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Hydrogen RD&D Collaboration Opportunities: Singapore

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Acknowledgments

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Executive summary: Singapore

Singapore has signalled their intent to develop a hydrogen economy that could contribute to longer-term decarbonisation targets under its Long-Term Low Emissions Development Strategy, supported by its strong innovation landscape, and potential role as a hydrogen hub. Singapore has established bilateral and multilateral relations with other countries to enable future hydrogen offtakes, and collaborates on the development of technical codes, regulations and standards with respect of hydrogen production, transport and supply-chain operations. The *Hydrogen RD&D Collaboration Opportunities: Singapore* chapter aims to enhance country-to-country engagement by providing stakeholders with an overview of Singapore's hydrogen priorities and ecosystem. This report also includes a publication and intellectual property (IP) scan, identifying the key stakeholders in Singapore actively undertaking hydrogen RD&D, both at the early research and commercialisation stage.

Singapore's hydrogen strategy

While Singapore has not published a national hydrogen strategy document, Singapore's hydrogen strategy is informed by studies such as the 'Study of Hydrogen Imports and Downstream Applications for Singapore', which was commissioned by National Climate Change Secretariat in the Prime Minister's Office, the Singapore Economic Development Board (EDB) and the Energy Market Authority (EMA) and completed in 2020. Some of the key factors that will influence Singapore's hydrogen strategy include resource limitations, enhanced air quality and lowered carbon emissions, and the creation of new industries and jobs. Singapore's hydrogen industry priorities are underpinned by its overarching Green Plan 2030 which has highlighted the intent to import green energy sources globally, particularly within the ASEAN region. This will facilitate Singapore's *Long-Term Low-Emissions Development Strategy* which is founded on the three pillars of transforming industry, economy, and society; harnessing emerging technologies as they mature; and pursuing international collaborations. Based on the analysis and recommendations of the 2020 study, Singapore's plans for hydrogen deployment could include domestic hydrogen production via steam methane reforming (SMR), gasification, and methane pyrolysis with carbon capture, utilisation and storage (CCUS), exporting hydrogen knowledge and technologies such as solid oxide electrolysis (SOE), international supply chains (for hydrogen import), and industrial manufacturing including oil refining, chemicals, auto producers and hydrogen merchants.

Singapore's targets and RD&D priorities

Singapore has not yet published national hydrogen targets but the 2020 '*Study of Hydrogen Imports and Downstream Applications for Singapore'* developed low, medium and high hydrogen deployment scenarios for 2030 and 2050, under which Singapore has envisioned the import of 1.3 million tonnes of hydrogen by 2050.

To achieve these goals, the 2020 study recommended investing in RD&D in the following areas.

Production
Electrolysis: Solid oxide
Fossil fuel conversion: Methane pyrolysis

Storage and distribution
Compression and liquefaction: liquefaction
Chemical: ammonia

Utilisation
Gas blending: gas separation
Fuel cells
Electricity generation: ammonia turbines, hydrogen turbines
Other: Cold energy recovery

Cross-cutting
Technoeconomic Analysis

Singapore's domestic hydrogen landscape

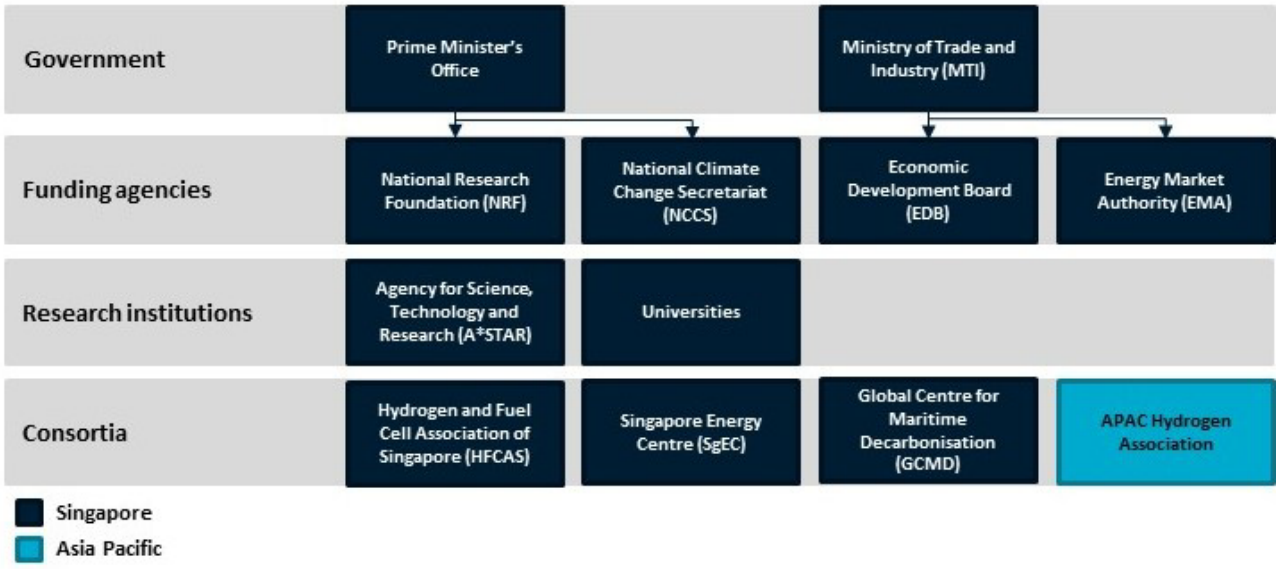
Singapore's science, technology and innovation (STI) system is led by the Research, Innovation and Enterprise Council (RIEC) that is housed within the National Research Foundation in the Prime Minister's Office. The RIEC oversees Singapore's five-year plans regarding the country's STI policy. Underneath the Office, several ministries – including the Ministry of Trade and Industry (MTI) – lead policy and provide RD&D funding within their respective areas. Hydrogen-specific strategy and funding is governed by the National Research Foundation (NRF) and the National Climate Change Secretariat (NCCS) which lie under the Prime Minister's Office, and the Economic Development Board (EDB) and Energy Market Authority (EMA) under the MTI.

RD&D implementation is carried out by research institutes, universities, large multinational company labs, small and medium enterprises (SMEs), and defence science labs, with the Agency for Science, Technology and Research (A*STAR) being the lead R&D agency in Singapore.

Singapore also has a number of consortia of industry, public sector and research sector players; including advocacy groups like the Hydrogen and Fuel Association of Singapore (HFCAS) and research consortia like the Singapore Energy Centre (SgEC). Private hydrogen funding is provided through the SgEC consortium, founded by Nanyang Technological University (NTU), the National University of Singapore (NUS), and ExxonMobil, and now also includes A*STAR. Private hydrogen funding is also provided by Temasek to the Centre for Hydrogen Innovations (CHI) at NUS. The Global Centre for Maritime Decarbonisation and the Singapore Maritime Institute have also funded studies and RD&D in hydrogen related technologies as part of their efforts on decarbonisation of the maritime sector. There are also a number of MoUs that have been signed between companies collaborating in the development of the hydrogen value chain.[1]

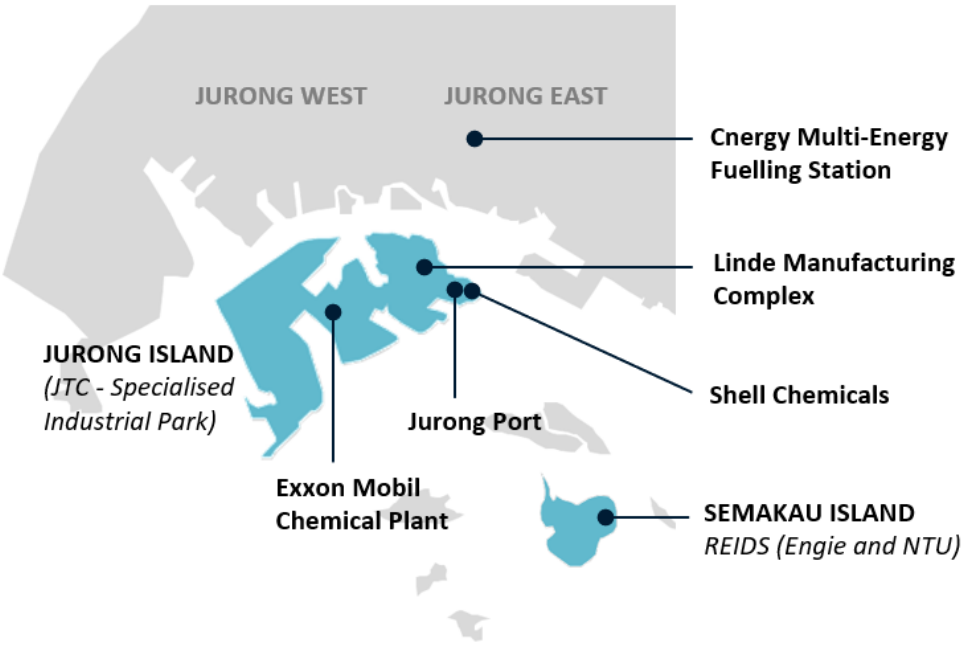
[1] https://www.nccs.gov.sg/media/press-release/singapore-looks-to-develop-and-deploy-lc-technological-solution

Figure 1: Singapore's hydrogen RD&D ecosystem



Industry, academia and government are collaborating to bring about hydrogen clusters (also known as hydrogen valleys, hubs or ecosystems). These are hydrogen value chain demonstrations and pilot projects that cut across sector applications. The major clusters of integrated hydrogen value chain activity in Singapore are:

Figure 2: Singapore's hydrogen clusters



IP and publications scan

Several universities, public research institutions and private companies are highly active in early-stage hydrogen research and late-stage technology commercialisation. This is reflected in hydrogen research publication and patent output data.

Table 1: Top institutions active in early-stage and late-stage hydrogen RD&D

Rank	Top organisations (Research publication output)	Top organisations (Hydrogen patent output)
1	NTU	NTU
2	NUS	A*STAR
3	A*STAR	HES Energy Systems PTE; Horizon Fuel Cell Technologies PTE; Lummus Technology; Temasek Polytechnic (all rank 3rd)
4	Institute of Materials Research and Engineering (IMRE)[2]	
5	Institute of Chemical and Engineering Sciences (ICES) (now known as Institute of Sustainability for Chemicals, Energy and Environment - ISCE[2])	

International collaboration

International collaboration is central to Singapore's hydrogen strategy. Singapore has identified the following areas for international collaboration in hydrogen, which include: conducting techno-economic analysis of hydrogen projects, facilitating a hydrogen export economy, and developing hydrogen regulations and standards.

In 2020, Australia and Singapore entered into a MoU to work together on low-emissions technologies and solutions. Key hydrogen-specific focus areas of the MoU include supply-chain studies, standards, and RD&D across the value chain, including CCUS. In 2021, Singapore established a similar MoU with Chile and an 'Arrangement of Cooperation' with New Zealand which focus on accelerating the development of low-carbon technologies. In 2022, Singapore and Japan signed a memorandum of cooperation on low-emissions solutions in multiple areas including long-term emissions reduction strategies and pathways, hydrogen, CCUS, ammonia fuel, measurement, reporting and verification (MRV), and transition finance.[3]

Singapore's NRF has also established the Campus for Research Excellence and Technological Enterprise (CREATE) – an international program for the purpose of RD&D collaboration. This program enables the creation of dedicated research centres with international partners, in various technology areas including sustainable energy and carbon emissions reduction. While no hydrogen-specific centres have yet been established with Australian institutions or other country institutions, this program could support sustained research collaborations in the future. The NRF also issues International Grant Calls, often resulting from MoUs between Singapore and partner countries, as another avenue for future RD&D collaboration.

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 reports in the series, and is non-exhaustive.

[2] IMRE and ISCE[2] are research institutes within A*STAR organisation

[3] MTI (2022) Singapore and Japan Sign Memorandum of Cooperation on Low-Emissions Solutions https://www.mti.gov.sg/Newsroom/Press-Releases/2022/01/Singapore-and-Japan-Sign-MOC-on-Low-Emissions-Solutions

1 Country analysis: Singapore

1.1 Introduction

Singapore has recently begun to explore the potential for hydrogen in its economy and has several comparative advantages at its disposal. Singapore has been dubbed Asia Pacific's most innovative economy for seven consecutive years by the Global Innovation Index, thanks to its strong institutions, sound regulatory environment, business friendliness, and its technologically skilled workforce.[4]

Singapore's strategy centres around its unique position as an international trading hub and its high-tech skills base. As such, trade of hydrogen and its derivatives, utilisation across maritime, industrial, and heavy vehicle applications, and hydrogen technology export, have been cited as promising areas for development in Singapore. To prepare for this, Singapore has established international partnerships with countries such as Australia to secure off-take agreements, facilitate the development of hydrogen supply chains, and to collaborate on regulations and standards.

Singaporean research institutions produce world class hydrogen-related research and have established research-industry partnerships with major multinational chemicals manufacturers based domestically. There is significant hydrogen RD&D occurring around the Jurong area, where several ports, chemical plants and manufacturing complexes are located. With strong synergies across facilities, and networks between multinational chemical corporations and research institutions, this area has been designated as a test-bed for sustainable energy and carbon capture technologies.

The *Hydrogen RD&D Collaboration Opportunities: Singapore* chapter presents an overview of the hydrogen RD&D landscape in Singapore, starting from the national strategy level, down to activity in specific hydrogen technology areas.

1.2 Singapore's hydrogen drivers, strategy and RD&D priorities

1.2.1 Singapore's key drivers

A hydrogen study commissioned by key government agencies analysed that Singapore's hydrogen strategy would be driven by:[5]

Resource limitations: Singapore generates 95% of its electricity from natural gas all of which is imported,[6] and has limited renewable and alternative energy production options due to its small geographical area.

Enhanced air quality and lower carbon emissions: Singapore in March 2020 updated its Paris climate pledge to an absolute target of peaking emissions at 65 metric tons of CO_2 equivalent (MtCO2e) by 2030,

[4] WIPO (2020) Global Innovation Index 2020: Singapore https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020/sg.pdf

[5] 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

[6] MFA (2021) Climate Change https://www.mfa.gov.sg/SINGAPORES-FOREIGN-POLICY/International-Issues/Climate-Change

and to halve these emissions to 33 MtCO2e by 2050[7] and recently revised their climate ambitions to achieve net zero emissions by or around mid-century.[8]

The creation of new industries and jobs: Singapore can leverage its technologically advanced society, strong RD&D community, and position as a trading and business 'hub' in the Asia Pacific region to unlock hydrogen opportunities.

1.2.2 Singapore's strategic hydrogen industry priorities

Singapore has released a number of overarching green economy and energy strategies that highlight the role of hydrogen as a part of its decarbonisation future:

- Singapore's *Green Plan 2030*[9] has signalled an intent to import green energy sources from the Association of Southeast Asian Nations (ASEAN) region and globally through electricity imports and hydrogen.
- Singapore's Energy Market Authority (EMA) published *Singapore's Energy Story*, outlining "Four Switches" to power Singapore in the future: natural gas, solar, regional power grids, and emerging low-carbon technologies (carbon capture, utilisation and storage [CCUS] and hydrogen).[10]
- Singapore's *Long-Term Low-Emissions Development Strategy*[11] is based on three pillars:
  - Transforming industry, economy and society;
  - Harnessing emerging technologies as they mature (including low-carbon hydrogen[12] and CCUS), and;
  - Pursuing and leveraging international collaborations (including in the areas of carbon storage and energy imports). Key sectors identified for decarbonisation include energy, industry, transport, buildings, and waste.

While Singapore has not published a national hydrogen strategy document, Singapore's hydrogen strategy is informed by studies such as the *Study of Hydrogen Imports and Downstream Applications for Singapore,*[13] published in 2021 by KBR and Argus Media on behalf of Singapore's National Climate Change Secretariat (NCCS). With respect to hydrogen, areas of strategic interest for Singapore are:

- **Imports:** Imports of low-carbon hydrogen from international projects in progressively large volumes, and developing trade partnerships with renewable energy-rich countries. Singapore has identified international hydrogen production projects that could bring down the landed price of hydrogen imports into Singapore. Singapore sees collaboration with major Asia Pacific importing countries

[7] MFA (2021) Climate Change https://www.mfa.gov.sg/SINGAPORES-FOREIGN-POLICY/International-Issues/Climate-Change

[8] NCCS (2022) Singapore Will Raise Climate Ambition to Achieve Net Zero Emissions By or Around Mid Century, and Revises Carbon Tax Levels from 2024 https://www.nccs.gov.sg/media/press-release/Singapore-will-raise-climate-ambition

[9] SG Green Plan 2030 (2021) Introducing the Green Plan. https://www.greenplan.gov.sg/key-focus-areas/overview

[10] EMA (2021) Singapore's Energy Story https://www.ema.gov.sg/ourenergystory

[11] NCCS (2020) Charting Singapore's Low-Carbon and Climate Resilient Future. https://www.nccs.gov.sg/files/docs/default-source/publications/nccsleds.pdf

[12] Singapore refers to hydrogen production from renewables and fossil fuel conversion with CCUS as low-carbon hydrogen. This aligns to Australia's terminology 'clean hydrogen'.

[13] 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.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

(Japan and Korea) and exporting countries (Australia, New Zealand and Malaysia) as key to developing a regional hydrogen economy.

- **Production:** Despite its reliance on hydrogen imports and anticipated low volumes of hydrogen production, Singapore has identified several actions in this area. Singapore already produces hydrogen using fossil fuels and can leverage its existing natural gas infrastructure to pilot hydrogen applications early on. Singapore can diversify its hydrogen sources by developing onshore methane pyrolysis, for domestic production, potentially with carbon capture and storage (CCS) or carbon capture and utilisation (CCU). This can be integrated into existing natural gas infrastructure and make use of bio-feedstocks (e.g. waste). Singapore can also leverage its RD&D capabilities in solid oxide electrolysis (SOE) to export production technologies.
- **Storage and Distribution:** Given its position as an international trading hub, Singapore may need to develop several complementary infrastructure options to cater for different forms of hydrogen transport and storage in international supply chains, and uncertainties around future carriers of choice. Gaseous hydrogen, liquefied hydrogen, ammonia, methanol and liquid organic hydrogen carriers (LOHCs) are considered the most viable for differing reasons.
- **Utilisation:** Singapore has identified maritime and ports, mobility (heavy vehicles), industry and manufacturing (including oil refining, chemicals, auto producers and hydrogen merchants), gas network blending, and power generation as feasible application options.
- **Technology export:** Singapore also seeks to position itself as a hydrogen 'hub' to export hydrogen knowledge and technologies developed by its strong RD&D community.

Singapore's hydrogen targets

While Singapore has not published national hydrogen targets, the 2020 '*Study of Hydrogen Imports and Downstream Applications for Singapore'* has built low, medium, and high hydrogen deployment scenarios for 2030 and 2050. Table 2 below illustrates the ranges envisioned between low and high deployment scenarios in 2030 and 2050.

Table 2: Singapore's hydrogen targets[14]

	2030	2050
Imports		1.3 million tonnes (assuming 10% southeast Asian demand)
Power Generation	0-5%	0-100%
Gas networks	0-65%	0-65%
Mobility (FCEVs)		
Private Cars	0	0
Taxis	0-20%	0-50%
LGVs (Large Goods Vehicle)	0	0-20%
HGVs (Heavy Goods Vehicle)	0-30%	100%
Bus	0-30%	0-50%
Industry		
Auto Producers	0-5%	0-100%
Hydrogen Merchants	0-33%	0-100%
Maritime		
Yard Trucks	0	25%-75%
Cranes	0	0-75%
Tugboats	20%-30%	50%-100%
Passenger Boats	20%-30%	50%-100%
Bunker Tankers	0-100%	0-100%

In addition to the above targets, Singapore's *Green Plan 2030*[15] has set a target to achieve carbon-neutral growth for aviation from 2020, and to reduce greenhouse gas emissions from international maritime shipping by at least 50% by 2050 compared to 2008 levels.

[14] 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

[15] SG Green Plan (2021) SG Green Plan https://www.greenplan.gov.sg/

1.2.3 Singapore's hydrogen RD&D priorities

According to the 2020 '*Study of Hydrogen Imports and Downstream Applications for Singapore',* Singapore's approach to hydrogen RD&D prioritisation could be based on technology readiness level (TRL), and its own capabilities and strengths: [16]

- For TRLs 1-4 (Development), Singapore can leverage its R&D capabilities to build domestic hydrogen intellectual property (IP) capability, export its technologies globally, and influence design and integration in the Singaporean context.
- For TRLs 3-7 (Demonstration), Singapore sees itself collaborating in joint ventures or partnerships between Singaporean academics, and local or international original equipment manufacturers (OEMs) and developers. Singapore positions itself as a potential hub for testing and demonstration.
- For TRLs 6-9 (Deployment), Singapore seeks to undertake a procurement approach. Mature technologies may not be relevant to the Singaporean context but could be procured by Singapore in scenarios where an already commercialised solution is required. Singapore does not believe it has the RD&D capabilities to contribute to the development of already mature technologies. Technologies that Singapore seek to procure, but still require RD&D at large scale globally are LOHC dehydrogenation, and potentially hydrogen-fired combined cycle gas turbines (CCGTs).

The *Study of Hydrogen Imports and Downstream Applications for Singapore*[17] identified potential RD&D areas specific to Singapore based on the above. These are summarised in Table 3.

Table 3: Singapore's hydrogen RD&D priorities[18]

Supply chain area	Sub-technology areas	Singapore's key RD&D priorities
Production	Fossil fuel conversion	**Methane pyrolysis:** Development and demonstration of a cost-effective, regenerative catalyst.
	Electrolysis	**Solid oxide electrolysis (SOE):** Improving electrolyser efficiency to 80%
Storage and distribution	Liquefied hydrogen storage materials	Reducing CAPEX through the development of new materials to enable storage of liquefied hydrogen, and to withstand extreme operating conditions.
Utilisation	Ammonia cracking	Development of catalysts to provide high purity hydrogen. Improved process efficiency. Technology scale-up for commercial applications.

[16] 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

[17] 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

[18] Singapore's Key RD&D Priorities derived from: 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

Supply chain area	Sub-technology areas	Singapore's key RD&D priorities
	Fuel cells[19]	High performance nano-platinum catalysts, non-platinum based catalysts, catalyst-coated membranes (CCM), membrane-electrode-assembly (MEA), metalling bipolar plate design and coating, and stack development.[19]
	Hydrogen combined cycle gas turbines (CCGTs)	Testing and scale-up of turbines with potential to integrate into Singapore's existing power infrastructure. Operate CCGTs reliably and efficiently in Singapore's climate. Build operational capability and understand technical considerations for Singapore's power sector e.g. hot-switching to alternative fuels, and performing frequency regulation. Strategy for fuel stockpiling.
	Cold energy recovery	Overcoming boil-off losses and cold energy recovery (currently not done in Singapore). Singapore is seeking off-takers in this area. Singapore seeks to leverage its capability in modelling and simulation of liquefied natural gas (LNG) boil off and cold energy recovery from regasification to develop technologies and optimise hydrogen receiving facilities.
Cross-cutting	Technoeconomic analysis	Collaborative technoeconomic studies with regional partners to develop the hydrogen economy in Asia Pacific.

1.3 Singapore's hydrogen RD&D ecosystem

1.3.1 Regulatory bodies and policy ecosystem

Overview of Singapore's STI policy landscape[20]

Singapore has been dubbed Asia Pacific's most innovative economy for seven consecutive years by the Global Innovation Index, thanks to its strong institutions, sound regulatory environment, business friendliness, and its technologically skilled workforce.[21] Singapore's science, technology and innovation (STI) ecosystem is comprised of a number of actors including ministries, RD&D funding bodies and RD&D implementation institutions. At the governance level, Singapore's STI system is led by the Research, Innovation and Enterprise Council (RIEC), which sits within the Prime Minister's Office and oversees Singapore's five-year plans and policies regarding overall STI policy. This council is also supported by the National Research Foundation (NRF), which also sits in the Prime Minister's Office.

Underneath this sit several ministries, including Trade and Industry, Education, Health, and Defence. These ministries lead policy within their respective areas, including direction for RD&D funding bodies that sit within their remits. Finally, RD&D implementation is carried out by several players including research institutes, universities, large multinational company labs, small and medium enterprises (SMEs), hospitals,

[19] Consultation with in-country stakeholders

[20] NRF (2021) RIE Ecosystem https://www.nrf.gov.sg/about-nrf/rie-ecosystem

[21] WIPO (2020) Global Innovation Index 2020: Singapore https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020/sg.pdf

and defence science labs. The lead implementing agency in Singapore is A*STAR (Agency for Science, Technology and Research).

Overview of Singapore's hydrogen policy landscape

In the area of hydrogen, the key bodies responsible for strategy and policy are the NRF, the NCCS, the EDB (Economic Development Board) and the EMA. A*STAR is the key institution involved in the implementation of the RD&D tied to Singapore's hydrogen strategy and hosts the Coordination Office for the Low Carbon Energy Research Funding Initiative. Singapore also has several prominent universities, SMEs and large multi-national corporations making a significant contribution to hydrogen research globally (see *Section 1.6* for Singapore's leading universities and institutions in hydrogen). Figure 3 illustrates Singapore's hydrogen RD&D ecosystem, and Table 4 provides a more detailed description of stakeholder roles as well as their hydrogen-specific initiatives.

Figure 3: Summary of Singapore's hydrogen policy ecosystem

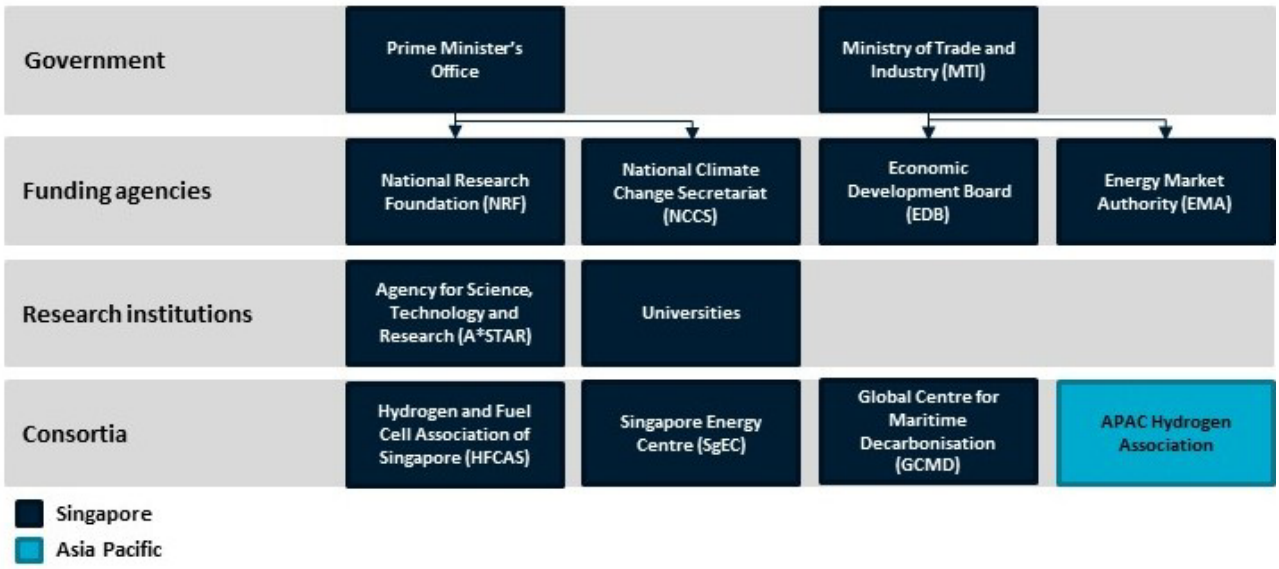


Table 4: Summary of key regulatory bodies

Body	Role in RD&D ecosystem	Hydrogen initiatives
NRF *The National Research Foundation*	The NRF is a department sitting within the Prime Minister's Office and is the key body setting the national RD&D, innovation and enterprise agenda.[22] The NRF oversees the Campus for Research Excellence and Technological Enterprise (CREATE) programs. CREATE is an international research campus and	The NRF is involved in the SGD 49 million Research Fund for Low-Carbon Energy Solutions, which includes hydrogen technologies and CCUS.[24]

[22] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[24] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

Body	Role in RD&D ecosystem	Hydrogen initiatives
	innovation hub.[23] Under CREATE, Research Centres have been established with key global research institutions in a number of research areas.	
NCCS *National Climate Change Secretariat*	The NCCS is part of the Strategy Group in the Prime Minister's Office. The NCCS develops and implements domestic and international policy and strategy around climate change.[25]	The NCCS is involved in the SGD 49 million Research Fund for Low-Carbon Energy Solutions, which includes hydrogen technologies and CCUS.[26]
MTI *Ministry of Trade and Industry* **(incl the EDB and the EMA)** *(Singapore's Economic Development Board)* *(Energy Market Authority)*	The MTI is concerned with the promotion of economic growth and development of trade and industrial policy. The EDB is a statutory board under the MTI, concerned with strategy around industry development, international business, investment and collaboration. [27] The EMA is a statutory board under the MTI, concerned with the supply and competition in the energy sector, and designing progressive energy landscape.[28]	The EDB and the EMA are co-leading the SGD 49 million Research Fund for Low-Carbon Energy Solutions, which includes hydrogen technologies and CCUS.[29]
A*STAR *Agency for Science, Technology and Research*	A*STAR is Singapore's leading public sector R&D agency. A*STAR's role is to bridge the gap between academia and industry, and to create economic growth for Singapore.[30]	A*STAR is leading the implementation of RD&D projects under the SGD 49 million Low-Carbon Energy Reaching Funding Initiative, which includes hydrogen technologies and CCUS.[31]

[23] CREATE. About CREATE. https://www.create.edu.sg/about-create

[25] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[26] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[27] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[28] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[29] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[30] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[31] EMA (2020) $49 Million Research Fund for Low-Carbon Energy Solutions. Media Releases https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

1.3.2 Hydrogen consortia

Outside of government ministries and agencies, hydrogen RD&D activity in Singapore is also undertaken by peak bodies and a consortia of industry, public sector and research sector players. Singapore is also active in hydrogen consortia at the Asia Pacific level. Table 5 outlines the key hydrogen peak bodies and consortia for Singapore.

Table 5: Singapore's hydrogen consortia

Consortium	Description
HFCAS *Hydrogen and Fuel Cell Association of Singapore*	HFCAS was launched in 2007 with support from the EDB. This association supports collaboration between members across the hydrogen and fuel cell value chain, and across government agencies, academia and industry players.[32]
SgEC *Singapore Energy Centre*	The SgEC is a consortium founded by Nanyang Technological University (NTU), the National University of Singapore (NUS) and ExxonMobil, and now also includes A*STAR. The centre serves as a collaboration platform between universities and industry. The SgEC leads a number of core projects in fundamental science and engineering research areas and facilitates member-directed projects defined by its industry members and undertaken with research partners.[33] Key research areas covered by the consortium includes hydrogen, but also energy efficiency, conversion and storage, water and energy security, climate change, energy policy and education.[34]
GCMD *Global Centre for Maritime Decarbonisation*	A non-profit organisation to support the marine industry's decarbonisation in line with the International Maritime Organisation's (IMO) goals. The GMCD was founded in 2021 by the Maritime and Port Authority of Singapore (MPA) in partnership with BHP, BW Group, Eastern Pacific Shipping, Foundation Det Norske Veritas, Ocean Network Express, and Sembcorp Marine.[35] The GMCD supports studies and demonstration projects including liquid hydrogen as a fuel, hydrogen-derived fuels, dual fuel internal combustion engines, fuel cells, and CCUs for maritime applications.[36]
APAC Hydrogen Association *Asia-Pacific Hydrogen Association*	The APAC Hydrogen Association is an international hydrogen association across the Asia Pacific region and was launched in Singapore in 2019. This association, established by industry players throughout Asia's renewable sector, is based in Singapore. The role of this organisation is to coordinate international policy, communication, research and analysis, as well as support networking opportunities.[37]

[32] HFCAS (2021) Background https://hfcas.org/background-1

[33] SgEC (2021) How the SgEC works https://sgec.sg/how-sgec-work/

[34] SgEC (2020) Key Research Areas https://sgec.sg/key-research-area-topics/

[35] MPA (2021) Maritime Energy Transition Picks Up Pace with Establishment of Global Centre for Maritime Decarbonisation in Singapore. News Releases and Speeches. https://www.mpa.gov.sg/web/portal/home/media-centre/news-releases/detail/bf2aaf98-833a-4515-8f3f-64d534fa36c3

[36] GMCD (2021) Projects https://www.gcformd.org/our-projects

[37] Renewables Now (2020) APAC Hydrogen Association launched in Singapore. https://renewablesnow.com/news/apac-hydrogen-association-launched-in-singapore-687299/

1.3.3 Funding mechanisms

Overview of Singapore's hydrogen public budget allocations

Several key government institutions are involved in the provision of funding support for hydrogen RD&D in Singapore. These are listed in Table 6 below.

Table 6: Public funding for hydrogen RD&D

Provider	Funding mechanism	International eligibility to participate
EDB and EMA	**Low-Carbon Energy Research Funding Initiative** Singapore announced (SGD 49 million for the Low-Carbon Energy Reaching Funding Initiative to support RD&D in low-carbon energy projects including hydrogen technologies and CCUS. This is a multi-agency initiative involving A*STAR, the EDB, the EMA, the NCCS, and the NRF. Co-leads are the EDB and EMA to ensure project relevance to the energy and industrial sectors, while A*STAR will be the implementing agency.[38] Calls for the first grant period (January 2021-May 2021) have now closed. Grants of up to SGD 10 million were awarded per project for Tier 1, and SGD 4 million per project for Tier 2, each for a period of 3 years. Project leads must hold 70% appointment in a Singaporean public sector research institute. Teams may choose to include collaborators, however collaborators cannot receive any funding from the award.[39]	Potential. Funding is only available for domestic public research institutes, and projects must take place domestically. Teams may be able to include international collaborators, but collaborators are not eligible to receive funding.
NRF	**Research, Innovation & Enterprise Plan 2025 (RIE2025)** Singapore's NRF (Prime Minister's Office) has launched the *Research, Innovation & Enterprise Plan 2025 (RIE2025)* to promote domestic innovation and attract companies to establish their RD&D activities in Singapore to develop sustainability solutions.[40] The program will fund activity in low-carbon energy technologies such as hydrogen and CCUS (among others) to support *Singapore's Energy Story*,[41] and *Singapore's Long-Term Low-Emissions Development Strategy*.[42] This initiative has a budget of approximately SGD 25 billion comprised of:[43] • SGD 7.3 billion to strengthen capabilities at universities and A*STAR Research Institutes. • SGD 6.5 billion for mission-oriented research.	Potential. The RIE may be open to international talent and partnerships. Current RIE grants complement prior grants such as the CREATE international collaboration initiative (see Section 1.5.3 for more detail.)

[38] EMA (2020) $49 Million Research Fund For Low-Carbon Energy Solutions https://www.ema.gov.sg/media_release.aspx?news_sid=20201025eyksiX0dgcEH

[39] A*STAR (2021) Low-Carbon Energy Research Funding Initiative (LCER FI) First Grant Call 2021 https://www.a-star.edu.sg/Research/funding-opportunities/lcer-fi-grant

[40] SG Green Plan (2021) Green Economy https://www.greenplan.gov.sg/key-focus-areas/vision/

[41] EMA (2021) Singapore's Energy Story https://www.ema.gov.sg/ourenergystory

[42] NCCS (2020) Singapore's Long-Term Low-emissions Development Strategy https://www.nccs.gov.sg/media/publications/singapores-long-term-low-emissions-development-strategy

[43] NRF (2021) RIE2025 Plan. Prime Minister's Office, Singapore https://www.nrf.gov.sg/rie2025-plan

Provider	Funding mechanism	International eligibility to participate
	• SGD 5.2 billion to develop enterprise innovation capabilities and entrepreneurial talent. • SGD 3.75 billion to support new programs for future needs and emerging opportunities. • SGD 2.2 billion for postgraduate programs and talent development	
Enterprise Singapore	**Enterprise Sustainability Programme** This program supports enterprises, particularly SMEs, to develop capabilities in the area of sustainability. [44] Enterprise Singapore will set aside up to SGD 180 million for the program over four years.[45]	No Data
A*STAR	**Industry Alignment Fund** The A*STAR leads two programs under the Industry Alignment fund; the *Pre-Positioning Programme* (IAF-PP) and the *Industry Collaboration Projects (IAF-ICP).* These are not hydrogen specific but are designed to support the transfer of capabilities, IP and technologies to industry application, with the aim of achieving tangible economic impact.[46]	No Data.
MAS	**Green Finance Action Plan** In its *Green Plan 2030*, Singapore announced it seeks to be the leading centre for Green Finance in Asia and globally.[47] The Monetary Authority of Singapore (MAS) launched the *Green Finance Action Plan in 2019*. This includes developing green finance solutions and markets as well as building international cooperation for green finance (through the International Platform on Sustainable Finance). The MAS is working to establish Centres of Excellence to drive green finance research and training, and is developing a grant scheme for green and sustainability-linked loans to provide a wider range of financing options for companies.[48]	Potential. The plan has partnered with the Imperial College Business School (UK) to provide Asia-Focused Climate Research and Training. This indicates potential international collaboration on cross-cutting areas (financial).

[44] Enterprise Singapore (2021) Business Development and leadership, Budget 2021 https://www.enterprisesg.gov.sg/Campaigns/budget-2021/business-development-and-leadership

[45] Enterprise Singapore (2021) Enterprise Singapore launches Enterprise Sustainability Programme to support enterprises in building sustainability capabilities. Media Release. https://www.enterprisesg.gov.sg/-/media/esg/files/media-centre/media-releases/2021/october/mr07221_enterprise-singapore-launches-enterprise-sustainability-programme-to-support-enterprises-in-building-sustainability-capabilities.pdf?la=en

[46] A*STAR (2021) Industry Alignment Fund – Pre-positioning Programme (IAF-PP) https://www.a-star.edu.sg/Research/funding-opportunities/iaf-pp; A*STAR (2021) Industry Alignment Fund – Industry Collaboration Projects (IAF-ICP) https://www.a-star.edu.sg/Research/funding-opportunities/iaf-icp

[47] SG Green Plan (2021) Green Economy https://www.greenplan.gov.sg/key-focus-areas/vision/

[48] MAS (2021) Greening the Financial System https://www.mas.gov.sg/who-we-are/annual-reports/annual-report-2019-2020/greening-the-financial-system

Private funding for hydrogen RD&D

The SgEC consortium (founded by NTU, NUS and Exxon Mobil) leads a number of core projects in fundamental science and engineering research areas. It also facilitates member-directed projects defined by its industry members and undertaken with research partners.[49]

In July 2022, the Centre for Hydrogen Innovations (CHI) commenced operations at NUS with funding support of SGD 25 million from Temasek Holdings and NUS[50]. The Centre aims to develop breakthrough technologies to make hydrogen commercially available as a green energy source.

1.3.4 Other key hydrogen policies, regulation and legislation

As the hydrogen economy is still in its infancy in Singapore, hydrogen policy, regulation and legislation is not yet fully defined. The Singaporean government is expected to adopt an incremental approach to safety risk management through the use of pilot projects, and over a period of time before commercial scale up. With the governments' responsive track record, legislation reforms are expected to take place as hydrogen solutions become more widely deployed in Singapore.[51]

As hydrogen deployment progresses in Singapore, an assessment of the applicability of existing laws with respect to gas will need to be conducted across the value chain. The *Study of Hydrogen Imports and Downstream Applications for Singapore*[52] recommends a review and adoption of measures taken by other economies around the world where hydrogen applications are already deployed. Further, in July 2021, Singapore and New Zealand signed an agreement to develop standards and certification for establishing a supply chain for low-carbon hydrogen and hydrogen derivatives.[53]

Current gas laws impacting hydrogen deployment are as follows:

- Hydrogen is subject to flammable material laws and regulations (the FS ACT and the FS Regulations), which requires licensing with respect to storage, import, transportation, dispensation and distribution via pipelines. [54]
- Hydrogen is subject to laws and regulations of the Maritime and Port Authority of Singapore ACT (MPA ACT and MPA Regulations), whereby vessels shipping compressed hydrogen are subject to stricter regulations. [55]
- Hydrogen is subject to the Workplace Safety and Health laws and regulations (WSH Act and WSH Regulations), where commercial premises storing, processing or manufacturing using hydrogen are deemed a 'major hazard installation'. [56]

[49] SgEC (2021) How the SgEC works https://sgec.sg/how-sgec-work/

[50] NUS (2022) New NUS Centre of Hydrogen Innovations embarks on cutting-edge research to power a hydrogen economy https://news.nus.edu.sg/new-nus-centre-for-hydrogen-innovations-to-power-a-hydrogen-economy/

[51] CMS (2020) Hydrogen Law and Regulation in Singapore. https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/singapore

[52] 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

[53] MFAT (2021) New Zealand and Singapore link up on Hydrogen https://www.mfat.govt.nz/br/trade/mfat-market-reports/market-reports-asia/new-zealand-and-singapore-link-up-on-hydrogen-august-2021/

[54] CMS (2020) Hydrogen Law and Regulation in Singapore. https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/singapore

[55] CMS (2020) Hydrogen Law and Regulation in Singapore. https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/singapore

[56] CMS (2020) Hydrogen Law and Regulation in Singapore. https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/singapore

1.4 Singapore's domestic hydrogen RD&D projects

1.4.1 Major domestic RD&D hydrogen projects

A*STAR Research Programs

The Urban and Green Technology Horizontal Technology Coordinating Office (UGT HTCO) within the A*STAR scopes and coordinates R&D programs in the areas of decarbonisation, energy efficiency/electrification, infrastructure, sustainability in manufacturing, and waste management. Major programs within this cluster are summarised in Table 7.

Nanyang Technological University Research Programs

The Energy Research Institute @ NTU (ERI@N) has 10 research focus areas, one of which is energy storage and hydrogen and fuel cells. The group has previously carried out research in polymer electrolyte membrane fuel cells and electrolysers (PEMFC and PEMEC), solid oxide fuel cells and electrolysers (SOFC and SOE), and catalyst developments.

To complement this, the group has expanded its focus to hydrogen generation, transportation and end use. The group's current research focus includes:

- Advanced materials, catalysis and electrochemistry;
- Multi-physics modelling and design;
- Techno-economic-environmental assessment with and without the support of policies; and
- Demonstration and commercialisation.

The group is also conducting hydrogen end-use test-bed activities in its Experimental Power Grid Centre (EPGC)[57] and on Semakau Island.[58]

The group is also working with A*STAR, and the SgEC consortium founded by NTU, NUS, and Exxon Mobil.

National University of Singapore Research Programs[50, 59]

The Green Energy Programme at NUS carries out fundamental and applied research to improve and develop commercial hydrogen solutions across production, storage and conversion. The program is made up of five components shown in Table 7.

[57] NTU (2021) Experimental Power Grid Centre https://www.ntu.edu.sg/erian/research-capabilities/experimental-power-grid-centre

[58] Engie (2020) Engie EPS contributes to Southeast Asia's transition towards a green economy with a hydrogen-based energy storage system on Semakau Island. https://engie-eps.com/corporate/engie-eps-hydrogen-technology-records-a-new-achievement-in-singapore/

[59] NUS (2021) Green Energy Programme. Faculty of Engineering, Faculty of Science. https://greenenergy.nus.edu.sg/

Table 7: NUS Green Energy Programme elements

NUS Green Energy Programme	Description
Catalyst Discovery and Design	Areas of study include electrocatalysis, integrated nano-catalysts, single-atom catalysts, and photo-catalysis. Application areas include selectivity and hydrogenation of CO_2 to methanol, and conversion of methanol to complex value-added chemicals.
Advanced Characterisation Tool	The advanced characterisation tools team is a key enabler, enhancing studies in areas such as catalytic nanomaterials, particularly in CO_2 utilisation and conversion.
Molecular Modelling	Research focuses on new approaches to nano-catalyst design and characterisation of catalytic processes, applied to improving CO_2 conversion to fuel.
Systems Engineering	Research areas include process systems engineering, and multi-scale systematic analysis. Applications include solar powered electrolysis, hydrogen conversion to fuels and platform chemicals and CCS.
Process Scale-up	This group is focused on efficient and sustainable commercialisation and scale up, integrated with other activities within the NUS Green Energy Programme.

The Centre for Hydrogen Innovations conducts research on creating technologies to make hydrogen commercially viable as a green energy source. The focus areas for the program include hydrogen carriers and supply chain for hydrogen imports, local production of hydrogen through electrolysis and methane pyrolysis powered by solar energy, chemical carriers of hydrogen and its conversion for distribution of hydrogen, utilisation of hydrogen as a fuel and as raw materials for the chemical industry, hydrogen regeneration from chemical carriers, and the safe and cost-effective storage and distribution of hydrogen.

1.4.2 Major domestic commercial hydrogen projects

The scope of this report is on research, development and demonstration (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.

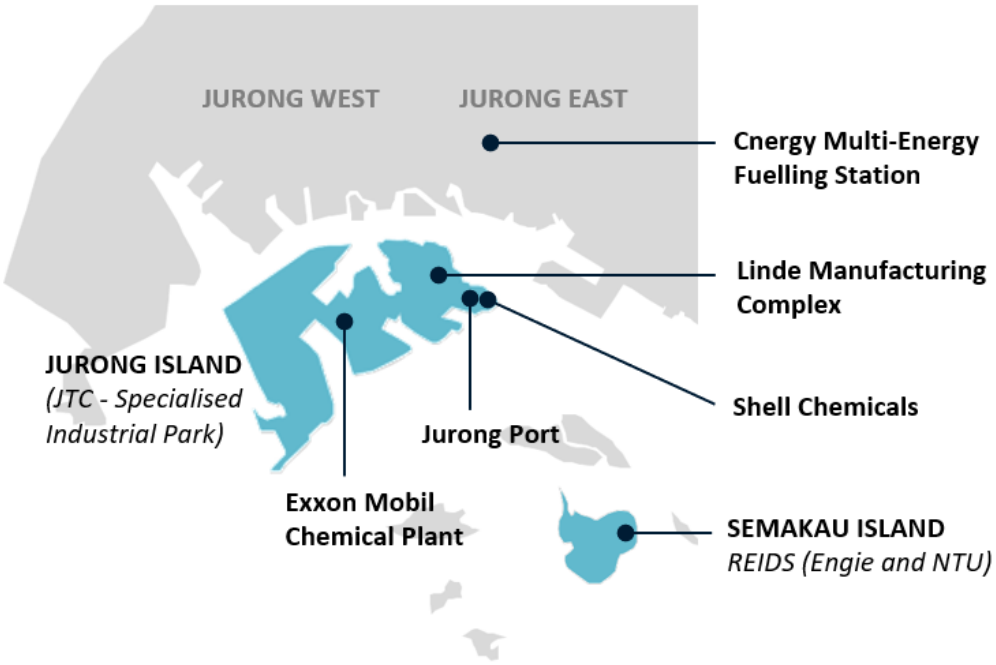
HyResource provides a directory of publicly available databases and information sources on international projects:

- https://research.csiro.au/hyresource/projects/international/

1.4.3 Singapore's hydrogen clusters

Singapore has begun to deploy integrated hydrogen value chain activities in some key locations related to chemicals manufacturing, ports, and waste management. The following section provides a detailed description of Singapore's hydrogen clusters (also referred to as valleys, hubs or ecosystems). Figure 4 provides a map of these key areas and the stakeholders involved.

Figure 4: Singapore's hydrogen clusters



Jurong Island

Jurong Island is the anchor of Singapore's energy and chemicals industry, and a major global chemical park. This industrial cluster is supported by shared infrastructure (pipelines, combined heat and power plants, storage facilities, and port terminals) which enables greater competitiveness. In Singapore's RIE2025 Plan, Jurong Island was designated as a test-bed for the adoption of sustainable energy and carbon capture technologies.[60]

This was spearheaded by the 2019 *Jurong Island Circular Economy (JICE)* study. The study identified scope for collaboration and synergies in the use of cleaner energy and emerging technologies. The JICE study also found that there is potential for further studies to roadmap the utilisation of cold energy (low temperatures from the LNG gas terminal) on the island.[61] The study was led by JTC Corporation (JTC) in collaboration with 51 companies (including Chevron, ExxonMobil and Shell). The JTC Corporation is leading planning, promotion and development of the industrial landscape in Singapore, including the industrial township on Jurong (Jurong Industrial Estate), and a chemical hub on Jurong.[62]

[60] SG Green Plan (2021) Our Vision https://www.greenplan.gov.sg/key-focus-areas/vision/; Witteveen+Bos (2021) Results of circularity study on Singapore's Jurong Island Presented https://www.witteveenbos.com/news/results-of-circularity-study-on-singapores-jurong-island-presented/

[61] JTC (2021) 51 companies including Chevron, ExxonMobil and Shell jointly support industry-first circular economy study by JTC to optimise resource use as Jurong Island transforms into a sustainable energy and chemicals park. News & Publications https://www.jtc.gov.sg/news-and-publications/press-releases/Pages/20210819.aspx

[62] JTC (2021) About Us https://www.jtc.gov.sg/about-us/Pages/default.aspx

Two innovation calls have been made, led by the JTC, to transform Jurong into a more sustainable energy and chemicals park:

- The Jurong Island Innovation Challenge (JIIC) will crowdsource innovation proposals from start-ups and SMEs in the areas of energy efficiency, emissions reduction, water management, and chemical waste management in Jurong. The JIIC will provide funding support to develop their solution. Grant support of up to SGD 2 million will come from the National Innovation Challenge.
- The Jurong Island Renewable Energy Request-for-Proposals (JI Renewable Energy RFP), which was launched 25 October 2021 and will close January 2022, be made in the area of energy solutions, to act as a test-bed for renewable energy and energy storage systems.

Jurong Port

In 2020, the PSA Corporation and Jurong Port announced the launch of a Hydrogen Import Study in Jurong, with Sembcorp Industries, Singapore LNG Corporation, City Gas, and Japanese companies Chiyoda Corporation and Mitsubishi Corporation. The study will demonstrate Chiyoda's SPERA Hydrogen LOHC technology to transport hydrogen. Jurong port is looking to set up a hydrogen hub to store, extract and transfer hydrogen produced from renewables to domestic markets using its existing infrastructure, as well as re-exporting to international markets.[63]

Linde's Jurong Manufacturing and Gasification complex

In 2019, Linde, in partnership with Exxon Mobil, announced a USD 1.4 billion investment to build a new manufacturing complex integrated with its existing gasification facility on Jurong Island. This complex will quadruple Singapore's capacity to produce hydrogen and syngas.[64]

Cnergy multi-energy filling station, Jurong

Surbana Jurong, and Union Gas have partnered to explore Singapore's first multi-energy filling station under the Cnergy brand. While the station currently offers natural gas and diesel the companies are exploring the possibility of transforming the site to include the on-site production of hydrogen fuel and dispensation for fuel cell vehicles.[65]

Semakau Island

The landfill island of Semakau has become a test-bed platform for the design, demonstration and testing of sustainable energy solutions for urban areas and for Southeast Asia. The Renewable Energy Integration Demonstrator (REIDS) on Semakau is led by ENGIE Lab Singapore and NTU. At the time of construction in 2019, this was the largest system of interconnected micro-grids in Southeast Asia.[66] At this site, ENGIE has supplied a hydrogen Power-to-Power (PtP) system comprising a proprietary electrolyser, and a fuel cell system.[67]

[63] Offshore Energy (2020) PSA, Jurong Port, Others to Launch Hydrogen Import Study https://www.offshore-energy.biz/psa-jurong-port-others-to-launch-hydrogen-import-study/

[64] Linde Engineering (2019) Linde Celebrates Groundbreaking for New US$1.4 billion (S$1.9 billion) Integrated Manufacturing Complex on Jurong Island, Singapore. https://www.linde-engineering.com/en/news_and_media/press_releases/news-20190827.html

[65] Surbana Jurong (2021) Union Gas partners Surbana Jurong to explore Singapore's first Multi-Energy Filling Station. https://surbanajurong.com/resources/press-releases/union-gas-partners-surbana-jurong-to-explore-singapores-first-multi-energy-filling-station/

[66] NTU (2021) Renewable Energy Integration Demonstrator – Singapore https://www.ntu.edu.sg/erian/research-capabilities/renewable-energy-integration-demonstrator---singapore

[67] Engie (2020) Engie EPS contributes to Southeast Asia's transition towards a green economy with a hydrogen-based energy storage system on Semakau Island. https://engie-eps.com/corporate/engie-eps-hydrogen-technology-records-a-new-achievement-in-singapore/

1.5 International collaboration and joint RD&D project

1.5.1 Overview of Singapore's approach to international collaboration

International collaboration is central to Singapore's strategy for incorporating hydrogen into its economy. This is because Singapore is reliant on energy imports to meet its energy needs, and is also an international trading hub with opportunities for re-export. This means that hydrogen supply chains will need to be built with key trading partners.

The 2020 'Study of Hydrogen Imports and Downstream Applications for Singapore[68]' identified key recommendations with respect to collaboration:

Securing off-take agreements and energy security by engaging in collaboration with key exporting nations or projects, early investment in projects, and techno-economic engagement with project developers to ensure funding and supply chain development.

Ministerial engagement with country counterparts to facilitate the development of a hydrogen export economy.

Collaboration in the development of hydrogen regulations and standards.

1.5.2 Singapore's bilateral hydrogen relationships

Singapore has several formalised relationships with international partners related to hydrogen. Major relationships are detailed in Table 8.

Table 8: Bilateral relationships with other countries

Country	Relationship	Description
New Zealand	Arrangement of Cooperation	In August 2021, Singapore's MTI and New Zealand's Ministry of Business, Innovation and Employment signed an Agreement of Cooperation on low-carbon hydrogen.[69]
Chile	MoU	In 2021, Singapore's Ministry for Trade and Industry and Chile's Ministry of Energy and Mining signed an MoU for collaboration on low-carbon hydrogen technologies.[70]
Australia	MoU	In mid-2021, Australia and Singapore announced they will establish an AUD 30 million (SGD 30 million) partnership for piloting and demonstration of a hydrogen supply chain with Singapore as a major shipping hub and Australia as a 'clean' producer of hydrogen and ammonia. Each country will commit

[68] 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. Available at https://www.kbr.com/en/insights-news/thought-leadership/study-hydrogen-imports-and-downstream-applications-singapore

[69] MFAT (2021) New Zealand and Singapore link up on Hydrogen. https://www.mfat.govt.nz/br/trade/mfat-market-reports/market-reports-asia/new-zealand-and-singapore-link-up-on-hydrogen-august-2021/

[70] MTI (2021) Singapore and Chile Sign Memorandum of Understanding for Collaboration on Low-Carbon Hydrogen Technologies https://www.mti.gov.sg/-/media/MTI/Newsroom/Press-Releases/2021/02/Press-Release--Singapore-and-Chile-sign-MOU-for-collaboration-on-lowcarbon-hydrogen-technologies-on.pdf

Country	Relationship	Description
		AUD 10 million (SGD 10 million) over 5 years, with an additional AUD 10 million (SGD 10 million) from industry.[71] In late-2021, Australia and Singapore undertook the first annual dialogue under the Singapore-Australia Memorandum of Understanding (MoU) for Cooperation on Low-Emissions Solutions. Priority areas for 2022 were agreed upon, which included: Collaborative research and development on low-emission solutions (such as establishing a joint research symposium); Conducting joint studies on low-emission solutions (such as a hydrogen supply chain study); Exploring large-scale renewable electricity trade; and Regional emissions measurement, verification and reporting capacity building efforts.[72]
Japan	Memorandum of Cooperation	In January 2022, Singapore's MTI and Japan's Ministry of Economy, Trade and Industry signed a Memorandum of Cooperation on Low-Emissions Solutions.[73]

1.5.3 Singapore's joint international RD&D projects

Country	Projects
Norway	In 2021, Norway's DNV and Singapore's Keppel Offshore & Marine signed an agreement to collaborate on the hydrogen value chain. This will include the implementation of new technologies, safety requirements, and infrastructure requirements for storage, transportation and offshore applications. Keppel will lead a floating test-bed in Singapore to host studies and pilot activities.[74]
Japan	Japan's Itochu and Dutch company Vopak (which has a terminal located in Singapore) have signed an MoU to study the ammonia marine fuel supply chain in Singapore. This is also integrated with another project for a zero-emission ship between Itochu and other partners (a group of 34 large industry members and multinationals).[75] In 2020, Japan's Chiyoda Corporation and Mitsubishi Corp have signed an MoU with City Energy (formerly known as City Gas), Jurong Port, PSA International, SembCorp Industries, and Singapore LNG Corporation to collaborate on the hydrogen economy. Chiyoda's SPERA LOHC technology will be used to demonstrate safe transport of hydrogen, and the other partners will evaluate the feasibility of hydrogen usage in Singapore's industry.[76]

[71] Hon Angus Taylor MP (2021) Australia partners with Singapore on hydrogen in maritime sector. Media Releases. https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-partners-singapore-hydrogen-maritime-sector

[72] DISER (2021) Australia and Singapore set focus for low emissions cooperation in 2022. https://www.industry.gov.au/news/australia-and-singapore-set-focus-for-low-emissions-cooperation-in-2022

[73] https://www.mti.gov.sg/Newsroom/Press-Releases/2022/01/Singapore-and-Japan-Sign-MOC-on-Low-Emissions-Solutions

[74] Offshore Energy (2021) DNV and Keppel to collaborate on hydrogen in Singapore https://www.offshore-energy.biz/dnv-and-keppel-to-collaborate-on-hydrogen-in-singapore/

[75] ITOCHU (2021) ITOCHU Announces the Expansion of the Joint Study Framework on Ammonia as an Alternative Marine Fuel to Include 34 Companies and Organisations https://www.itochu.co.jp/en/news/news/2021/210729.html

[76] Mitsubishi Corporation (2020) MC Signs MoU with Singaporean Companies on Sustainable Hydrogen Economy. Press Room https://www.mitsubishicorp.com/jp/en/pr/archive/2020/html/0000039621.html

Country	Projects
	In 2018 Mitsubishi Heavy Industries and Singapore's Keppel singed an MoU to collaborate on a joint project to explore hydrogen-powered combined cooling, heat and power (CHHP) to support data centres. This is aimed at providing clean energy supply for the expanding energy needs of the digital economy. This includes exploration of steam methane reforming (SMR) to produce hydrogen fuel for the tri-generation plant.[77]
UK & US	In 2015 Singapore's Horizon Energy Systems (HES) and Scottish unmanned aerial vehicle (UAV) developer Raptor UAS jointly developed a civilian fuel cell UAV (originally designed for search and rescue operations) to fly 300km from Scotland to Norway. This was a world record at the time set by Singapore's HES, who had previously broken records in 2007 with NASA backed Pterosoar UAV system.[78]
Australia	The joint piloting and demonstration projects under the Australia-Singapore AUD 30 million (SGD 30 million) partnership are yet to be announced.

The CREATE program

Singapore has established an international program for the purpose of international RD&D collaboration. The CREATE program is an international research campus and innovation hub, under the NRF.[79] CREATE has several Research Centres with international partners, such as the Singapore-MIT Alliance for Research and Technology (SMART), and the Cambridge Centre for Advanced Research and Education in Singapore (CARES).[80] Each Research Centre is an investment of roughly SGD 50 million over five years and is a major part of Singapore's growth strategy as it provides a platform for sustained research collaborations in line with long-term strategic planning.[81] While no hydrogen-specific research centres have yet been established, CREATE has the potential to establish a hydrogen and/or low emissions technology joint lab.

NRF International Grant Calls

Singapore's NRF participates in International Grant Calls which are joint bilateral grant calls with partnering research institutions or universities around the world. The grant calls are often the result of MoUs between Singapore and the partner country.

[77] MHI (2019) Keppel and Mitsubishi Heavy Industries to jointly explore hydrogen powered tri-generation plant concept for data centres in Singapore https://www.mhi.com/news/200618.html

[78] Eco-Business (2021) UK-Singapore collaboration prepares for record 300km hydrogen fuel cell UAV flight. https://www.eco-business.com/press-releases/uk-singapore-collaboration-prepares-for-record-300km-hydrogen-fuel-cell-uav-flight/

[79] CREATE. About CREATE. https://www.create.edu.sg/about-create

[80] CREATE. About CREATE: Research Centres. https://www.create.edu.sg/about-create

[81] Consultation with in-country stakeholders

1.5.4 Singapore's joint international commercial projects

The scope of this report is on research, development and demonstration (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:

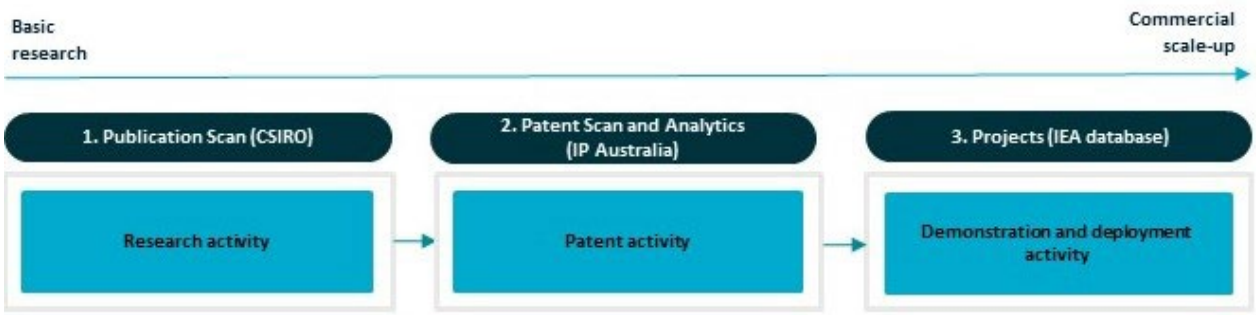
- https://research.csiro.au/hyresource/projects/international/

1.6 Data insights: Singapore's hydrogen RD&D activity

The following section provides data-driven insights on Singapore's RD&D activity in hydrogen technologies. Research publication data, patent data, and commercial project data has been used to understand hydrogen related activity. While limitations exist with such an approach, these data sources do provide an opportunity to consider activity across the innovation spectrum from basic research to demonstration. It also aims to help identify technology areas that have received significant focus in each country and key organisations to support international collaboration efforts.

The data for this section was sourced from CSIRO's publications team, CSIRO's IP team, IP Australia, and the IEA's hydrogen projects database.

Figure 5: Hydrogen innovation activity data



1.6.1 Research publication data

Research publications in hydrogen are an indicator of basic and applied research activity. CSIRO's publications team has conducted a research publication scan to identify Singaporean organisations conducting research across the hydrogen value chain. The publications search approach was developed in 2019 to support the report *Hydrogen Research, Development and Demonstration: Priorities and opportunities for Australia*.[82] This search approach was applied in 2021 to provide an updated dataset for

[82] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration (RD&D): Priorities and Opportunities for Australia. CSIRO. Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

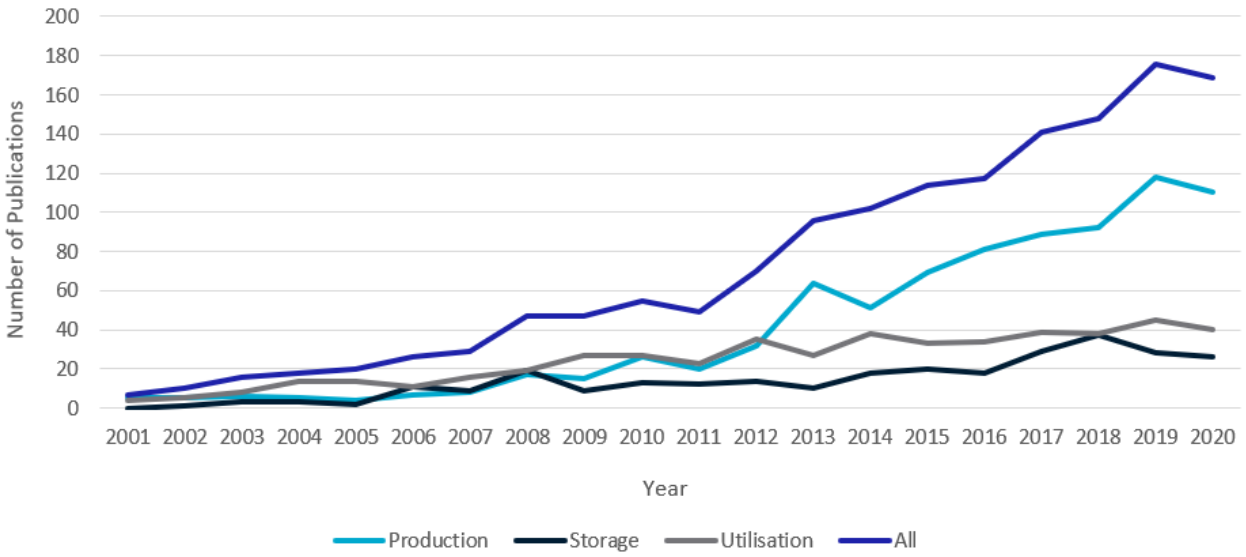
this report. The details of the search approach can be found in the *National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository*.[83]

Figure 6 shows Singaporean institutions ranked in terms of publication output across hydrogen production, storage and distribution, and utilisation from 2016-2020. Figure 7 shows Singapore's country-wide research publication output trends across the hydrogen value chain.

Figure 6: Top institutions by publication outputs (2016-2020)

Rank	Overall (hydrogen production, storage and distribution, utilisation)
1st	Nanyang Technological University (NTU)
2nd	National University of Singapore (NUS)
3rd	Agency for Science, Technology & Research (A*STAR)
4th	Institute for Materials Research & Engineering (IMRE)
5th	Institute of Sustainability for Chemicals, Energy & Environment (ISCE^2) (Formerly Institute for Chemical & Engineering Sciences - ICES)

Figure 7: Singapore's hydrogen-related research publication outputs (2001-2020)



1.6.2 Patent data

Patent activity in hydrogen is an indicator of applied R&D and innovation occurring across the value chain. This section draws on two different patent analytics approaches. CSIRO developed a search approach in 2019 to support the *Hydrogen Research, Development and Demonstration: Priorities and opportunities for*

[83] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository. CSIRO Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

Australia[84] 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*.[85] The second approach, performed by IP Australia, builds on the hydrogen technology taxonomy developed in CSIRO's 2019 report to provide information on specific hydrogen technologies that sit within production, storage and utilisation. The full data visualisations, details of the search approach and any limitations can be found at *Patent analytics of hydrogen technologies: an interactive visualisation.*[86]

It should be noted that analysis of patent data is not necessarily representative of patent impact. As such, this data should be viewed holistically with the other data presented in this section, particularly project deployment.

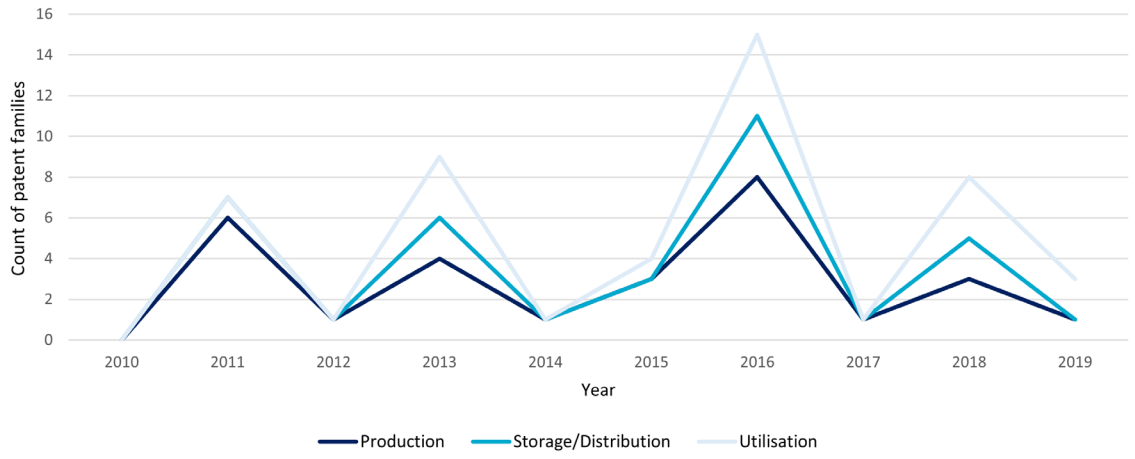
Patent landscape of hydrogen value chain

Performed by the CSIRO, this patent landscape analyses patent family[87] filings across the hydrogen value chain. Figure 8 outlines patent filings over time across the areas of hydrogen production, storage, distribution and utilisation.

Figure 9 shows the jurisdictions in which Singaporean patent applicants are filing patents, outside of Singapore. This provides an indication of which global markets, or manufacturing and commercialisation destinations are of interest to Singaporean patent applicants or inventors.

Note that patent databases have a delay of roughly 18 months, therefore 2020 and 2021 have been omitted from the graphs below. Some patent filings may also be counted twice as the categories of production, storage and utilisation may not be mutually exclusive in all instances and some could relate to multiple areas of the hydrogen value chain.

Figure 8: Patent filings over time across production, storage, distribution and utilisation



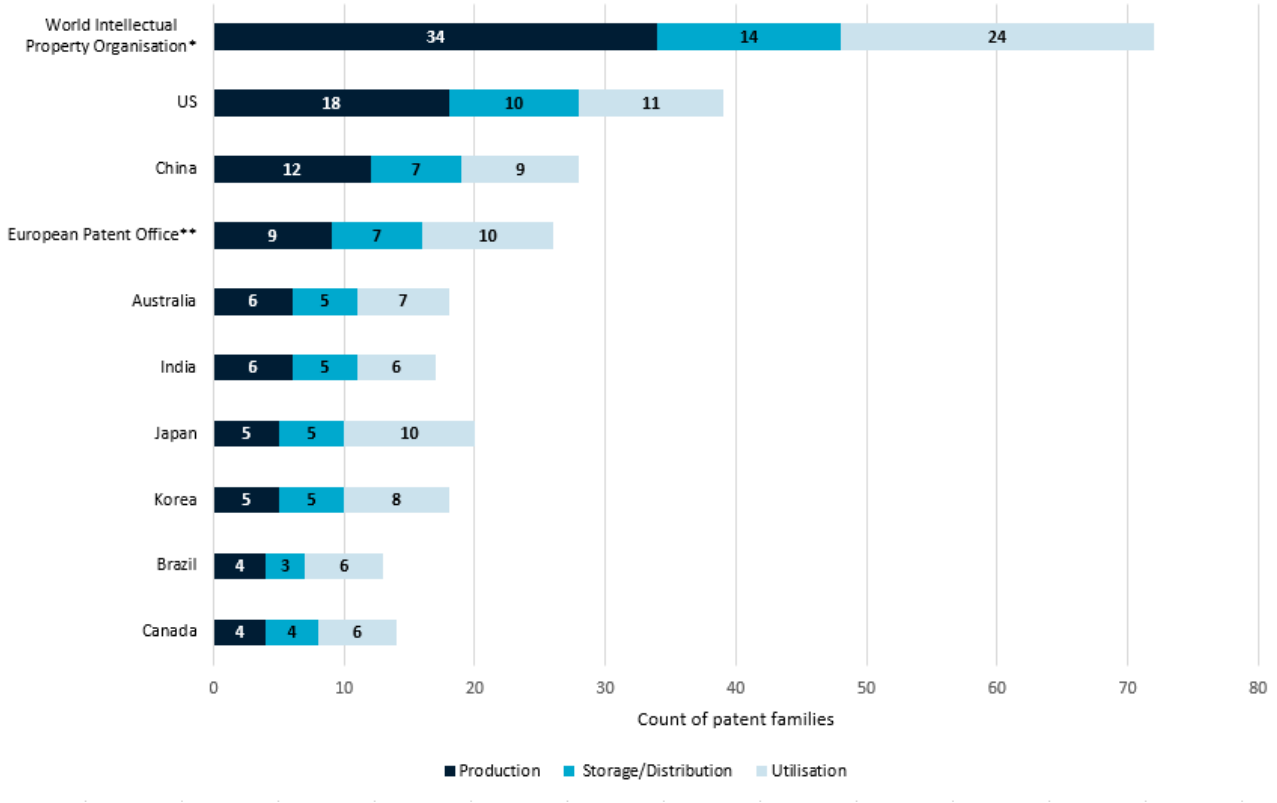
[84] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration (RD&D): Priorities and Opportunities for Australia. CSIRO. Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

[85] Srinivasan et al. (2019) National Hydrogen Research, Development and Demonstration (RD&D): Technical Repository. CSIRO Available at https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/futures-reports/hydrogen-research

[86] IP Australia (2021) Patent Analytics on Hydrogen Technology, Australian Government. Available at https://www.ipaustralia.gov.au/tools-resources/publications-reports/patent-analytics-hydrogen-technology

[87] Applications with the same priority, but filed in different jurisdictions, are known as patent families. Patent families enable us to analyse inventive activity regardless of the number of countries in which protection is sought. Patent families are used in analytics to represent a single invention.

Figure 9: Location of patent filings by Singaporean patent applicants



*** The World Intellectual Property Organisation (WIPO) is an international organisation that promotes the protection of intellectual property and supervises administrative cooperation amongst the intellectual unions regarding protection of intellectual property. Patents filed in the WIPO enable applicants to obtain protection for their inventions in up to 153 of the parties to the Patent Cooperation Treaty.**

**** The European Patent Office enables investors, researchers and companies to obtain protection for their inventions in up to 44 countries, including all 27 EU member states.**

Patent analytics of specific hydrogen technologies

Data extracted from IP Australia's interactive visualisation provides an in-depth analysis of specific hydrogen technology developments. Figure 10 shows the number of patent families filed since 2010 for specific technology areas by Singaporean applicants.

Table 9 shows the number of patent families filed by Singaporean applicants since 2010 by sub-technology area, expressed as a percentage of total global patent family filings. Table 9 also shows the top organisations in Singapore filing patents in each technology area. It should be noted that the majority of fuel cell technologies are categorised under the 'electricity generation' category.

Figure 10: Singapore's patent family output by sub-technology area (2010-2020)

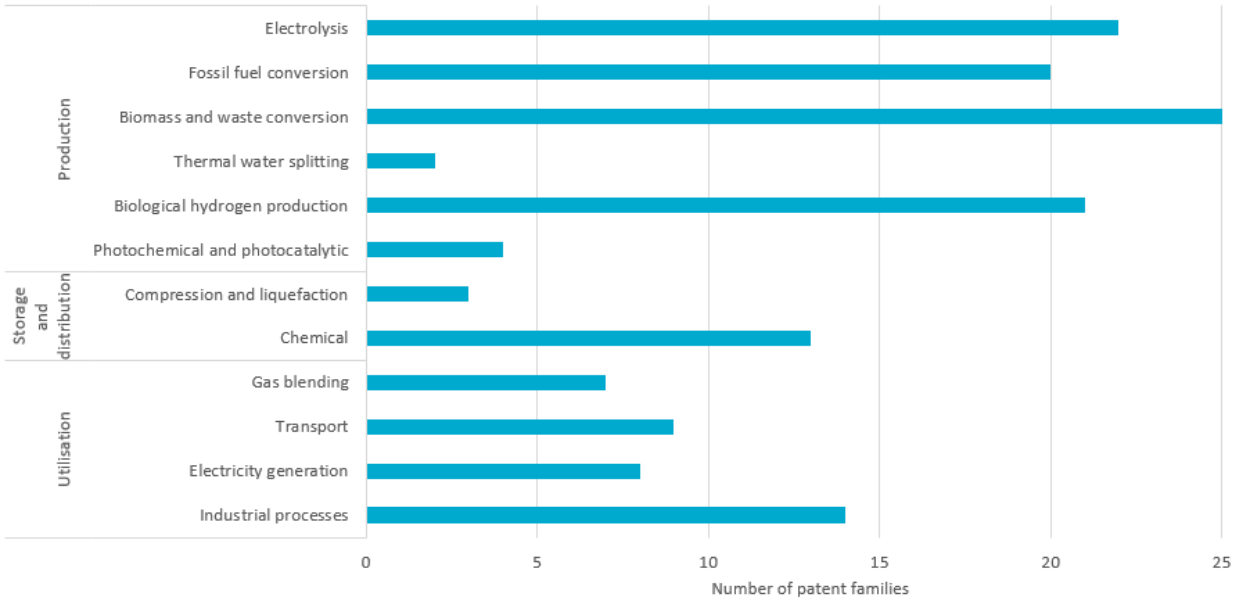


Table 9: Singapore's IP output (number of patent families filed by Singaporean applicants) by sub-technology area from 2010-2020

Technology area		IP output (% of global)	Leading companies	Leading non-profits and universities
Production	Electrolysis	0.3%	OMG Intellectual Properties, Inventure International, H2SG Energy, Horizon Fuel Cell Technologies	A*STAR
	Fossil fuel conversion	0.3%	N/A	NUS, Univ Singapore
	Biomass and waste conversion	0.8%	Real Time Engineering, AEL Environmental (Asia)	A*STAR, NUS, Univ Singapore, NTU
	Biological	0.9%	Semb-Eco R&D, Cube 2, Sphaera Pharma, Chemilink Technologies	NUS, NTU
	Photochemical and photocatalytic	0.2%	N/A	NUS, A*STAR
	Thermal water splitting	0.3%	N/A	NUS
Storage and distribution	Compression and liquefaction	0.4%	H3 Dynamics Holdings, Advanced Material Engineering	NTU
	Chemical storage	0.5%	Joil Company, Venture Corporation, Temasek Life Sciences Laboratory, Green Waste Recycling Company,	NTU

Technology area		IP output (% of global)	Leading companies	Leading non-profits and universities
			Advanced Material Engineering	
Utilisation	Gas blending	0.5%	N/A	NTU, NUS
	Transport	0.4%	OMG Intellectual Properties, Nostrum Energy, Neutrinos Engineering	A*STAR
	Electricity generation	0.2%	H3 Dynamics Holdings, Siemens, Advanced Material Engineering, Evoqua Water Technologies	N/A
	Industrial processes	0.3%	Scinopharm Singapore, Ecospec Global Technology	N/A

IP Australia patent analytics on hydrogen technology

IP Australia has developed an interactive visualisation tool to provide hydrogen insights to researchers, academics, business and policy sectors. For more hydrogen IP statistics including key destination markets, origin profiles, applicant profiles, collaborations and specific patent searches, refer to IP Australia's Hydrogen Patent Landscape tool:

- https://www.ipaustralia.gov.au/tools-resources/publications-reports/patent-analytics-hydrogen-technology

1.6.3 Project data

Data from the IEA Hydrogen Projects Database (as at October 2021)[88] provides insight on clean hydrogen technology value chains deployed at pilot and commercial scale across Singapore. Note that the following limitations should be taken into account:

The database does not indicate whether the technologies used are indigenous or purchased from an overseas provider. While many countries often deploy their own technologies at scale, many countries purchase technologies from overseas to deploy locally. As such the database indicates deployment activity, but not necessarily the ability to translate indigenous R&D into commercial scale-up.

This dataset counts only low-carbon hydrogen projects and their associated value chains. As such hydrogen production projects from gas, coal and oil without CCS are not included. Similarly, utilisation projects not related to a clean hydrogen project source are not included.

The dataset reflects only projects occurring domestically, and therefore does not count projects undertaken by Singaporean companies outside of Singapore. As such, the table may understate Singapore's activity, particularly its contribution to international supply chain development. This data should therefore be considered holistically with the rest of this report.

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

Any limitations stated in the data collection methodology, definitions and assumptions should be taken into account (see IEA Hydrogen Projects Database for details).

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. Projects without a specified date have been excluded from the table below. Further, only projects that are at the feasibility study, final investment decision, demonstration, or operational stage are included. Projects at the 'concept' stage are not included. It should be noted that the majority of projects listed span production, storage and multiple end-uses, and as such can be counted in more than one technology category.

Table 10: Singapore's domestic clean hydrogen project data

Technology	Sub-technology		Domestic project count	% of global
Production	Electrolysis	PEM	2	1.1
		Alkaline	-	-
		SOE	-	-
		Other or unspecified	2	0.8
	Fossil fuel conversion	Coal gasification with CCS	-	-
		Natural gas with CCS	-	-
		Oil with CCS	-	-
		Methane pyrolysis	-	-
	Biomass and waste conversion		-	-
	Photochemical and photocatalytic		-	-
	Biological production		-	-
	Thermal water splitting		-	-
Storage and distribution	Compression and liquefaction		4	0.8
	Chemical carriers	Ammonia	-	-
		Methane	-	-
		Methanol	-	-
		Synfuels	-	-
Utilisation	Gas blending		-	-
	Transport		4	1.7

Technology	Sub-technology		Domestic project count	% of global
	Electricity generation		2	1.5
	Industrial processes	Refining	-	-
		Ammonia	-	-
		Methane	-	-
		Iron and steel	-	-
		Biofuels	-	-
		Synfuel	-	-
		Other industry	-	-

IEA Hydrogen Projects Database

The latest version of the IEA Hydrogen Projects Database can be found at:

- https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

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