Patent insight report

Innovation trends in electrolysers for hydrogen production

Europäisches Patentamt
European Patent Office
Office européen des brevets

IRENA
International Renewable Energy Agency

Table of contents

Executive summary		**3**
1.	**Introduction**	**4**
1.1.	The role of electrolysers in energy transition	4
1.2.	About the study	6
2.	**Methodology**	**7**
2.1.	Using patent information	7
2.2.	Patent search	7
3.	**Results**	**9**
3.1.	Patent trends in hydrogen production processes	9
3.2.	Subtechnology areas	16
	3.2.1. Cell operation conditions and structure	18
	3.2.2. Electrocatalyst materials	21
	3.2.3. Separators (diaphragms, membranes)	25
	3.2.4. Stackability of electrolysers (stacks)	28
	3.2.5. Photoelectrolysis	31
4.	**Conclusion**	**36**

Executive summary

In a collaborative effort between the European Patent Office (EPO) and the International Renewable Energy Agency (IRENA), this patent insight report examines the global evolution of patent filings published between 2005 and 2020 in the domain of electrolysers used to produce hydrogen.

When policymakers and researchers agree on a vision for an innovative, low-carbon, affordable and safe hydrogen industry that would help the world to combat climate change and restrict global warming, resources and funding become available to accelerate the process of developing innovative solutions to produce, store and transport hydrogen. One of the key technical components in the production of hydrogen is the electrolyser. In an ideal world, electrolysers would be built out of raw materials that are cheap and abundantly available and would use only renewable electricity and water. Currently, technology is being developed to make electrolysers more efficient, cheaper and scalable up to market needs.

This report maps the various electrolyser technologies and trends revealed by an analysis of worldwide patent filings.

Main findings

- From 2005 to 2020, 10 894 patent families related to the electrolysis of water were published worldwide, with an average annual increase of 18%.
- In 2016, the number of patent families related to water electrolysis surpassed the number of patents related to solid or liquid coal- and oil-based hydrogen sources. By 2020, it was double that number.
- 73% of water electrolyser families have at least one granted patent that is still in force.
- Patent applications from China totalled 6 383 patent families, followed by Japan, Korea, United States, Germany and France. The more stringent definition of international patent families confirmed that 97% of the Chinese filings serve only to protect the domestic market.
- TOSHIBA (JP), CEA (FR), PANASONIC (JP), SIEMENS (DE), HONDA (JP) were the top applicants.
- In 2018, inventions related to non-noble metal electrocatalyst materials surpassed the number of inventions related to the use of noble metals. This trend continues to grow and can be attributed to the large influx of Chinese national filings.
- Photoelectrolysis (water splitting using light as the energy source) is a strong, newly emerging technology forming the basis of an above-average number of international patent families, with 50% of these patents being filed by universities.
- Europe and Japan account for more than 50% of the total number of international patents in all subtechnology areas. While Europe leads in the stackability of electrolysers (stacks) (41% of the total patents in this area), electrocatalyst material (34%) and cell operation conditions and structure (32%), Japan ranks first in photoelectrolysis (39%) and separators (diaphragms, membranes) (36%).
- Patent data shows increased invention activity in technologies leading to reduced costs of electrolysers. We observed an increase in international patent filings for cells operating at high-pressure, use of non-noble materials and thinner organic membranes.
- The United States of America averages 18% across all technology areas while the Republic of Korea registers its highest share in separators (diaphragms, membranes) (16%) compared with an average of 7% across the other categories.
- Chinese international patents account for only about 4% across the five technology areas but China dominates in terms of the number of pure domestic patent filings.

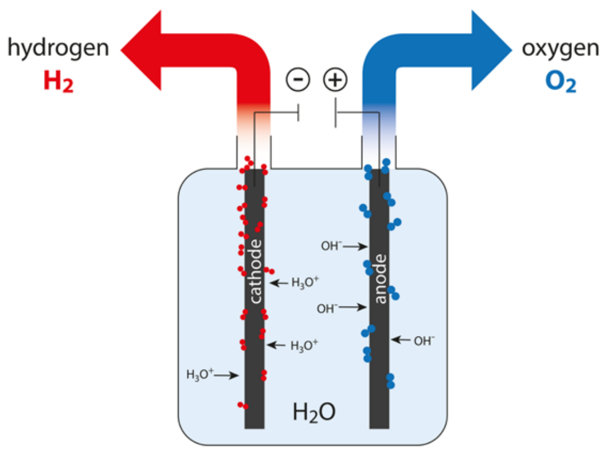
1. Introduction

1.1. The role of electrolysers in energy transition

Climate change is widely acknowledged by the largest economies and developing countries as a significant problem that needs to be tackled urgently. A growing number of countries are developing programmes and strategies on greenhouse gas mitigation and decarbonisation roadmaps to overhaul their energy systems and infrastructures within the next decades. Through a combination of renewables, energy storage, energy efficiency and smart grid technology, a large share of end-use applications will be decarbonised in the coming decades. As more countries foster deep decarbonisation strategies, green hydrogen produced from renewables via water electrolysis is expected to be at the very heart of energy transition as a key piece of the clean energy puzzle. IRENA's 1.5°C scenario projects that hydrogen and derivatives will account for up to 12% of final energy consumption by 2050.[1]

A significant capacity increase in the manufacture and deployment of electrolysers will be needed to respond to the growing demand for green hydrogen, and this should be clean, hence powered by renewable energy sources. In this scenario, the installed water electrolysers capacity needs to grow to some 350 GW by 2030, up from the approximately 0.5-GW electrolysis capacity currently available.[2] This projection implies an extraordinary expansion of the market for electrolysers, which will play a crucial role in the effort towards economy-wide decarbonisation. Several countries have already specifically included electrolyser capacity deployment targets in their national hydrogen strategies.

The process based on water electrolysis allows hydrogen to be produced using electricity and water as inputs. Electrolysis is a well-known chemical process that requires wider adoption to lower production costs. Therefore a reduction in electrolyser system costs is essential and technology innovation is crucial to this end. According to IRENA, investment costs for electrolyser plants can be reduced by 40% in the short term and 80% in the long term through key strategies such as improved electrolyser design and construction, economies of scale, replacing scarce materials with abundant metals, increasing efficiency and flexibility of operations and learning rates with high technology deployment aligned with a 1.5˚C climate target.[3] Electrolysers suffer from rapid degradation, meaning that development is also needed to increase both process efficiency and technology life cycle.



1 IRENA (2022), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.

2 IRENA (2022), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.

3 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

BOX 1

The use of water and land for electrolysis[4]

Green hydrogen production depends on two key inputs: water as the main feedstock and renewable electricity as the energy source. According to the International Energy Agency (IEA), electrolysis currently corresponds to about 2% of global hydrogen production. However there is a significant momentum for electrolysis to replace fossil-fuel based hydrogen production. If all current demand for hydrogen were produced via water electrolysis, this would lead to an electricity demand of 3 600 TWh and 617 million m^3 of water. To put these numbers into perspective, this would amount to more than the annual electricity generation of the European Union and 1.3% of the water consumption of the global energy sector today, roughly twice the current water consumption for hydrogen production from natural gas.[5]

Water electrolysis has the smallest water footprint relative to other hydrogen production processes. 1 kg of hydrogen requires 9 kg of water as input, from a purely stoichiometric perspective. In contrast, production of hydrogen from natural gas with CCUS uses 13–18 kg H_2O/kg H_2 and coal gasification uses 40-86 kg H_2O/kg H_2 depending on water consumption for coal mining.[6] However, about 20 kg of water is needed to produce about 1 kg of hydrogen via electrolysis when process inefficiencies and the gasification process are taken into account. IRENA put these numbers into perspective with an example to determine the impact of hydrogen production on freshwater availability. Accordingly, a large-scale (1-GW) electrolyser, operating with 75% efficiency for 8 000 hours (about 11 months) per year and producing 0.15 million tons of hydrogen, would consume about 3 million tons of water based on 20 kg of water use per kg of hydrogen consumption. This amount of water corresponds approximately to the water consumption of a small town with 70 000 inhabitants.[7]

Water does not present a bottleneck for scaling up electrolysis, even in territories with high water stress, if seawater desalination is kept as an option. High purity level is required considering the negative impact of impurities (equipment corrosion and chlorine formation) on the lifetime of the electrolyser stack. Reverse osmosis for desalination requires 3 to 4 kWh of electricity per m3 of water with a minor impact on the total cost of electrolysis, driving up total hydrogen production cost by merely 0.01-0.02 USD/kg H_2.[8]

In terms of land area, IRENA estimates that 1 000 GW of electrolysis capacity would occupy a land area the size of Manhattan, New York. However, this large-size electrolyser would have an energy density of almost 7 500 MW/km^2, which is about 1 500 times larger than the onshore wind density of 5 MW/km^2. This indicates that a substantial amount of land area needs to be occupied by wind turbines or solar panels to produce renewable electricity, which is essential for green hydrogen production, while the space occupied by electrolysers, relatively speaking, represents only a small fraction of the total.[9]

4 Blanco H. (2021) Hydrogen production in 2050: how much water will 74EJ need?

5 IEA (2019) The Future of Hydrogen Report Seizing today's opportunities.

6 IEA (2021) Global Hydrogen Review 2021.

7 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

8 IEA (2021) Global Hydrogen Review 2021.

9 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

1.2. About the study

The primary objective of this study is to examine the global evolution of patent filings in order to identify major trends in the uptake of new technologies to facilitate the further implementation of the large-scale use of hydrogen. The report provides useful insights for interested players in the field and for policymakers to leverage actions and initiatives to further develop and deploy electrolyser-related technologies, thus enabling a wider uptake of hydrogen. For this purpose, the study uses various resources, including EPO patent databases and registers and other available public reports, and it benefits from the long standing technical expertise in the field of both IRENA and the EPO.

By virtue of their respective missions and activities, the EPO and IRENA share a common interest in the study of patent filing statistics to improve understanding of trends affecting the transition to a sustainable energy future using renewable energy sources. In 2017, IRENA and the EPO signed a memorandum of understanding on bilateral co-operation to promote innovation in the field of renewable energy technologies. [10] This memorandum of understanding was extended in 2021 and a decision was made to publish regular patent landscape reports focusing on a specific technological area.

Building on a long-standing EPO-IRENA collaboration, this study assesses patent filing statistics in the very specific domain of electrolyser technologies. The growing political interest around the globe in climate-neutral energy production and energy storage technologies and the promise that hydrogen technology offers is the driving force behind a great momentum for innovation in electrolyser technology. The use of hydrogen has been recognised as a disruptive technology sector with possible fundamental implications for society and the economy. Although patent filings show a steep increase in the last 10 years, major innovations in electrolyser technology are still needed to make this technology market-ready at industrial levels.

This situation could change in the future with the recent introduction in several geographical regions of major programmes dedicated to the development and deployment of a strategy on hydrogen that would bring together different strands of action, from research and innovation to production and infrastructure to the international dimension.[11]

10 EPO and IRENA enhance cooperation on patent information about renewable energy technologies.

11 IRENA (2022), Geopolitics of the Energy Transformation: The Hydrogen Factor, International Renewable Energy Agency, Abu Dhabi.

2. Methodology

2.1. Using patent information

Patents are exclusive rights that can only be granted for inventions that are novel and inventive.[12] High-quality patents are assets which can help attract investment, secure licensing deals and provide market exclusivity. Patent owners pay annual fees to maintain patents in those countries that are of commercial value to them and protect their inventions from being used by competitors, for example. In exchange for these exclusive rights, all patent applications are published, revealing the technical details of the protected inventions. This allows other researchers to build on the published inventions of other inventors and also avoid the mistake of investing in developing a solution for a problem that has already been solved by others.

Patent databases therefore contain a wealth of technical information, much of which cannot be found in any other source. The EPO's free Espacenet [13] database contains more than 130 million documents from over 100 countries. Patent filing statistics provide interesting indicators to measure and examine innovation, commercialisation and knowledge transfer trends. They also provide a means of observing changes in technology trends as well as identifying new players or consolidation efforts.

This can reveal new insights into trends in the sector of electrolysers and help to support informed decision-making processes.

2.2. Patent search

This patent insight report provides a snapshot of the patent situation of a very specific technology, namely electrolysers. Patent insight reports can cover patents filed either within a given country or region, or globally. They can inform policy discussions, strategic research planning and technology transfer.

Each patent insight report begins with a state-of-the-art search for the relevant technology in selected patent databases. A search strategy is developed with an expert examiner in the relevant field(s). The search results are then analysed to answer specific questions about patterns of patenting activity or innovation, for example. The results are presented visually to assist understanding, allow conclusions to be reached or recommendations based on the empirical evidence to be made.

12 epo.org/learning/materials/inventors-handbook/novelty.html.
13 https://worldwide.espacenet.com/.

The information, data and analysis provided in this report are primarily based on a dedicated exploitation of EPO patent databases (PATSTAT, Espacenet, EP register). Only relevant patent publications in the period 2005–2020 (earliest publication year of the patent family) were considered. The identification of the relevant areas of technology and the creation of the technology-specific search strategies were undertaken by an EPO examiner expert in the electrolyser/hydrogen field and IRENA experts. All search queries (summarised in Figure 1) were adapted as far as possible to the free Espacenet tool. The queries and the data are provided as a separate excel document and the queries are numbered sequentially from Q01 to Q35. Not all documented queries have been used in this report. Although the report centres around the technology used for the electrolysis of water, two additional queries (Q02 and Q03) provide datasets on using liquid and solid hydrocarbon as feedstock for the electrolyser. The purpose was to provide a baseline to illustrate the exponential increase in patents being filed which are relevant to the electrolysis of water. No further analysis was done with these datasets.

The report analyses five groups of subtechnologies relevant for the electrolysis of water, which are important for reducing the cost of electrolysers [14]:

- **Cell operation conditions and structure**
  Rationale: operating conditions at higher temperature and pressure are needed to increase efficiency of electrolysers without compromising durability and performance of membranes while also reducing costs.
- **Electrocatalyst materials**
  Rationale: scarce materials are a major barrier to electrolyser cost and scale-up, and solutions to replace such materials are needed, for example by using non-noble materials.
- **Separators (diaphragms, membranes)**
  Rationale: reducing membrane thickness enables an increase in efficiency, which in turn enables a reduction in electricity consumption.
- **Stackability of electrolysers (stacks)**
  Rationale: electrodes, bipolar plates and porous transport layers can contribute significantly to the stack cost. Improvements in these components, including their manufacturing, can lead to lower capital costs.
- **Photoelectrolysis**
  Rationale: photoelectrolysis can integrate electricity and hydrogen production in a single step potentially leading to cost benefits with the current challenges of low technology maturity and pathway efficiency.

14 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

Water electrolysis (Q01)

Cell operation conditions and structure
- Temperature (Q04, Q05)
- Pressure conditions (Q06, Q07)
- Cell structure (Q08. Q09, Q10)

Electrocatalyst materials
- Carbon (Q15, Q16, Q20)
- Metals and ceramics (Q17, Q18)
- Noble metals (Q19)

Separator (diaphragm, membrane)
- Polymer (organic) (Q24)
- Inorganic (ceramic mostly) (Q25)

Stackability of electrolysers
- with bipolar elements being plates (Q26)
- with bipolar elements being electrodes (Q27)
- with membranes (Q28)
- without bipolar elements (Q29)

Photoelectrolysis
- with PV power source (Q30)
- with photoelectrode, photoabsorber a. electrocatalyst (Q31)
- with photoelectrode, with photo-electrocatalyst (Q32)

Figure 1: This figure shows a summary of the technology and subtechnology areas analysed in this report and associated identification of the search queries run to gather data.

When using IPC and CPC classification codes to extract patents for statistical analysis, readers must bear in mind that it is in the patent applicant's interest to get the broadest possible scope of protection for the invention. Therefore a patent will not be restricted to the combination of elements in which the applicant is developing its technology. As a result, some aspects may be inaccurately attributed to a patent application in the sense that a technical aspect may be developed for a specific electrolysis process without being explicitly indicated in the patent application or reflected in the patent classification. The patents grouped under "electrocatalyst materials" provide an example of this as just over 50% of these are also flagged as being technologically relevant for water electrolysis. When looking at electrolyser technology, it is also clear that there is often no explicit reference to the electrolysis of water but rather to fuel cell stacks.

Data mining (optimising search queries) and curation were conducted by the EPO in line with existing best practices of EPO experts and patent examiners. A challenge in this report was defining the boundaries for the different datasets of patents. For example, an electrolyser operating at high temperatures will usually also involve high-pressure technology. This leads to quite large overlaps between the different technologies and the patent families tagged as relevant for the respective technologies. Keywords were often used to create a better separation of the different technologies.

Throughout the report, patent filing statistics are addressed at different levels of aggregation whenever appropriate. Patent counts are quantified by the number of patent families.[15] In addressing the patent filing data through the lens of origin of innovation, it is important to note that different filing strategies by stakeholders from different countries can have an impact on the overall statistics and on the conclusions. For instance, Chinese applicants choose predominantly domestic filings and do not file for patents on a comparable scale internationally.[16] In addition, Chinese applicants often file utility models as well as patents on the same or similar inventions, which increases Chinese filing numbers when simply counting patent filings or families. We have mitigated this bias by using a stricter concept of patent families called international patent families (IPFs). This concept excludes single national patent families that have only being filed in the country of the applicant. Patent families with applications having applicants or inventors from different countries were also considered to be international patent families.

Detailed search queries based on the EPO's free Espacenet tool are provided in the supplementary material. This allows the reader to monitor future changes in the covered technologies.[17]

15 epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families.html.

16 Pasimeni, F., Fiorini, A., & Georgakaki, A. (2021). International landscape of the inventive activity on climate change mitigation technologies. A patent analysis. Energy Strategy Reviews, 36, 100677.

17 IPC and CPC patent classification codes as well as the keywords used may change when a technology matures.

3. Results

This section presents and explains key results, including key insights and possible interpretations. In this section, results are firstly presented by looking at patent trends in hydrogen production processes by comparing processes based on water electrolysis with processes using liquid or solid hydrocarbon feedstock. More detailed results are shown for water electrolysis only. The focus of the analysis then moves to the five subtechnology areas identified: (i) cell operation conditions and structure, (ii) electrocatalyst material, (iii) separators (diaphragms, membranes), (iv) stackability of electrolysers (stacks) and (v) photoelectrolysis.

In each subtechnology, results are presented based on the following structure. Firstly, global patenting trends are shown. The focus then moves to country level, considering both the country of the applicants and the national jurisdictions where patents are filed. Each subtechnology section concludes with a look at the top players (in general and/or per subtechnology area).

3.1. Patent trends in hydrogen production processes

In terms of real patent filings (left-hand chart in Figure 2), in 2017 the number of patent families linked to hydrogen production processes based on water electrolysis surpassed the number of filings based on electrolysis using liquid hydrocarbon sources. Liquid hydrocarbon patents remain at the same level even after 2017. This shows the incremental priority given to research focusing on electrolysis processes based on water rather than on liquid hydrocarbon. This shift is because water electrolysis has a higher level of adaptability to different sources of power, including solar and other renewable sources, which allows a reduction in the energy input and in the use of non-renewable sources for production via hydrocarbons.

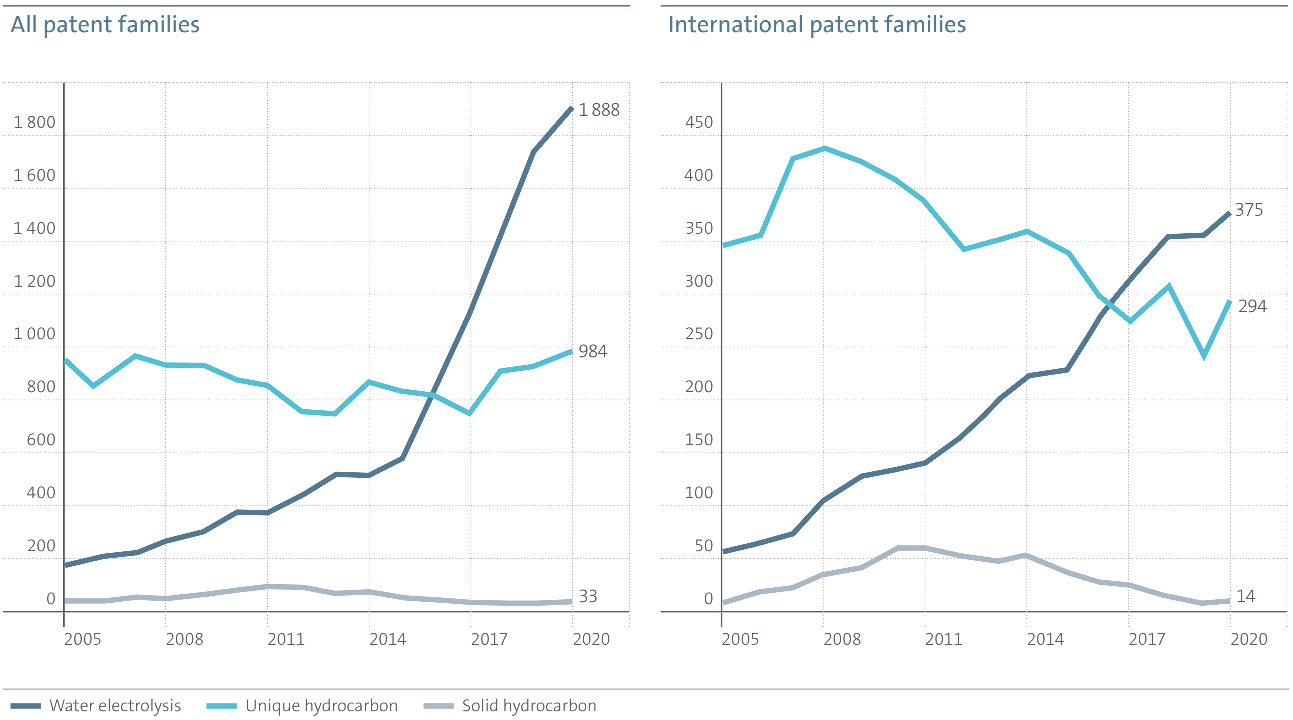


Figure 2: This figure shows the 2005-2020 trend of patent families (left-hand side) and international patent families (right-hand side), comparing hydrogen production processes based on water electrolysis with processes using liquid or solid hydrocarbon feedstock.

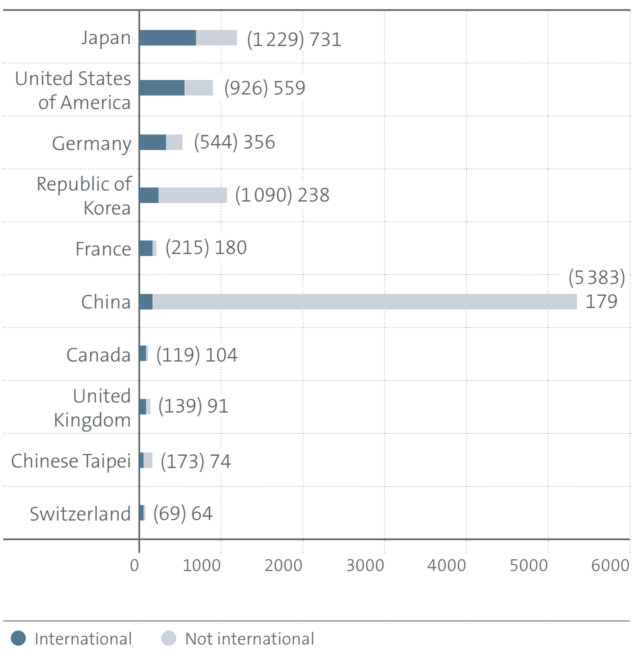
Interactive data in public Tableau workbook

The main source of this upswing is patents filed in China, mostly by exclusively Chinese applicants and their high focus on the domestic market (only about 3% of Chinese patents are international, see left-hand chart in Figure 3). In addition, detailed analysis shows that patents filed in China are often utility models that do not have any further patent filings in other patent jurisdictions. Moreover, Chinese applicants often file patents for the same or similar inventions, which increases filing numbers. This is followed by Japan, the Republic of Korea, the United States of America, Germany and France. Europe's rather minor position is an important finding in view of the strategic importance attributed to the "European Green Deal", which identifies hydrogen as key to a clean and circular economy. However, we may assume that the effect of the European Union hydrogen strategy launched in 2020,[18] which bundles measures to promote a fast and targeted development of production capacities for green hydrogen, is not yet reflected in the current data on patent filings.

In summary, looking at the patent filing data by origin of innovation, it is also important to note that different filing strategies by stakeholders from different countries have an impact on the overall statistics.

To reduce this "noise", we introduced the concept of the international patent family, which takes into account the geographical scope of the patent family via the family members and the country of the applicant. There is still a slight upward trend in water electrolysis but also a faster decline in liquid hydrocarbon filings. The right-hand chart in Figure 3 shows the trend of international patent families related to water electrolysis filed by the top six countries. International filing is led by Japan, the USA and Germany, which accounted for about 52% of the total international patent families related to water electrolysis from 2005 to 2020. Despite its domestic focus, China has recently increased its international patent production while Japan has reduced it, showing a sharp decline in the last two years. Comparing the year 2020 with 2018, Japan has a smaller number of international patent filings per year (-30%) while China has an increase of about 38%.

Patent families: top 10 country



Trend international patent

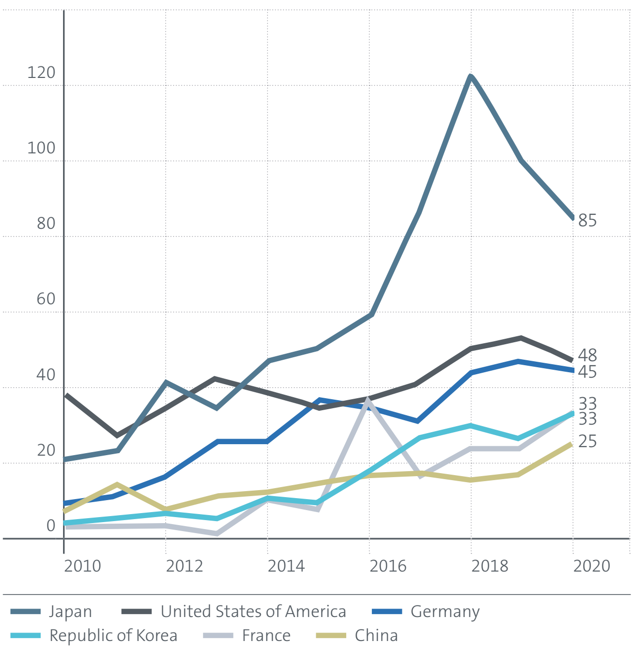
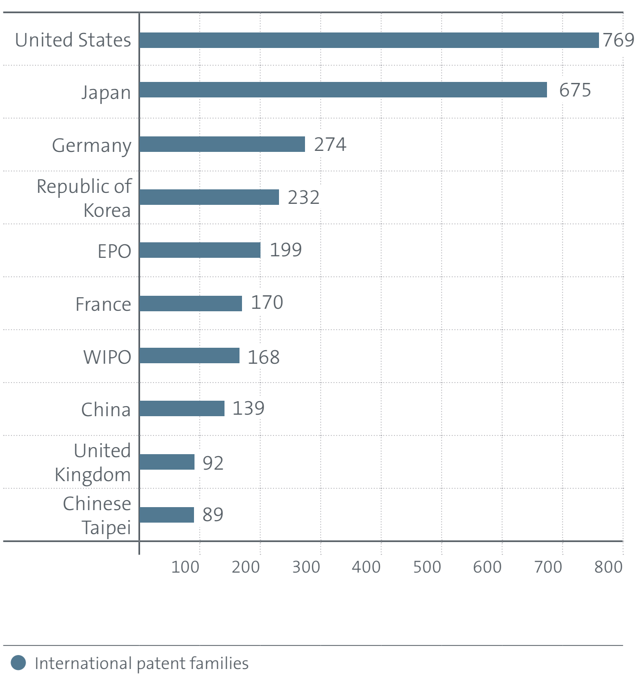


Figure 3: This figure shows the total number of patent families related to hydrogen production processes based on water electrolysis in the period 2005-2020. The top 10 countries are listed on the left-hand side (the number in brackets is the total; the number not in brackets refers to international patents only). The trend of international patent families for the top 6 countries is listed on the right-hand side.

18 European Commission (2020) Powering a climate-neutral economy: Commission sets out plans for the energy system of the future and clean hydrogen.

Japan and the USA are also the most important countries in terms of patent protection. Of the total international patent families, 24% were protected in the USA and 21% in Japan in the period 2005-2020 (chart on the left-hand side in Figure 4). A large home market can be seen by an applicant as an incentive to first file a patent in the patent office that covers an intended market. Applicants and inventors located in smaller countries can be expected to have a higher need to file their patent applications abroad. As the data in this graph covers international patent families, we may conclude that this graph more accurately reflects the place where inventions are taking place, as the international aspect is covered by the sample selection. The portion of Japanese and American filings decreasing over time is partly compensated for by patent filings at other patent authorities such as Germany, the Republic of Korea and, more recently, China (chart on the right-hand side in Figure 4).

Top 10 patent offices



Patent offices of first filing

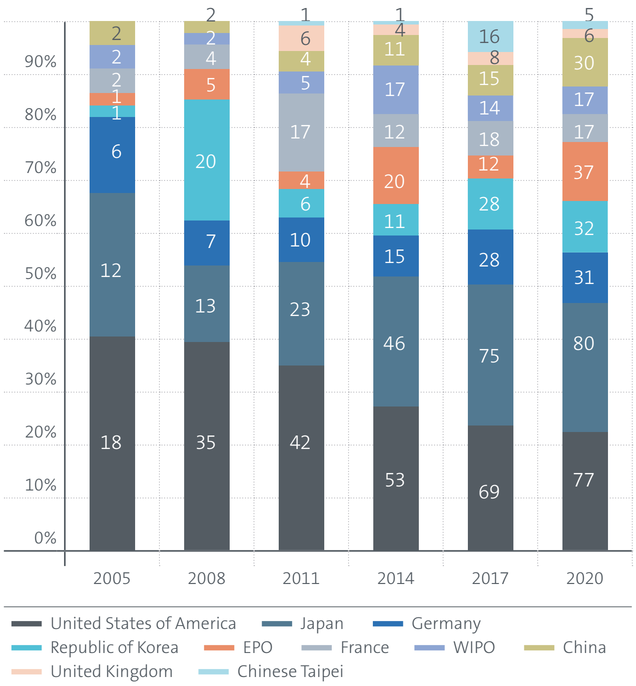
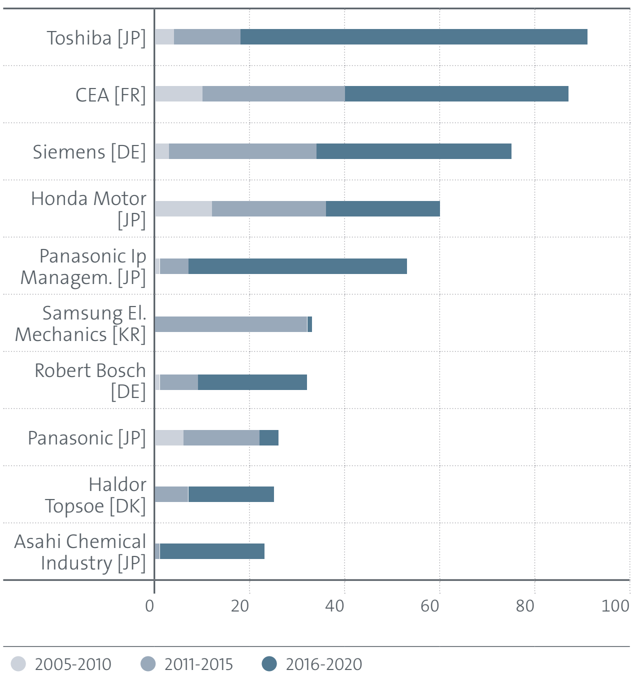


Figure 4: This figure shows the total number of international patent families filed in patent jurisdictions and related to water electrolysis in the period 2005-2020. Data is based on the first priority country in the family. The top 10 patent jurisdictions are shown on the left-hand side and the annual share for the top 10 patent jurisdictions is shown on the right-hand side. EPO denotes the European Patent Office and WIPO the World Intellectual Property Organization.

The recent push (from 2017 onwards) to international patenting in water electrolysis (on the left-hand side in Figure 5) is driven by Japanese companies, particularly by Toshiba, Panasonic and Honda, among the top 10 companies, together with Siemens and CEA. These companies account for about 15% of the total activity in water electrolysis.
In contrast, almost all of the top 10 companies active in electrolysis processes based on liquid hydrocarbon in the period 2005-2014 (on the right-hand side in Figure 5) show a reduction in their patenting activity in the period 2015-2020, which explains the decline shown in Figure 2 above. Only European players seem to have a similar number of international filings each year. These companies account for about 20% of the total activity in electrolysis processes based on liquid hydrocarbon.

Top 10 patent assignees (water)



Top 10 (2005-2014) Liquid hydrocarbon

	2005-2014		2015-2020		Change	
	Tot.	Avg.	Tot.	Avg.	Diff.	%
Panasonic [JP]	132	13.2	5	0.8	-12.4	-94%
Samsung Sdi [KR]	120	12.0	0	0.0	-12.0	-100%
Air Products & Chemicals [US]	115	11.5	43	7.2	-4.3	-37%
Air Liquide [FR]	105	10.5	81	13.5	3.0	29%
Jx Nippon Oil & Energy [JP]	75	7.5	2	0.3	-7.2	-96%
Honda Motor [JP]	62	6.2	11	1.8	-4.4	-71%
Haldor Topsoe [DK]	59	5.9	68	11.3	5.4	92%
Linde [DE]	57	5.7	48	8.0	2.3	40%
Shell [NL]	56	5.6	21	3.5	-2.1	-38%
Basf [DE]	45	4.5	28	4.7	0.2	4%

Figure 5: The top 10 patent assignees in hydrogen production processes based on water electrolysis in the period 2005-2020 are shown on the left-hand side. The top 10 patent assignees in hydrogen production processes based on liquid hydrocarbon in the period 2005-2014 and comparison with their activity in the period 2015-2020 are shown on the right-hand side.

International patent families

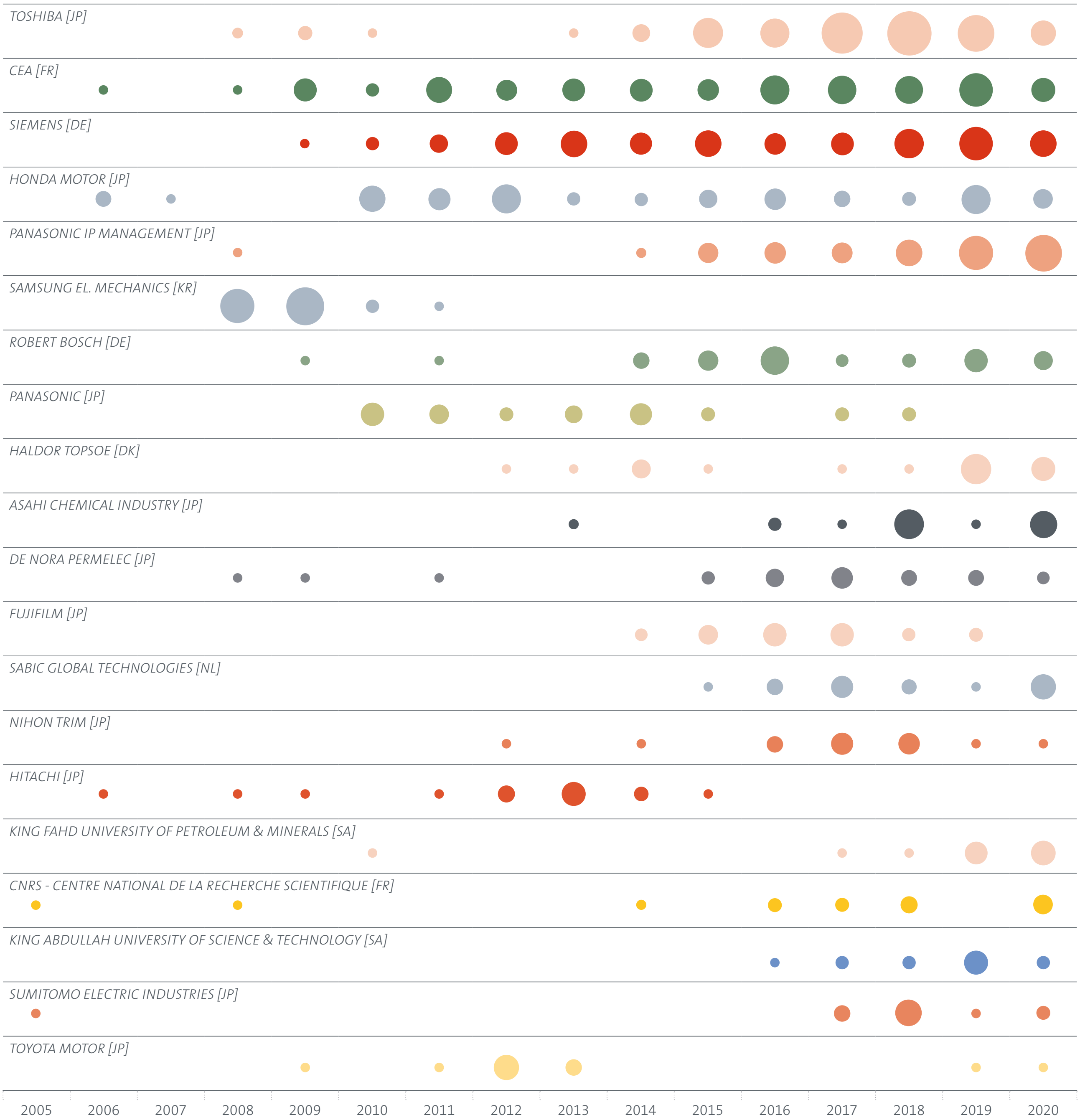
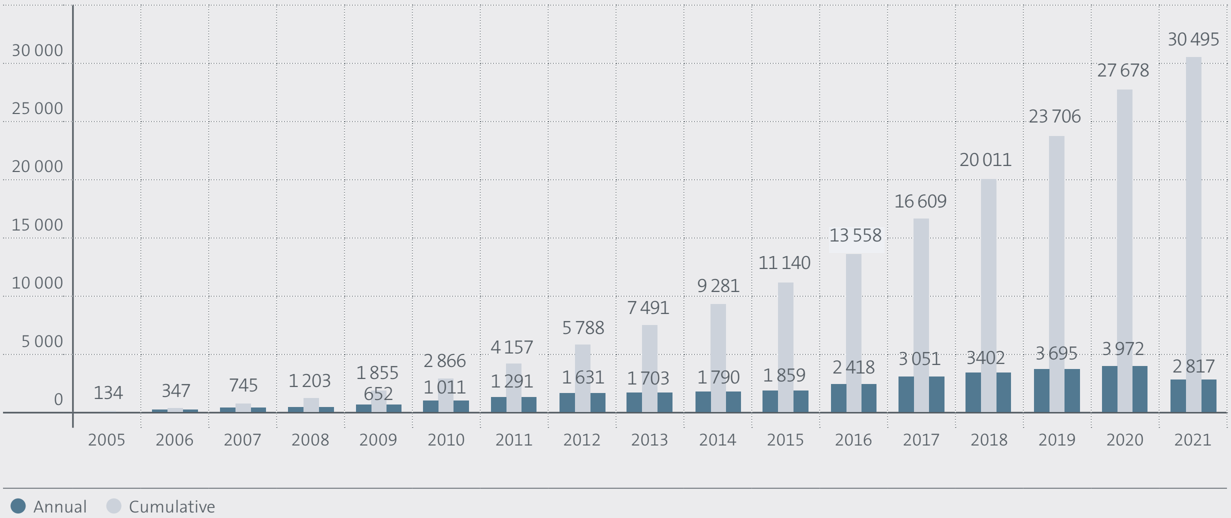


Figure 6: This figure shows the top 20 patent assignees in hydrogen production processes based on water electrolysis and the annual trend in the period between 2005 and 2020. The size of the bubble indicates the number of international patent families.

BOX 2

Granted patents for water electrolysis

Trend of granted patent applications in water electrolysis



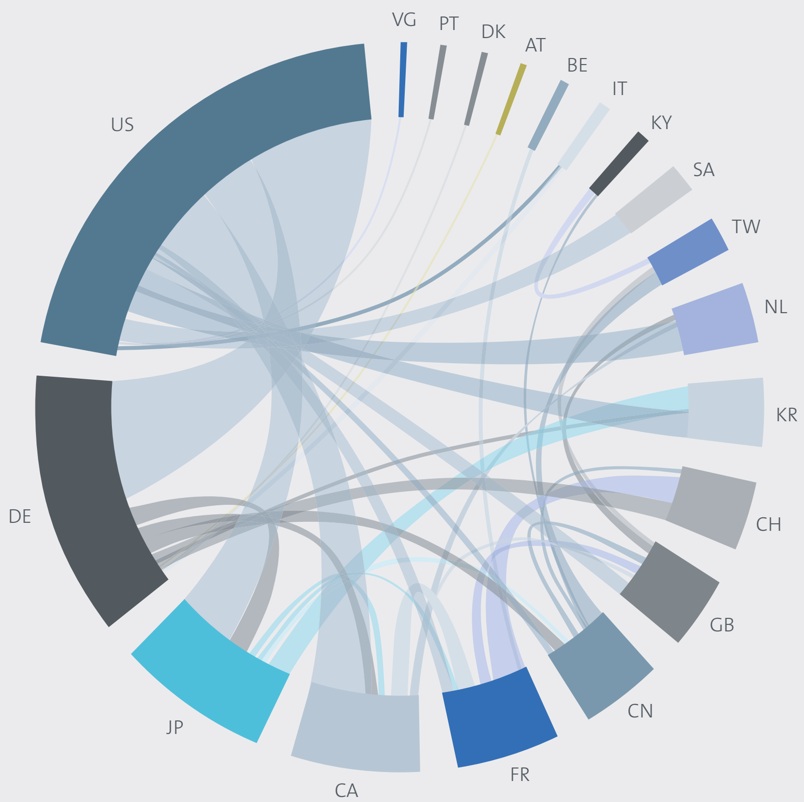
Although there is a long relationship between the number of patents filed and economic growth, the number of granted patents is a good measure of innovative quality and economic importance. The latter is usually considered to be a better indicator of the quality of the patents because only patents respecting the patent granting requirements will effectively be granted. The bar chart above shows the trend of granted patent applications, both in net values (darker colour) and in cumulative values (lighter colour). Years on the horizontal axis refer to the publication year of the grant. Please note that data for 2021 only includes data for the first six months, which is the reason for the lower total. The evolution over time illustrates the willingness of the patent owner to invest resources to protect the market share where the invention might be used to generate income. A sustained increase can be observed over time in the number of granted patents, which indicates a general increase in the capacities acquired for the development of new electrolyser technology.

BOX 3

International patenting co-operation in water electrolysis and subtechnology areas

Analysis of international collaboration based on the location of the applicants shows that there is considerable involvement of the member states of the European Patent Organisation[19] in cross-country developments and subsequent patent applications. Most prominently, this applies to Germany, France, Great Britain, Switzerland, and the Netherlands having a high level of collaboration with the United States. Connections can also be observed between Canada, France, Switzerland and Belgium, which can probably be attributed to having French as a common language. Strong co-operation with the United States is equally true for Japan, Canada and South Korea. Co-operation with China is marked by co-applicant filings with mainly Germany, Taiwan and South Korea. Overall, just over 2% of all patent families show indicators of international co-operation between the patent applicants, which is on a par with the average for the entire population of all patent families available in the PATSTAT database.

Patent families with international co-operation[20]



International applicant collaboration

Country collaboration	Families
US,DE	118
JP,US	57
US,CA	55
NL,US	33
FR,CH	29
US,KR	24
KR,JP	24
SA,US	22
GB,US	21
DE,JP	20
CA,FR	19
DE,CH	18
TW,CN	16
CN,DE	15
DE,CA	13
GB,FR	11
GB,NL	8
CN,US	8
FR,US	8
CN,JP	7

19 Member states of the European Patent Organisation: epo.org/about-us/foundation/member-states.html.

20 Country pairs representing applicants from different countries (complete dataset without Q02 and Q03, having a minimum of four patent families).

3.2. Subtechnology areas

This section presents the patenting trend in five main subtechnology areas identified. These are: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks) and photoelectrolysis. Figure 7 gives an overview at country level.

Europe and Japan account for more than 50% of the total number of international patents in all subtechnology areas. While Europe leads in the stackability of electrolysers (stacks) (41% of the total patents in this area), electrocatalyst materials (34%) and cell operation conditions and structure (32%), Japan ranks first in photoelectrolysis (39%) and separators (diaphragms, membranes) (36%). The United States of America averages 18% across all technology areas while the Republic of Korea registers its highest share in separators (diaphragms, membranes) (16%) compared with an average of 7% across the other categories. Chinese international patents account for only about 4% across the five technology areas.

Country patent share per technology areas (total 2005-2020)

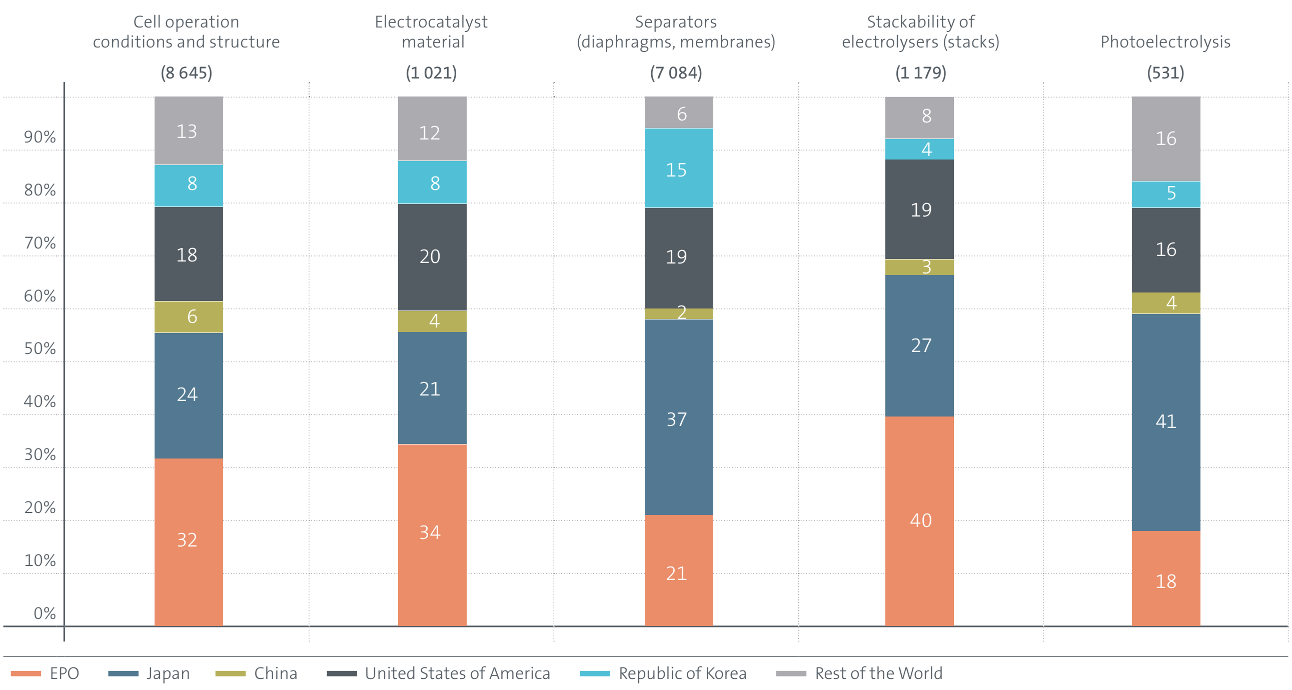


Figure 7: This is a summary chart of the country share of international patents in relation to the five subtechnology areas identified. The country refers to the country of the patent applicants. Europe groups together the 38 member states of the European Patent Organisation.[21] Numbers in bold and in parenthesis at the top of each column are the total number of international patent applications in that technology area.

21 Member states of the European Patent Organisation: epo.org/about-us/foundation/member-states.html.

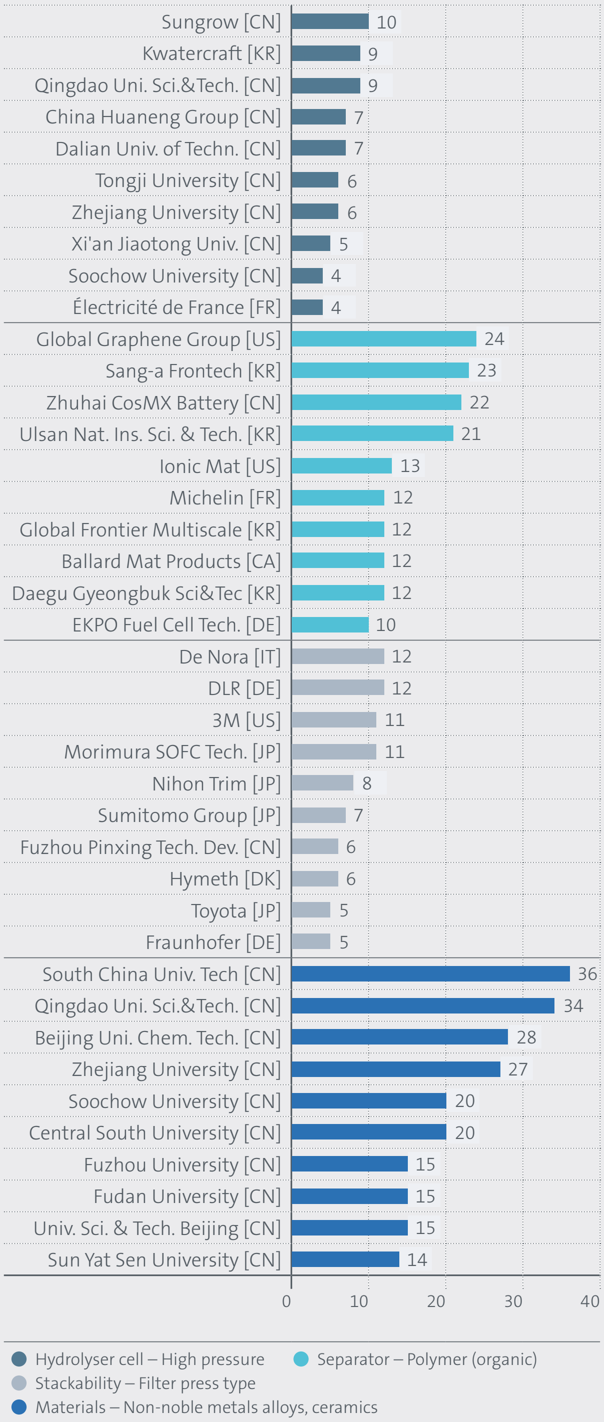
Newcomers in the area of electrolyser technologies

While certain players display a long-term continuing interest in the technologies in question, a temporal perspective, looking at players that only recently started filing patents, allows us to identify geographical specialisations as well as levels of intensity. Some of the data also confirms strategic policy decisions. We know that China has been increasing investments in hydrogen technology in its drive towards decarbonisation.

The key challenge of electrolytic hydrogen production is to overcome the technological obstacles to reducing production costs. Therefore, the development of noble-metal-free electrocatalysts for water splitting is indispensable for the cost-efficient production of hydrogen. The fact that the ten largest newcomers (as well as non-newcomers) in this area are Chinese universities is a telling sign of China's efforts to become independent of the use of noble metals to produce hydrogen. It can be observed that these patents filed by Chinese universities are nearly all national patent filings and are not filed in any other countries.

In the polymer exchange membrane group, we see a strong representation of newcomers from Korea, while new European players are mainly present in the stackability technology for electrolysers.

Note: The graph shows patent applicants not active (no patent filed) before 2015 in those areas but which filed patents in 2015 or later. Additionally, the applicant had to have at least one international filing to make it onto the list.



3.2.1. Cell operation conditions and structure

The electrochemical process takes place in the cell, which is the core of the electrolyser. In a drive for better efficiency, various electrolyser cell operating parameters such as temperature, pressure and the cell unit structure are being explored to make them more cost-effective over a wider range of operating conditions, such as voltage fluctuations.

On average across the seven categories analysed in Figure 8, 42% of the total patent filings were international. International patent filings accounted for about 70%, 65% and 49% in the divided zero gap (membrane electrode assembly or MEA), cell structure: divided and high temperature categories respectively.

Hydrolysers cells – International patent families

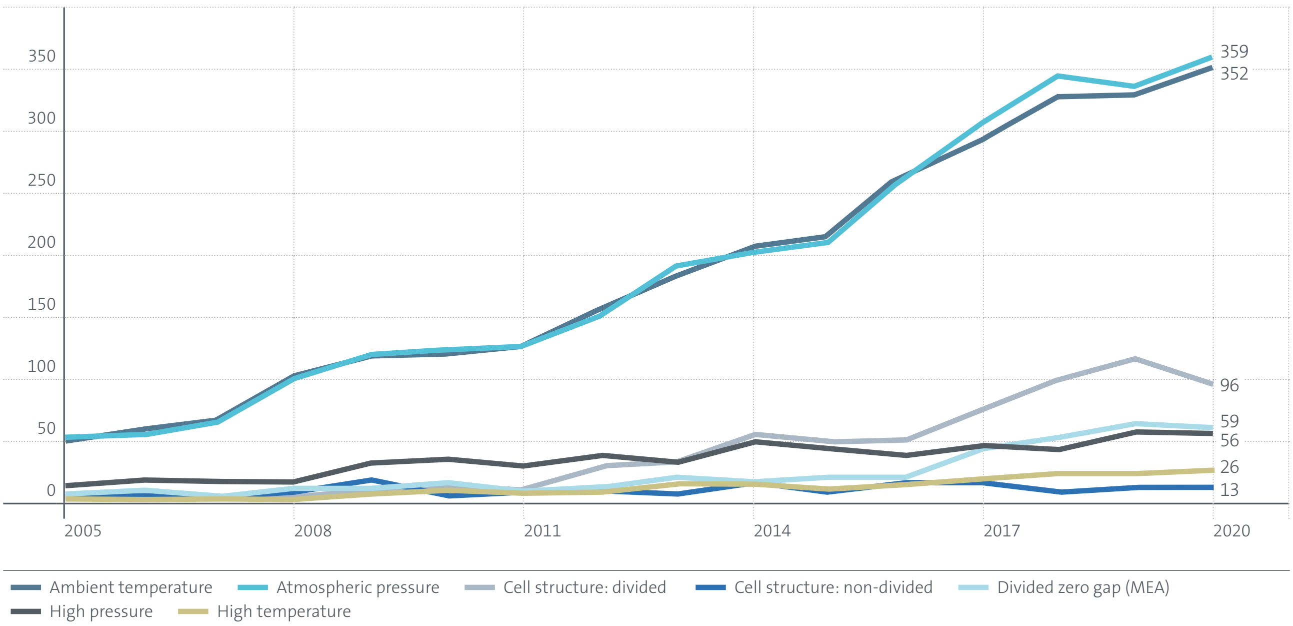


Figure 8: This figure shows the 2005-2020 trend of international patent families focusing on the following electrolyser cell operating parameters: ambient temperature, atmospheric pressure, cell structure: divided, cell structure: non-divided, divided zero gap (membrane electrode assembly or MEA), high pressure and high temperature.

Observations

Cells operating at higher pressure may reduce costs for green hydrogen production.

- However, the number of international patent filings per year for technology based on electrolyser cells operating at atmospheric pressure under ambient temperature leads the subcategory and increased by 70% between 2015 and 2020.
- For patents covering high-pressure cell technology, despite low absolute numbers in comparison to ambient pressure, the number of patent family showed a sharp increase in 2020, almost doubling the number in 2016.

It can be observed from the data that technology based on electrolyser cells operating under atmospheric pressure at ambient temperature is increasing at the same rate because most of those patents cover both concepts. The two samples represent almost the same patent families and the number of international filings increased by 70% each year between 2015 and 2020. However, looking more closely at international patent filings outside those samples, it can be seen that there is an even sharper increase in patents covering high pressure, divided zero gap and divided cell structure technology, for which the number of patent families in 2020 is almost double that in 2016. High temperature and non-divided cells have relatively low numbers of international patent filings.

The leading countries in these components are Japan, the United States of America, Germany, the Republic of Korea, China and France (see the left-hand chart in Figure 9), and overall they cover around 80% of the total international patent filings in these areas in the period 2016-2020. The national patent offices of these same countries are the most targeted for protection of international patents. Three Japanese companies (namely Toshiba, Panasonic and Honda Motor) are the first-ranked entities for international patent filings focusing on cell structure: divided, divided zero gap (MEA) and high pressure. These three companies alone cover about 17% of the total number of international patents in these categories.

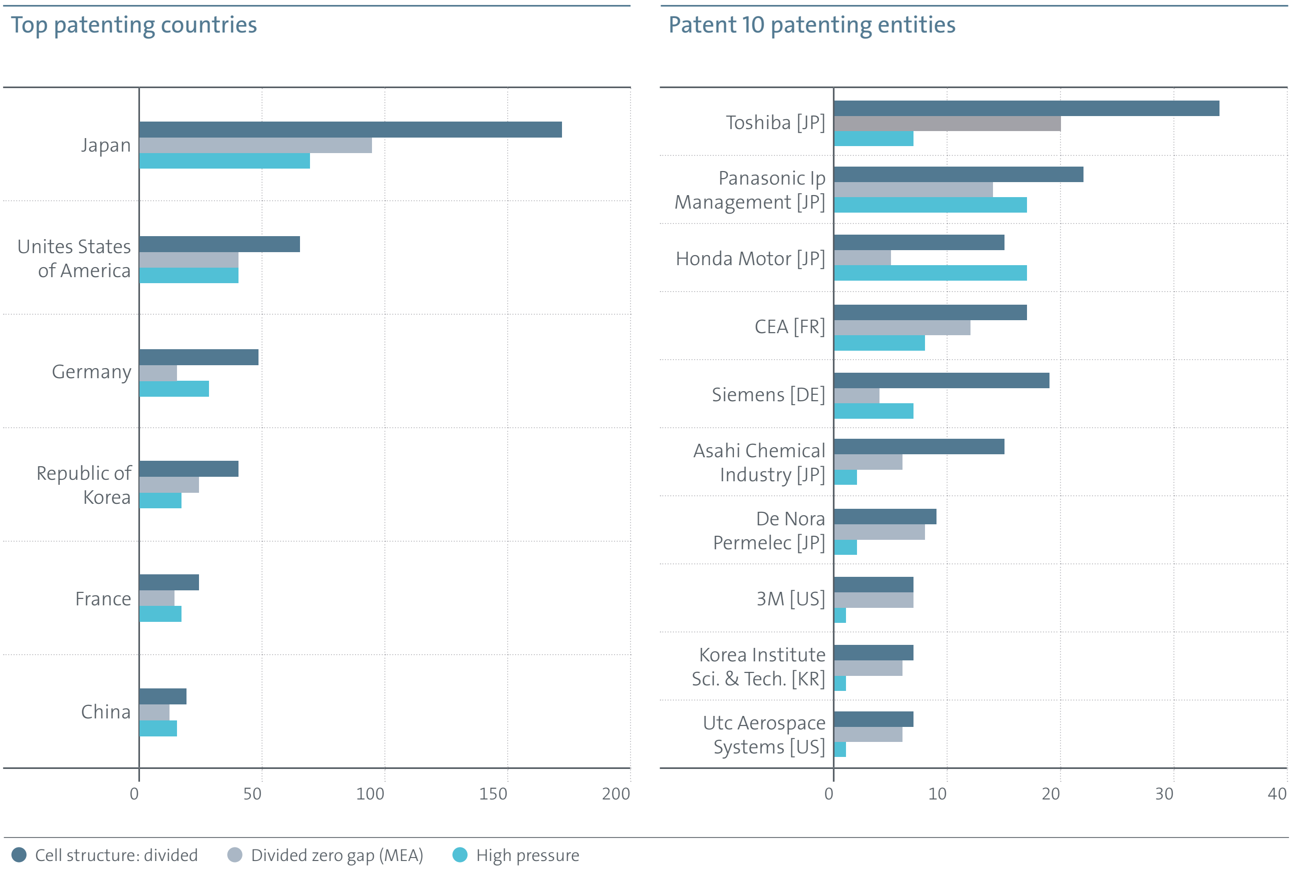


Figure 9: The left-hand side of this figure shows the 2016-2020 top countries for international patent families focusing on cell structure: divided, divided zero gap (MEA) and high pressure. The right-hand side shows the 2016-2020 top patenting entities for international patent families focusing on cell structure: divided, divided zero gap (MEA) and high pressure.

In the high pressure category (Figure 10) 25% of the applications were filed by the top 12 applicants. The total number of applicants filing in this area was about 600 from 2005 to 2020, which shows that research is dispersed, with many applicants only having one or a few patent families in their portfolio.

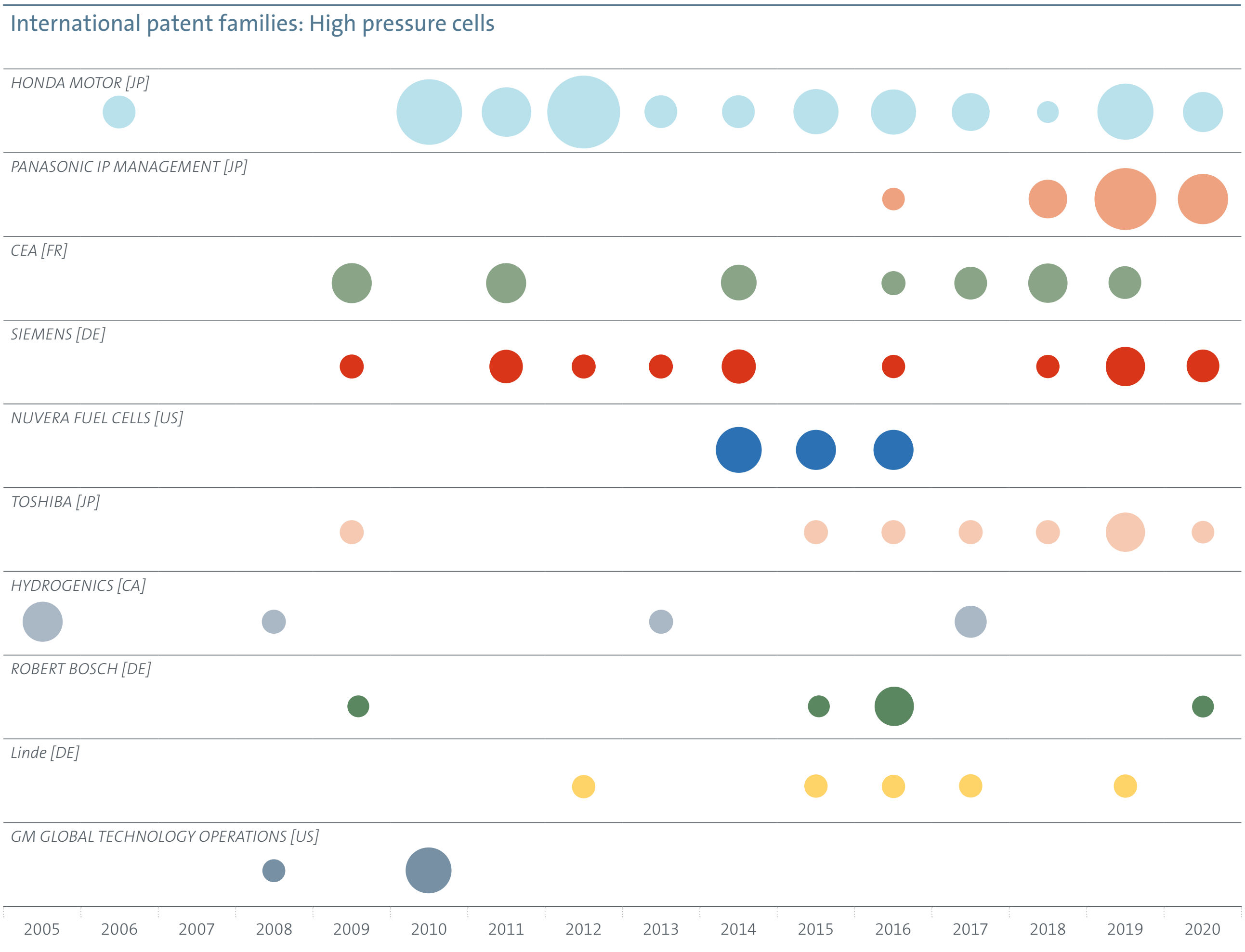


Figure 10: This figure shows the top 12 patent assignees in high pressure with the annual trend in the period between 2005 and 2020. The size of the bubble indicates the number of international patent families.

3.2.2. Electrocatalyst materials

One of the major barriers to reducing electrolyser costs is the use of scarce materials. Current material availability can supply only a fraction of the manufacturing capacity and new solutions are needed to reduce dependence on scarce materials. There is also a trade-off between using a new material for higher efficiency and catalyst robustness. In this section, we analyse the trends in electrocatalyst materials, categorised in patents related to noble metals (including oxides), non-noble metal alloys and ceramics, and organic, diamond and non-diamond materials.

It can be seen on the right-hand side of Figure 11 that between 2005 and 2020 international patents accounted for less than 50% of the total and only 21% of those related to non-noble metal alloys, ceramics (right-hand side of Figure 11). As in the other graphs, it can be seen that increases were steady and gradual without too many variations until around 2011. From 2011 onwards we see a sharp increase in technology using noble metals, followed closely by an increase in international patents covering non-noble metals, alloys and ceramics in 2015. 2020 patent publication figures show the non-noble metals and ceramics category overtaking the organic, diamond and non-diamond category (left-hand side of Figure 11).

Electrocatalysts material – International patent families

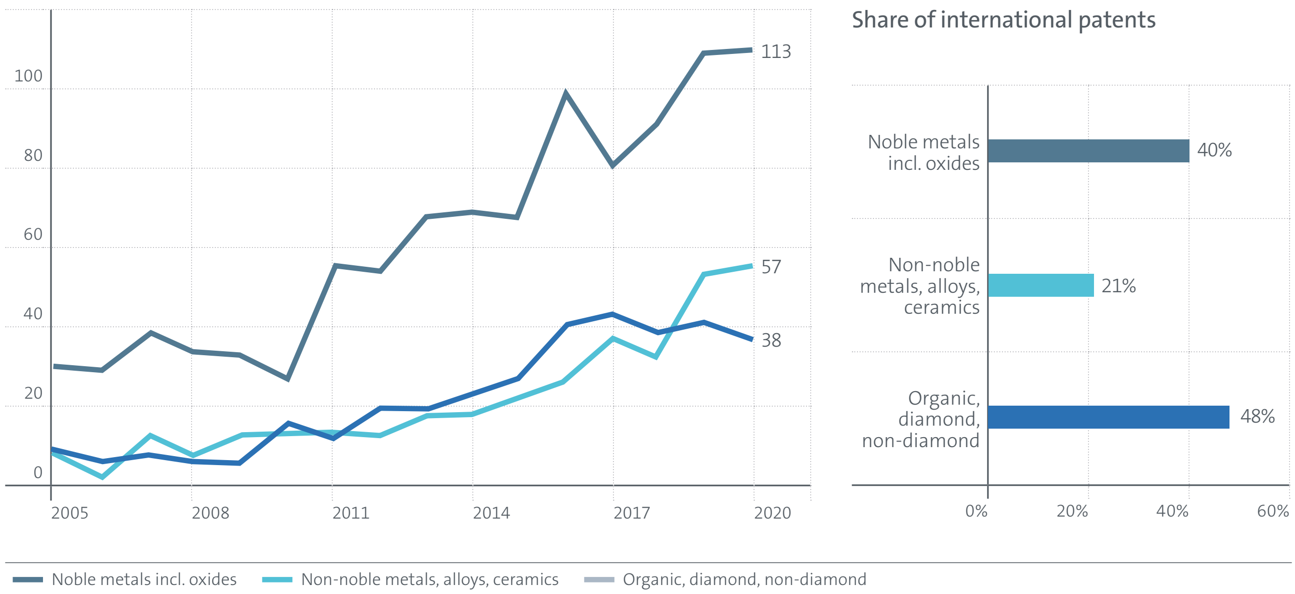


Figure 11: This figure shows the 2005-2020 trend of international patent families focusing on electrocatalyst materials: noble metals incl. oxides, non-noble metal, alloys, ceramics and organic, diamond, non-diamond. The average share of international patents of the total number of patents filed in the three categories between 2005 and 2020 is shown on the right-hand side.

Observations

Scarce materials are a major barrier to electrolyser cost and scale-up, and solution to replace such materials are needed, for example by using non-noble materials.

– Starting from 2011, there has been a sharp increase in international patents for technology using noble metals.
– From 2015, there has been a steady increase in international patents covering non-noble metals, alloys and ceramics, which may reduce materials costs.
– In 2020, non-noble metals and ceramics overtook the organic, diamond and non-diamond category in terms of the number of international patent filings per year.

Japan and the United States of America are the two most active countries focusing on electrocatalyst materials (Figure 12). On average the number of their international patent filings accounts for about 42% of the total across the three categories. Germany comes third in the categories noble metals incl. oxides and organic, diamond, non-diamond, and fourth in the category non-noble metal alloys, ceramics after the Republic of Korea. Italy, France and the United Kingdom also appear in the top 5, while China ranks fifth for non-noble metal alloys and ceramics.

Top 5 countries – International patent filing 2005-2020

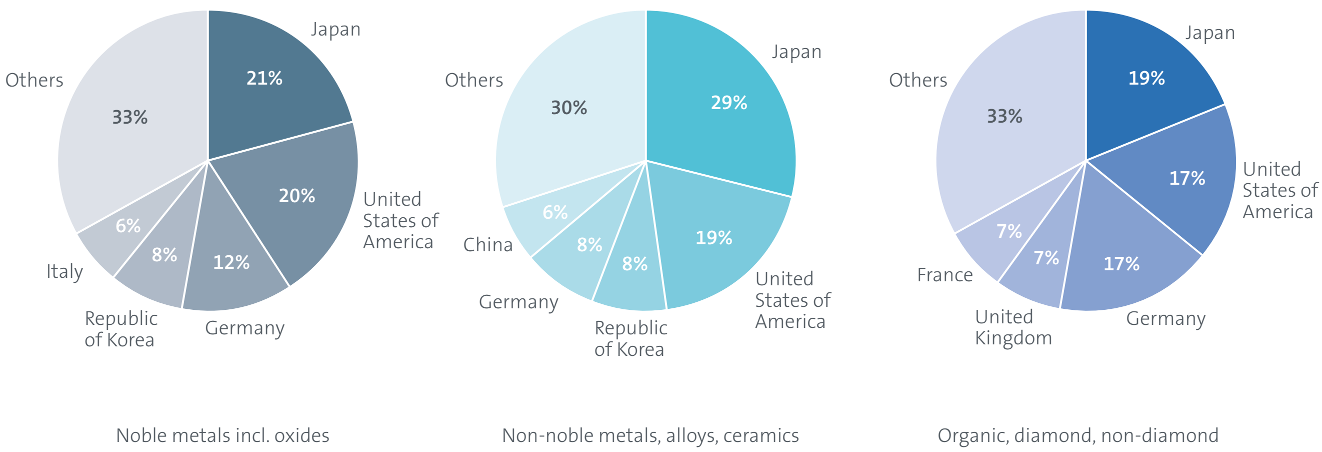


Figure 12: This figure shows the 2005-2020 top countries for international patent families focusing on electrocatalyst materials: noble metals incl. oxides (on the left-hand side), non-noble metals, alloys, ceramics (in the centre) and organic, diamond, non-diamond (on the right-hand side).

Figure 13 shows the top 15 patenting entities, which together account for about 23% of the total patenting activity related to electrocatalyst materials. The Italian company De Nora Elettrodi and the Japanese company De Nora Permelec are the two companies with the highest number of international patents. While De Nora Elettrodi leads the ranking in noble metals, De Nora Permelec leads the ranking in the organic, diamond and non-diamond category. The Japanese company Panasonic (and the IP subsidiary) leads for the highest number of international patent filings in non-noble metals. There are six Japanese companies, seven from Europe, and one each from the Republic of Korea (the Korea Institute of Science and Technology) and Saudi Arabia (the King Fahd University of Petroleum and Minerals) among the top 15.

Top 15 patenting entities – 2005-2020

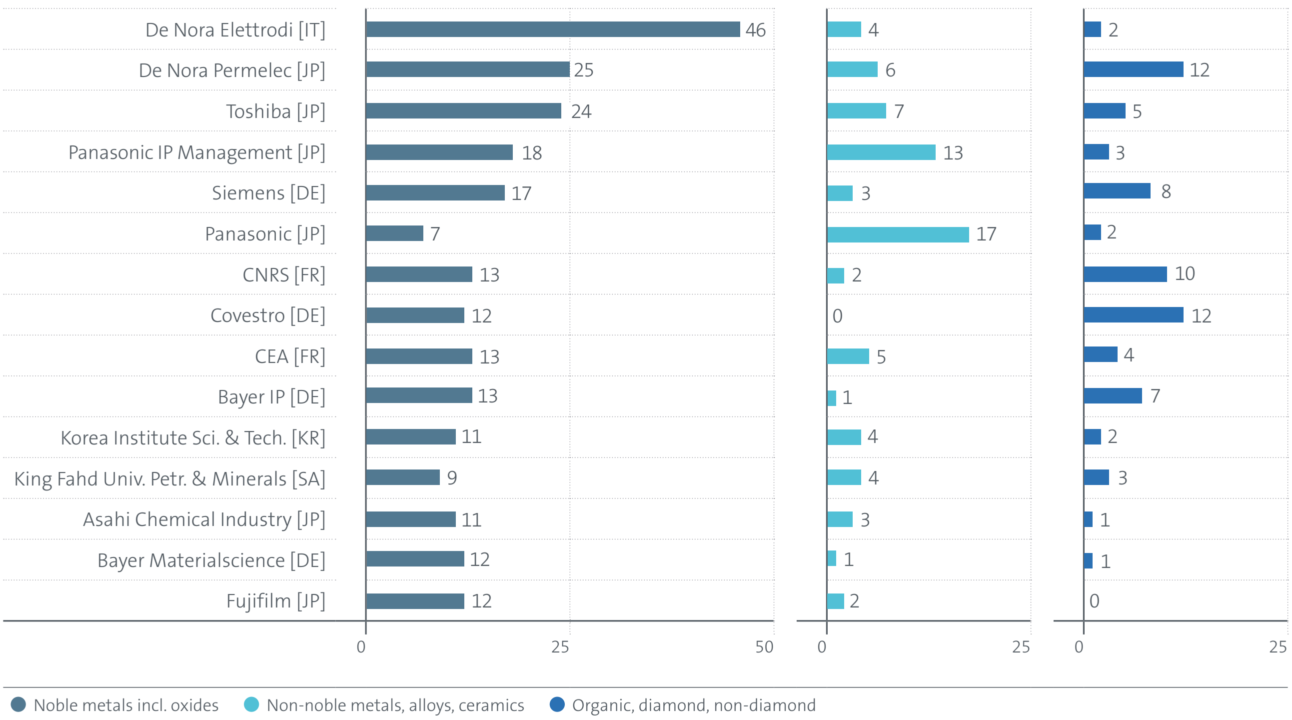


Figure 13: This figure shows the 2005-2020 top 15 patenting entities by total of their international patents focusing on noble metals incl. oxides (on the left-hand side), non-noble metal alloys, ceramics (in the centre) and organic, diamond, non-diamond (on the right-hand side).

BOX 5

Critical material challenge of PEM water electrolysis

According to IRENA's 1.5˚C scenario, hydrogen and derivatives will account for 12% of final energy use by 2050 and electrolyser capacity needs to grow to some 350 GW by 2030 to meet the clean hydrogen demand. [22] The largest European economies have started to announce their targets for the broader deployment of electrolyser technologies. [23] The European Commission's hydrogen strategy sets out a strategic objective of installing 40 GW of renewable hydrogen electrolyser capacity by 2030. France, Germany, Spain and Italy have country-specific targets for installed electrolyser capacity by 2030, varying between 5 and 10 GW. [24] Despite the high momentum in the market and ambitious targets for more electrolyser deployment, there are still major limitations hindering the development of the electrolyser market and creating uncertainty for the future.

PEM electrolysers offer several advantages over alkaline electrolysers, such as flexible operation, higher output pressure and small size, but are associated with higher investment costs and shorter lifetimes. [25] A high upfront cost driven by the use of precious materials is certainly one of the major barriers to the wider deployment of PEM electrolysers. For instance, bipolar plates constitute a significant part of the total cost at stack level due to the use of gold- or platinum-coated titanium material. [26] For the core of the stack, rare metals account for a significant part of the cost at cell level. Given that the anode side is subject to a high potential for oxidising (> 1.4 V), iridium – a scarce material – is used for longer durability under harsh operational conditions. For the cathode side, platinum is very often used, although other materials such as tantalum are emerging as promising alternatives.

On a system level, rare metals used in the cell represent less than 10% of the overall PEM electrolyser system cost. Nevertheless, these rare metals might represent a bottleneck for scaling up the deployment of PEM electrolysers, not because of their high cost but because of their limited availability in the supply chain. [27] Currently, primary platinum production is approximately 200 tons per year, with 20% more being obtained from the recycling of catalytic reformers in cars and electric equipment. In the light of such information, IRENA estimates that this can facilitate the deployment of 2 000 GW of electrolyser capacity in the next decade and 4 000 GW by the 2030s, considering an electrolyser lifetime of 10 years and full recycling of platinum from decommissioned stacks. In this regard, platinum does not represent a major supply chain bottleneck given that innovations are expected to reduce the platinum requirement of PEM electrolysers in the coming years. However, iridium use currently accounts for approximately 1-2.5 g/kW, while global iridium production is around 7-7.5 t/year. With today's technology, worldwide iridium production is only sufficient for 10-12 GW electrolysers/year. [28] IRENA estimates that this can support 30-75 GW of electrolyser capacity in the next decade. [29] In this regard, scarcity of precious metals can impede the accelerated deployment of PEM electrolysers and renewable hydrogen uptake. To prevent this, further innovations are needed to reduce the use of these critical materials and replace these rare metals with more common materials where possible.

22 IRENA (2022), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency, Abu Dhabi.

23 DERA (2022): Mineralische Rohstoffe für die Wasserelektrolyse. - DERA Themenheft: 26 S.; Berlin

24 Burgess (2021) Hydrogen fever in EU puts 2024 target of 6-GW electrolyzer capacity in reach

25 Gielen, D. (2021), Critical minerals for the energy transition, International Renewable Energy Agency, Abu Dhabi

26 A. Hermann, T. Chaudhuri and P. Spagnol, "Bipolar plates for PEM fuel cells: A review", International Journal of Hydrogen Energy 30(12), 2005, 1297-1302. dx.doi.org/10.1016/j.ijhydene.2005.04.016.

27 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

28 M. Garside, Demand for iridium worldwide from 2010 to 2019, Statista, 2019; statista.com/statistics/585840/demandfor-iridium-worldwide/ (accessed 31-03-2022).

29 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi.

3.2.3. Separators (diaphragms, membranes)

Separators are another key component of electrolysers, and innovation is needed in this area to increase efficiency and reduce costs. The trade-off between the structure of the membrane and its efficiency needs to be considered. The development and use of thicker membranes with stronger mechanical resistance has a positive effect on lifetime but, on the other hand, increases resistance to transport and therefore reduces efficiency. Similarly, during the production of hydrogen, for example, it is important to limit rapid degradation of the membrane, even if a longer use implies higher production, but also frequent replacement of membranes and related components. Gas permeation can also generate inefficiencies due to the creation of local hot spots. The use of polyphenylene sulphide fabric diaphragms may be a solution to increasing the lifetime, but it also reduces production efficiency since it may limit gas permeation. In this section we analyse inorganic (ceramic) and polymer (organic) separator membranes.

Figure 14 (left-hand side) shows the trend of international patent families focusing on separator membranes. The number of international families related to inorganic (ceramic) separator membranes remained at about the same level over the years analysed, apart from the period 2010-2014 when the number of international patents almost tripled, from 55 in 2010 to 136 in 2014. In contrast, the number of international patent families related to polymer (organic) membranes saw a rapid increase after 2010, ending in 2017 when the trend started to reverse. On average, in the period 2016-2020, international filings accounted for about 50% of the total patents filed in both the inorganic and polymer categories, while this share was 66% in the earlier period (2005-2015). Domestic patent filing, particularly in China, is the reason for this reduction in the share of international patents.

Separator membrane – International patent families

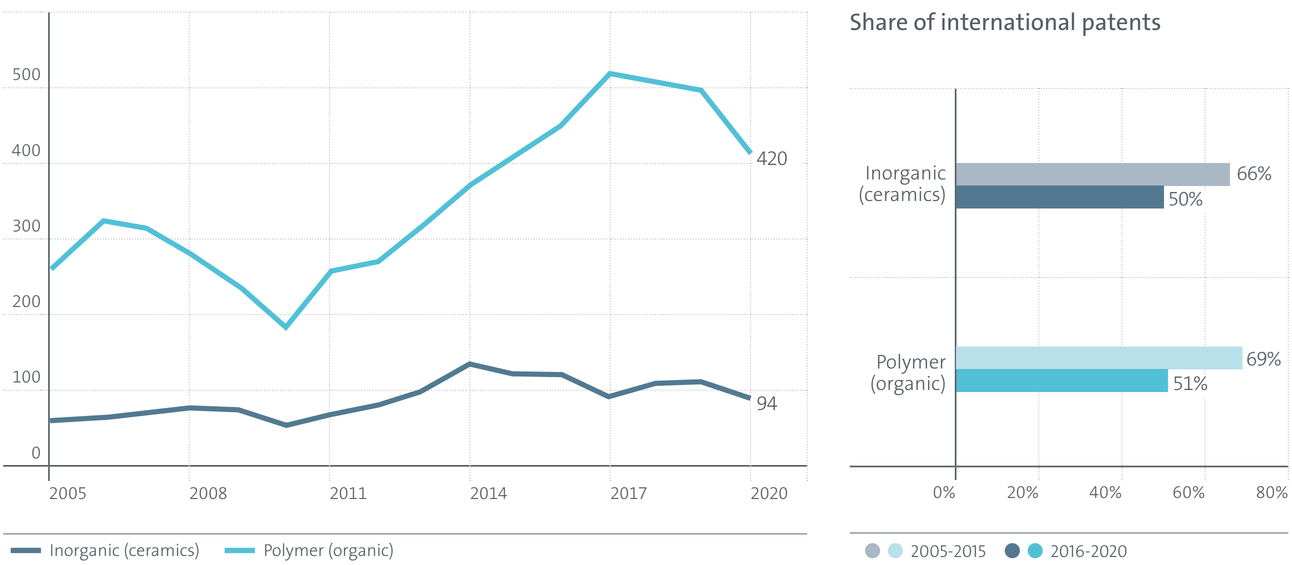


Figure 14: This figure shows the 2005-2020 trend of international patent families focusing on separator membranes: inorganic (ceramic) and polymer (organic). The average share of international patents of the total patents filed in 2005-2015 and in 2016-2020 is shown on the right-hand side.

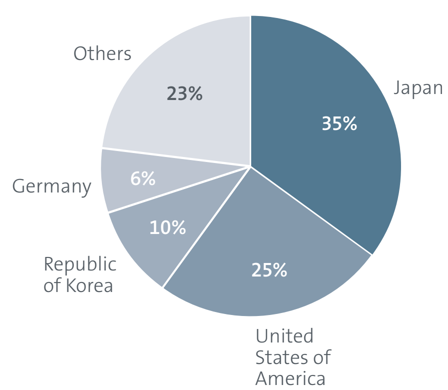
Observations

Reducing membrane thickness enables an increase in efficiency, which in turn enables a reduction in electricity consumption.

– International patents in polymer (organic) membranes (thinner) lead, showing a rapid increase after 2010 that lasted until 2017 when the trend started to reverse.

The pie chart on the left in Figure 15 shows that Japan, the United States of America, the Republic of Korea and Germany are the top countries with the highest number of international patent filings on the subject of inorganic separator membranes, and together they account for about 77% of the total patenting activity in the period 2005-2020. Japan alone accounts for about 37% of the total international inventions in the polymer (organic) separator membranes category (see Figure 15, right-hand side). Combined with the contribution of the next three countries (United States of America, Republic of Korea and Germany), the top countries owned about 81% of the total inventions from 2005 to 2020. The trend of polymer (organic) patents analysed in Figure 14 above is linked to the activity of Japan. In the period 2011-2017, Japan developed about 142 new patents a year on average, with a 14% annual increase. However, between 2018 and 2020 this activity decreased in Japan, while in other countries it increased: the average annual production of international patents increased by 45%, 76% and 67% in the United States of America, the Republic of Korea and Germany respectively.

Top 10 countries – Inorganic 2005-2020



Top 10 countries – Polymer

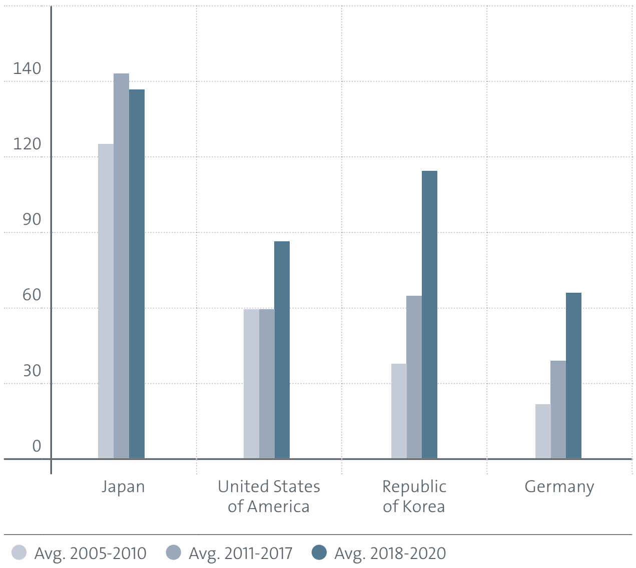
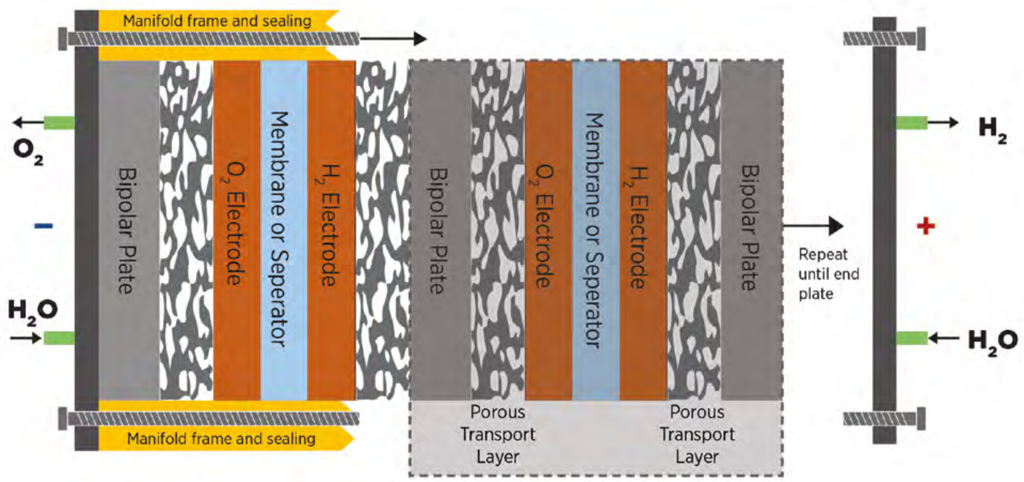


Figure 15: This figure shows the top countries for international patent families focusing on separator membranes. It shows the top countries for inorganic (ceramic) separator membranes on the left-hand side and the top countries for polymer (organic) separator membranes on the right-hand side.

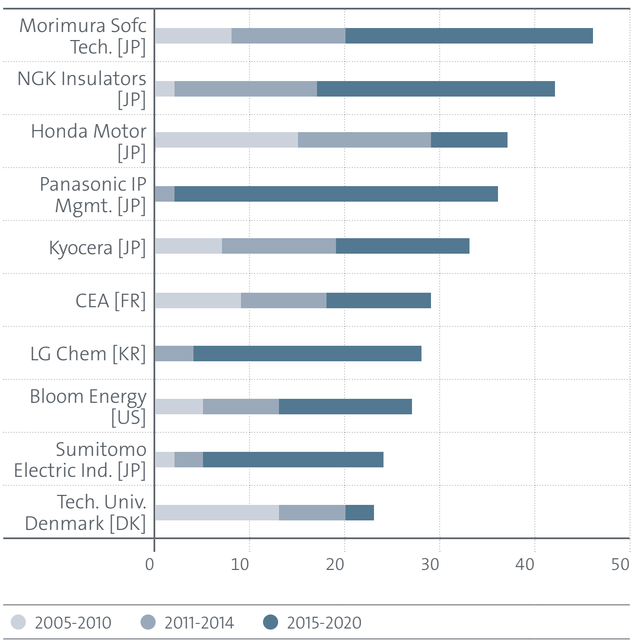


Source: IRENA_Green_hydrogen_cost_2020.pdf

In the 2005-2020 period, five Japanese companies were at the top of the ranking for international patent filings for separators with inorganic (ceramic) membranes (Figure 16, left-hand side). Most international patents in this category were developed in the period 2015-2020. For example, 57% of international patents by the top-ranking company, Morimura SOFC Technology Co., were filed in this period, as well as 60% by NGK Insulators.

The presence of Japanese companies among the top 10 entities filing international patents for separators with polymer (organic) membranes is much lower than in the previous category. Figure 16 (right-hand side) shows four Japanese companies and four from the Republic of Korea among the top 10, plus one from the United States of America (GM) and another from Germany (Robert Bosch). In this category, most of the top patenting entities are from the automotive sector, indicating this sector's focus on polymer (organic) membranes.

Top 10 enity – Inorganic



Top 10 enity – Polymer

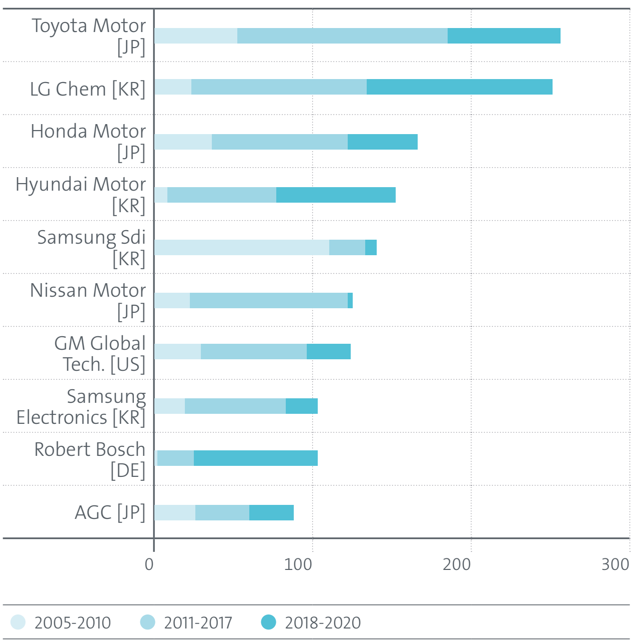


Figure 16: This figure shows the 2005-2020 top 10 international patenting entities for inorganic (ceramic) separator membranes on the left-hand side, and polymer (organic) separator membranes on the right-hand side.

3.2.4. Stackability of electrolysers (stacks)

In electrolysers, a stack consists of multiple cells connected in series and other components such as spacers between electrodes, end plates to contain fluids and mechanical supports (i.e. frames and seals). The stack accounts for about 45% of the total cost of the electrolysers, and a cost reduction can be achieved by scaling up production and via standardisation. As for other components analysed in previous sections, new innovations are needed to increase performance and durability, taking into consideration the costs and benefits of having increased operating hours but faster degradation, since more current flows through the stack. This section analyses patenting trends in the stackability of electrolysers (stacks), divided into four categories: stacks with bipolar elements – electrodes, stacks with bipolar elements – plates, stack types without bipolar elements and stack types with membranes.

In all four categories, the share of international patents is very high: bipolar elements – electrodes, bipolar elements – plates and stack types with membranes account for 80%. The share of international patents for the category stack types without bipolar elements is 60%. This is also the most prominent category of the four in the area related to stack technology used in electrolysers. Membrane technology is continuing its upward trend, but the number of filings is modest.

In technologies involving electrode-diaphragm assemblies, filter-press type assemblies without bipolar elements constitute the majority of the patents being filed, with a trend that is still increasing (Figure 17). Over the past 15 years, there was a near tenfold increase in applications being filed followed by a decline in 2019 and 2020. The trend for stacks can be split into four major periods: 2005-2011 when the number of patent filings was almost stable, 2012-2014 when the first period of increase is noticeable (in 2014 the number of annual filings tripled compared with 2012), 2015-2018 when a new increase is visible after a steady year in 2015 (in 2018 the number of patents was double that in 2016) and 2019-2020 when the number of new filings appeared to start decreasing. This final reduction in patent filings may be explained by the fact that the advantages of compactness/space-saving and high space-time yield of this technology have already reached an optimum.

Source: DQ1000 ©John Cockerill Renewables

Stackability of electrolysers – International patent families

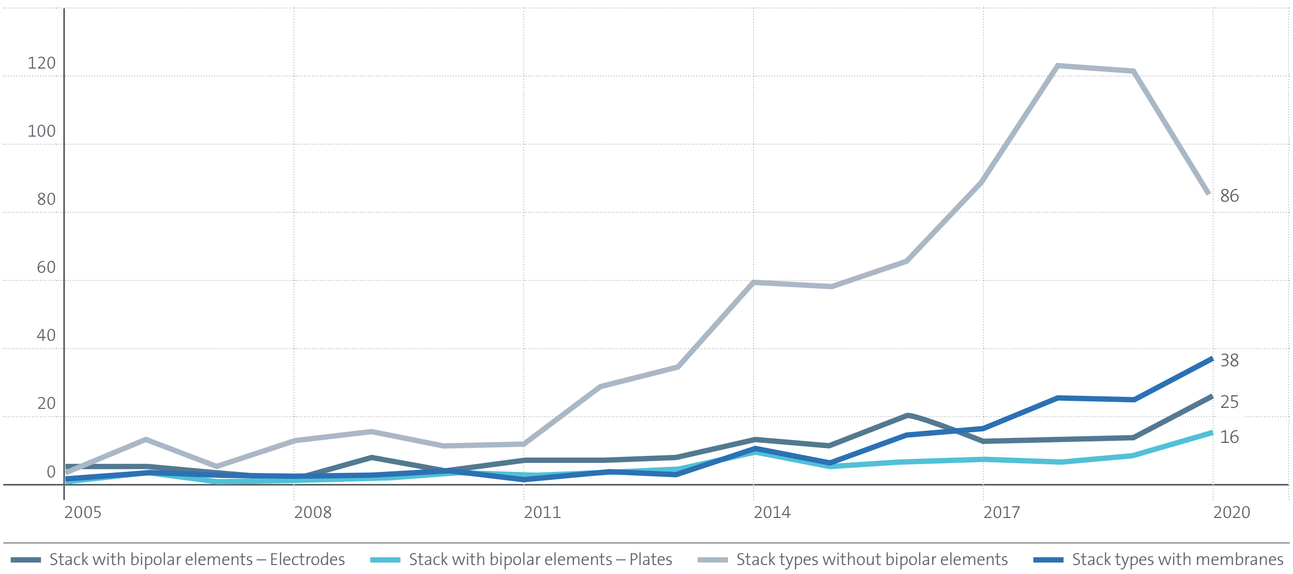


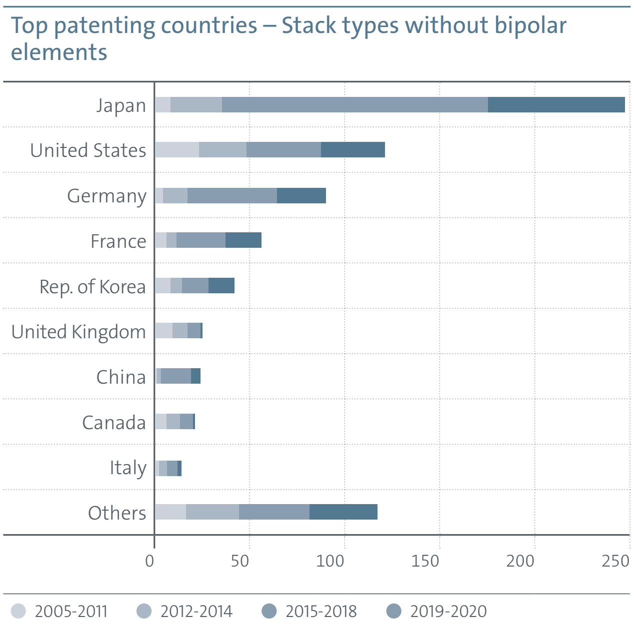
Figure 17: This figure shows the 2005-2020 trend of international patent families focusing on stackability of electrolysers (stacks): stack with bipolar elements – electrodes, stack with bipolar elements – plates, stack types without bipolar elements and stack types with membranes.

Observations
Increasing stack production to automated production in GW scale manufacturing facilities can achieve a step-change cost reduction by economies of scale:

- 2005-2011: the number of patent filings is almost stable;
- 2012-2014: the first rising period is noticed (in 2014 the number of annual filings tripled compared to 2012);
- 2015-2018: a new increase is visible after a steady year in 2015 (in 2018 the number of patents doubled that in 2016);
- 2019-2020: the number of new filings seemed to start decreasing. This final reduction in patent filings may be explained by the fact that the advantages of compactness/space-saving and high space-time yield of this technology have already reached an optimum.

Between 2005 and 2011, the United States of America led in the number of international patent filings in stack types without bipolar elements and singlehandedly accounted for 28% of the total number of patent filings (Figure 18 on the left-hand side). The United Kingdom was second, accounting for 11% of the total. During the first period of increase (2012-2014), Japan emerged as the top-ranking country (22% of the total in this period), followed by the United States of America (20%). In 2014, therefore, the United States of America had already developed 40% of its total international patents in the stack type category, while Japan had only 14%. Interestingly, the United Kingdom, third in the ranks in terms of the sum of all of its patent filings up to 2014, had already developed 68% of its total, meaning that its contribution to this category stopped in more recent years. In the following period, from 2015 to 2018, Japan drove the increase in the number of patent filings relating to stack types without bipolar elements. It singlehandedly accounted for 41% of the patents in this period, and 57% of its total patents in this category. Japan registered an average annual increase of 50% in this period, while the United States of America had an increase of only 11%. In the period 2015-2018, the second highest-contributing country was Germany, registering an average annual increase of 63%, and 52% of its total international patents in the stack type category. Germany and Japan reduced the number of new patent filings in 2019 by 9% and 29% respectively compared with 2018, determining the decreasing trends. In contrast, France and the Republic of Korea filed more patents in 2019 compared with 2018 and developed about 34% of all of their inventions between 2019 and 2020.

Figure 18 on the right-hand side shows the top patent jurisdictions where patents on stack type technology are filed. The ranking follows the same trend we saw for patents filed by country, with Japan and the United States of America taking the lead. What is interesting to note is that in China about 73% of the total inventions are protected in the period from 2015 to 2018, the fifth most targeted national jurisdiction after Japan, the United States of America, Germany and France.



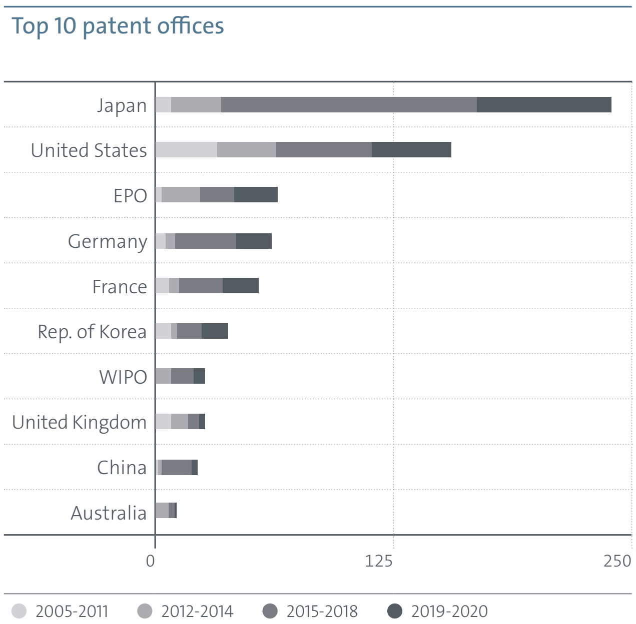


Figure 18: This figure shows the total number of patent families in stackability of electrolysers (stacks) focusing on stack type. The top countries are shown on the left-hand side and the top 10 patent jurisdictions based on the first priority country in the family are shown on the right-hand side.

Among the top 20 patenting entities in stack technology (Figure 19), only three had at least one patent filed between 2005 and 2011: the French Alternative Energies and Atomic Energy Commission (CEA) and the Japanese Honda Motor and Chlorine Engineers. The first rising trend in the 2012-2014 period is a result of higher interest in the stackability of electrolysers, involving more players. The number of patenting entities increased from 55 in the period 2005-2011 to 87 in the period 2012-2014, many of whom had not previously been active. Together with the CEA, the German company Siemens registered the highest number of new patents. The period from 2015 to 2018 is when the stack type category shows its largest increase in the number of international patents. In this period, Japanese companies took the lead in developing new patents: 8 of the top 10 patent entities were from Japan and they averaged about 10 international filings each. Toshiba ranked first with 28 international patents, followed by the CEA (with 18) and Asahi Chemical Industry (with 12). In the last two years analysed, 2019 and 2020, Japanese companies reduced their number of new patents, indicating a lower focus on this category of stack for electrolysers. Interestingly, four Japanese companies that were active in the previous period (2015-2018) did not file any patents between 2019 and 2020. In contrast, European companies remained active in these last years, or became active for the first time, as was the case with the Danish company Hymeth, which entered the top 20 due only to its recent activity.

Top 20 patenting entities – Stack types without bipolar elements

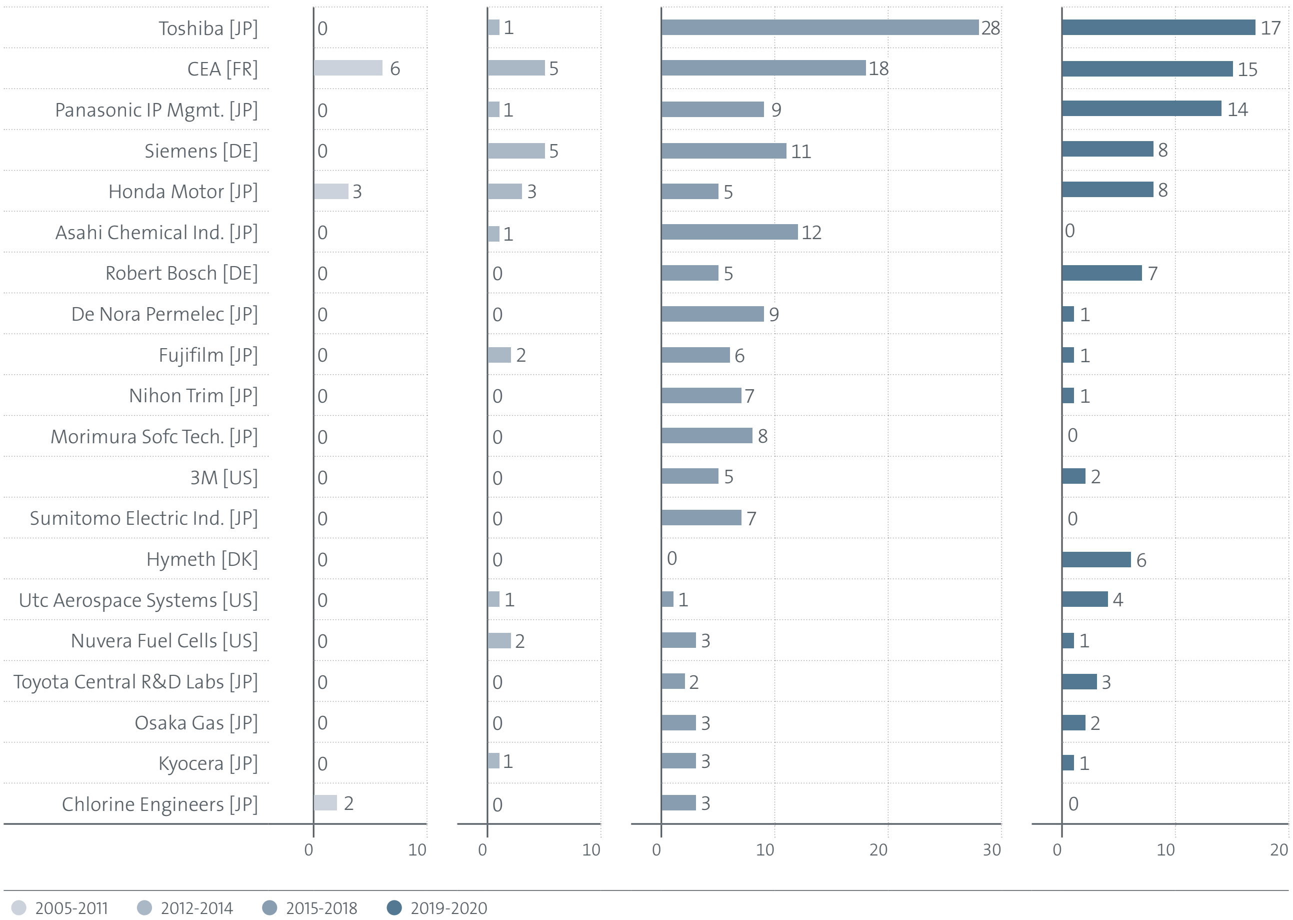
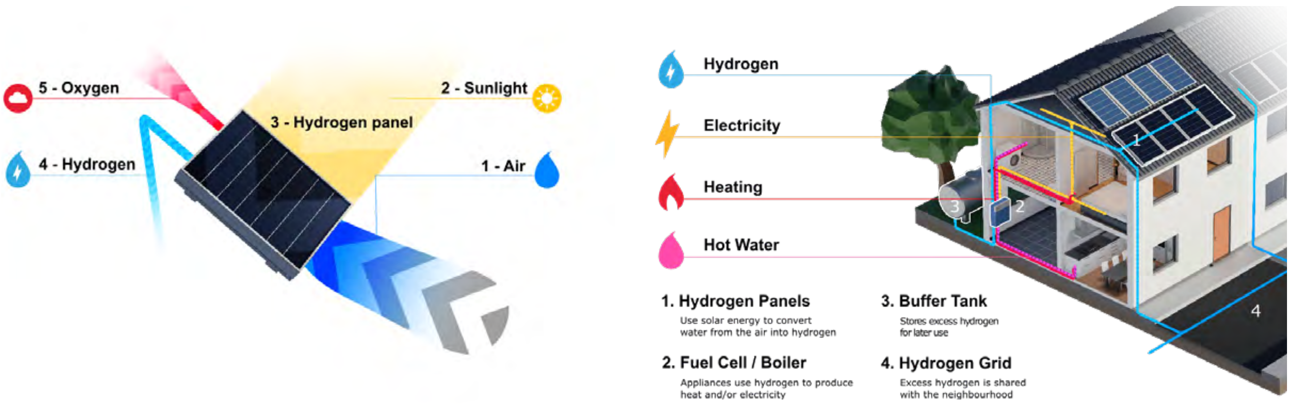


Figure 19: This figure shows the top 20 patent assignees in stackability of electrolysers (stacks) focusing on four periods: 2005-2011, 2012-2014, 2015-2018 and 2019-2020.

3.2.5. Photoelectrolysis



Source: ©Solhyd https://solhyd.org/en/technology/

Water photoelectrolysis, using semiconductor photoelectrodes, is a sustainable and clean approach to the production of hydrogen. Sunlight is used as the energy source to split water in a photoelectrochemical cell. This process of electrolysis of water produces dihydrogen which in turn can be stored, used to produce electricity or even delivered to fuel cells to generate electricity and heat. It can also be used in a combined-cycle gas turbine to produce larger quantities of centrally produced electricity or burned to run a combustion engine.

Three different areas have been identified: photoelectrolysis using a photovoltaic solar panel, photoelectrolysis using a photoelectrode with a photoabsorber and photoelectrolysis with a photoelectrocatalyst. In terms of the pure number of patent filings, the photoelectrolysis area is still quite a niche area, accounting for 6.5% of all water electrolysis patents. However, 37% (on average across the three categories) are international patent families, which underscores the importance the applicants place on protecting their inventions outside the domestic market. In Figure 20 a major jump can be observed in the number of patent filings from 2015 to 2017, particularly in the category of photoelectrolysis with PV power source.

Photoelectrolysis – International patent families

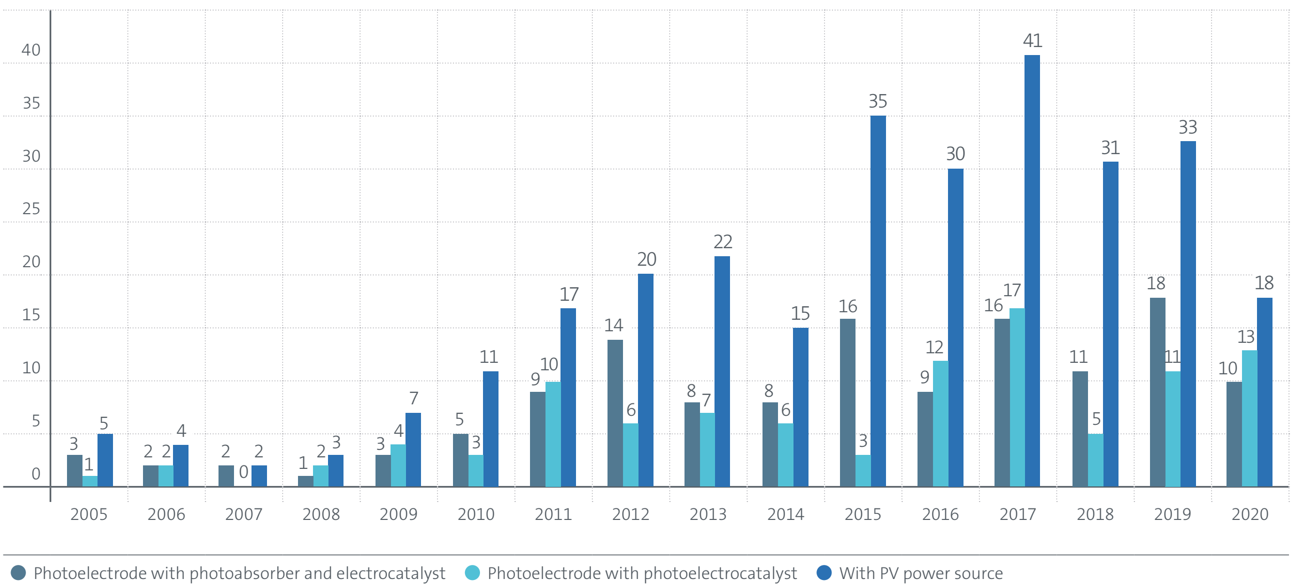


Figure 20: This figure shows the 2005-2020 trend of international patent families focusing on photoelectrolysis: photoelectrode with photoabsorber and electrocatalyst, photoelectrode with photoelectrocatalyst and with PV power source.

Observations

Photoelectrolysis may make electrolysers more cost-competitive than being supplied by fossil-based electricity.

– A major jump in the number of patent filings for photoelectrolysis was observed from 2015 to 2017, particularly in the category of photoelectrolysis with PV power source.

Japan and the United States of America have been active in the three categories of photoelectrolysis since the period 2005-2014 (Figure 21). These two countries accounted for about 40% and 16% respectively on average across these categories. While 67% of the total international patent filings from the United States of America were developed mainly between 2005 and 2014, 63% of patent filings from Japan were filed later, between 2015 and 2020. Apart from the two frontrunners, other countries were also active in photoelectrolysis. Interestingly, countries like Saudi Arabia, the Netherlands and China have only had international patents in more recent years, from 2015 to 2020. Saudi Arabia ranked third in photoelectrolysis, focusing on the categories of photoelectrode with photoabsorber and electrocatalyst, and with PV power source, while the Netherlands ranked third for photoelectrolysis, focusing on the category of photoelectrode with photoelectrocatalyst.

Top 10 patenting countries – Photoelectrolysis

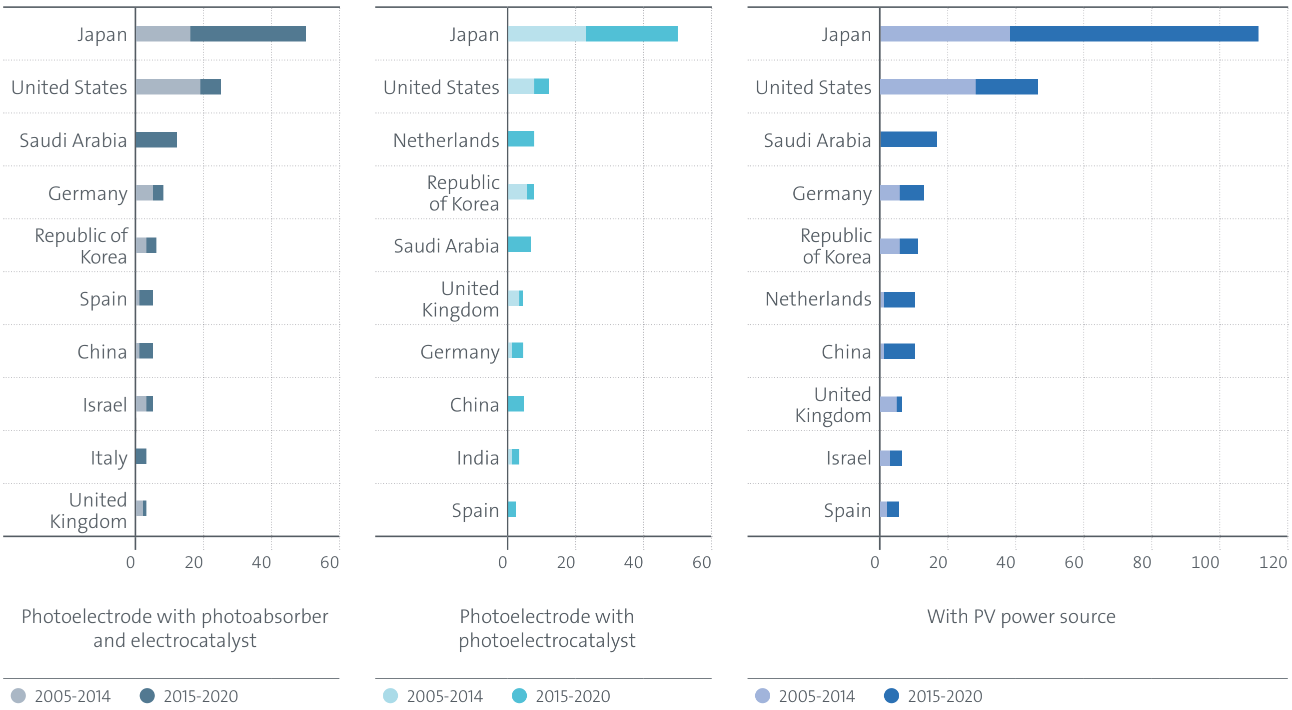


Figure 21: This figure shows the top 10 countries for international patent families focusing on photoelectrolysis: photoelectrode with photoabsorber and electrocatalyst (on the left-hand side), photoelectrode with photoelectrocatalyst (in the centre) and with PV power source (on the right-hand side)

As with previous technology areas and categories, Japanese companies led the ranking for number of international filings (Figure 22). Toshiba, the most active in the categories of photoelectrode with photoabsorber and electrocatalyst, and with PV power source, saw very little activity in the second category (photoelectrode with photoelectrocatalyst). It is interesting to note that two Saudi Arabian universities were active in this field of photoelectrolysis, namely the King Fahd University of Petroleum & Minerals and the King Abdullah University of Science and Technology. It is also noticeable that while 50% of all the filings were prepared by universities, only three universities from the United States of America were in the top 15 and no companies were present there.

As regards European patenting entities, only two companies were present in the top 15 list: the Dutch company Sabic Global and the German company Evonik Degussa. Sabic Global ranked third in the category related to photoelectrode with photoelectrocatalyst and was also active in the category with PV power source, while Evonik Degussa was active only in the categories photoelectrode with photoabsorber and electrocatalyst and with PV power source.

Top 15 patenting entities

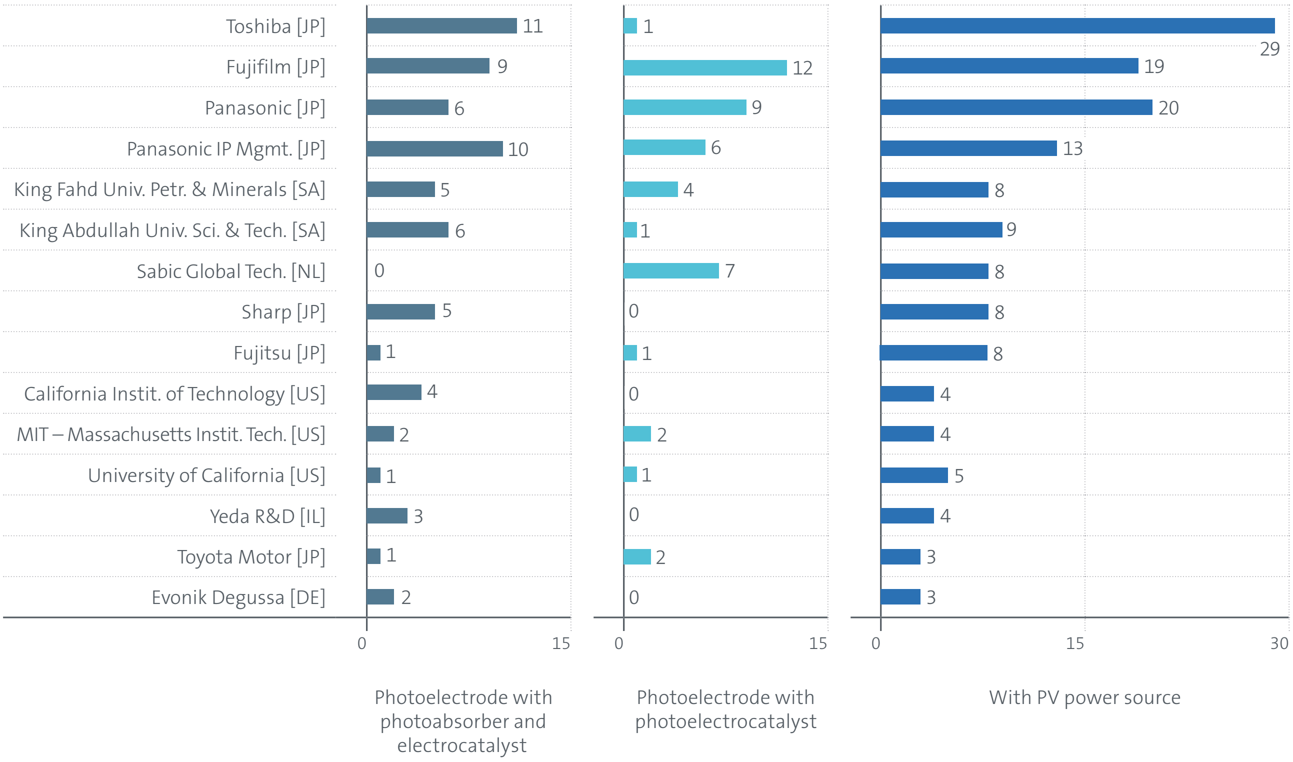
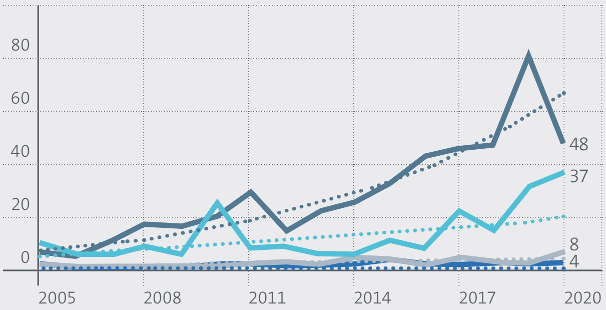


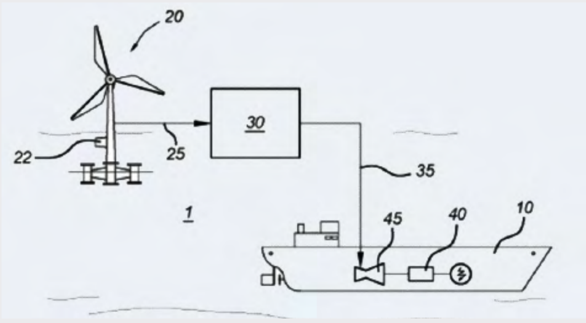
Figure 22: This figure shows the 2005-2020 top 15 patenting entities by total of international patents focusing on photoelectrode with photoabsorber and electrocatalyst (on the left-hand side), photoelectrode with photoelectrocatalyst (in the centre) and with PV power source (on the right-hand side).

BOX 6

Green hydrogen (wind, water or sun)

Electrolysers using a variety of renewable energy resources





Source: EP3831981

Placing electrolyser modules suitable for offshore operations close to (or on) offshore wind turbines is a technology currently being explored by several pilot projects. A direct electrical connection to the (direct current) link in the wind turbine and an abundance of water supply seems like an ideal match. Such an idea may represent a better design concept for bulk hydrogen production as opposed to remotely located electrolysers on shore, away from the wind turbine generator, for example. This presents an opportunity to reduce overall costs and energy losses, as hydrogen pipes cost less per km than power cables. The efficiency of such a system shows the potential to define new standards by removing the need for AC rectification. Offshore-produced hydrogen also has the potential to address the environmental target of creating a zero-emission offshore fleet. Wind farms could become hydrogen refuelling stations for vessels. The number of patent families specifically combining hydrogen production and offshore wind energy is about 80. Most of the patent applications are filed by applicants from China, Japan and the Republic of Korea.

Patent	Applicant	Title
KR20100099590	Samsung Heavy Industries [KR]	A plant for producing hydrogen using offshore wind power generator
KR20190010887	Samsung Heavy Industries [KR]	An offshore plant for producing hydrogen
WO2006CA01447	Burtch, John Christopher [CA]	Apparatus for production of hydrogen gas using wind and wave action
JP20000255160	Mitsubishi Heavy Ind. [JP]	Aquatic wind force power generation facility for hydrogen production
KR20190053138	University Of Ulsan [KR]	Hydrogen generation system using seawater and renewable energy
KR20100088494	Hyundai Heavy Ind. Comp. [KR]	Hydrogen generator for offshore wind turbine
WO2006JP300914	Kubo, Masaharu [JP]	Hydrogen producing, storing, transporting, power converting device and method
EP20180723779	Siemens [DE]	Hydrogen production system
JP20030060593	IHI Corp. [JP]	Hydrogen-producing facility using wind-power generation
WO2006US35992	Nicholson, David, Wayne [US]	Maritime hydrogen generation system
WO2017SE50150	Ecomb Ab (Publ) [SE]	Method of oxygenating water and producing hydrogen
CN201911403370	Shenzhen Xima Tech. Comp. [CN]	Offshore floating type hydrogen production and storage system
EP20190213940	Single Buoy Moorings [CH]	Offshore production facility arrangement
CN202010959819	Zhejiang University [CN]	Seawater hydrogen production conveying system and method based on existing offshore wind plant
US201313849308	Borden, Robert M. [CA]	Structure and method for capturing and converting wind energy at sea
WO2016ES70150	Bound4Blue [ES]	System for the production of hydrogen from sea water
US20070936011	Devine, Timothy J. [US]	Systems and methods for producing, shipping, distributing, and storing hydrogen
CN202010274156	Univ. of Sci. & Tech. Beijing [CN]	Underground oil-gas reservoir hydrogen storage system for hydrogen production from offshore wind power and regulating and controlling calculation method
KR20080107862	Korea Aerospace Res. Ins. [KR]	Vessel for producing fuel of hydrocarbon

BOX 7

Key patents

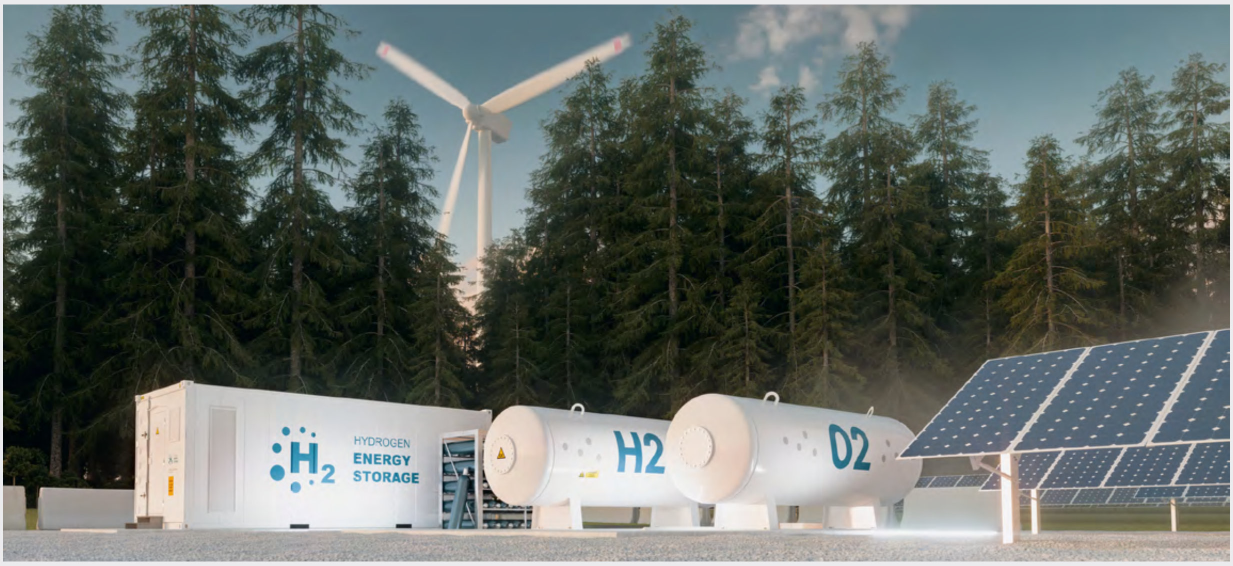
Forward citations indicate that the technology is being referred to or used by more recent patent applications.

Patent – Top 10 Forward Citation		Applicant	Publ. Year	Total
EP1716272	Method and apparatus for hydrogen generation	GM [US]	2006	129
EP2132820	Electrochemical system, apparatus, and method to generate renewable hydrogen and sequester carbon dioxide	New Sky Energy [US]	2009	123
EP2167706	Electrolysis of carbon dioxide in aqueous media to carbon monoxide and hydrogen for production of methanol	Uni South California [US]	2010	109
EP2702623	H2O-based - based electrochemical hydrogen - catalyst power system	Blacklight Power [US]	2014	103
EP1938406	Electrochemical cell for the production of synthesis gas using atmospheric air and water	Ceramatec [US]	2008	91
EP2334590	Energy supply system and operating method	ZSW [DE]	2011	90
EP1975279	Apparatus for renewable hydrogen fuel generation by electrolysis using combined solar and grid power	GM [US]	2008	74
US8405242	Wind power system	Polestar [CA]	2013	74
EP2895642	Process using high surface area electrodes for the electrochemical reduction of carbon dioxide	Avantium [NL]	2015	64
EP2419553	Method for producing solid carbon by reducing carbon oxides	Seerstone [US]	2012	57

The size of the family indicates the willingness of the applicant to expend resources (costs)

Patent – Top 10 Family Size		Applicant	Publ. Year	Total
EP3027789	Modular electrochemical cells	AquaHydrex [AU]	2016	47
EP3173509	Electrochemical systems and methods using metal oxidation	Calera [US]	2017	28
EP3018103	A gas generator comprising a water tank and an electrolysis device	Lin [CN]	2016	27
EP2162140	Highly stable electrolytic water with reduced nmr half line width	Akuatech [IT]	2010	27
EP2681792	Energy unit with safe and stable hydrogen storage	CNicolas Kernene [US]	2014	27
EP3322777	Device and method for producing synthetic gas	Engie [FR]	2018	25
EP2419553	Method for producing solid carbon by reducing carbon oxides	Seerstone [US]	2012	24
EP2861784	Electrolytic cell equipped with concentric electrode pairs	De Nora Elettrodi [IT]	2015	24
EP3615713	Method for operating a water electrolysis device	Hoeller Electrolyzer [DE]	2020	24
EP2702623	H20 - based electrochemical hydrogen - catalyst power system	Blacklight Power [US]	2014	23

Note: Key patents are related to hydrogen production processes based on water and the family has a "granted" member (this negatively biases more recent applications as they might still be pending but it is also less probable that a very recent patent is a key patent). Furthermore, we have only considered patent families with at least one "live" member and the patent family must be international.



4. Conclusion

Water electrolysis is an enabling chemical process that can make hydrogen technology play a crucial role in global energy transition. Thanks to hydrogen technology, several energy-intensive industries and sectors can be decarbonised, especially if hydrogen production is powered by renewable energy sources. From this perspective, electrolysers have become the key component in empowering the shift toward a hydrogen-based energy system. This report has analysed patent trends and statistics in electrolysers, digging into key parts and components that are receiving higher attention.

In 2016, patenting activity related to water electrolysis surpassed the activity related to liquid hydrocarbon feedstocks (mostly coal- and oil-based sources), which is reducing over time. This follows national and international strategies, where a global consensus exists on the necessity to spur technological development in the field of water electrolysis. Countries such as Japan, the United States, Germany, France and China are frontrunners in such an effort, boosted by R&D activity in companies, universities and research institutions.

Five patenting trends are emerging in key areas where technological innovation is needed to enhance the efficiency of electrolysers and reduce costs. Firstly, great attention is being paid to the search for optimal operation conditions and electrolyser structure to increase the efficient production of hydrogen. Secondly, the surge in patents related to non-noble metal electrocatalysts indicates that R&D is moving towards finding new solutions and aims to mitigate the effect of material scarcity. Thirdly, in searching for a simultaneous increase in technological performance and durability, patenting activity is moving towards polymer (organic) separator membranes. Generally speaking, about 5% of the patent filings make explicit reference to increased durability or a longer service life.[30] Fourthly, in order to scale up the efficient and economic production of hydrogen, there is increased patenting activity with regard to the stackability of electrolysers without bipolar elements and, more recently, with membranes. Lastly, photoelectrolysis is the emerging patenting area where many universities worldwide are focusing on the development of new inventions to split water using (sun)light as the energy source.

The great momentum observed in electrolysers is expected to continue and to spur future innovation. In fact, the rising trend in patent filings signals that more will come soon, addressing the urgent need for new solutions to lower the cost of electrolysers in parallel with raising technological efficiency and production capacity. Innovation in the field of electrolysers is a widely recognised strategy for making the production of hydrogen cost-competitive with other technologies and as green as possible, thus helping to tackle challenges such as decarbonisation and accelerating energy transition.

30 Espacenet link to patents specifically referring to technology for prolonging the service life of electrodes, membranes etc.

Glossary and notes

AC	Alternating current: current which periodically reverses direction and changes its magnitude continuously over time.
Alkaline electrolyser	Electrolyser characterised by having two electrodes operating in a solution composed of water and liquid electrolyte.
Anode	The terminal or electrode from which electrons leave a system. Typically oxygen (O2) will be formed on the anode part in an electrolyser.
Applicant	A person (natural person) or an organisation (i.e. legal entity, company) that has filed a patent application. There may be more than one applicant per application.
Assignee	The person or company owning the patent or patent application. Usually used in relation to US patent applications. Synonym for "applicant".
Bipolar plate	BPP: used to separate single cells in an electrolyser stack. Conducts heat and current between single cells in a stack and distributes reacting agents within the electrolyser.
CEA	Commissariat à l'énergie atomique et aux énergies alternatives: the French Alternative Energies and Atomic Energy Commission.
Citation (in a patent)	Mainly used to describe a reference within a patent search report that documents the prior art relevant to the claims.
Classification (CPC, IPC, F-term, FI)	CPC or IPC classifications: classification scheme or system of codes that groups inventions according to technical area. Often used in patent analytics to create uniform patent samples.
Co-applicant	Used when more than one applicant is listed on a patent application.
Decarbonisation	Increasing the share of low-carbon energy sources, particularly renewable energy sources such as wind and sun.
Electrocatalyst	Materials (such as at the surface of electrodes) that facilitate electrolysis processes. In electrolysers, these are often noble metals or oxides.
Espacenet	Free service from the EPO for searching patents and patent applications. Includes more than 130 million documents.
IEA	The International Energy Agency.
International patent family	IPF: patents that have more than one country in the list of publications, assignees, inventors or first priority countries. Using this concept excludes single national filings that have no family members.
Invention	Practical embodiment which involves, requires or produces a technical effect.
Inventor	A person designated as an inventor in a patent application. An inventor can also be an applicant. An inventor is always a natural person. There may be more than one inventor per application.
Jurisdiction	A country or countries (territory) for which a patent may be granted by the corresponding intellectual property office.
MEA	Membrane electrode assemblies.
Noble metal	Most patents which make reference to noble metals in the claims will list all noble metals to ensure as wide a scope as possible. In descending order of occurrence frequency, they are: platinum (Pt), gold (Au), ruthenium (Ru), silver (Ag), iridium (Ir), palladium (Pd), rhodium (Rh), rhenium (Re) and osmium (Os). Other (non-noble) metals often referred to in the same sequence are tantalum (Ta), thallium (Tl), niobium (Nb) and hafnium (Hf).
Patent application	Document summarising, describing and defining the scope of an invention for which patent protection is sought.
Patent authority	The patent office where a patent was filed. Normally represented using a WIPO STANDARD ST.3 code: wipo.int/export/sites/www/standards/en/pdf/03-03-01.pdf.
Patent family	A set of patents covering the same invention but filed at different patent offices. Counting patent families is a good proxy for counting inventions and removes possible bias introduced by the geographical coverage of the envisaged protection for the invention leading to an increased number of publications. The family size refers to the patents included in a patent family.
PATSTAT	The EPO's PATSTAT database has become a point of reference in the field of patent intelligence and statistics. It helps users perform sophisticated statistical analyses of bibliographical and legal event patent data.
Photoabsorber	Any material that absorbs light.
Priority filing	The first-filed patent application of a family. The priority year/date is the year/date in which a first filing is filed.
Reverse osmosis	Water purification process using a semi-permeable membrane to filter out unwanted molecules (salt) from sea water to avoid a negative impact on the lifetime of an electrolyser.
Separator, diaphragm, membrane	Synonymous terms used to define the separator material within electrolysers and fuel cells.

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