common European Interest (IPCEI) programme are examples of policies that aim to establish technological leadership, cut emissions and reduce future fossil fuel demand. Projects are more likely to take investment decisions in the near future as a result, and thereby generate revenue for many holders of patents in this area, but it will take several years before the projects cumulatively have an impact on energy demand and emissions.

3.1 Main patenting trends in hydrogen production

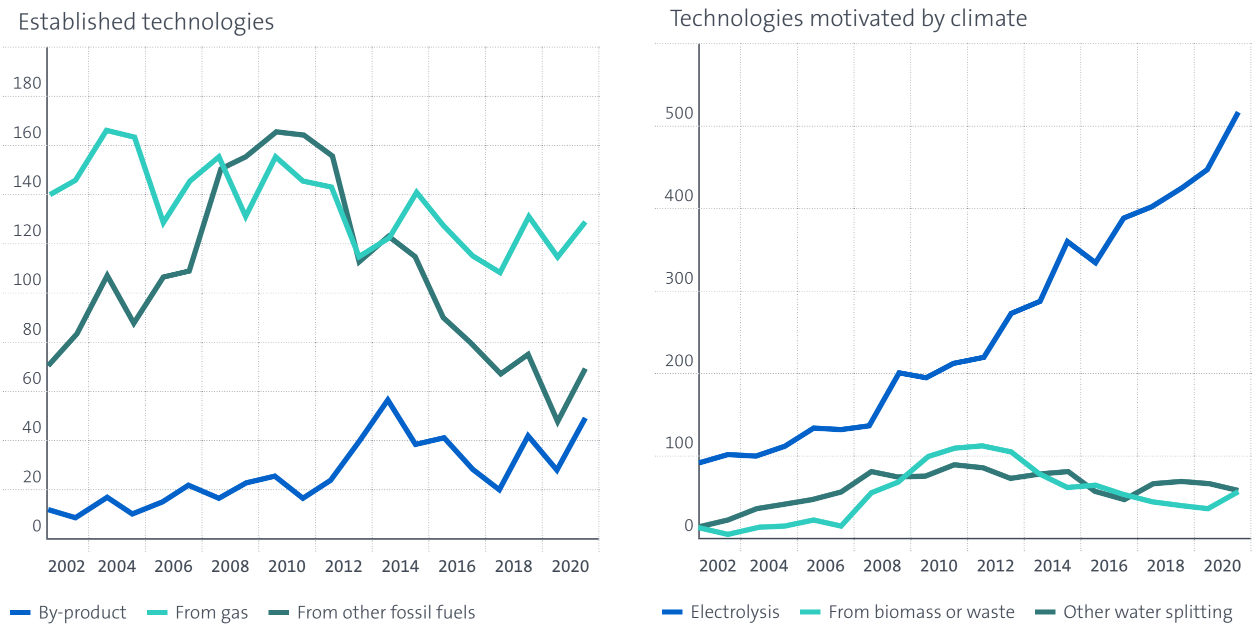
A comparative analysis of patenting trends in hydrogen production technologies over the past twenty years shows a clear shift from traditional, carbon-intensive methods to new technologies with the potential to decarbonise hydrogen production (Figure 3.1). Specifically, the growth of patenting in hydrogen production technologies since 2001 has been chiefly driven by the rapid rise of innovation in electrolysis, whereas patenting in hydrogen production from fossil fuels has been decreasing over the past decade after a peak in IPF publications in 2007.

In contrast to the strong dynamic observed in electrolysis, other emerging technologies for hydrogen production that are motivated by climate concerns appear to have been overlooked. Patenting activities in hydrogen production from biomass or waste (via gasification or pyrolysis) boomed between 2007 and 2011, but decreased significantly after that, until 2020. The number of IPFs related to water splitting via non-electrolytic routes showed an increase in IPF publications until 2010, but remained relatively constant afterwards. In 2020, this represented 12% of the total number of IPFs published in the field of electrolysis.

The geographic origins of the IPFs in the period 2011–2020 reveal a strong lead by European, US or Japanese applicants in most hydrogen production technologies. EU-based applicants account for a large share (39%) of IPF publications related to any type of hydrogen production from gas, whereas US applicants are dominant in hydrogen production from other fossil fuels or as a by-product of other chemical processes. While Japan generated only a modest share of IPFs in established production technologies, it is leading patenting activities in electrolysis technologies with 28% of all IPFs in this field. EU countries follow with 24% (including 10% for Germany alone). The US is a distant third in electrolysis with 13% of IPFs, but has been leading patenting activities in hydrogen production from biomass or waste with a third of all IPFs in that field – in line with its general specialisation in bioenergy technologies (EPO-IEA, 2021).

Figure 3.1

IPF trends in hydrogen production technologies, 2001–2020

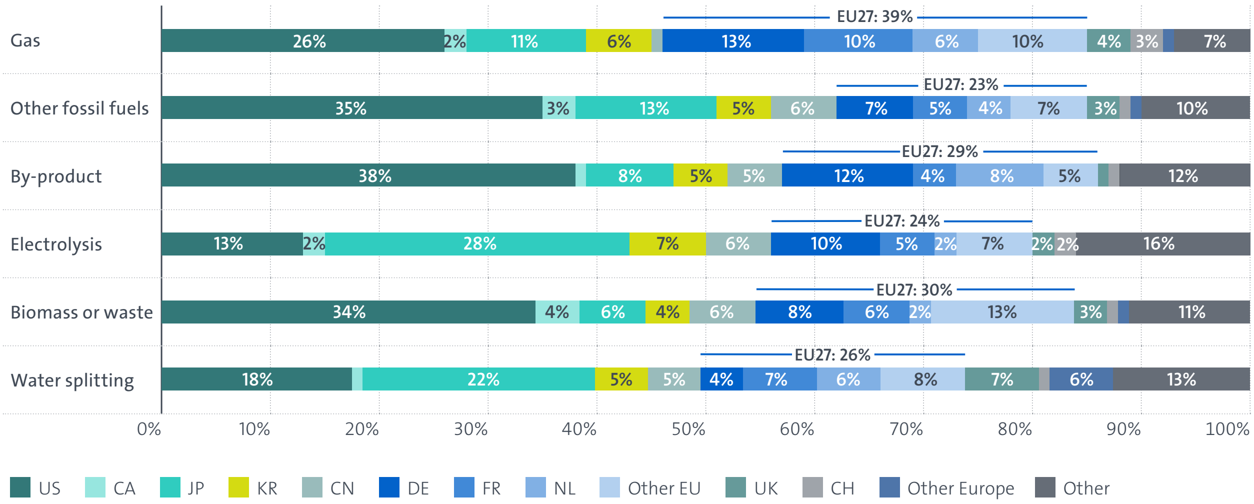


Note: Technologies for hydrogen production from alcohols and separation/purification technologies generate comparatively lower numbers of IPFs and are not reported in this chart. For the purposes of this chart, technologies related to low-emission hydrogen production from gas and other fossil fuels have been pooled with the respective categories of established technologies.

Source: author's calculations

Figure 3.2

Origins of patents related to hydrogen production, 2011–2020



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications. The value labels are not reported for shares below or equal to 1%. For the purposes of this chart, technologies related to low-emission hydrogen production from gas and other fossil fuels have been pooled with the respective categories of established technologies.

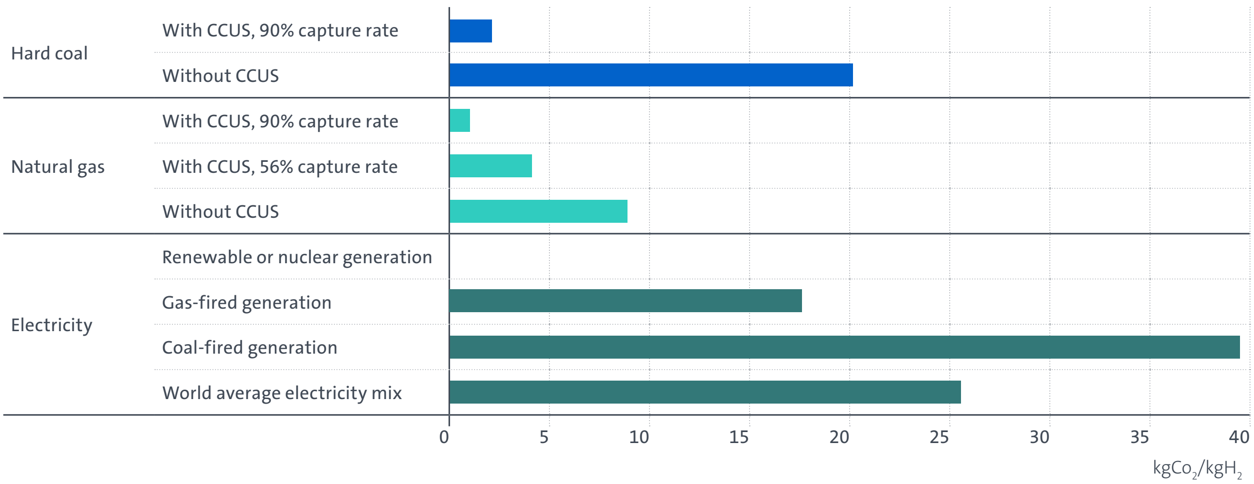
Source: author's calculations

3.2 Technologies for low-emission hydrogen production

A successful transition to an energy system with net zero greenhouse gas emissions ultimately requires all hydrogen produced to be low-emission hydrogen. However, it is hard to draw a clear boundary between patents for low-emission hydrogen production and those for unabated fossil fuel-based hydrogen. Many of the technologies can be powered by renewable energy, nuclear energy or fossil fuels, whether equipped with CCUS or not. Water electrolysers do not produce greenhouse gas emissions during their operation, but if they are powered by electricity derived from natural gas, the climate impact is almost twice that of hydrogen production from steam reforming of natural gas (not accounting for any upstream methane emissions in the supply of the gas). Facilities to reform natural gas to fossil fuels are mostly not equipped with CCUS today and if they are, then it is often only partial CCUS, but this could conceivably change if CCUS technology becomes more attractive. Innovations that improve the efficiency of natural gas reforming might therefore be a key enabler of CCUS or facilitate the reforming of bioenergy to low-emission hydrogen.

Figure 3.3

CO_2 intensity of hydrogen production



Note: Neither upstream methane emissions from fossil fuel production nor emissions related to downstream distribution of hydrogen are included in the calculations. There is, however, a consensus that all life-cycle emissions should be taken into account for comparisons of hydrogen CO_2 intensities. Global median upstream methane emissions would increase the emissions intensity of hydrogen from natural gas with 90% CO_2 capture by 4 $kgCO_2/kgH_2$, although there is wide variation between different natural gas sources.

Source: IEA, "Future of Hydrogen", 2019

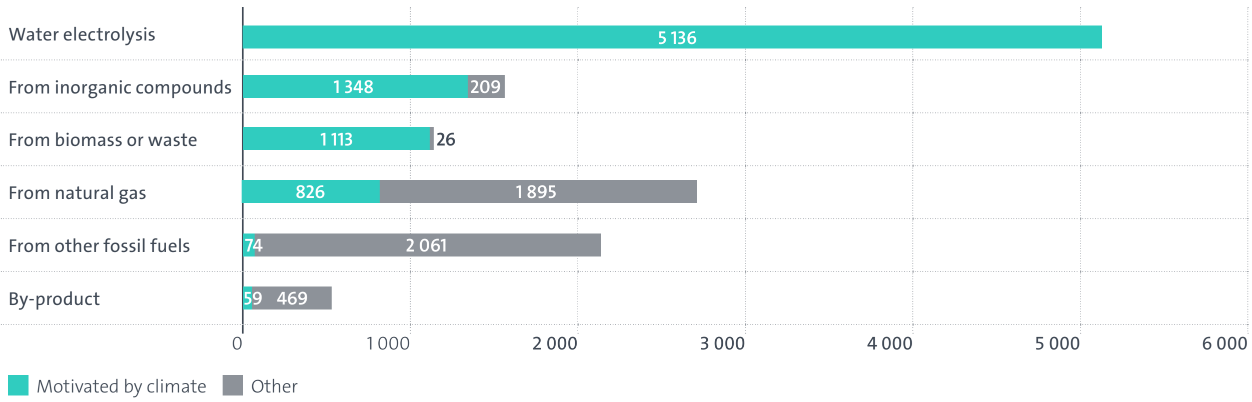
The cartography for this study distinguishes between incremental improvements to established technologies that rely on fossil fuels and technology areas that are motivated by climate concerns. The latter category includes low-emission hydrogen production technologies: electrolysis, which has the potential to be powered by renewable or nuclear energy; hydrogen production from biomass; recovery of by-product hydrogen from chlor-alkali electrolysis; methane pyrolysis; and fossil fuel-based approaches that state in their patent applications that they can be combined with CO_2 capture (see Box 3).

In recent years, climate-motivated hydrogen production technologies have come to dominate patenting activity (Figure 3.4). The steady increase in these technology areas since 2005 has now been complemented by a consistent decrease in IPFs for established technologies (Figure 3.5).

Electrolysis technologies, having the potential to be powered exclusively by renewable or nuclear energy, are classified, for the purposes of this report, as low-emission. Likewise, hydrogen production from biomass is classified as low-emission (for the purposes of this report, non-organic waste is not classified as low-emission). Among the technologies designed for use with natural gas as the primary input, only methane pyrolysis and those IPFs that state that they can be combined with CO_2 capture are classified as net-zero aligned (see Box 3). A similar approach is applied to other fossil fuels, while, in the by-product category, only technologies for the recovery of hydrogen from processes like chlor-alkali electrolysis are defined as net-zero aligned.

Figure 3.4

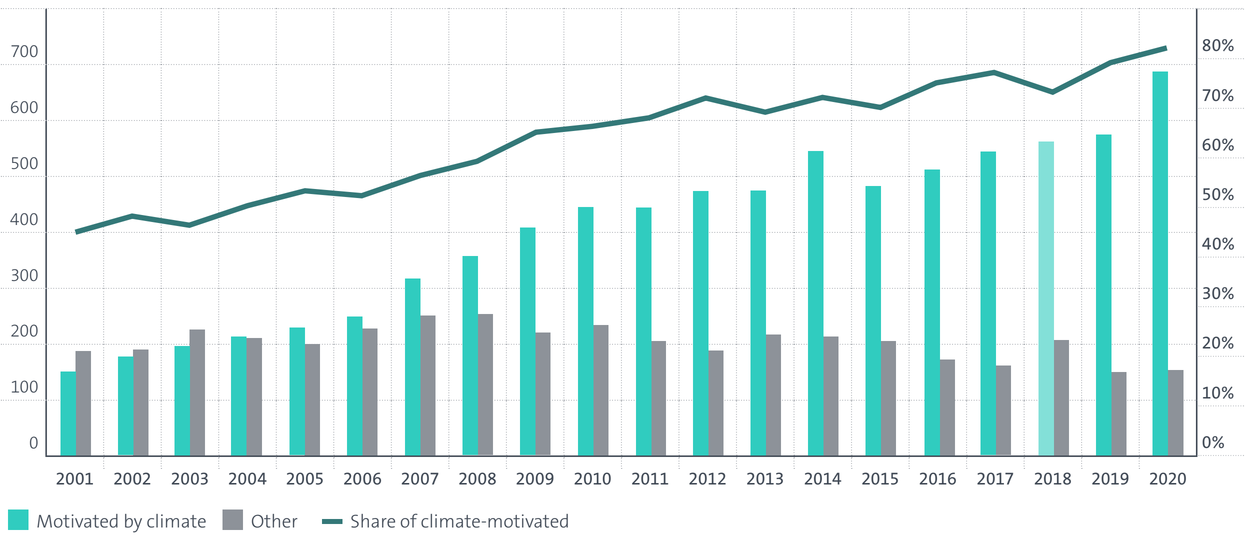
Inventions related to hydrogen production that are primarily motivated by climate change concerns (IPFs, 2001-2020)



Source: author's calculations

Figure 3.5

Share of IPFs in climate-motivated production technologies, 2001–2020



Note: For the preparation of this chart, IPFs related to the production of hydrogen from alcohols and to separation/purification methods have also been included in the "Other" category.

Source: author's calculations

Box 3: New approaches to hydrogen production from natural gas

Hydrogen production for the refining and chemicals sectors is estimated to account for as much as 3% of global CO_2 emissions today, and around 60% of this hydrogen is produced from natural gas. The most common means of making hydrogen from natural gas is with a steam methane reformer (SMR), which typically emits 7–11 kg CO_2 per kg of hydrogen, depending on fuel and efficiency. Not all of the CO_2 results from the separation of the carbon in methane from the hydrogen: up to 41% is due to the combustion for the heat supply to the SMR.[8]

The SMR process is not compatible with a net zero emissions future for either the chemicals sector or new applications of hydrogen as an energy vector. However, the extensive existing asset base of SMRs and the widespread infrastructure for supplying natural gas – a fuel with a high hydrogen content – would be highly valuable if technologies for converting natural gas to hydrogen with significantly reduced CO_2 emissions can be made cost-competitive. The necessary speed of capacity scale-up in a net zero emissions scenario, coupled with variability in countries' energy resources, further support a diversification of low-emission hydrogen sources (IEA, 2022d).

One "end-of-pipe" technology approach is to capture the CO_2 from an SMR before it is emitted to the atmosphere and safely store it underground (a type of CCUS). This is currently in operation at a large scale at several fertiliser facilities in the United States, where the CO_2 is stored during the process of extracting oil, and at a bitumen upgrader in Canada. There is also work on technologies whereby "stranded" hydrocarbon reserves would be reformed to hydrogen in situ underground and then extracted, with the resulting CO_2 stored in the same oil or gas field. Other approaches that are less mature, but integrate emissions reduction into the process more fully, include sorption-enhanced steam methane reforming (SE-SMR), electrically-heated reforming, plasma reforming and methane pyrolysis. However, these technologies represent only a minor share of recent patenting activities related to hydrogen production from natural gas (Figure 3.4), though pyrolysis IPFs are rising towards the level of approaches integrating CCUS.

Table 3.1

Emerging lower-carbon technologies for hydrogen production from light hydrocarbons

Technology	Technology readiness level	
Sorption-enhanced steam reforming	Early prototype	TRL 4
Electrically-heated reforming	Large prototype	TRL 5
Plasma reforming	Concept	TRL 3
Methane pyrolysis	Pre-commercial demonstration	TRL 7

Sorption-enhanced SMR (SESMR)

In the SMR process, methane is first reformed with steam to separate its carbon from its hydrogen. Then, in a second step the resulting carbon monoxide (CO) is reacted with more steam as a means of extracting additional hydrogen from the water molecules.

$$CH_4(g) + H_2O(g) \rightleftharpoons H_2(g) + CO(g) \quad (1)$$

$$CO(g) + H_2O(g) \rightleftharpoons H_2(g) + CO_2(g) \quad (2)$$

This two-step process suffers from the need for high temperature and pressure (800–1 000°C and 1.53 MPa), as well as difficulties in reaching very high conversion rates. SE-SMR combines these steps into a single step that has more moderate operating conditions and can result in an output that may contain as much as 98% H_2 and much lower levels of CO and CO_2. It therefore needs to burn less natural gas, less energy for purification of the H_2 product and cheaper reactor materials that do not need to tolerate such harsh conditions. In addition, separation of the CO_2 can be achieved much more easily for CCUS. Furthermore, the high-temperature, high-alloy steels required in the reforming reactor can be replaced with less expensive construction materials.

Patenting activity in this area is limited, however. Just 19 IPFs have been identified from six different applicants, including two research institutions (TNO and Ohio State University) and four SMEs.

Electrified SMR (eSMR)

One means of tackling the two-fifths of SMR emissions that arise from the heating requirements is to use electricity for this purpose instead of natural gas combustion. Innovation in this area has focused on designing compact reformers that can avoid the need for a large gas furnace with an array of hundreds of reformer tubes, each more than 10 m long and loaded with a catalyst. Whereas the gas-based heating system requires flame temperatures above the reaction temperature to account for heat transfer losses, an electrical resistance heating system can use much more precise and efficient heating, varied in real time according to the profile of the chemical reactions to achieve higher methane conversion ratios. If such systems were applied to all SMRs, using renewable or nuclear electricity, global CO_2 emissions could potentially be reduced by 1%.[9] Because an eSMR can be operated with some flexibility, it is conceivable that it could be ramped down when renewable electricity is in short supply if incentives are in place to encourage "system friendly" operation.

Between 2011 and 2020, eSMR was a relatively active field of patenting with 22 IPFs published, of which nine originated from Danish firm Topsoe.

Plasma reforming

A more radical means of shifting to electricity-based reforming heating involves the creation of a hot plasma of ionised gas in which the reaction takes place. This has several advantages:

- water inputs are not required
- the equipment can be made very compact
- it can process biomass or heavy hydrocarbons, as well as natural gas, to form hydrogen
- smaller amounts of catalyst can potentially be used, with the free radicals in the plasma itself helping to achieve higher yields
- the reaction conditions could potentially be adjusted so that the hydrogen product is further converted to synthetic fuels using the same equipment.

8 Sources: Wismann et al., Science 364, 6642, 756–759, 2019; Wismann et al., Chemical Engineering Journal 425, 2021, 131509.

9 The most efficient natural gas-based ammonia plants produced an average of 1.6 tonnes of CO_2 per tonne of ammonia (the average being 1.9 tonnes of CO_2/tonne ammonia). About 30% of the natural gas entering an ammonia plant is used to provide heat, mainly in the reforming unit. Electrified heating of this SMR unit could result in a reduction of the carbon intensity to 1.1 tonnes of CO_2 per tonne of ammonia.

However, the electricity requirements for forming the plasma remain high. Its suitability as a small-scale and flexible option for hydrogen production is yet to be demonstrated. There are only a few related IPFs, mostly from Korean research institutes.

Going even further, the need for water inputs can be eliminated in "dry methane reforming" by operating in the presence of CO_2.

$$CH_4(g) + CO_2(g) \rightarrow 2\,CO(g) + 2\,H_2(g)$$

This has the additional attraction of generating carbon monoxide that could potentially be reacted with the hydrogen in the same equipment to produce synthetic liquid fuels. However, sustainable sources of CO_2 remain costly.

Methane pyrolysis

With pyrolysis, methane can be decomposed into hydrogen and carbon without any CO_2 emissions from the chemical process.

$$CH_4(g) \rightarrow C(s) + 2\,H_2(g)$$

Understandably, there is considerable interest in such an approach, and innovation is focused on reducing the temperatures required to overcome the strong C-H bond, leading to different technological routes: thermal, catalytic and plasma pyrolysis. In thermal decomposition (TRL 4), the reaction occurs without the presence of a catalyst and temperatures above 1 200°C are typically needed to obtain a reasonable yield. In catalytic decomposition (TRL 6) this can be reduced to below 1 000°C. Achieving such high temperatures without fossil fuel combustion is a challenge, and plasma (generated by electricity) is thought to be a promising option. Moreover, it is the most advanced pyrolysis route (TRL 7), with a pre-commercial demonstration plant being operated by Monolith Materials in the United States since 2021 and a plant 14 times larger being planned.

Further areas of research include improving product purity by preventing side reactions that lead to unwanted hydrocarbons and managing the solid carbon by-product. So-called "carbon black" can block reactors, deactivate catalysts and cause respiratory problems. While there is a market for over 12 Mt of carbon black for ink, rubber and materials like graphene, this would be dwarfed by the output from large-scale low-emission hydrogen production.

Caphenia, Thyssenkrupp, SABIC and ExxonMobil lead patenting for methane pyrolysis. Caphenia is an example of a start-up in this area, one of several that have emerged in the past decade. Notably, the German company has a specialisation in plasma decomposition. ExxonMobil is also a top patenter for CCUS-related patents for hydrogen from natural gas, alongside Topsoe and Casale.

Figure 3.6

Emerging lower-carbon technologies for hydrogen production from light hydrocarbons

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Steam methane reforming										
With CCUS	15	7	12	12	8	5	11	10	9	15
Electrically heated	3	4	1	3	2	3	2	2	9	10
Sorption-enhanced	6	1				1	3	3	1	4
Plasma reforming	3	3	3	2	2		4	1	2	7
Methane pyrolysis										
Plasma decomposition	1	4	3	2	3	3	7	3	1	1
Other pyrolysis	25	12	14	16	10	10	11	12	12	18

Source: author's calculations

3.3 Recent developments in electrolysers

Electrolysis technologies have been the key driver of innovation in hydrogen production over the past two decades. They are currently the most promising method of hydrogen production from water, with higher efficiency than thermochemical and photocatalytic methods. By enabling the production of hydrogen from renewable-powered electrolysis on an industrial scale, they have the potential to unlock its use in replacing existing demand for unabated fossil fuel-based hydrogen and in new applications in so-called "hard-to-abate" sectors. Technologically, they operate like a fuel cell in reverse and some types of cells can be used in both directions: to make hydrogen or to produce electricity from it. Electrolytic technologies under development also have the potential to further react the hydrogen output to form hydrogen-based fuels by adding nitrogen or CO_2 to the cell under the right conditions.

However, the technology landscape of water electrolysis has not yet reached a single dominant design, with several families of electrolysers of varying maturity levels currently competing (Table 3.2). Ongoing research for each family targets increased efficiency, more affordable materials, easier stackability for large-scale production and low-cost mass-manufacturing (EPO and IRENA, 2022). The present section focuses specifically on patenting activities related to these main categories of electrolysers.

Alkaline water electrolysis is the oldest of these technologies. It involves two electrodes made of a non-noble metal (typically nickel) operating in a liquid alkaline electrolyte solution, and presents the advantage of being less expensive to build and more durable than more recent and sophisticated electrolysis technologies that use noble materials to achieve higher efficiency. Alkaline electrolysers are currently the most commonly used to enable energy conversion and storage to produce hydrogen, and they have continued to generate a steady flow of inventions over the past decade (Figure 3.7).

Table 3.2

Emerging electrolysis technologies

Technology	Technology readiness level	
Alkaline	Market uptake	TRL 9
Anion exchange membranes	Large prototype	TRL 6
Polymer electrolyte membranes	Market uptake	TRL 9
Solid oxide electrolyser cells	Pre-commercial demonstration	TRL 7

Polymer electrolyte membrane (PEM) electrolysis and solid oxide electrolyser cells are two other promising solutions, with a higher number of published IPFs than alkaline water electrolysis, and an average compound growth rate of 12.5% and 13.5% respectively in the period 2011–2020. Both technologies are promising solutions to addressing the challenge of integrating the growing share of renewable (and thus more variable) sources of electricity into a power infrastructure that must meet continuous demand.

PEM was first introduced in the 1960s as a fuel cell technology with a solid polymer electrolyte that is responsible for the conduction of protons, separation of product gases, and electrical insulation of the electrodes. As an electrolyser or fuel cell, this technology can operate at high current densities. It is expected to be advantageous in combination with intermittent renewable energy, which can generate sudden spikes in energy input. It can also produce compressed hydrogen (eliminating the need for an external compressor) as well as high purity hydrogen (increasing storage safety). However, unlike alkaline electrolysers, PEM electrolysers require the use of noble metals due to the highly acidic environment in which they operate, and the high cost of these materials is currently a barrier to their broader use and deployment.

Solid oxide electrolyser cells (SOEC) achieve the electrolysis of water using a solid oxide, or ceramic, electrolyte to produce hydrogen gas and oxygen. These devices can use nonprecious metals as catalysts, which allows for scalable production methods. They operate above 600°C, thereby enabling a high conversion efficiency thanks to favourable thermodynamics and kinetics. Performance and durability improvements as well as increased scale-up efforts have led to a hundredfold gas production capacity increase within the past decade and to commissioning of the first demonstration-scale SOEC plants.

Anion exchange membranes (AEM) use alkaline water (although less alkaline) and can thus be regarded as an evolution of alkaline water electrolysis. AEM can increase the performance of existing materials while ensuring durability, and may be used in electrolytic cells as well as fuel cells for electricity generation. However, they have emerged more recently and are not yet exploited on an industrial scale. The number of published IPFs remains small in this field, but it grew rapidly between 2011 and 2020, with an average compound growth rate of 11.3% during this period.

Figure 3.7

Patenting trends in emerging technologies for electrolysers (IPFs, 2011–2020)

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Alkaline	8	10	19	26	25	22	29	30	21	35
Anion exchange membranes	2	1	1	1	4	6	7	7	8	14
Proton exchange membranes	15	20	35	41	29	40	47	58	72	68
Solid oxide electrolyser cells	18	15	29	25	23	34	37	50	43	55

Source: author's calculations

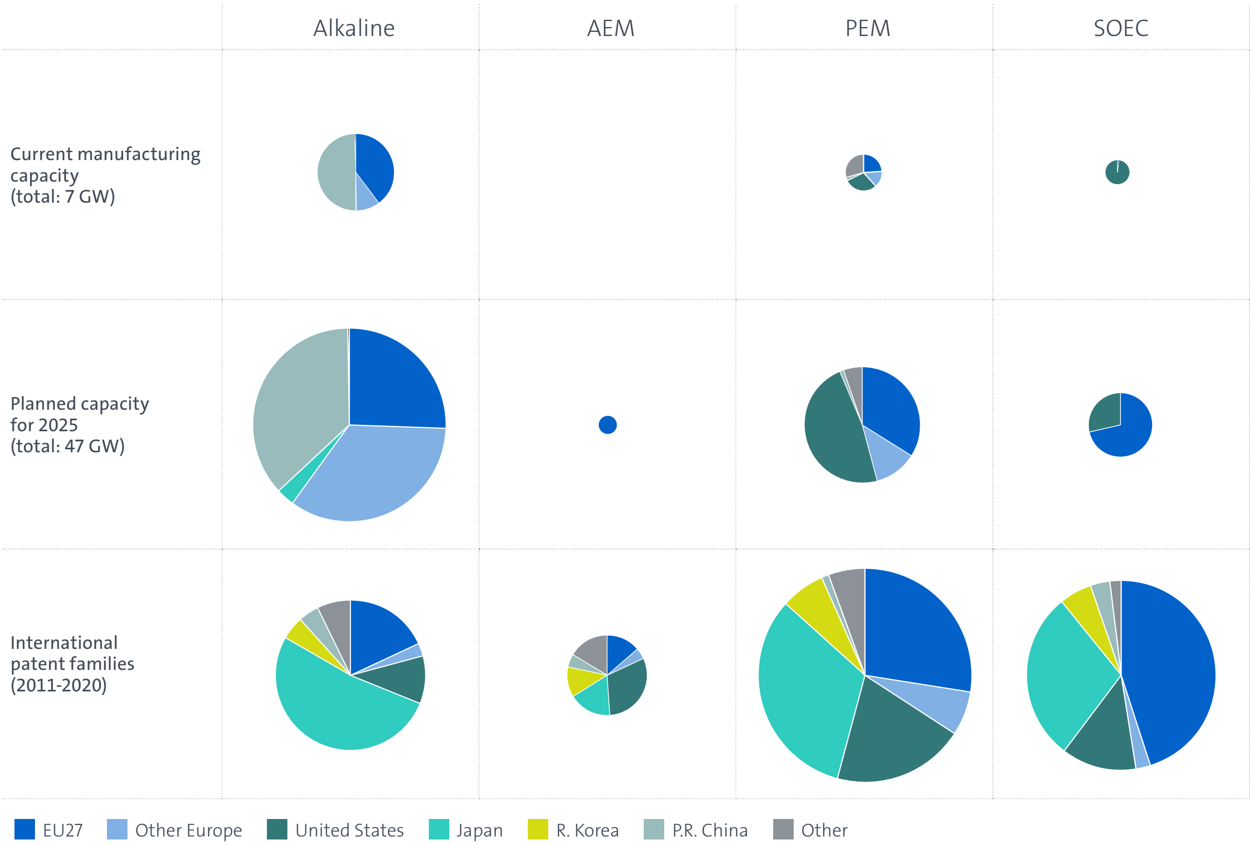
Figure 3.8 compares the geographic origins of these inventions with current and planned investments in manufacturing capacity for the respective types of electrolysers. It shows that alkaline water electrolysis is set to remain the dominant technology in industry in the years to come. However, PEM and SOEC generated more patenting activities in the period 2011–2020, and related investment in manufacturing capacity is now taking off.

While Japan has been pushing the frontiers of the science for decades in these technologies, deployment has hardly started in Japan so far (with the same observation applying also to R. Korea). Whether or not Japan can get involved in the deployment depends on whether (i) project developers are willing to pay a premium for performance, (ii) there are domestic alternatives and (iii) whether subsidies favour local producers. By contrast, P.R. China is only a small contributor to the international patenting of electrolyser technologies, but is investing heavily in manufacturing capacity, with a nearly exclusive focus on the more mature and non-cutting edge alkaline technology.

Europe appears as a clear leader in SOEC patenting but also as an important contributor to PEM, alkaline and AEM. Unlike in Japan, there is now a genuine industry being built in Europe, also spanning all main electrolyser technologies. There are several established German and Norwegian companies that can supply alkaline water electrolysis and have a large market share, while investment in manufacturing capacity for PEM and SOEC is driven by younger companies or new market entrants. The US is likewise currently a leader in developing manufacturing capacity, with a market for premium (PEM) products scaling up, and enough local supply for a small market. However, the US appears to be lagging behind in patenting in PEM technology as well as in other electrolyser categories, except for the newly emerging AEM.

Figure 3.8

Origins of inventions related to electrolysers and manufacturing capacity



Note: The calculations are based on the country of the investors and IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations (based on announcements by electrolyser manufacturers)

Finally, the top ten applicants in electrolyser technologies are reported in Figure 3.9. Together they accounted for around a quarter of published IPFs in alkaline water electrolysis (27%) and PEM (25%), but up to 39% in SOEC and only 6.7% in anion exchange membranes. As reported in Figure 3.9, they consist exclusively and in equal proportions of Japanese and European entities. PEM is the only technology in which all top applicants have been active. Two of them – Asahi Kasei and Italian company De Nora – focus mainly on alkaline water electrolysis, whereas SOEC accounts for the largest share of the portfolios of five other applicants. Among the latter, France's CEA alone generated 19% of the published IPFs in SOEC, thanks to its long-term interest in electrolysis based on (high-temperature) nuclear energy. Danish firm Topsoe also specialises in SOEC, likewise reflecting its experience of high-temperature energy sources. German firm Siemens and Japanese firm Toshiba are the only top applicants that are active in all four technologies, while Panasonic and Sumitomo are also active in alkaline, PEM and SOEC technologies. While top Japanese applicants are yet to significantly invest in manufacturing capacity, European Siemens and De Nora (as part of nucera, their joint venture with Thyssenkrupp) are already producing and commercialising electrolysers.

Figure 3.9

Top ten applicants in electrolyser technologies (IPFs, 2011-2020)

	Alkaline	AEM	PEM	SOEC
CEA (FR)			18	63
Asahi Kasei (JP)	21		17	
Panasonic (JP)	4		14	15
De Nora (IT)	20	1	8	
Toshiba (JP)	7	2	8	10
Siemens (DE)	3	1	13	8
Topsoe (DK)			1	19
Sumitomo (JP)	1		3	13
Bosch (DE)			12	3
AGC Group (JP)	6		13	

EU27 Japan

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents. Ranking is based on the size of applicant portfolios of IPFs in electrolyser technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolios due to some IPFs being relevant to two different categories of electrolyser technologies.

Source: author's calculations

Box 4: Comprehensive analysis of hydrogen-related innovation, production and use will require more co-operation on data

It is not currently possible to map hydrogen-related innovation activities to data on hydrogen production and use at the national level. Nearly all hydrogen produced today comes from fossil fuels converted within industrial facilities such as refineries and chemical plants. Statistics of energy flows in the economy – commonly called "energy balances" – have not historically included any information on this hydrogen as it has not been treated as a traded "energy product". As much of it is produced "on-site", it is not reflected in the energy balances for these sectors, which report only the *purchased* fuel input, such as natural gas, used and not the total amount of hydrogen used. Such on-site production, which is largely absent from published energy statistics, is not expected to be phased out as hydrogen production becomes cleaner; in the IEA NZE Scenario, nearly one-quarter of the low-emission hydrogen produced in 2050 would be produced on-site.

To ensure that global reporting of energy remains complete and relevant, the IEA is working with international partner organisations to develop robust data collection by countries on hydrogen and hydrogen-based fuels. A new annual questionnaire, which will initially be piloted and completed by reporting countries with data for years 2022 and 2023, will complement the existing five annual questionnaires that collect data relating to coal, oil, gas, electricity and renewable energy sources.

Data flows being considered for collection include:

- production of hydrogen and ammonia, by energy input (e.g. natural gas, renewable electricity etc.)
- storage of hydrogen, by type (e.g. pressurised or liquefied)
- transformation within and outside the energy sector
- final consumption, by sector (e.g. industry, transport etc.)
- cross-border trade, by origin and destination
- hydrogen production capacity, by technology

Complementary work is ongoing to develop an appropriate methodology to identify and incorporate hydrogen within the wider framework of the IEA's energy data collection efforts. This will help to maintain consistency between other fuels and hydrogen production and use, and to ensure that accounting for the energy system as a whole is consistent. Such efforts will be key to understanding all the flows of energy within the economy as new patterns emerge during energy transitions.

4. Hydrogen storage, distribution and transformation

Hydrogen is the lightest and smallest element, and also highly flammable. It therefore needs specialist equipment to contain it and move it around. Without effective and cost-efficient systems for storing and transporting hydrogen between where it is produced and where it is consumed, large-scale hydrogen deployment will not be possible. Standardised infrastructure for hydrogen trade is essential for a market that can optimise the location and timing of supply and demand at lowest cost. Innovation in this technology category aims to help tackle the challenges of storing, moving and delivering the energy in hydrogen, or transforming it into a commodity that does not face the same challenges. It is essential that rapid progress is made in these areas because uncertainty about which means of storage and transport will become dominant is a major risk facing investors and governments.

In this study, the technology areas are split into those that are established on the market today and those that are emerging due to climate change concerns. Innovation in all these areas will support the scale-up of hydrogen as a clean energy carrier. Today, hydrogen is stored in small amounts as a compressed gas in tanks on industrial sites, at refuelling stations or on trucks for distribution. For a specialist product, these relatively expensive forms of storage can be tolerated. In a small number of locations (notably in northern Europe and Texas, US), regional demand for hydrogen as a commodity for refining and chemicals is high enough to justify larger-scale storage underground in salt caverns and overland pipelines to distribute it in a compressed form. Improvements in the technologies using compressed hydrogen would certainly improve the prospects for hydrogen as a clean energy carrier. Cost improvements could arise through innovation in the repurposing of existing natural gas pipelines, ships and stores to handle combined hydrogen and natural gas streams. Performance improvements could be achieved if storage facilities could be charged and discharged more quickly, in line with the variability in renewable electricity supply.

However, if low-emission hydrogen becomes more competitive as an energy carrier, regions with potentially low production costs (such as Latin America, the Middle East or Africa) are expected to be able to profitably supply distant users (such as those in Japan, R. Korea or Europe) with other forms of hydrogen. Liquefaction is an established technology for hydrogen trucks that could also facilitate the long-distance transportation of hydrogen in ships, followed by regasification upon arrival, if the high costs related to the liquefaction of energy inputs and losses across the supply chain are reduced.

To cut costs further, the climate imperative has spurred on efforts in emerging areas such as hydrogen-based fuels, solid hydrogen storage and other molecules that can reversibly incorporate hydrogen. These may require more energy to transform the hydrogen but present significant lower transport costs and, in some cases, can be used without being transformed back to hydrogen at the point of use, minimising total energy losses. By converting hydrogen (which has very low energy density) into fuels that have similar properties to oil and gas, not only can the costs of storage and transport be reduced but it also becomes easier to use low-emission hydrogen in long-distance road, air and maritime transport, which rely heavily on liquid fossil fuels without a clear alternative in a net zero emissions future.

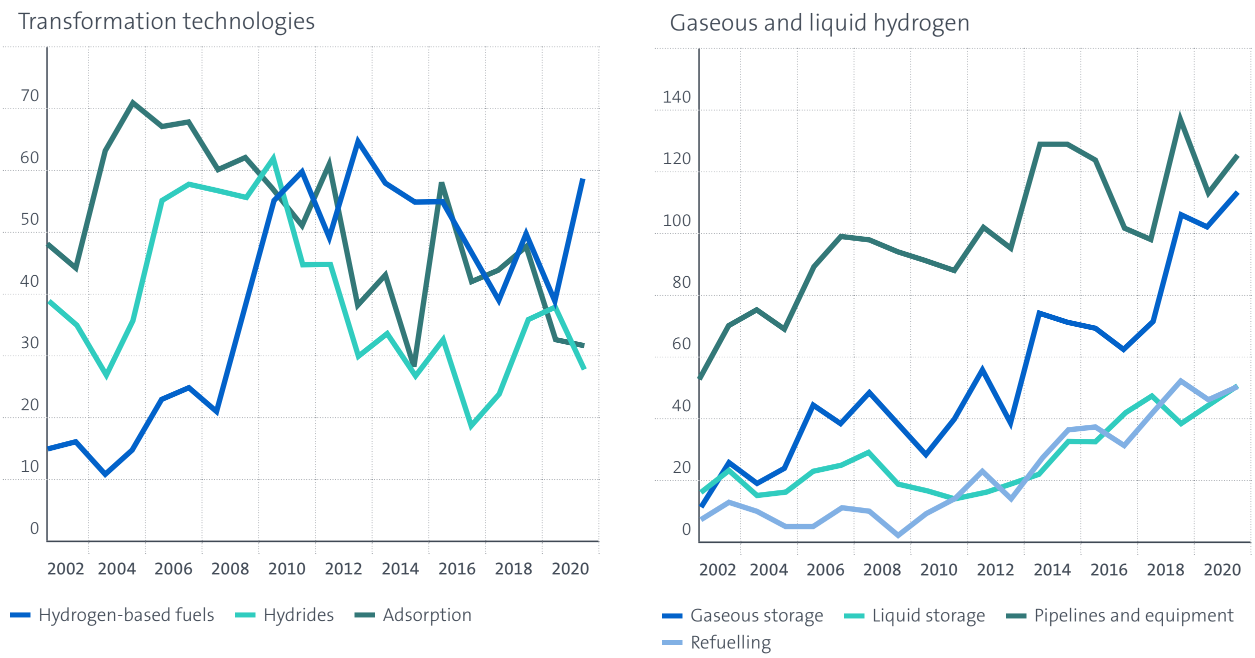
4.1 Main patenting trends in hydrogen storage, distribution and transformation

Patenting trends since 2001 show that established technologies have attracted increasing innovation efforts over the last two decades (Figure 4.1). Innovation in distribution infrastructure, such as pipeline networks and related ancillary equipment (e.g. cryogenic heat pumps, valves), has generated high levels of patenting activities, with an increasing trend over the period. Having experienced rapid growth since 2001, the number of published IPFs related to the storage of pure hydrogen in 2020 was almost equivalent to a compound average growth rate of 13%. Innovation has taken off more recently in liquid storage and vehicle refuelling, but still with high compound average growth rates of 13% in both cases in the period 2011–2020.

By contrast, the search for alternative solutions involving low-emission hydrogen-based fuels (such as synthetic methane, diesel or kerosene) and the storage of hydrogen in solid carriers lost momentum over the same period. A decrease in the number of IPFs can in particular be observed in the case of solid hydrogen storage technologies, after a period of concerted interest in potential mobile applications of these technologies in the period 2001–2010. There are two main types of solid hydrogen storage: hydrides, such as sodium borohydride, that chemically bind hydrogen into a crystalline solid; and adsorption, whereby hydrogen "sticks" to the surface of a solid, vastly increasing its density without the need for high pressures.

Figure 4.1

Patenting trends in hydrogen storage, distribution and transformation technologies (IPFs, 2001–2020)



Note: For the purposes of this chart, technologies related to vehicle refuelling have been pooled with established hydrogen technologies.

Source: author's calculations

As shown in Figure 4.2, the EU bloc led patenting activities in most areas of hydrogen storage and distribution in the period 2011–2020. The EU shows a particularly strong lead in established technologies supporting the storage and transport of pure hydrogen, with half of published IPFs in liquid storage, 38% for gaseous storage, 39% in refuelling and 32% in networks and related equipment. The EU is also ahead in the field of low-emission hydrogen-based synthetic fuels and solid hydrogen storage by adsorption. The share of EU countries shrinks to 20% in the field of hydrides.

The US made a significant contribution to patenting activities related to networks and equipment (26%), hydrogen-based alternative fuels (23%), hydrides (26%) and adsorption (22%) but otherwise has relatively low shares of IPFs in other established hydrogen transport and storage technologies. Japan has been more active than the US in these established fields as well as in refuelling, and is only overtaken by the US in technologies involving low-emission alternative fuels.

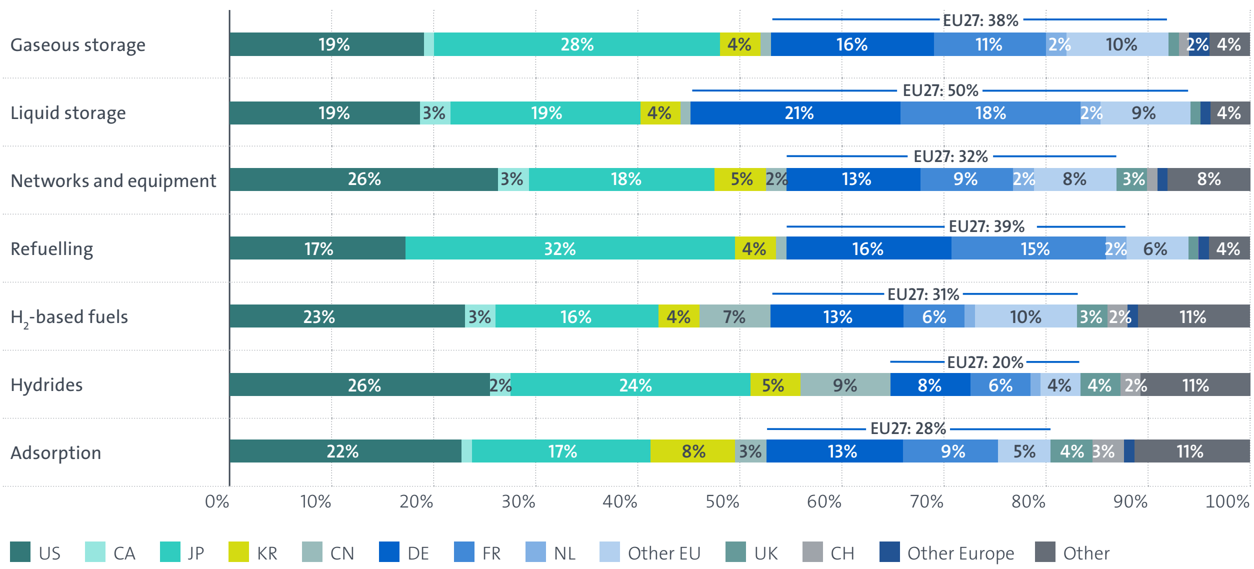
4.2 Recent developments in established storage and distribution technologies

The storage and distribution of hydrogen in gaseous or liquid form is currently the dominant paradigm in hydrogen supply chains, involving the use of relatively mature technologies such as hydrogen containers, pipelines and liquefaction technologies (Table 4.1). However, it remains subject to a number of challenges, such as the high weight and volume of current hydrogen storage systems, energy losses associated with compression and liquefaction, durability and cost of the storage systems and the challenges of scaling up.

An analysis of the leading innovators in these technologies provides further insights into the industries involved in this innovation ecosystem. In the period 2011–2020, the top applicants listed in Figure 4.3 accounted for up to 43% of the IPFs related to gaseous storage, 31% for liquid storage and 46% for refuelling, and a smaller 21% in networks and equipment where a broader range of actors are involved in innovation. The modest contribution of universities and research organisations (below 10% in all these fields) suggests a relatively high degree of maturity of the technologies, with a focus on incremental innovation.

Figure 4.2

Origins of IPFs related to storage, distribution and transformation, 2011–2020



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications. The value labels are not reported for shares below or equal to 1%. For the purposes of this chart, technologies related to vehicle refuelling have been pooled with established hydrogen distribution technologies.

Source: author's calculations

Air Liquide, Linde and Air Products, three chemical companies specialising in industrial gases which combined own the majority of existing hydrogen pipelines in the world, stand out with significant patent positions in all categories of established technologies and in particular combined shares of 22% in liquid hydrogen and up to 25% in refuelling. The automotive industry is another major driver of innovation in hydrogen storage and distribution, with a main focus on gaseous storage technologies (typically hydrogen tanks), and significant patenting activities in networks and equipment and in refuelling. Japanese companies Toyota and Honda dominate this group. Finally, equipment suppliers such as Bosch, General Electric and Siemens appear to specialise in distribution networks and related equipment, and to some extent in gaseous storage technologies.

While patented inventions related to hydrogen storage typically concern vessels for gaseous and liquid hydrogen, some of them also address the specific instances in which hydrogen will be stored. As shown in Figure 4.4, the most frequent of these instances involves the storage of hydrogen in fuel stations, thus denoting the importance of hydrogen-fuelled vehicles as a driver of innovation in hydrogen storage and distribution. The storage of hydrogen in terminals or platforms and its transport by truck are other important areas of innovation in storage technologies. Other forms of storage include the stationary storage of hydrogen, or its transport by railway or ships, but they represent only a modest number of IPFs.

Figure 4.3

Impact of top applicants from different industries on patenting in hydrogen storage and distribution technologies (share of IPFs, 2011–2020)

		Liquid storage	Gaseous storage	Networks and equipment	Refuelling
Chemicals	Air Liquide (FR)	31	59	37	44
	Linde (DE)	39	21	48	30
	Air Products (US)	6	17	24	15
Automotive	Toyota (JP)	9	94	21	24
	Honda (JP)	1	42	9	15
	BMW (DE)	14	25	13	10
	Hyundai (KR)	1	18	21	9
	General Motors (US)	3	24	11	6
Equipment	Bosch (DE)		14	30	3
	General Electric (US)	2	5	24	4
	Siemens (DE)	1	5	5	1

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents. Ranking is based on the size of applicant portfolios of IPFs in hydrogen storage and distribution technologies. The sum of the applicants' IPFs reported in the chart may exceed the actual size of their portfolios due to some IPFs being relevant to more than one storage or distribution technology.

Source: author's calculations

Figure 4.4

Recent trends in specific forms of liquid and gaseous hydrogen storage, 2011–2020

		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Gaseous hydrogen											
Stationary storage	Fuel stations	10	6	13	12	18	12	12	24	27	26
	Terminals or platforms	3	1	1	2	1		1	1	2	
	By burying tanks	1			1			1			
	By digging cavities	2			1	3	4	1			
	By using natural cavities					2		1			
Other storage	Deep sea				1	1					2
	Offshore	1			2	1		1	3		
Transport by	Trucks	4	1	6	11	6	7	6	5	11	16
	Railway	4		4	2	3	1	2	1	2	7
	Ships	1		2					2		
Liquid hydrogen											
Stationary storage	Fuel stations	4		5	3	8	5	6	8	3	9
	Terminals or platforms	2	2	1	2	4	1	1	1	2	
	By burying tanks	1			1	1					
	By digging cavities				1						
Other storage	Offshore	1		1	1	1	2	1	2		
	Deep sea				1						
Transport by	Trucks	3	2	2	4	4	2	3	1	6	8
	Railway	1		1	2	1	1	2		2	
	Ships	1		2			2		2		

Source: author's calculations

4.3 Recent developments in storage, distribution and transformation: the case of hydrogen-based fuels

Emerging technologies, such as those for the transformation of hydrogen into synthetic fuels or other hydrogen carriers, could support the scale-up of widespread hydrogen distribution and its penetration into parts of the energy system that are the hardest to wean off fossil fuels. These include sectors such as aviation, shipping and power plants running on coal or natural gas to provide flexibility to the grid. To reduce emissions, hydrogen-based fuels must be produced from low-emission hydrogen and other sustainable inputs (Box 5).

The four broad technology areas in Table 4.1 involve combining the hydrogen with carbon and are at different technology readiness levels (Table 4.1). Liquid organic hydrogen carriers (LOHC) are molecules, such as cyclohexane, that can be "loaded" with hydrogen and then cheaply transported long distances as liquids in oil tankers and pipes before being dehydrogenated to release the hydrogen. LOHCs have only recently been seriously considered for potential use in the energy system. Ammonia production, which is another recent hydrogen-based fuel candidate based on hydrogen and nitrogen, is not included here because the IPFs for ammonia and methanol fuel production cannot be easily distinguished from the much more numerous IPFs for ammonia chemical and fertiliser production. However, low-temperature ammonia "cracking" to release pure hydrogen from ammonia is included here as it is solely motivated by climate concerns and relatively immature.

Table 4.1

Technology areas for hydrogen-based fuels

Technology	Technology readiness level	
Synthetic methane	Pre-commercial demonstration	TRL 7
Synthetic liquid hydrogen-based fuels	Large prototype	TRL 6
Low-temperature ammonia cracking	Early prototype	TRL 4
Liquid organic hydrogen carriers	Pre-commercial demonstration	TRL 7

Most patenting activity in hydrogen-based fuels has occurred in the US and Europe and is related to synthetic methane and liquid hydrocarbons (Figure 4.5). However, the number of IPFs in these fields has been decreasing following a peak in 2011. The rate of decrease has been faster for synthetic liquid fuels than synthetic methane.

There are two possible explanations for this trend: one is that there is diminishing scope to improve conversion technologies for which the fundamental reactions have been known for a century, another is that interest in the production of synthetic fuels from coal – which shares the same process as production from other hydrogen sources – has dropped due to the regulation of emissions from coal. European companies in the gas industry, such as Topsoe, Engie, Air Liquide and Linde, had all previously been active in trying to make coal-to-gas processes more competitive. Innovation targeting synthetic diesel and kerosene was more concentrated in the US, though IFP (France), Expander Energy (Canada), JX Nippon Oil & Gas Exploration (Japan), Sasol (South Africa) and Topsoe (Denmark) were also among the top applicants. Both fields involve a relatively large (22% and 16% respectively) proportion of patents stemming from research institutions, signalling an enduring role for fundamental research, particularly in catalysis.

Figure 4.5

Profiles of main regions in hydrogen-based fuels (IPFs, 2011-2020)

		Synthetic fuels		Hydrogen carriers	
		Synthetic methane	Synthetic hydrocarbons	LOHC	Ammonia cracking
United States	Research	11	3	8	3
	Industry	44	39	7	9
EU27	Research	10	7	13	3
	Industry	79	22	21	8
Other Europe	Research	5		1	
	Industry	16	4	3	5
Japan	Research	2		1	14
	Industry	16	8	12	36
R. Korea	Research	9	3	2	
	Industry	7	1		
P.R. China	Research	4	3	3	4
	Industry	18	5	4	2

Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications.

Source: author's calculations

Patenting in the fields of LOHC and ammonia cracking increased rapidly between 2011 and 2020, with compound average growth rates of 12.5% for LOHC and 7.8% for ammonia decomposition, but they still represent a small number of patent families (Figure 4.6).

Innovation in all categories of hydrogen carriers remains concentrated among a small number of actors. It is still close to upstream science-based research, with a large proportion of IPFs stemming fully or partly from universities and PROs (49% for LOHC and 59% for ammonia cracking) in the period 2011–2020 (Figure 4.5). Japan has a strong specialisation in ammonia cracking, with 61% of the IPFs published in that field and eight of the top ten applicants in that field in the period 2011–2020 (including Toyota, Mitsubishi, Hitachi and five Japanese universities or PROs). Patenting activities targeting LOHC are spearheaded by Europe, which provided six of the top ten applicants in this emerging field (including four from Germany). Overall, Europe accounted for 49% of published IPFs in LOHC in the period 2011–2020, and Germany alone for 30%.

Figure 4.6

Recent trends in hydrogen-based fuels (IPFs, 2011–2020)

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Low-emission hydrogen-based synthetic fuels										
Synthetic methane	26	34	24	23	28	27	13	19	19	20
Synthetic hydrocarbons	8	20	20	20	12	7	4	8	6	7
Hydrogen carriers										
Ammonia cracking	6	3	6	7	3	7	11	10	12	17
Liquid organic hydrogen carrier	4	5	6	3	9	7	10	10	3	13

Source: author's calculations

Box 5: Hydrogen to hydrogen-based fuels

The leading processes for making hydrogen-based fuels are not new, but are receiving fresh attention now that their potential to enable net zero emissions has been recognised. The main route for producing synthetic oil products from hydrogen is the Fischer-Tropsch (FT) reaction, for which a patent was first sought in 1926. The main route for producing synthetic methane and methanol from hydrogen is the Sabatier reaction, which saw its first patent application in 1908. For producing ammonia from hydrogen, the patent for the Haber-Bosch reaction, which is still the main process, was filed in 1908 and was the subject of the 1918 Nobel Prize in Chemistry. However, despite improvements over a century, each process is energy intensive and optimised for fossil fuel inputs rather than separate streams of hydrogen and highly stable molecules such as CO_2.

The innovation challenge is to find new catalysts and configurations for low-emission fuels, or to invent entirely new pathways from sustainable inputs to fuel products. If innovators are successful, the potential market is large. In the IEA Net Zero Emissions by 2050 Scenario, demand for low-emission hydrogen-based liquid fuels reaches the equivalent of nearly six million barrels of oil per day in 2050, around 6% of today's oil market. This demand in 2050 is roughly evenly split between aviation, power generation and shipping.

Synthetic oil products

The FT reaction was developed to make longer-chain hydrocarbon fuels (so-called alkanes) from carbon monoxide and hydrogen (so-called syngas):

$$n\,CO + (2n+1)\,H_2 \rightarrow C_nH_{2n+2} + n\,H_2O$$

By varying the process conditions, catalyst and post-processing, different mixtures of hydrocarbons can be obtained, including light hydrocarbons (n<4), gasoline (roughly 5<n<12), kerosene (roughly 12<n<15), diesel (roughly 16<n<18) or waxes (n>18). The FT reaction helped to reduce Germany's dependence on oil during World War II and is still used in large-scale facilities, such as those in South Africa that were first built in the 1950s in pursuit of energy independence.

While carbon monoxide (CO) is readily obtained from fossil fuels, it is harder to find non-fossil fuel sources. One option is to gasify biomass to make syngas, in which case it is not necessary to produce hydrogen separately. Another option is to start with CO_2 and convert it to CO via a reverse water-gas shift reaction (first patented in 1925). However, this option is energy intensive and additional production of hydrogen is needed just to make CO. A further option is to use a solid oxide electrolyser cell (SOEC) that consumes CO_2 and steam in the production of syngas but is yet to reach commercial scale. Non-fossil CO_2 is a by-product of bioethanol or biomethane production or can be captured from the atmosphere or even the ocean. While bio-based sources may be limited by the availability of sustainable biomass, atmospheric CO_2 is costly and energy intensive to obtain.

Synthetic methane

Producing synthetic methane gas via the Sabatier reaction requires less CO_2 than FT for the same energy output, but generally has higher energy input requirements. However, there has been some progress towards a biological conversion process that reduces the reaction heat using enzymes. As a fuel, methane can be blended with natural gas or used in power plants directly, but is less useful than liquid fuels for replacing fossil fuels in transport.

The largest low-emission synthetic methane plant started operation at Werlte in Germany in 2013, combining around 330 tonnes of hydrogen per year with the CO_2 by-product from biomethane production. In 2022, a pilot for synthetic kerosene was started at the same location, with a capacity of around 350 tonnes of hydrocarbon per year.

Ammonia

For a century, the Haber-Bosch reaction has been used for the production of chemicals – for fertilisers, polymers and explosives – and over 31 Mt of hydrogen from fossil fuels is already used for this purpose each year (IEA, 2019). Attention has only been paid to ammonia as a possible fuel, or a means of transporting hydrogen energy, as part of the recent search for low-emission hydrogen-based fuels. In the Haber-Bosch process, hydrogen is reacted with nitrogen from the air at high temperature and pressure, which makes ammonia a sustainable option only if enough low-emission energy is available to power the process at the right price or if alternatives to the Haber-Bosch process can be found. Some attention is currently being directed at electrochemical approaches at lower pressure. Nevertheless, as a means of storing and transporting hydrogen, ammonia benefits from widespread existing infrastructure and the absence of CO_2 emissions, though other greenhouse gases, such as nitrous oxide, must also be carefully avoided (Wolfram et al., 2022).

The largest low-emission ammonia plants in the world are located in the US and use fossil fuels with CCUS. They each have the capacity to produce around 60 000 tonnes of low-emission hydrogen per year (i.e. the fraction of total hydrogen that no longer has associated CO_2 emissions). The largest plant producing low-emission ammonia via electrolysis today is at Puertollano in Spain, with a capacity for 3 000 tonnes per year of hydrogen input.

Methanol

Like ammonia, methanol is a bulk commodity that is produced today from fossil fuels, often via hydrogenation of CO in a version of the Sabatier reaction. Interest in methanol as a fuel increased as a result of the 1970s oil crisis and again recently driven by the challenge to find cost-effective low-emission fuels. Low-emission methanol can be used more easily in existing engines in the shipping sector than ammonia and can be converted to petrochemicals, but has the drawback of needing a sustainable carbon feedstock. The use of CO_2 as a feedstock for synthetic methanol is scientifically more advanced than for other carbon-containing fuels, and a plant in Iceland with capacity to use 765 tonnes of low-emission hydrogen per year has been in operation since 2015, with CO_2 being captured from a power plant. In mid-2022, Maersk ordered 19 methanol-powered container ships and plans to source low-emission methanol.

Upgrading biofuels

Vegetable oils can be treated with hydrogen to make molecules of smaller size that are more suitable biofuels for engines. The resulting hydrotreated vegetable oil (HVO) has been commercialised at large-scale plants in the past decade, and global output grew by 65% to around seven million tonnes between 2019 and 2021 (IEA, 2022c). With further expansion of HVO production expected, the demand for low-emission hydrogen will increase. This is likely to stimulate innovation in hydrotreatment, hydrogen production and sustainable sources of vegetable oil, possible including lignocellulosic materials and algae.

5. End-use applications

Global hydrogen demand was around 94 Mt H_2 in 2021, more than 50% higher than in 2000. Almost all of this demand comes from established refining and industrial applications. Refineries consumed close to 40 Mt H_2 as feedstock and reagents or as a source of energy. Chemical production accounted for nearly 50 Mt H_2 of demand, with roughly three-quarters directed at ammonia production (for fertilisers, explosives and other chemicals) and one-quarter at methanol (for solvents, fuels and petrochemicals). Although the equipment supplied for these applications is dominated by a small number of large companies, there is a competitive market for cheaper and more profitable products that continues to drive innovation for marginal gains, even for processes that have changed only marginally in many decades. In recent years, many of these companies, their customers and their suppliers have begun to expect that they will need to radically curtail fossil fuel emissions and are exploring technologies for integrating low-emission hydrogen sources directly into their processes.

Just as significantly, a pathway to net zero emissions is likely to require the penetration of hydrogen use into sectors where it plays almost no role today. While interest in hydrogen as a fuel for passenger vehicles has passed through several "hype" cycles since the 1970s, often for energy security motives, applications for trucks, trains, aircraft, ships and steelmaking now attract more attention. Progress with pilot and demonstration projects in these areas has been encouraging in the past five years, but attracting sufficient investment and policy attention to drive commercialisation will require continual technological improvements that reduce costs and raise performance.

5.1 Recent developments in established applications

Patent data indicate an increase in innovation since 2005 for the established applications of hydrogen for the production of methanol and ammonia. The underlying inventions are typically directed at energy efficiency; they focus on optimising the heat integration of hydrogen and ammonia or methanol synthesis, as well as the efficiency of ammonia purification. However, the key difference in patenting since 2005 compared with previous years is the response of equipment suppliers to the interest in using low-emission hydrogen.

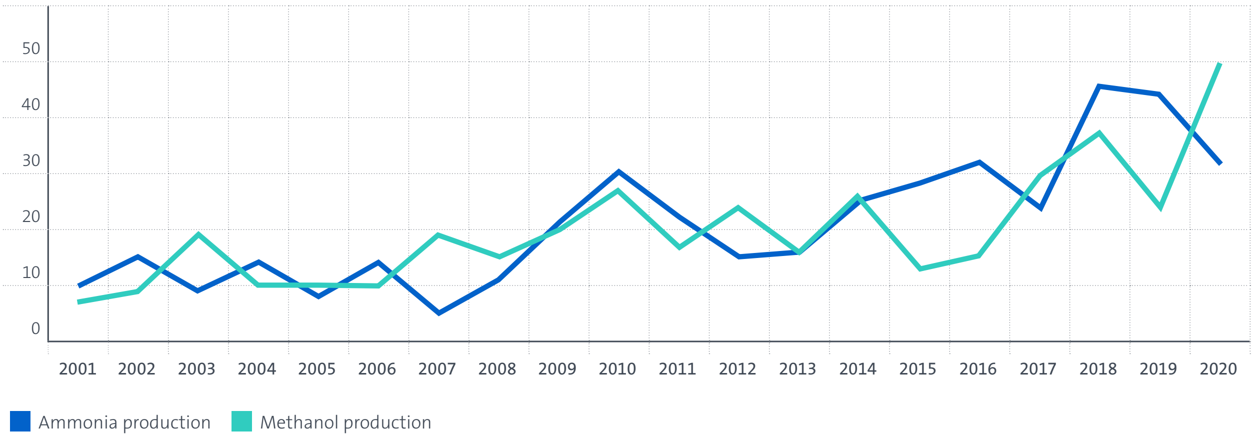
Interest in low-emission ammonia and methanol stems from the imperative to reduce fossil fuel emissions from these energy-intensive industrial processes, as well as the identification of these chemicals as potential hydrogen-based fuels for transport and power generation in a clean energy future (see section 4). Given the advantages they offer as fuels compared with hydrogen, coupled with extensive existing infrastructure and experience in trading these commodities, demand for ammonia and methanol could expand significantly if they can be produced cleanly and cheaply enough. In the IEA Net Zero Emissions by 2050 Scenario, demand for low-emission hydrogen for making ammonia for the power generation and shipping sectors grows to 75 Mt in 2050, 50% higher than the market for all hydrogen for chemicals today. In Japan, the largest power generation company, JERA, issued a tender in 2022 for up to 0.5 Mt of low-emission ammonia to replace 20% of the coal at a large power plant unit from 2027.

Growing targets for patenting in this area include electrically-heated reactors for ammonia synthesis that reduce the need for fossil fuel combustion and have the potential to eliminate fossil fuels on-site if the hydrogen is sourced from water electrolysis. However, it will prove trickier to remove fossil carbon from the fertiliser value chain; often only 35% of the hydrogen from fossil fuels can be replaced (or fitted with CCUS) due to the common practice of converting ammonia to urea using carbon from the integrated fossil fuel-to-hydrogen production process. This raises the issue of sustainable sourcing of carbon inputs for hydrogen-based fuels, particularly how to reduce the energy intensiveness of extracting the carbon from captured CO_2 and integrating it into products like methanol.

Europe dominated patenting in these fields over the period 2011 to 2020, with 34% and 48% respectively of IPFs in the production of ammonia and methanol. With 14% of IPFs in each field, Germany is a strong innovation leader within the block. Other European countries are also very significant contributors, in particular Switzerland and Denmark for ammonia production (13.5% and 9.0% respectively) and Denmark, the UK and the Netherlands for methanol production (11.4%, 9.9% and 9.1% respectively). The combined contributions of the US and Japan fall just short of that of Europe in ammonia production, and well short in the case of methanol.

Figure 5.1

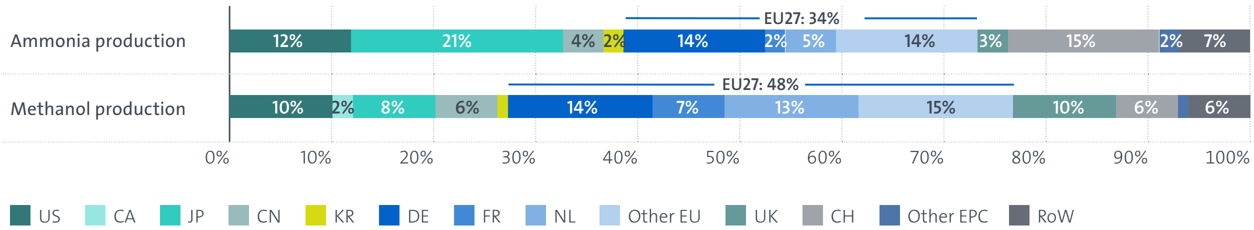
Patenting trends in hydrogen use for methanol and ammonia production (number of IPFs, 2001–2020)



Source: author's calculations

Figure 5.2

Origins of IPFs related to existing hydrogen applications, 2011–2020



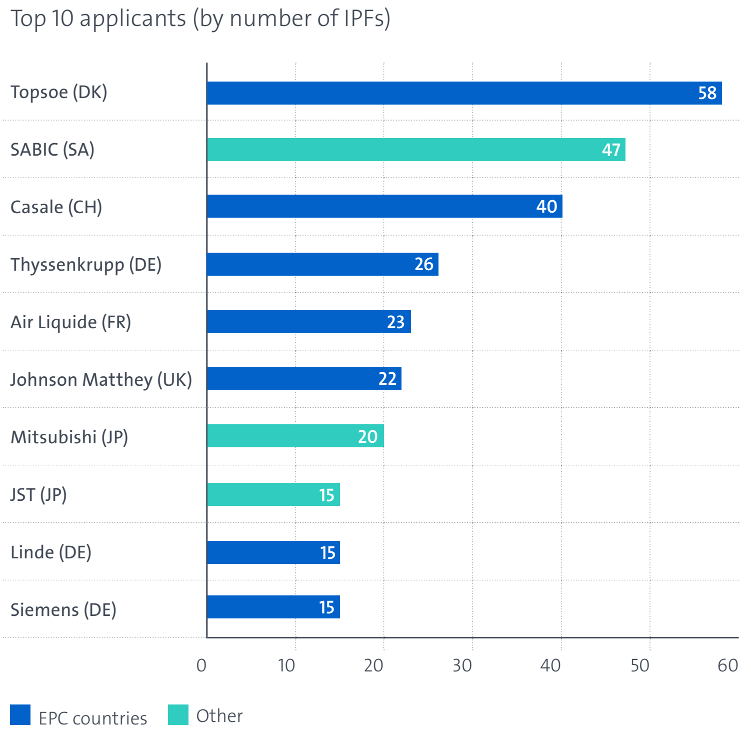
Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications. The value labels are not reported for shares below or equal to 1%.

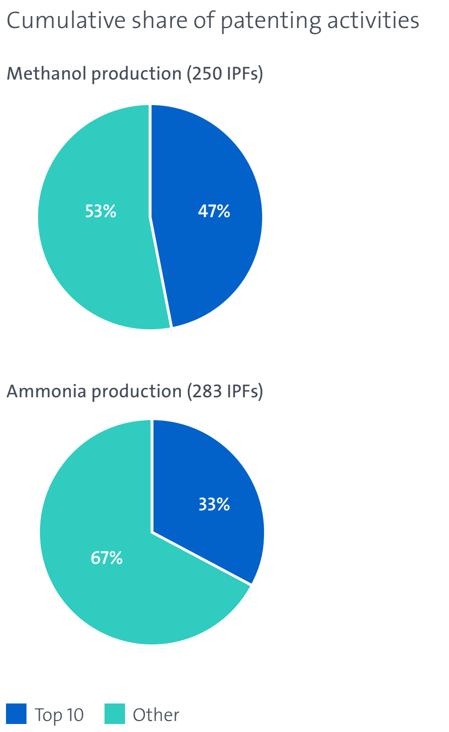
Source: author's calculations

European companies likewise dominate the list of leading applicants in the production of ammonia or methanol, with 70% of the IPFs stemming from the top ten applicants. All these applicants innovate in both hydrogen-based ammonia and methanol production. Together they generated nearly half of all IPFs in methanol production and a third in ammonia production in the period 2011–2020, denoting a strong concentration of innovation in both sectors. The relatively large share of IPFs originating from research institutions in ammonia (23%) compared with methanol (13%) production suggests a stronger focus on fundamental research.

Figure 5.3

Top applicants in methanol and ammonia production, 2011-2020





Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents.

Source: author's calculations

5.2 Recent developments in applications motivated by climate

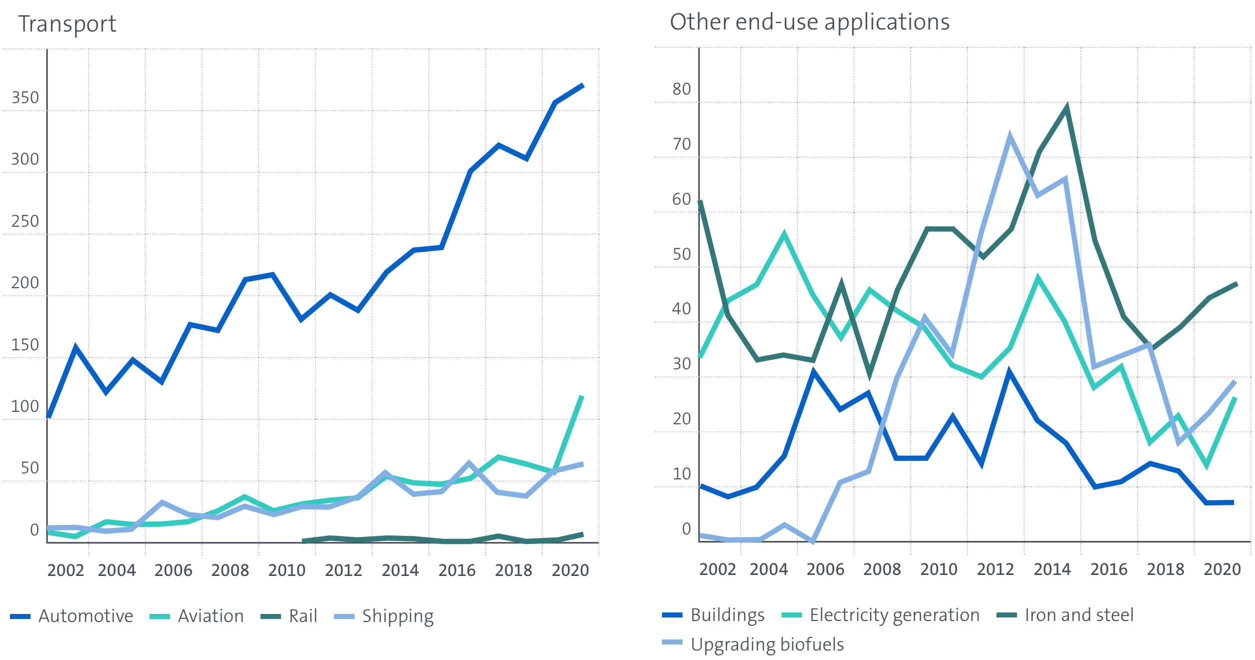
Since 2001, there have been more IPFs for automotive applications of hydrogen than for all the other emerging uses of hydrogen combined (Figure 6.1). Patenting in this area continues to grow, at an average annual rate of 7% over the past decade. Road transport, particularly passenger cars, has been the main focus for hydrogen innovation since the oil crises of the 1970s. That crisis launched interest in hydrogen fuel cells alongside investment in nuclear power, which was perceived to be more secure than oil, and in the absence of adequate batteries for electric vehicles. The accumulated knowledge base in this area is now being commercialised in pursuit of low emissions. By the end of 2021, the global fuel cell electric vehicle (FCEV) stock was more than 51 000, up from about 33 000 in 2020, representing the largest annual deployment of FCEVs since they became commercially available in 2014. Cars and buses are the biggest source of demand for hydrogen outside established applications, and much of the intellectual property is now being applied to trucks, where hydrogen is considered to have a more competitive advantage over batteries.

Demand for low-emission hydrogen for road transport in the IEA Net Zero Emissions by 2050 Scenario soars to more than 90 Mt H_2 in 2050, but is overtaken by 200 Mt of demand for other modes of transport (including the hydrogen inputs to make hydrogen-based fuels for aviation and shipping). The challenge of decarbonising aviation and shipping, for which hydrogen is the leading option over long distances, has become much more prominent in recent years and this is reflected in the patent data. IPFs for aviation applications have grown at an average annual rate of 15% over the last decade, and for shipping the rate has been 8%.

Progress has mainly been led by Japan in the automotive sector, by the US in aviation and by European applicants in the case of shipping, suggesting a trend towards a pattern of global specialisation in these sectors (Figure 6.2). Japan in particular shows a strong lead in hydrogen applications for the automotive sector – the most important application field by far in terms of patenting activities – with 39% of IPFs in that field. Only 33 IPFs were published for rail applications over the whole period despite there being more trains running on hydrogen in the world today (around 14) than aircraft or ships.

Figure 5.4

Patenting trends in hydrogen end-use applications (IPFs, 2001–2020)



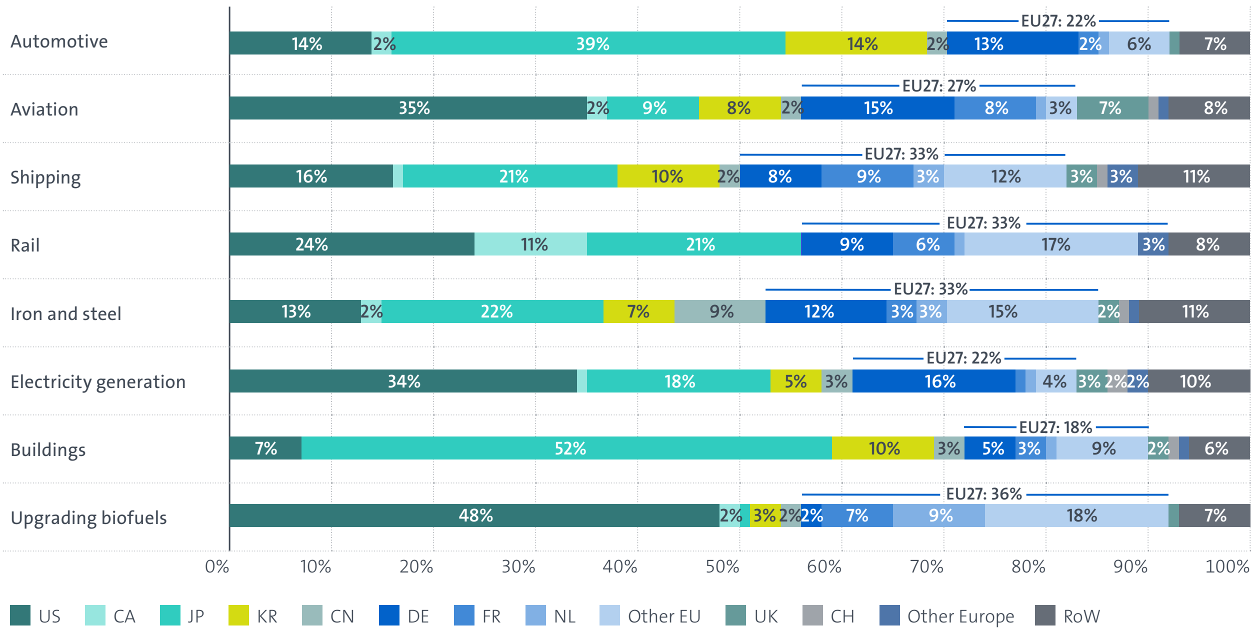
Source: author's calculations

In other applications, there is no clear trend towards more innovation. The global level of patenting for technologies that enable hydrogen use for steelmaking, power generation and the buildings sector (for heat, electricity or cooking) was lower in 2020 than in the 2000–2015 period. For power generation and buildings, the trend is one of decline. However, these sectors may need to rely on hydrogen technologies for decarbonisation. The first commercial iron and steel plant using low-emission hydrogen could come online as early as 2026 (see Box 6). In the IEA Net Zero Emissions by 2050 Scenario, use of low-emission hydrogen in the iron and steel sector reaches around 50 Mt H_2 in 2050. Patenting in the use of hydrogen for iron and steel production has mainly been led by European and Japanese applicants, which together accounted for more than half of IPF publications over the period 2011–2020. With more money and interest being dedicated to this topic, it seems likely that the current upturn will accelerate and become more globalised as technical challenges are overcome on ever larger scales.

In the power sector, demand rises to 90 Mt in the Scenario, including for stationary fuel cells and hydrogen that is transformed to ammonia and co-fired with fossil fuels. These flexible forms of generation help to balance increasing generation from variable renewables by responding rapidly to imbalances in supply and demand and using hydrogen as a means of storing or transporting electricity. Hydrogen use in buildings also increases, although its penetration is limited to certain situations in which it offers clear advantages over other technology options.[10] In both cases, the decline in patenting appears somewhat correlated with rising expectations for batteries as a means of storing electricity at grid-scale or in buildings. For buildings in particular, the higher level of patenting between 2005 and 2015 is likely to have been underpinned by government action. The applications are heavily concentrated in Japan (52% of IPFs in the period 2011–2020), where several programmes sought to develop "micro" fuel cells for buildings as an alternative to natural gas. Nonetheless, cost reductions for stationary fuel cells, particularly fuel cell manufacturing, are still considered fundamental to the prospects for hydrogen in these sectors and the fall in patenting is not a promising sign.

Figure 5.5

Origins of IPFs related to hydrogen applications, 2011–2020



Note: The calculations are based on the country of the IPF applicants, using fractional counting in the case of co-applications. The value labels are not reported for shares below 2%.

Source: author's calculations

10 Some countries also expect to blend small percentages of low-emission hydrogen into their natural gas grids, though the requirements for new technologies for power plants and in buildings would be modest.

5.3 Recent developments in transport technologies

Patent data can be disaggregated to explore trends within individual transport applications. As different applications advance towards high levels of technology readiness, and then overcome challenges related to commercial production, the focus of innovation evolves. Fuel cell road vehicles are in some cases already discovering the hurdles to mass production, while aviation and shipping applications are at a much earlier stage of troubleshooting pilot projects.

Table 5.1

Emerging hydrogen technologies in transport

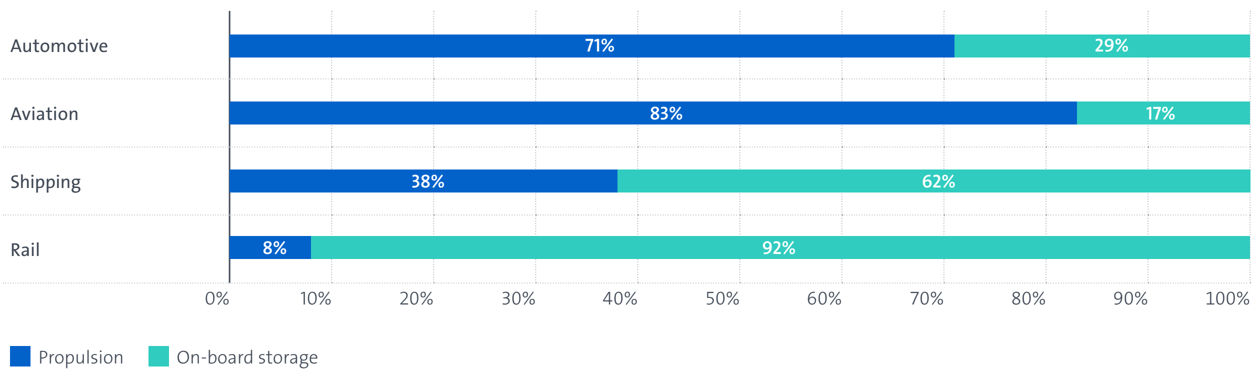
Technology	Technology readiness level	
Fuel cells for light duty road	Market uptake	TRL 9
Fuel cells for heavy duty road	Market uptake	TRL 9
H_2 ICE for road	Pre-commercial demonstration	TRL 7
Fuel cells for shipping	First-of-a-kind commercial	TRL 8
H_2 ICE for shipping	Large prototype	TRL 5
Small aircraft	Pre-commercial demonstration	TRL 7
Medium aircraft	Early prototype	TRL 4
Rail	First-of-a-kind commercial	TRL 8

For each application of hydrogen, there are technical challenges relating to on-board storage of hydrogen and propulsion – i.e. how to convert the chemical energy into motive force, for example via a fuel cell combined with an electric motor. For automotive and aviation sectors, the areas with the highest levels of patenting, propulsion dominates, mainly driven by innovation in fuel cells during the period 2011–2020 (Figures 5.6 and 5.7). The number of IPFs increased significantly over this period for fuel cell-related inventions in both sectors, with compound average growth rates of 15% in the automotive sector and nearly 18% in aviation.

In aviation, this trend is dominated by innovation for unmanned aircraft or drones, which accounted for two-thirds of IPFs in fuel cell propulsion for aviation in 2020. For passenger and cargo aircraft, there is an expectation that hydrogen and fuel cells could be the most competitive options for medium-haul flights that might require prohibitive numbers of batteries to electrify by other means. The patent data offer some evidence of a technical consensus in favour of fuel cells, as the number of IPFs for a competitor - hydrogen internal combustion engines on aircraft - decreased over the past decade. Since 2021, ZeroAvia, a start-up founded in 2017, has raised USD 78 million to develop a fuel cell aircraft with up to 100 seats. However, for longer distances, the higher power of turbines and the greater energy density of hydrogen-based fuels are expected to be more competitive. Airbus is aiming to develop the world's first zero-emission commercial aircraft by 2035 using a hydrogen turbine. Universal Hydrogen, a start-up founded in 2020, has raised over USD 80 million for hydrogen turbine drivetrains. Despite this activity, patenting activity for aviation gas turbines using hydrogen, ammonia or methanol for long-haul aviation increased only slightly from 2011 to 2020.

Figure 5.6

Hydrogen propulsion versus on-board storage in transport technologies, 2011–2020



Source: author's calculations

Patenting activities related to rail and shipping (including patents for ammonia and methanol engines) suggest that the on-board storage of hydrogen is the main innovation concern for these applications. Moreover, the patenting of hydrogen-related propulsion technologies for shipping remains largely focused on the specific application of these technologies to submarines. In terms of the type of propulsion for ships, patenting activities remain evenly distributed between fuel cells and internal combustion engines, with an increase in both cases during the past decade.

Figure 5.7

International patenting trends in hydrogen-based propulsion technologies, 2011–2020

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Automotive										
Fuel cells	64	72	105	98	107	187	170	171	182	234
Internal combustion engines	80	67	51	69	58	47	54	60	79	61
Aviation										
Fuel cells	16	19	34	18	22	25	30	25	23	71
Gas turbines	6	12	10	17	14	15	16	12	15	16
Shipping										
Fuel cells	3	5	15	12	8	14	10	8	16	19
Internal combustion engines	5	10	16	11	11	15	14	12	16	24

Source: author's calculations

The top ten applicants with the largest number of IPFs related to fuel cells for automotive propulsion include nine automotive OEMs and one of their key suppliers, Bosch. It is noticeable that "pure play" fuel cell developers, such as Ballard, a Canadian company, or Plug Power, a US company, have fewer patents in this area, though they also own intellectual property in more generic fuel cell technology unrelated to automotive integration. These top ten applicants together account for nearly 80% of the IPFs published in that field between 2011 and 2020 (Figure 5.8). They are led by two Japanese companies (Toyota and Honda) and two Korean companies (Hyundai and Kia).

Three German companies, two US companies and a third Japanese company complete the list. The right-hand part of Figure 5.8 shows that innovation in fuel cells for the automotive sector also generates technology knowledge for electrolysis. Specifically, a large part of the OEMs' patent portfolios relates to polymer separator membrane materials that are also relevant for PEM electrolysis. This is due to the reversibility of PEM fuel cells, which can be used in reverse for electrolysis, and therefore allows for important synergies between innovation efforts aimed at electricity use and electricity generation using PEM technology.

Figure 5.8

Top ten applicants in automotive applications, 2011–2020

	IPFs on fuel cells for propulsion	IPFs with relevance to electrolysis			
		Polymer separator membrane materials	Inorganic separator membrane materials	Electrocatalyst materials	Stacking
Toyota (JP)	431	257	10	8	4
Hyundai (KR)	223	158	3	3	
Honda (JP)	168	122	16	9	16
Kia (KR)	111	101	2	3	
General Motors (US)	49	94	1	1	
Nissan (JP)	44	125	9		
Audi (DE)	35	80	1		
BMW (DE)	33	15			
Bosch (DE)	34	118	12	2	15
Ford (US)	22	48			

DE EU27 JP KR US

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single of co-applicant of the related patents.

Source: author's calculations

Box 6: Hydrogen in steel manufacturing

The iron and steel industry is currently responsible for 8% of global final energy demand and about 7% of the energy sector CO_2 emissions, making it the largest industrial source of such emissions (IEA, 2020). Producing steel requires iron (Fe), and producing iron requires the reaction of iron ore (usually in the form of Fe_2O_3) with a reducing agent at high temperature. The main route today uses a blast furnace, in which the ore and the reducing agent (coke) are exposed to hot air and metallic iron is produced in a liquid state. Most of the CO_2 emissions stem from the use of fossil fuels to produce the high temperature and from the carbon in the coke, which accepts the oxygen leaving the ore in accordance with the following reactions:

$$2C + O_2 \rightarrow 2\,CO$$

$$Fe_2O_3 + 3\,CO \rightarrow 2\,Fe + 3\,CO_2$$

$$2\,Fe_2O_3 + 3\,C \rightarrow 4\,Fe + 3\,CO_2$$

Use of hydrogen as the reducing agent is one of the most promising ways to reduce the carbon footprint of primary steel production, alongside approaches such as CCUS, bioenergy and direct electrification. With hydrogen, water is produced rather than CO_2.

$$Fe_2O_3 + 3\,H_2 \rightarrow 2\,Fe + 3\,H_2O$$

The hydrogen can be used in a blast furnace where it can be blended with coke to achieve up to around 20% lower CO_2 emissions (Yilmaz, 2017). It can also be blended with natural gas in a direct reduced iron (DRI) plant that produces a sponge-type of iron that can be processed into steel in an electric arc furnace, potentially running on electricity generated either from renewables or from nuclear power plants. Hydrogen can be blended with the natural gas in a DRI plant, partially reducing emissions. To go further towards decarbonisation of the iron and steel sector, DRI plants can be operated using only hydrogen as the reducing agent, but this requires the facility to be redesigned and the input of very large quantities of hydrogen. The first 100% hydrogen DRI pilot project started operating in Sweden in 2021 and the first industrial plants are currently under construction (one in Sweden) or at an advanced stage of planning in Germany, Spain and P.R. China. If all are completed as planned, they could meet 1.8 Mt of low-emission hydrogen demand by 2030.

Smelt reduction is a third option that could also incorporate hydrogen. Pellets or fine ore are first partially reduced and then fed to a gasifier-melter in a second step. Hydrogen could potentially be the sole reducing agent in this process but there are currently no immediate plans to build commercial-scale facilities using this technology.

Table 5.2

Emerging applications of hydrogen in steel manufacturing

Technology	Technology readiness level	
Direct reduced iron	Full prototype	TRL 6
Blending in blast furnaces	Pre-commercial demonstration	TRL 7
Smelting reduction	Early prototype	TRL 4

Patent data show similar trends for all three processes, with a drop in the number of published IPFs after a peak in 2014, and growth resuming in the period 2017–2020 (see Figure 5.4). It is likely that this reflects efforts stimulated by two major research programmes – ULCOS in Europe and COURSE50 in Japan – that were initially supported by governments between 2005 and 2015. Between these programmes a range of different approaches to reducing emissions from the sector were pursued. In recent years, hydrogen-based DRI has emerged as the main focus area for investment in R&D and demonstration. This is largely due to the increased ambition of governments and companies to achieve significant emissions reductions and not just partial decreases, as well as higher expectations about the costs and availability of low-emission hydrogen.

Nearly 40% of patenting activities in the period 2011–2020 were concentrated among a small number of steel producers and equipment suppliers (Figure 5.9).

Japanese companies appear to be leading among the top OEMs, with three applicants featuring in the top five. The portfolios of most OEMs tend to focus on easier-to-implement blast furnace technology, in particular in the case of JFE Steel and Thyssenkrupp, with Posco standing out with a relative specialisation in DRI. By contrast, three European companies and two from the US form the top five equipment suppliers. Compared with OEMs, their portfolios are more diversified and signal a stronger focus on DRI and smelting reduction. Moreover, a significant proportion of their patented inventions are of relevance for two or more hydrogen-based steel production technologies. This suggests that suppliers are better positioned than OEMs to combine these different routes in new equipment and to facilitate the diffusion of new hydrogen-based technologies towards the different OEMs.

Figure 5.9

Profile of top applicants in steel manufacturing, 2011–2020

		Total	Blast furnace	Direct reduced iron	Smelting reduction
OEMs	JFE Steel (JP)	39	29	3	9
	Posco (KR)	28	10	20	2
	Kobe Steel (JP)	16	7	8	1
	Thyssenkrupp (DE)	14	13	2	4
	Nippon steel (JP)	13	6	2	7
Suppliers	Siemens (DE)	35	16	21	21
	Primetals (UK)	34	9	22	15
	Midrex (US)	19	9	18	3
	Technical Resources (US)	12	1	3	10
	Danieli (IT)	11	1	10	2

Note: IPFs have been allocated to the listed entities based on the identification of these entities as a single or co-applicant of the related patents.

Source: author's calculations

References

BCG, "Deep Tech and the Great Wave of Innovation", 2021. Retrieved from bcg.com/de-de/publications/2021/deep-tech-innovation

Bogaerts et al., "Plasma Technology for CO_2 Conversion: A Personal Perspective on Prospects and Gaps", 2020, Frontiers in Energy Research. Retrieved from https://www.frontiersin.org/articles/10.3389/fenrg.2020.00111/full

EPO and IEA, "Patents and the energy transition – Global trends in clean energy technology innovation", April 2021, epo.org/trends-energy; iea.org/reports/patents-and-the-energy-transition

EPO and IRENA, "Innovation trends in electrolysers for hydrogen production", Patent Insight Report, April 2022. Retrieved from https://www.epo.org/searching-for-patents/business/patent-insight-reports.html

Harrison, D.P. "Sorption-Enhanced Hydrogen Production: A Review" 2008. Ind. Eng. Chem. Res. 47, 6486–6501. Retrieved from https://pubs.acs.org/doi/full/10.1021/ie800298z

Holladay et al., "An overview of hydrogen production technologies", 2009. Catalysis Today, vol. 139, 4, 244–260. Retrieved from https://www.sciencedirect.com/science/article/pii/S0920586108004100?via%3Dihub

IEA, "The Future of Hydrogen – Seizing today's opportunities", Technology report, June 2019. Retrieved from iea.org/reports/the-future-of-hydrogen

IEA, "Iron and Steel Technology Roadmap", Technology report, October 2020. Retrieved from iea.org/reports/iron-and-steel-technology-roadmap

IEA, "Net Zero by 2050 – A roadmap for the Global Energy Sector", Flagship report, May 2021. Retrieved from iea.org/reports/net-zero-by-2050

IEA, "World Energy Investment 2022", Flagship report, June 2022a. Retrieved from iea.org/reports/world-energy-investment-2022

IEA, "Global Hydrogen Review 2022", Technology report, September 2022b. Retrieved from iea.org/reports/global-hydrogen-review-2022

IEA, "Biofuels", September 2022, Tracking report, September 2022c. Retrieved from iea.org/reports/biofuels

IEA, "World Energy Outlook 2022", Flagship report, October 2022d. Retrieved from https://www.iea.org/reports/world-energy-outlook-2022

Masoudi S. et al., "Sorption-enhanced Steam Methane Reforming for Combined CO_2 Capture and Hydrogen Production: A State-of-the-Art Review", 2021. Carbon Capture Science & Technology, vol. 1, 100003. Retrieved from https://www.sciencedirect.com/science/article/pii/S2772656821000038?via%3Dihub

Sánchez-Bastardo et al., "Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a Renewable and Sustainable Hydrogen Economy", 2021. Ind. Eng. Chem. Res. 2021, 60, 32, 11855–11881. Retrieved from https://pubs.acs.org/doi/10.1021/acs.iecr.1c01679

Schneider et al., "State of the Art of Hydrogen Production via Pyrolysis of Natural Gas", 2020. ChemBioEng Rev, vol. 7, issue 5, 150-158. Retrieved from https://onlinelibrary.wiley.com/doi/10.1002/cben.202000014

Wismann et al., "Electrified methane reforming: A compact approach to greener industrial hydrogen production", 2019. Science, vol. 364, issue 6442, 756–759. Retrieved from https://www.science.org/doi/abs/10.1126/science.aaw8775

Wismann et al., "Electrified methane reforming: Elucidating transient phenomena", 2021, Chemical Engineering Journal 425, 131509. Retrieved from https://www.sciencedirect.com/science/article/pii/S1385894721030904

Wolfram et al., "Using ammonia as a shipping fuel could disturb the nitrogen cycle", Nature Energy, 2022. Retrieved from https://www.nature.com/articles/s41560-022-01124-4

Yilmaz, C., Wendelstorf, J., Turek, T. "Modeling and simulation of hydrogen injection into a blast furnace to reduce carbon dioxide emissions", 2017. Journal of Cleaner Production, vol. 154, 488–501. Retrieved from https://www.sciencedirect.com/science/article/pii/S0959652617306169?via%3Dihub

Authors
José Alconchel y Ungria, Cristina Alvarez Rodriguez,
Paolo Burattini, Ioana Cristescu, Valérie Desbois, Irene Gattinger,
Lluis Gimeno-Fabra, Dirk Göritz, Muzio Grilli, Elisabeth Harf-Bapin,
Régis Jung, Ralph Lux, Laurent Mauriès, Yann Ménière, Thomas Ott,
Michail Papagiannis, Vasiliki Papanikolaou, Olivier Porté, Ilja Rudyk,
Christof Sodtke, Victor Veefkind, Ansgar Wansing (EPO)

Simon Bennett, Nick Johnstone, Jose Miguel Bermudez Menendez
(IEA)

Design
PD Communication (EPO)

The report can be downloaded from:
epo.org/trends-hydrogen
iea.li/hydrogen-innovation

ISBN 978-3-89605-314-5