CSIRO

Australia's National
Science Agency

Hydrogen RD&D Collaboration Opportunities: Global Report

As at 18 August 2022

Australian Government
Department of Climate Change, Energy, the Environment and Water

MISSION INNOVATION
CATALYSING CLEAN ENERGY SOLUTIONS FOR ALL

Citation

Benedicte Delaval, Trevor Rapson Raghav Sharma, Will Hugh-Jones, Erin McClure, Max Temminghoff, Vivek Srinivasan (2022) Hydrogen RD&D Collaboration Opportunities: Global Report. CSIRO, Australia

Copyright

Disclaimer

Acknowledgments

CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pays its respect to Elders past, present and emerging. CSIRO recognises that Aboriginal and Torres Strait Islander peoples have made and will continue to make extraordinary contributions to all aspects of Australian life including culture, economy and science.

We are grateful for the time and input of the stakeholders from industry, government, academia who were consulted throughout this project and across the report series. In particular, the CSIRO project team would like to thank:

- Colleagues at CSIRO, members of the Australian Hydrogen Research Network (AHRN) and staff at the Department of Industry, Science, Energy and Resources (DISER), DFAT, Austrade who provided invaluable contributions to the report.
- CSIRO's Intellectual Property team and IP Australia who contributed the hydrogen patent analytics used in this series of reports: Greg Maloney (CSIRO), Catriona Shaw (IP Australia), Pushpika Wijesinghe (IP Australia).
- CSIRO's Science Impact & Policy team who contributed the hydrogen research publication analysis used in this series of reports: Tadro Abbott (CSIRO)
- The project Working Group who provided valuable feedback throughout the course of the project: Ben Aldham (CSIRO), Linda Stalker (CSIRO), Craig Buckley (Curtin University), Amalia Pearson (DISER).
- The CSIRO-DISER Hydrogen RD&D International Collaboration Program leadership team who provided oversight and guidance throughout the project: James Hetherington (DISER), Amalia Pearson (DISER), Patrick Hartley (CSIRO), Vicky Au (CSIRO), Dan O'Sullivan (CSIRO).

Finally, we would like to thank the following organisations and individuals for their time and feedback on this country report:

CSIRO: Amelia Fyfield, Doki Yamaguchi, Greg Maloney, Joel Sarout, Nawshad Haque**,** Sebastian Charnock, Yuko Wakamatsu, Yunxia Yang**.**

AHRN: Andrew Dicks (Griffith University, AHRN Convenor), Peter Grubnic (Future Fuels CRC), Peter Majewski (University of South Australia)

International Stakeholders:

National Research Council (NRC), Canada
University of British Columbia (UBC), Canada
China Policy
The Embassy of France in Australia
Ecological Transition Agency (ADEME), France
Alternative Energies and Atomic Energy Commission (CEA), France
National Centre of Scientific Research (CNRS), France
National Academy of Science and Engineering (acatech), Germany
German Aerospace Centre (DLR), Germany
PT Jülich (PtJ), Germany
New Energy and Industrial Technology Development Organisation (NEDO), Japan
H2Korea, Korea
Korea Institute of Energy Research (KIER), Korea
Korea Institute of Science and Technology (KIST), Korea
Nanyang Technological University (NTU), Singapore
UK Hydrogen Fuel Cell Association (UK HFCA), United Kingdom
University of Chester, United Kingdom
Lawrence Livermore National Laboratory (LLNL), United States
Fuel Cell & Hydrogen Energy Association (FCHEA), United States

Contents

1.1 Introduction

The hydrogen economy has gathered significant political and business momentum across the world. While ambitious hydrogen targets and projects have been announced by many governments, there remains considerable uncertainties related to cost, efficiency and technology selection. The rapid pace of change and concurrent country activities can also create considerable uncertainty and duplication of effort. Overcoming these challenges will require focused and collaborative global research, development and demonstration (RD&D) activity.

1.1.1 Report objective, approach and structure

The study undertaken for this report comprises of two parts: the *Hydrogen RD&D Collaboration Opportunities: Global Report*, and an in-depth analysis of ten countries. The featured countries were selected based on interdependent factors including the complementarity of research activities; the synchronicities within hydrogen strategies and the balance between countries planning to be either future net neutral, net importer, or net exporter of clean hydrogen as this will likely influence the mode and approach of demonstration in the RD&D paradigm. The featured countries are:

- Canada
- China
- France
- Germany
- India
- Japan
- Republic of Korea
- Singapore
- United Kingdom
- United States of America

This investigation is based on desktop analysis of research opportunities in countries with hydrogen strategies and activities, and initial engagement with key governmental and research, development and demonstration (RD&D) organisations in those countries.

The report aims to provide:

- A global understanding of some countries that are highly active in hydrogen RD&D.
- A review of the hydrogen RD&D priorities and activities in selected countries.
- The identification of high-level RD&D opportunities of mutual interest based on the complementarity of strategies and research activities which could form the basis for bilateral or multilateral research collaborations.
- An understanding of connections to key research organisations in selected countries to help lay the foundations for future research collaborations.

Activity levels for hydrogen and net-zero initiatives is high. While effort has been made to capture major announcements and key information as at 18 August 2022, the content is intended to provide a starting point for informing international engagement, particularly when used in conjunction with other chapters in the series, and is non-exhaustive.

1.2 Global hydrogen industry status: the importance of RD&D

The global hydrogen economy is at its nascency and will require a range of enabling actions to mature. The hydrogen industry is important not just to achieve stated net zero targets,[1] but also to achieve other priorities that countries have identified such as economic growth and energy security. In its *Global Hydrogen Review 2021,* the International Energy Agency (IEA) outlined five key enabling actions, one of which is the focus of this report: RD&D. This section gives an update on global progress in hydrogen development and highlights the importance of RD&D to overcome innovation gaps that remain.

In its 2021 report, the IEA outlined the state of hydrogen industry development in the world.[2] The key findings of the report with respect to global progress on hydrogen is shown in Figure 1 and Figure 2. Figure 2 shows projections for the current global commitments to hydrogen supply and demand, relative to the 2030 target, within the Net zero emissions scenario. The clear shortfall in commitments points to the need for concrete policies to be developed, which support implementation, particularly focused on creating demand. Also shown in Figure 3 are the current funding and fuel cell vehicle deployment commitments relative to targets. Again, significant additional commitments will be required in these areas to achieve the targets. Additionally, the IEA highlighted the importance of international co-operation to accelerate the adoption of hydrogen underpinned by innovation provided by RD&D to lower the cost and increase the competitiveness *of* hydrogen technologies.

Figure 2 shows the levelized cost of hydrogen (LCOH) production in 2021 for different forms of hydrogen production pathways (renewable, fossil fuel with carbon capture and storage (CCS) and natural gas). This is shown in ranges as costs differ by country. This is compared against the IEA's 2030 and 2050 cost goals to make 'low-carbon hydrogen'[3] economically competitive. For additional context, Mission Innovation's target of 'clean hydrogen'[4] production under USD 2/kg has also been included.[5]

[1] Almost 130 countries have set or are considering setting a target of net zero greenhouse gas emissions by 2050; UN (2021) Climate Action. https://www.un.org/en/climatechange/net-zero-coalition

[2] IEA Global Hydrogen Review 2021 https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

[3] 'Low-carbon hydrogen' as defined by the IEA includes hydrogen produced from renewables, nuclear electricity, biomass, and fossil fuels with carbon, capture, utilisation and storage (CCUS).

[4] 'Clean hydrogen' as defined by Mission Innovation refers to hydrogen produced with very low or no carbon emissions. This definition includes hydrogen produced from renewables and hydrogen produced from fossil fuel conversion with CCS and CCUS.

[5] DISER (2021) *Technology Investment Roadmap.*

Figure 1: Global progress towards achieving net zero by 2050

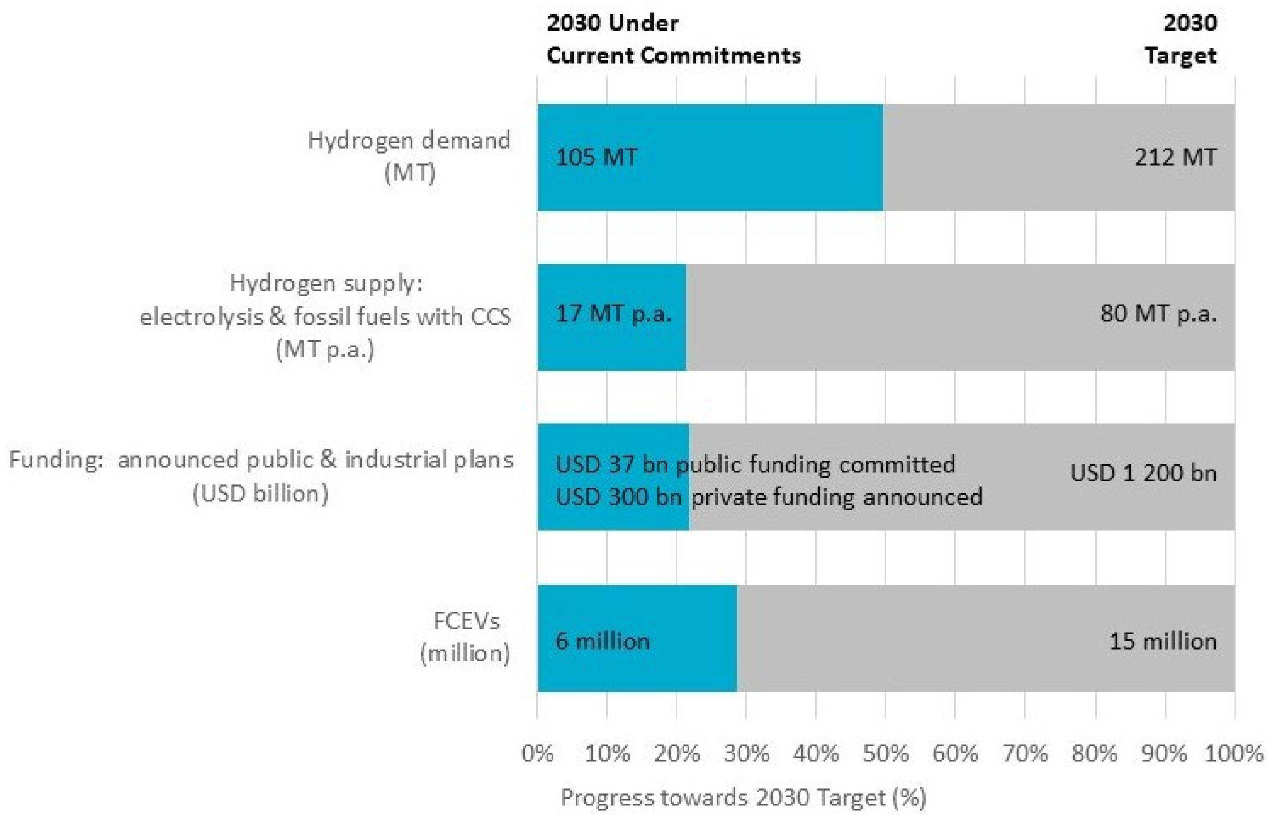
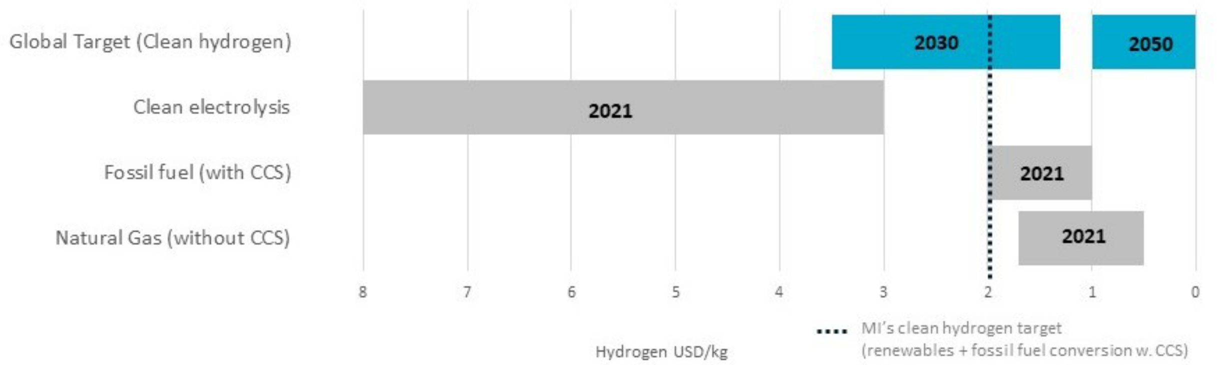


Figure 2: Global levelised cost of hydrogen (USD/kg) production in 2021 vs global 2030 and 2050 targets



Derived from IEA (2021) Global Hydrogen Review 2021; IEA (2021) Net Zero by 2050 – A Roadmap for the Global Energy Sector, and Department of Industry, Science, Energy and Resources (2021) Technology Investment Roadmap.

To bring hydrogen development in line with global net zero objectives by 2050, and to decrease the cost of hydrogen to a level competitive with other fuels, the IEA outlined five key recommendations for all countries:[6]

- **Road-mapping:** Setting targets and policy goals
- **Demand creation:** Creating incentives for low-carbon hydrogen use
- **Mobilising investment:** De-risking investment in production, infrastructure and factories

[6] IEA (2021) Global Hydrogen Review 2021 <https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf>

- **RD&D and innovation:** Developing, demonstrating and commercialising critical technologies faster
- **Harmonising standards:** Establishing certification, standardisation and regulation

With respect to RD&D and innovation, the IEA found 88% of cumulative emissions reductions to 2050 will need to come from emerging technologies that are still currently under development, including hydrogen technologies.[7] With respect to hydrogen production, RD&D and innovation will be required globally to bring down the cost of production from renewable electrolysis, fossil fuel conversion with CCS, and other clean hydrogen production methods. With respect to hydrogen utilisation, global innovation gaps are concentrated in the areas of:[8]

- Hydrogen co-firing in coal or natural gas plants
- Electrolytic hydrogen used for steelmaking and chemicals production including ammonia
- Heavy road transport
- Ammonia and methanol use in shipping
- Hydrogen and hydrogen-derived fuels in aviation

The IEA report estimates that globally, USD 25 billion of public money has been budgeted towards hydrogen RD&D until 2030. However, USD 90 billion globally is required to complete the required development and demonstration of emerging technologies by 2030.[9]

Hydrogen RD&D is not only important for meeting global net zero objectives, but also to meet the other objectives driving country strategies. The most commonly cited drivers across the majority of international hydrogen roadmaps and strategies are:

- **Environmental:** Such as the global drive to reduce carbon emissions or the domestic drive to improve local air quality.
- **Industrial strategy and economic growth:** Either growing hydrogen exports or leveraging comparative advantages to develop key hydrogen technologies or sectors.
- **National technology development:** Leading technological advances and exporting energy technologies to gain a competitive edge.

Less frequently mentioned drivers, but critical for several countries are:

- **Energy security:** Diversifying energy supply chains and expanding renewable energy.
- **Hydrogen export:** Producing hydrogen for the global market, particularly to energy importing nations less endowed with energy resources.

---

[7] IEA (2021) Global Hydrogen Review 2021 https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf

[8] IEA (2021) Global Hydrogen Review 2021 https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf

[9] IEA (2021) Global Hydrogen Review 2021 https://iea.blob.core.windows.net/assets/3a2ed84c-9ea0-458c-9421-d166a9510bc0/GlobalHydrogenReview2021.pdf

1.3 Strategic hydrogen priorities

Globally, there are now more than 30 national hydrogen documents, whether plans, roadmaps or strategies (Figure 3).

Figure 3: Major international hydrogen strategies, plans and roadmaps

1.3.1 Global strategic hydrogen priorities

Each of the more than 30 international hydrogen strategies and roadmaps, differ in level of technical detail. Common elements across international plans are:[10]

- Key drivers and comparative advantages;
- Strategic industry priorities, and related technologies;
- Roadmapping how to progress the hydrogen value chain towards an at scale hydrogen economy. This may include RD&D priorities to overcome technical barriers; required infrastructure transitions; timing and scale of activities; cross-cutting actions; and the role of government.

Mutual priorities in hydrogen production

Different countries envision different pathways for commercial hydrogen production. Figure 4 shows the likely production pathways in the selected countries in the short (2030) and long (2050) term.

In the short term (to 2030) countries will likely still be reliant on producing hydrogen from fossil fuels and possibly methane pyrolysis to meet demand. However, many are prioritising the development and deployment of clean hydrogen (such from renewables and fossil fuels with CCS).

[10] DIIS and Business CRC-P (2019) Advancing Hydrogen: Learning from 19 plans to advance hydrogen from across the globe. Future Fuels CRC.

In the long run (to 2050) the majority of countries aim to produce clean hydrogen from electrolysis or fossil fuels with carbon management.[11] Therefore, clean hydrogen is likely the area with the most sustainable long-run potential for RD&D collaborations and supply chain development.

Figure 4: Production pathways identified in country industry strategies in the short term, and to 2050 (not including imports)

■ Long Term (2050)
✓ Short Term (2030)
□ Likely by 2050 but not specified or less emphasis in a national strategy/roadmap document
✓* Likely by 2030 but not specified or less emphasis in a national strategy/roadmap document

	Renewable	Fossil Fuels + CCS	Fossil Fuels	Methane Pyrolysis
Australia	■ ✓	■ ✓		
Canada [B]	■ ✓	■ ✓		✓*
China	■ ✓	■	✓	
France [B]	■ ✓	✓*		
Germany	■ ✓	✓		✓
India	□ ✓*		✓*	
Japan [A]	■	■ ✓	✓	
Republic of Korea [A]	■	■	■ ✓	
Singapore [A]				■ ✓
United Kingdom (UK)	■ ✓	■ ✓	✓*	■
United States (US)[B]	■ ✓	■ ✓	■ ✓	■ ✓

[A] Singapore, the Republic of Korea and Japan are focused on importing renewable and low-carbon hydrogen rather than onshore production, although Singapore maintains interest in onshore production of blue and brown H_2

[B] France, Canada and US have also considered production of hydrogen from nuclear power

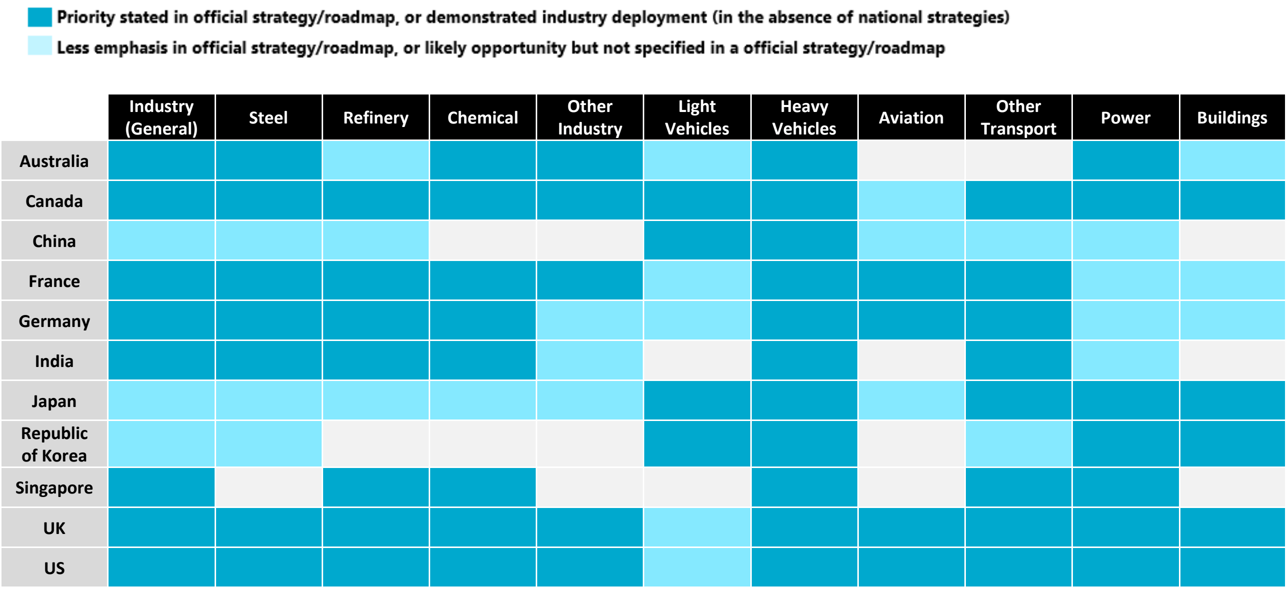
Inferred from national strategies and roadmaps, or industry and consultancy publications (where national strategies are not available), and consultations with in-country stakeholders. See Appendix B for full reference list of documents used.

[11] Ludwig-Bölkow-Systemtechnic GmbH (2020) International Hydrogen Strategies: A study commissioned by and in cooperation with the World Energy Council Germany. World Energy Council Germany; World Energy Council, EPRI and PwC (2021) Working Paper: National Hydrogen Strategies https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf

Mutual priorities in hydrogen utilisation

Country strategies vary in prioritised end-uses for hydrogen. The utilisation pathways featured as a primary focus in global country strategies are summarised below in Figure 5.

Figure 5: Primary utilisation sectors identified end uses in country industry strategies



***Industry (general) includes end use of hydrogen in industrial processes either for heat or as a feedstock. Other industry includes process heat, mining, cement industry, glass, electronics**

Inferred from national strategies and roadmaps, or industry and consultancy publications (where national strategies are not available), and consultations with in-country stakeholders. See Appendix for full reference list of documents used.

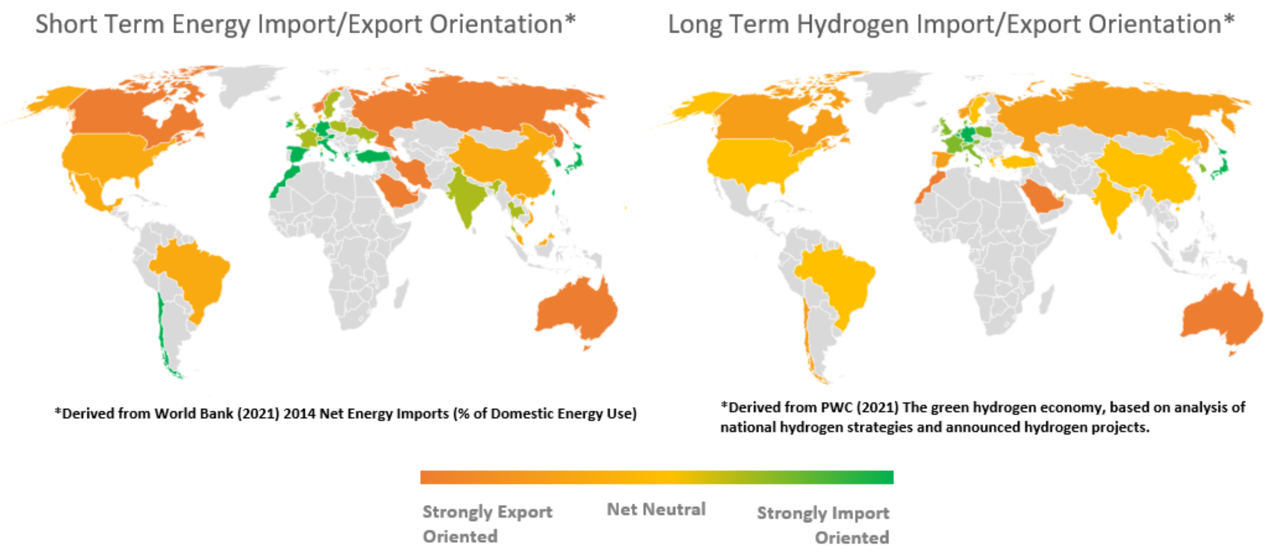
Import and export priorities

In order to realise cost-effective international supply chains, RD&D collaboration between exporting and importing countries will be critical to align technology choices, and to harmonise regulations, standards and certification schemes. Figure 6 provides an overview of countries' likely import statuses over time, by looking at current energy imports (as a percentage of domestic energy use),[12] and future hydrogen imports (as indicated by country hydrogen strategies and hydrogen project deployments).[13]

[12] World Bank (2021) 2014 Energy imports, net (% of energy use). IEA Statistics. https://data.worldbank.org/indicator/EG.IMP.CONS.ZS

[13] PwC (2021) The Green Hydrogen Economy: Predicting the decarbonisation agenda of tomorrow https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

Figure 6: Global energy and hydrogen import and export orientation



Germany, Japan and the Republic of Korea, are strongly import oriented both now and in the longer term. The majority of countries in the European Union indicate a slight import focus both now and in the future in terms of energy and hydrogen. Regions with a strong export focus now and in the future include the Middle East, North Africa, Canada and Norway. Countries currently importing energy but looking at exporting hydrogen in the future include Morocco, Spain and Chile. Countries trending towards self-reliance, or net neutral hydrogen imports include China, the US and India.

1.4 Global hydrogen RD&D activity

1.4.1 Global hydrogen RD&D activity

Research publications by country

Key countries producing the highest levels of hydrogen research output across all areas of the value chain (production, storage and utilisation) are China, the US, Japan, India, Germany, the UK and France (see Table 1). Large countries (i.e. with a high population and GDP) are likely to produce large volumes of research. As such, NCI[14] was also used to identify smaller countries with lower publication volumes but producing high quality research. Examples of countries achieving high NCI scores include Australia, Singapore, Saudi Arabia, Hong Kong, Denmark, the UK, Canada and Vietnam.

[14] Normalised Citation Impact is calculated by dividing the count of citing items by the expected citation rate for that document type, year and subject area.

Table 1: Country research publication strengths by value chain area

Production			Storage and Distribution		
#	Publication Output	Normalised Citation Impact	#	Publication Output	Normalised Citation Impact
1st	China	Singapore	1st	China	Australia
2nd	USA	Australia	2nd	USA	United Kingdom
3rd	India	Hong Kong	3rd	Germany	Canada
4th	Germany	Saudi Arabia	4th	Japan	USA
5th	Japan	Denmark	5th	India	China
6th	South Korea	Vietnam	6th	South Korea	Iran
7th	United Kingdom	China	7th	United Kingdom	South Korea
8th	Italy	United Kingdom	8th	France	France
9th	Spain	USA	9th	Australia	Italy
10th	Canada	Malaysia	10th	Iran	Germany

Utilisation			Overall		
#	Publication Output	Normalised Citation Impact	#	Publication Output	Normalised Citation Impact
1st	China	Australia	1st	China	Singapore
2nd	USA	Saudi Arabia	2nd	USA	Australia
3rd	Japan	Hong Kong	3rd	India	Hong Kong
4th	India	USA	4th	Germany	Saudi Arabia
5th	Germany	China	5th	Japan	Vietnam
6th	South Korea	Sweden	6th	South Korea	China
7th	United Kingdom	Denmark	7th	United Kingdom	Denmark
8th	France	Canada	8th	France	USA
9th	Canada	Switzerland	9th	Italy	Ireland
10th	Iran	Iran	10th	Canada	Switzerland

Data was drawn from the Web of Science (WoS) from Clarivate and InCites by Clarivate Analytics. The search strategy and keywords used can be found in Hydrogen Research, Development and Demonstration: Technical Repository.

Research publications by organisation

At the organisational level, most hydrogen publication outputs globally have come out of research institutions and universities across China. However, institutions in the US, France, Germany, Russia, Italy, Spain, India and Singapore also feature in the top 20 in terms of hydrogen publication outputs (Figure 7). NCI metrics[15] indicate that high impact hydrogen publications originate from several universities in China, Singapore, Saudi Arabia and the US (Figure 8).

[15] Normalised Citation Impact: The number of times a publication is cited, divided by the expected citation rate for similar publication types, year or subject area

Figure 7: Top institutions globally by overall hydrogen publication output

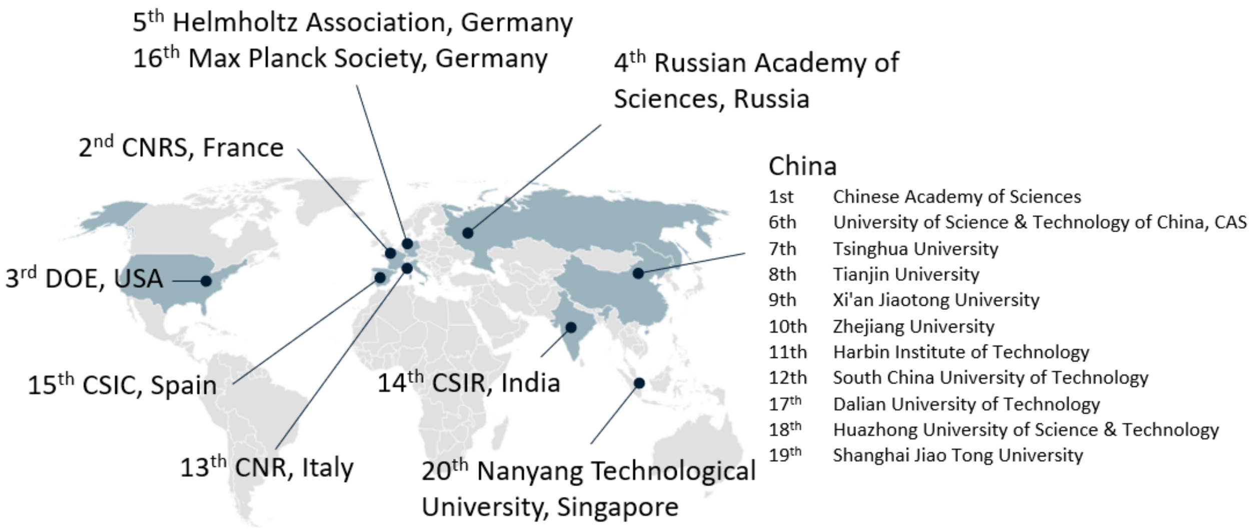
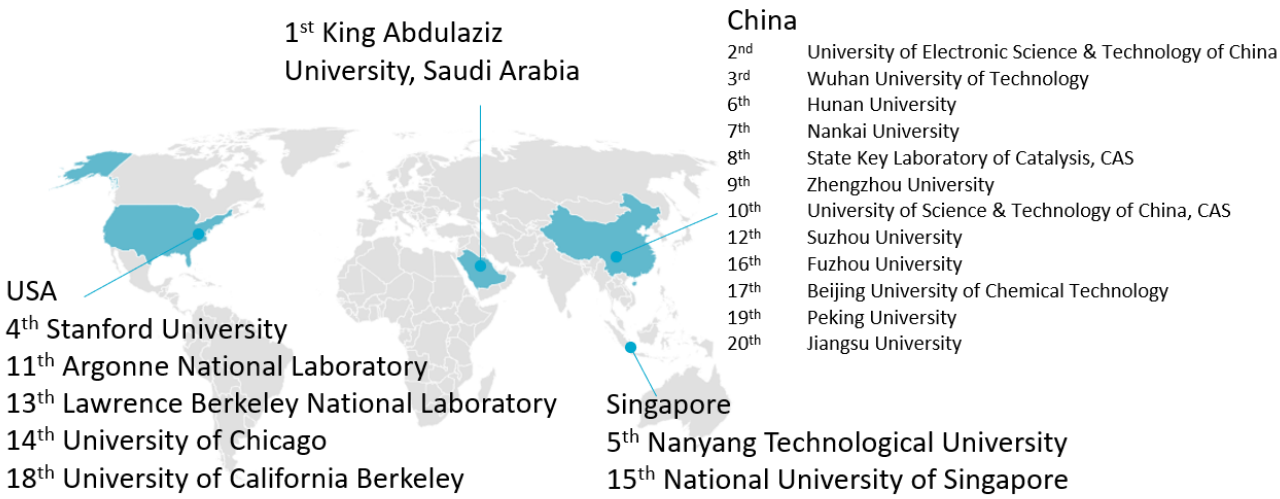


Figure 8: Top institutions globally by normalised citation impact



Global hydrogen patents

CSIRO developed a search approach in 2019 to support the *Hydrogen Research, Development and Demonstration: Priorities and opportunities for Australia*[16] report. CSIRO applied this approach to provide a patent landscape across the hydrogen value chain for each country. The details of the search approach and any limitations can be found in the *National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository*.[17] The global patents landscape shows that the majority of patent assignees are private companies, and to a lesser extent universities and research institutions. Figure 9 illustrates the countries of origin for patents in hydrogen production, storage and utilisation from 2010 to 2021.

In 2021, China was the leading country from which hydrogen-related technologies originated, with 32,514 patent families (~46% of the total). Japan had 14,089 (~20% of total), the US had 8,955 (~13% of the total) and Australia was 11th with 338 patent families.

---

[16] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia. CSIRO.

[17] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository. CSIRO.

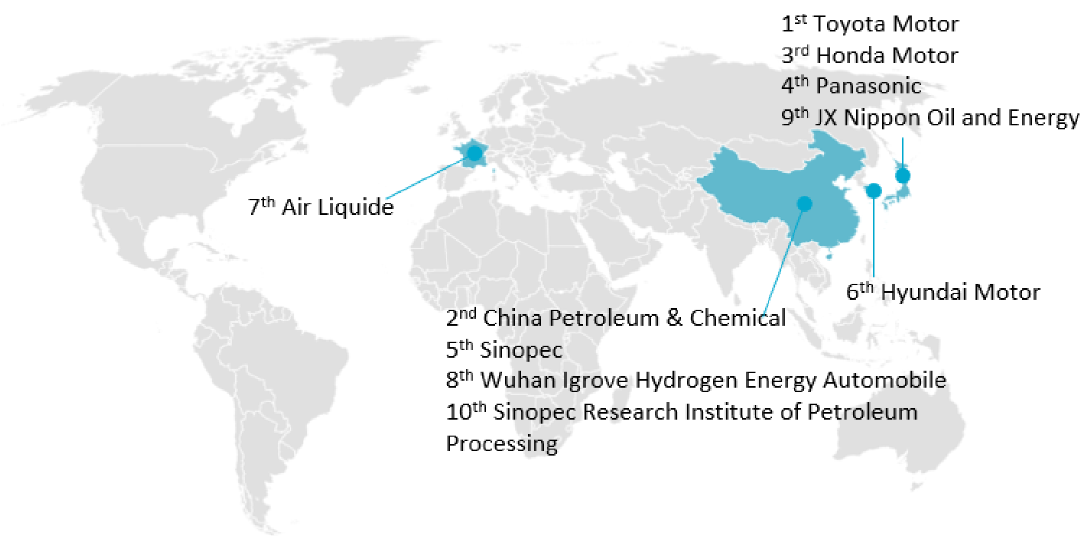
Our independent research revealed that the top five countries in hydrogen-related patent family outputs were also consistently the top five across each area of the value chain, i.e. patent family outputs in hydrogen production, storage and utilisation. These top five countries were China, Japan, US, the Republic of Korea and Germany. The top 10 organisations that hold patents in hydrogen related technologies are shown in Figure 10 below. The majority of these are headquartered in China and Japan, and some large multinational players also headquartered in France (Air Liquide) and the Republic of Korea (Hyundai Motors).

Figure 9: 2010-2021 Patent families by country of origin - production, utilisation and storage

	Country	Number of patent families held
1	**China**	32,514
2	**Japan**	14,089
3	**US***	8,955
4	**Republic of Korea**	5,369
5	**Germany**	3,257
6	**France**	1,551
7	**Russia**	1,085
8	**UK**	732
9	**Taiwan**	704
10	**India**	368
11	**Australia**	338

*** Current US analysis has tracked 1,256 US patents**

Figure 10: Top 20 organisations (patent assignees by number of hydrogen patent families held 2010-2021)

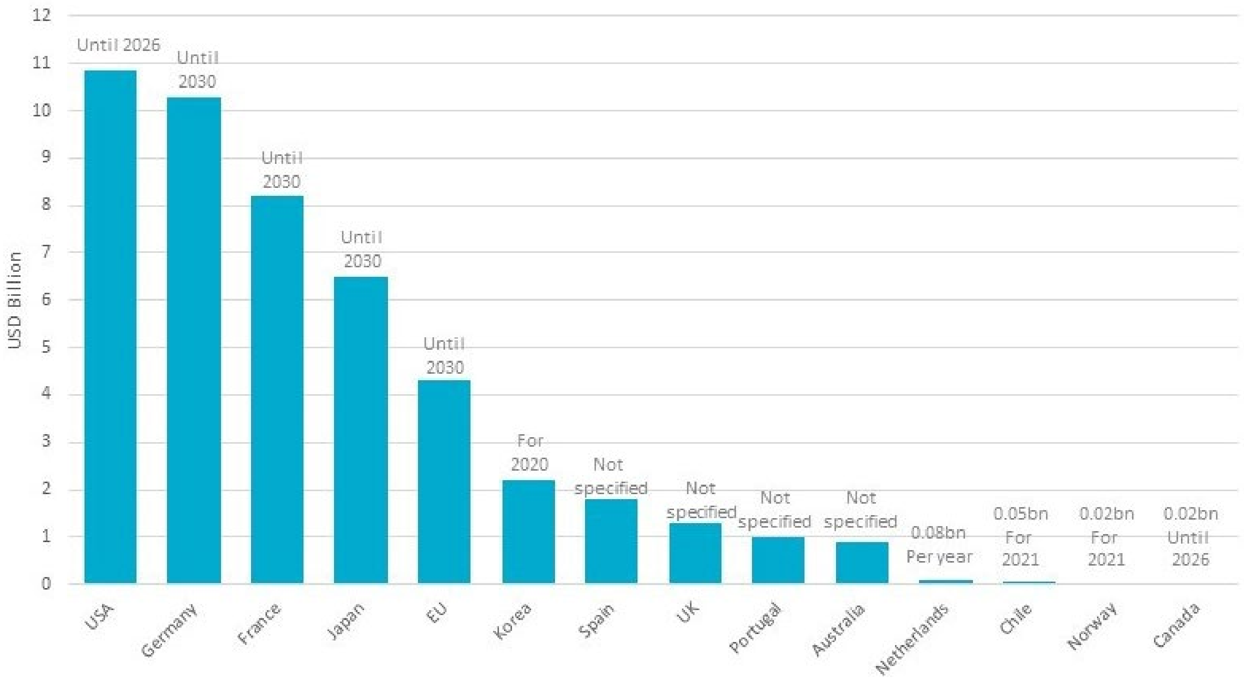


The search strategy and keywords used can be found in Hydrogen Research Development and Demonstration: Technical Repository.

1.5 Global public funding commitments for hydrogen

In their national strategies, countries have committed public funds to the development of a hydrogen economy. This includes funding for several elements including early-stage R&D through to supporting commercial projects and skills development. The following graph shows the public commitments made by respective countries in their national hydrogen strategies:

Figure 11: Public funding committed for hydrogen development (USD billion)

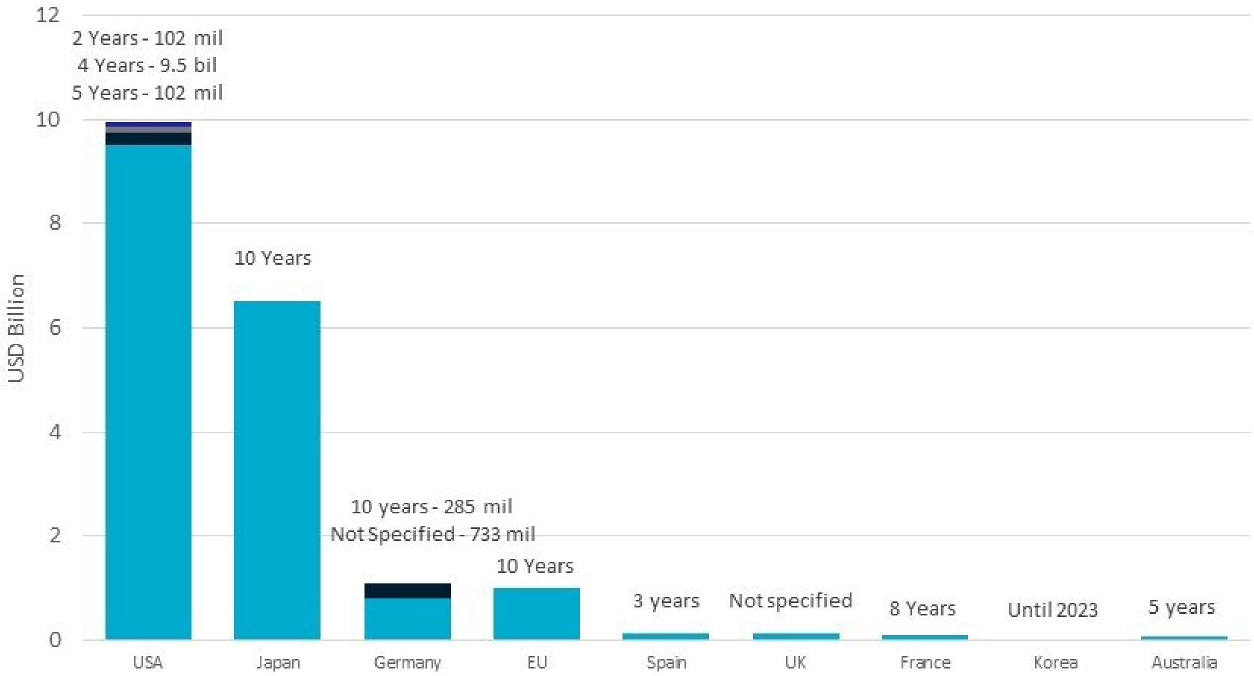


Derived from IEA (2021) Global Hydrogen Review 2021; IEA (2021) Net Zero by 2050 – A roadmap for the Global Energy Sector; Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America.

Note: For some countries data was unavailable.

A portion of these commitments are dedicated to hydrogen RD&D specifically. Figure 12 illustrates country funding for major RD&D programs and projects that are currently underway, and their indicative timeframes.

Figure 12: Public funding towards major hydrogen RD&D programs



Derived from IEA (2021) Global Hydrogen Review 2021; IEA (2021) Net Zero by 2050 – A roadmap for the Global Energy Sector; Yoon Y (2020) Current Status of the Korean Hydrogen Economy. H2Korea and MOTIE; Infrastructure Investment and Jobs Act, H.R. 3684 (2021) 117th Congress of the United States of America.

1.6 Summary of global commercial project pipeline

While this report is focused on projects from early-stage research through to demonstration and pilot projects, several announcements have been made internationally for the deployment of mature hydrogen technologies and funding for commercial hydrogen projects (summarised in Figure 13).

Approximately 359 hydrogen projects have been announced, with roughly USD 500 billion in funding projected for commercial projects. The bulk of this amount is for 'immature' projects (announced, requires additional funding or in preliminary study stage). Roughly USD 150 billion is funding for mature projects (at feasibility study stage and beyond, including work on operational projects).[18]

The majority of projects are either hydrogen production projects or hydrogen utilisation projects. European projects cover the entire hydrogen value chain with a particular focus on industrial usage and transport applications, as well as championing integrated hydrogen projects.[19] The Republic of Korea and Japan also have a strong focus on industrial use and transport applications, particularly road transport, green ammonia, liquid hydrogen (LH2), and liquid organic hydrogen carriers (LOHC).[20]

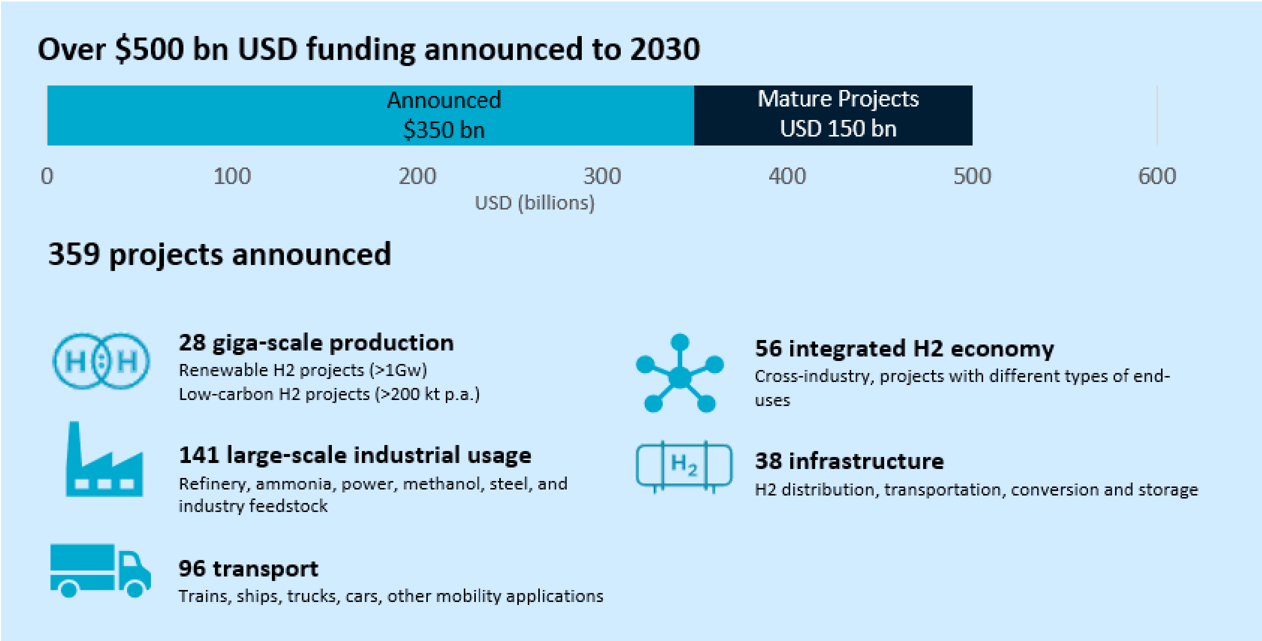
---

[18] Hydrogen Council and McKinsey & Company (2021) Hydrogen Insights: An updated perspective on hydrogen investment, market development and momentum in China, Hydrogen Council. https://hydrogencouncil.com/wp-content/uploads/2021/07/Hydrogen-Insights-July-2021-Executive-summary.pdf

[19] Hydrogen Council and McKinsey & Company (2021) Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, Hydrogen Council.

[20] Hydrogen Council and McKinsey & Company (2021) Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, Hydrogen Council.

Figure 13: International hydrogen commercial project pipeline[21]



Derived from McKinsey and Hydrogen Council (2021) Hydrogen Insights: An updated perspective on hydrogen investment, market development and momentum in China. McKinsey & Company

The scope of this report is on RD&D projects. For information on commercial hydrogen projects, see *HyResource*, an online knowledge sharing platform across the hydrogen community, led by CSIRO, Future Fuels CRC, NERA and the Australian Hydrogen Council.

HyResource provides a directory of publicly available databases and information sources on international projects: https://research.csiro.au/hyresource/projects/international/

1.7 Summary of findings from individual country reports

The *Hydrogen RD&D Collaboration Opportunities* country reports provide detailed analysis on 10 countries. This section summarises the key findings of these reports. Hydrogen RD&D collaboration opportunities were identified using qualitative and quantitative metrics across each detailed hydrogen area. This includes:

- The RD&D priorities stated in country documents (supplemented by in-country consultations); and
- Hydrogen activity at different stages of technology development (research, patent and deployment activity).

The individual country report chapters also provide an overview of each selected country's hydrogen innovation system, and key players in government, research and industry consortia across the hydrogen landscape. The reports examine hydrogen policy, hydrogen RD&D funding, key domestic and international RD&D programs and projects.

---

[21] Figure derived from Hydrogen Council and McKinsey & Company (2021) Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, Hydrogen Council.

1.7.1 Detailed breakdown of country RD&D priorities

The country level analysis includes a deep dive into the technical RD&D priorities related to each country. These priorities are collated from national strategies, plans and roadmaps, and RD&D publications from public institutions, including government commissioned publications (see individual country reports for references used). Further, consultations held with in-country experts were used to validate these findings. It is important to note that for some countries, RD&D priorities can vary between government and industry, and also between different research institutions. For others, technology priorities are centralised and consistent across stakeholders. In light of the rapidly changing landscape, these will likely change over time.

Figure 14: RD&D collaboration opportunities across the value chain

Legend:

■ RD&D collaboration opportunity based on stated RD&D priorities in key country documents

Production

RD&D Opportunities	Canada	China[A]	France	Germany	India[B]	Japan	Rep. Korea	Singapore	UK	USA	Australia
Electrolysis	■	■	■	■	■	■	■	■	■	■	■
PEM	■	■	■	■	■	■	■			■	■
Alkaline (incl. chlor alklali)	■	■		■	■	■	■			■	■
SOE	■	■	■	■		■		■		■	■
AEM				■		■				■	■
C / HC Assisted											■
Fossil Fuel Conversion	■	■		■	■	■	■	■	■	■	■
CCS / CCUS	■					■			■	■	■
Coal Gasification	■					■				■	■
Coal/Oil Pyrolysis											■
Methane Pyrolysis	■			■				■	■	■	■
SMR / CO2 reforming / CST methane reforming / Autothermal reformin	■				■		■		■	■	■
Other (incl. chemical looping, partial oxidation)				■							■
Biomass & Waste conversion	■			■	■		■		■	■	■
Thermal Water Splitting					■				■	■	■
Biological hydrogen production			■		■					■	■
Photochemical / Photocatalytic		■	■		■	■				■	■
Nuclear electrolysis	■					■			■	■	

***In the Australian context, fossil fuel conversion technologies are only considered a priority with CCS**

[A] Further detail pending the release of China's hydrogen roadmap

[B] Further detail pending the release of India's hydrogen mission publications

Storage and distribution

RD&D Opportunities	Canada	China[A]	France	Germany	India[B]	Japan	Rep. Korea	Singapore	UK	USA	Australia
Compression and Liquefaction	■	■	■	■	■	■	■	■	■	■	■
Compression	■	■	■	■	■	■	■		■	■	■
Liquefaction	■	■	■	■		■	■	■	■	■	■
Pressurised storage	■	■	■	■	■	■	■		■	■	■
Pipelines (Pure H2)	■	■	■	■			■		■	■	■
Underground Storage	■		■						■	■	■
Chemical	■	■	■	■	■	■	■		■	■	■
Ammonia	■	■	■	■		■	■	■	■	■	■
LOHCs		■	■	■		■				■	■
Hydrides (metal, organic, complex)		■	■		■		■			■	■
Synthetic fuels (incl. methanol, DME and others)	■	■		■		■	■			■	■
Physisorption	■	■	■		■				■		■
Tube trailers and tank lorries	■			■	■		■			■	■
Carrier Ships	■						■				■

[A] Further detail pending the release of China's hydrogen roadmap

[B] Further detail pending the release of India's hydrogen mission publications

Utilisation

RD&D Opportunities	Canada	China[A]	France	Germany	India[B]	Japan	Rep. Korea	Singapore	UK[B]	USA	Australia
Gas Blending	■	■		■	■			■	■		■
Pipelines (Blended H2)	■	■		■					■	■	■
Appliances	■				■						■
Gas separation	■		■			■		■			■
Transport	■	■		■	■	■	■	■	■	■	■
PEMFCs	■	■	■	■	■	■	■	■	■	■	■
Refuelling stations	■	■	■	■	■	■	■		■	■	■
Aviation	■	■				■				■	■
Internal combustion engines	■		■			■					■
Electricity Generation	■	■	■	■	■	■	■	■	■	■	■
Ammonia turbines				■		■		■		■	■
Hydrogen turbines	■	■		■		■	■	■	■	■	■
Fuel Cells	■	■	■	■	■	■	■	■	■	■	■
AEMFC		■								■	■
PEMFC		■	■		■	■				■	■
AFC											■
SOFC		■	■		■	■				■	■
Reversible fuel cells			■							■	■
Other Fuel Cells (ammonia, molten carbonate, methanol, microbial)			■		■	■					■
Industrial Processes	■	■	■	■	■	■	■		■	■	■
Steel processing	■	■		■	■	■	■		■		■
Combustion	■	■	■	■			■			■	■
Synthetic fuels	■			■		■			■	■	■
Methanol production				■		■			■		■
Fuel Cell Ships	■			■			■				■
Carbon recycling technology				■		■					
Cold-energy recovery								■			
Other industry (incl. cement, pulp/paper, agriculture)	■										■

**** In the Australian context, heavy and long-distance vehicles are a priority**

***** In the Australian context, electricity generation for remote area power systems, back-up power and grid support are a priority**

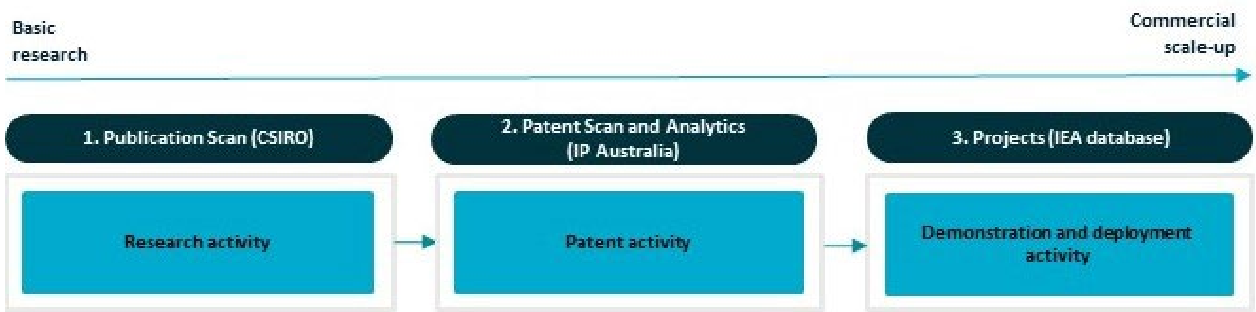
[A] Further detail pending the release of China's hydrogen roadmap

[B] Further detail pending the release of India's hydrogen mission publications

1.7.2 Detailed breakdown of country activity

Hydrogen innovation activity occurs at different stages of technology development. This spans the innovation cycle from basic research, applied research and demonstration to deployment at scale. The country reports have analysed respective country activities at each stage of the innovation cycle by drawing on three different datasets: a research publication scan performed by the CSIRO, patent analytics performed by IP Australia,[22] and the IEA's low-carbon hydrogen projects database.[23]

Figure 15: Hydrogen innovation activity



[22] IP Australia (2021) Patent analytics on hydrogen technology https://www.ipaustralia.gov.au/tools-resources/publications-reports/patent-analytics-hydrogen-technology

[23] IEA (2021) Hydrogen Projects Database, October 2021. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

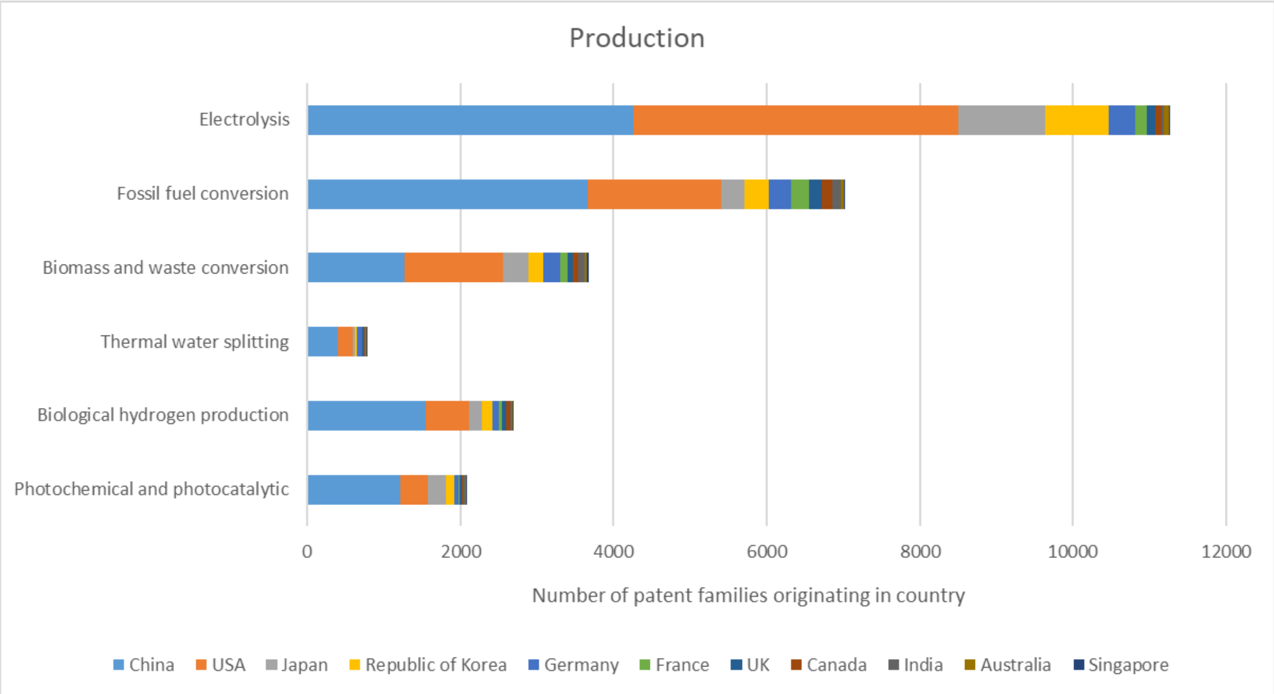
Research activity

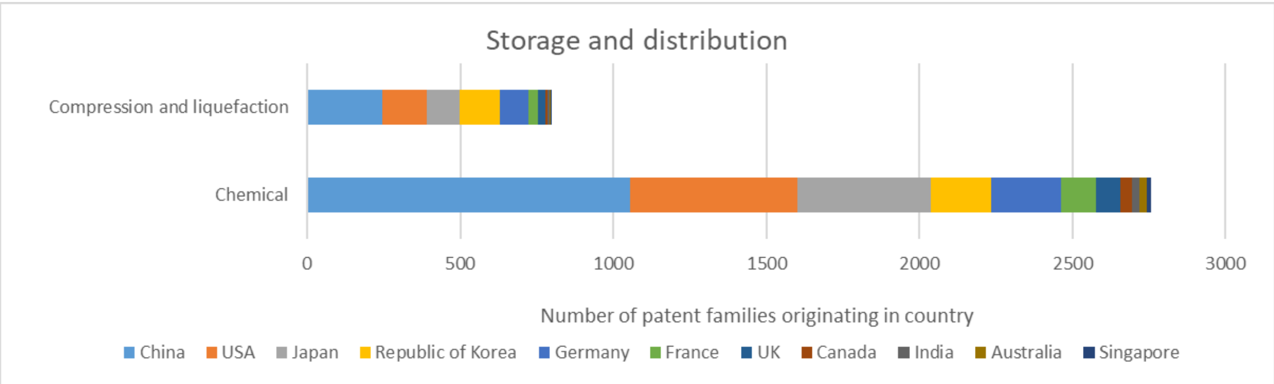
Basic and applied research usually relates to technologies with a lower TRL. These are often next generation technologies, with a longer-term commercialisation outlook.

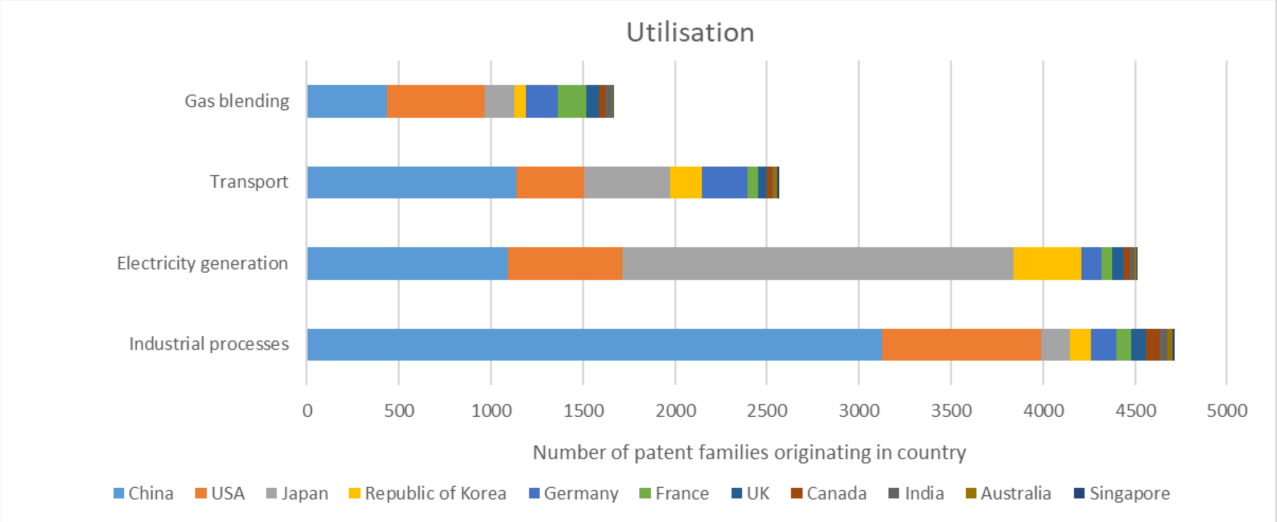
Patent activity

Patent data gives an indication of research and development activity occurring at a higher TRL. These are usually cutting-edge technologies that have potential for demonstration, scale-up and commercialisation in the short- to medium- term. The following graphs were derived from data extracts provided by IP Australia's *Patent analytics on hydrogen technology*. Figure 16 shows the number of patent families originating in each country for each hydrogen sub-technology area.

Figure 16: Patent families originating in each country by sub-technology





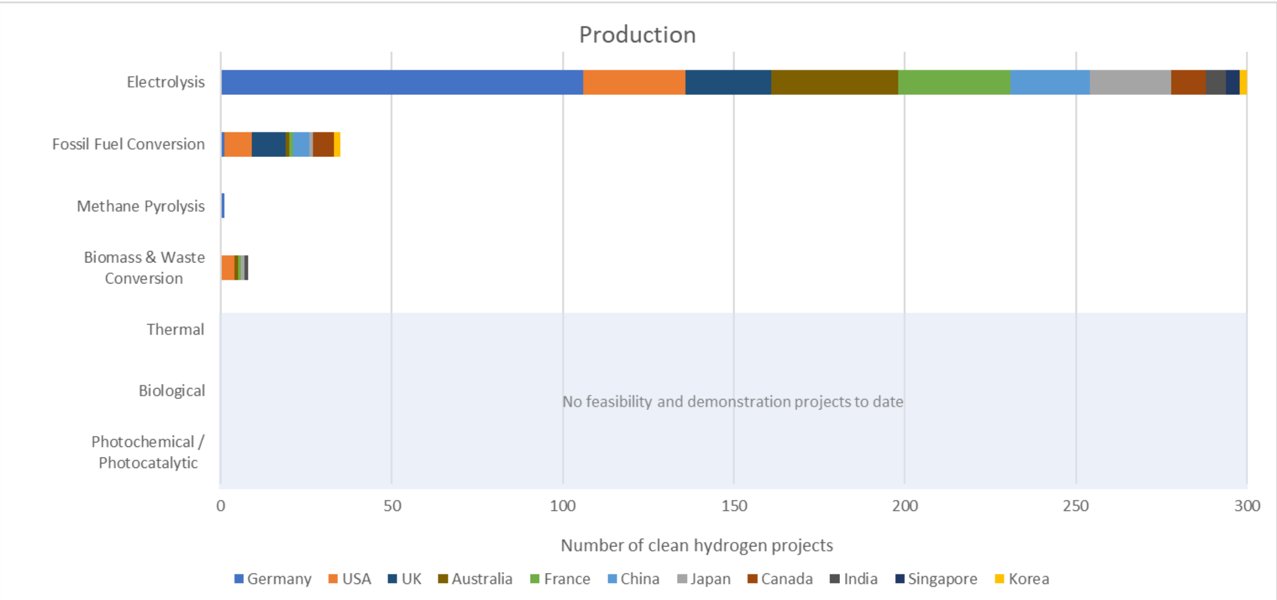


Domestic demonstration and deployment activity

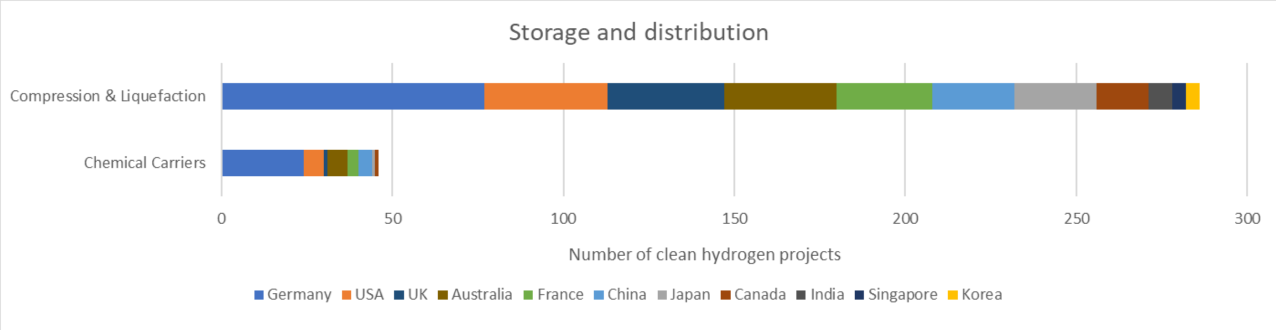
Feasibility studies and demonstration and commercial project activity give an indication of commercial implementation and scale-up focus areas. It should be noted that technologies used on domestic projects may have been developed domestically or obtained from an overseas technology provider. In either case, project activity can also speak to the potential for collaboration and knowledge sharing in skills, trades and implementation 'know-how'.

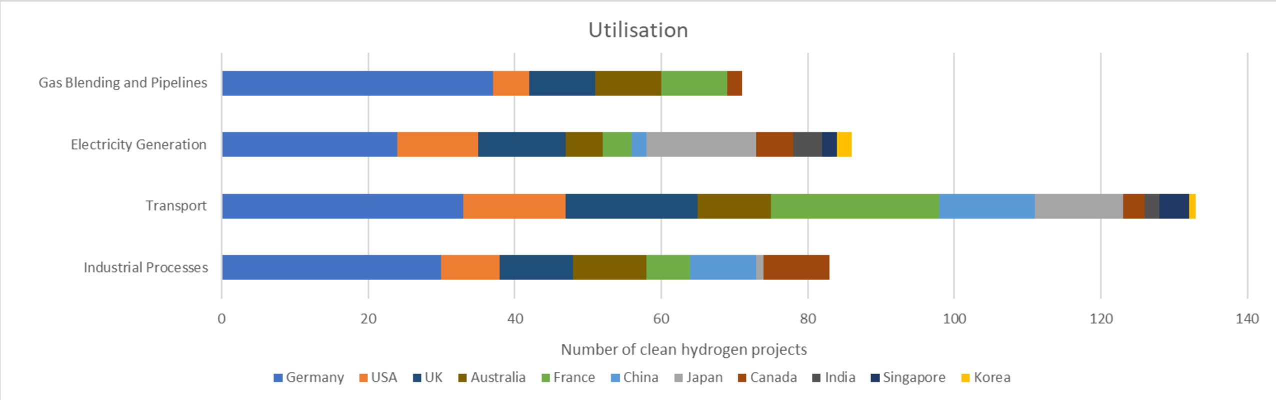
The following graph was derived from the *IEA's Hydrogen Projects Database*[24] (data as at October 2021). The IEA project database, specifically the 'clean hydrogen' projects (i.e. hydrogen production from renewable electrolysis, biomass and waste, and fossil fuel conversion with CCS or CCUS, and their value chains). For the purposes of this report, the dataset has been filtered to include only projects from 2010 through to projects expected to be operational by 2030 as this timespan best reflects current activities. Further, only projects that are at feasibility study, final investment decision, demonstration, or operational stage are included.

Figure 17: Count of 'Clean Hydrogen' projects in each country by sub-technology area



[24] IEA (2021) Hydrogen Projects Database. Available at https://www.iea.org/reports/hydrogen-projects-database





1.7.3 Summary of key stakeholders in the international landscape

Table 2 presents a non-exhaustive summary of the key bodies at the national level that are most active in the policy, funding, and implementation of RD&D in country hydrogen ecosystems. A complete list of key players for each country can be found in individual country report chapters. This includes a description of their roles in the science and innovation ecosystem, and a description of their specific activities with respect to hydrogen.

Table 2: Key global hydrogen stakeholders

Country	Government	Research	Consortia
Canada	Innovation, Science and Economic Development Canada (ISED) Natural Resources Canada (NRCan) Natural Sciences and Engineering Research Council of Canada (NSERC)	National Research Council (NRC) CanmetENERGY Ontario Tech University McGill University University of British Columbia	Canadian Hydrogen Fuel Cell Association (CHFCA) Hydrogen Business Council of Canada (HBCoC)
China	NEC – National Energy Commission National Development and Reform Committee (NDRC) Ministry of Science and Technology (MOST)	Chinese Academy of Sciences (CAS) Energy Research Institute (ERI) Chinese Academy of Engineering (CAE) Tsinghua University	China Hydrogen Alliance (H2CN) China Society of Automotive Engineers

Country	Government	Research	Consortia
	Ministry of Industry and Information Technology (MIIT)	Tianjin University Zhejiang University	
France	National Research Agency (ANR) Agency for Ecological Transition (ADEME)	Centre Nationale de Recherche Scientifique (CNRS) Alternative Energies and Atomic Energy Commission (CEA)	France Hydrogène **Europe:** Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Germany	Ministry of Economic Affairs and Climate Action (BMWK, was BMWi) Ministry of Education and Research (BMBF)	Fraunhofer Institute Helmholtz Association	National Organisation for Hydrogen and Fuel Cell Technology (NOW GmBh) **Europe:** Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
India	Ministry of New and Renewable Energy (MNRE) Department of Scientific and Industrial Research (DSIR) Department of Science and Technology (DST)	Council of Scientific & Industrial Research (CSIR) National Institute of Technology (NIT System) Academy of Scientific and Innovation Research (AcSIR)	Indian Hydrogen Alliance (IH2A)
Japan	Ministry of Economy, Trade and Industry (METI) New Energy and Industrial Technology Development Organisation (NEDO) Japan Science and Technology Agency (JST) Japan Oil, Gas and Metals National Corporation (JOGMEC)	National Institute of Advanced Industrial Science and Technology (AIST) Kyushu University Kyoto University University of Tokyo	CO2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA) Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) Japan Hydrogen Association (JH2A) Clean Fuel Ammonia Association (CFAA)
Singapore	Ministry of Trade and Industry/Economic Development Board/Energy Market Authority	Agency for Science, Technology and Research (A*STAR) Nanyang Technological University	Centre for Hydrogen Innovations (CHI) Singapore Energy Centre (SgEC)
Republic of Korea	Ministry of Trade Industry and Energy (MOTIE)	Korea Advanced Institute of Science and Technology (KAIST)	H2KOREA HyNet Consortium

Country	Government	Research	Consortia
	National Research Council of Science and Technology (NST)	Korea Institute of Energy Research (KIER)	
US	Department of Energy (DOE): Office of Energy Efficiency & Renewable Energy (EERE) Office of Fossil Energy and Carbon Management (FECM) Office of Nuclear Energy (NE) Office of Science (SC) Office of Clean Energy Demonstrations (OCED)	Department of Energy (DOE) national laboratories DOE Hydrogen and Fuel Cell Technologies Office research consortia[25]	H2@Scale[26] Fuel cell and Hydrogen Energy Association (FCHEA) 21st Century Truck Partnership
UK	Department for Business, Energy and Industrial Strategy (BEIS) UK Research and Innovation (UKRI) Engineering and Physical Sciences Research Council (EPSRC)	UK Research and Innovation-Engineering and Physical Sciences Council (UKRI-EPSRC) Imperial College London	UK Hydrogen and Fuel Cell Association (UK HFCA)

[25] EERE (2022) Hydrogen and Fuel Cell Technologies Office consortia. https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-consortia

[26] H2@Scale Initiative: https://www.energy.gov/eere/fuelcells/h2scale

Appendix

International Hydrogen strategy references

The assessment of global production and end-use pathways was inferred from a range of documents including national strategies and roadmaps, consultancy and industry documents and roadmaps where national strategies were not available, and in consultations with in-country stakeholders.

Multiple countries:

Ludwig-Bölkow-Systemtechnic GmbH (2020) International Hydrogen Strategies: A study commissioned by and in cooperation with the World Energy Council Germany. World Energy Council, Germany https://www.weltenergierat.de/wp-content/uploads/2020/10/WEC_H2_Strategies_finalreport.pdf

World Energy Council, EPRI and PwC (2021) Working Paper: National Hydrogen Strategies https://www.worldenergy.org/assets/downloads/Working_Paper_-_National_Hydrogen_Strategies_-_September_2021.pdf

Canada

Natural Resources Canada (2020) Hydrogen Strategy for Canada: Seizing the Opportunities for Hydrogen – A Call to Action https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

China

MarkLines (2021) China Energy-saving Vehicle & NEV Roadmap 2.0: Curbing Carbon Emissions for a Green Society https://www.marklines.com/en/report/rep2142_202104

Energy Iceberg (2021) China's Hydrogen Market in 14th Five-Year Plan: Provincial Strategy Breakdown. https://energyiceberg.com/hydrogen-14th-fyp-provincial-strategy/#Provinces_Prioritizing_Hydrogen

France

French Government (2020) National strategy for the development of decarbonised and renewable hydrogen in France. https://www.bdi.fr/wp-content/uploads/2020/03/PressKitProvisionalDraft-National-strategy-for-the-development-of-decarbonised-and-renewable-hydrogen-in-France.pdf

Ministry of Ecological Transition (2018) Hydrogen deployment plan for the energy transition. (In French) https://www.ecologie.gouv.fr/sites/default/files/Plan_deploiement_hydrogene.pdf

Fuel Cell Joint Undertaking (2020) Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans: France. https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20France%20%28ID%209473038%29.pdf

Germany

BMWi (2020) The National Hydrogen Strategy. The Federal Government, Germany https://www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

Fuel Cell Joint Undertaking (2020) Opportunities for Hydrogen Energy Technologies Considering the National Energy & Climate Plans: Germany. https://www.fch.europa.eu/sites/default/files/file_attach/Brochure%20FCH%20Germany%20%28ID%209473039%29.pdf

India

FTI Consulting (2020) India's Energy Transition Towards a Green Hydrogen Economy: White Paper on Building a Green Hydrogen Economy and Policy Roadmap for India
http://images.info.fticonsulting.com/Web/FTIConsultingInc/%7Ba15cdad1-1916-4f95-bad9-34cf950f842c%7D_FTI_Hydrogen_Green_Energy_Report_20201202.pdf

Japan

METI (2019) The Strategic Road Map for Hydrogen and Fuel Cells
https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf

METI (2021) Green Growth Strategy.
https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/pdf/ggs_full_en1013.pdf

Ministerial Council on Renewable Energy, Hydrogen and Related Issues (2017) Basic Hydrogen Strategy, Ministry of Economy, Trade and Industry (METI)

Singapore

KBR and Argus Media (2020) Study of Hydrogen Imports and Downstream Applications for Singapore. Prepared for the National Climate Change Secretariat, Strategy Group, Prime Minister's Office.
https://www.nccs.gov.sg/docs/default-source/default-document-library/hydrogen-study-report.pdf

The Republic of Korea

Government of the Republic of Korea (2020) 2050 Carbon Neutral Strategy of the Republic of Korea.
https://unfccc.int/sites/default/files/resource/LTS1_RKorea.pdf

United Kingdom

HM Government (2021) UK Hydrogen Strategy.
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

United States

DOE (2020) Department of Energy Hydrogen Program Plan
https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf

Fuel Cell and Hydrogen Energy Association (2020) Road Map to a US Hydrogen Economy
https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf

2022 AMR Plenary Session, Dr Sunita Satyapal

https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf

As Australia's national science agency and innovation catalyst, CSIRO is solving the greatest challenges through innovative science and technology.

CSIRO. Unlocking a better future for everyone.

Contact us

1300 363 400
+61 3 9545 2176
csiro.au/contact
csiro.au

For further information

CSIRO Hydrogen Industry Mission
Dr Patrick Hartley, Research Director
+61 3 9545 2595
patrick.hartley@csiro.au

CSIRO Energy
Dan O'Sullivan, Program Manager
+61 7 3833 5569
dan.osullivan@csiro.au

CSIRO Futures
Vivek Srinivasan, Associate Director
+61 3 9545 8057
vivek.srinivasan@csiro.au