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National Hydrogen Research, Development and Demonstration (RD&D)

Technical Repository

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CSIRO acknowledges the Traditional Owners of the lands that we live and work on across Australia and pay their 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.

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1 Introduction

Australia’s hydrogen research, development and demonstration (RD&D) community is diverse, with participation from many research institutions and companies. This document serves as a technical appendix to the CSIRO National Hydrogen RD&D Report,[1] providing a resource for stakeholders across Australia’s hydrogen RD&D community. As a supporting document, it serves as a technical repository of the summary content described in the main report.

It is intended that this repository act as the foundation for a 'living document' which is updated over time. The document is accompanied by a digital edition of the report and repository, which allow navigation through the main elements of the report and technical summaries for hydrogen production and storage. The website aims to facilitate collaboration between institutions, industry, and government across various hydrogen research areas.

The report and digital repository, created by CSIRO’s Innovation Catalyst Global team and CSIRO’s Web Solutions Team, are available at: https://www.csiro.au/en/Showcase/Hydrogen. This document covers the following:

- **Australian RD&D capability summary** – A collation of data regarding active research currently being conducted by Australian research institutions in various hydrogen technology areas.
- **Australian demonstration projects and research infrastructure** – A list of active, under completion, or proposed research and demonstration facilities across Australia. Locations and key organisations are described alongside summaries of each project.
- **Technology repository** – A collection of hydrogen production, storage, and utilisation technologies across the value chain. These summaries were created from literature review and consultation with hydrogen researchers across Australia.
- **Publications and search strategy** – Technical details of the search strategy conducted to provide an overview of Australian and global hydrogen-related publications.
- **Patent landscape research** – Technical details of the patent landscape search conducted to provide an overview of Australian and global hydrogen-related patents.

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[1] Srinivasan, V., Temminghoff, M., Charnock, S., Hartley, P. (2019). *Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia*, CSIRO.

2 Snapshot of current Australian hydrogen RD&D project activity

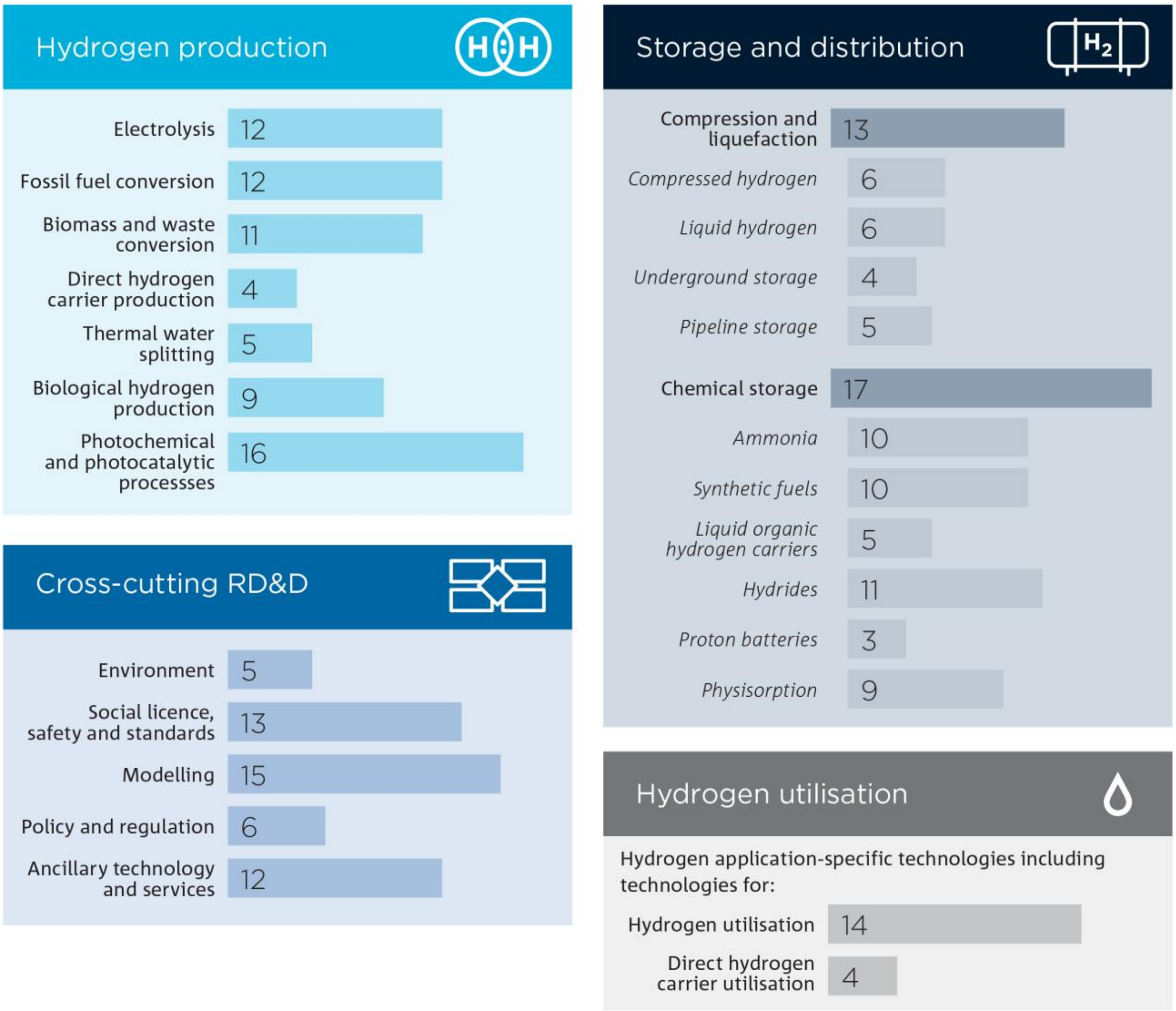
Australia has significant RD&D capability across various institutions, including universities, publicly funded research agencies and cooperative research centres. This summary showcases the active research currently being conducted by Australian research institutions in various hydrogen technology areas across the value chain, as identified through consultations and desktop research.

The objectives of this summary are to assist institutions with developing their own strategies, stimulating collaboration between institutions, and helping international partners understand the hydrogen-related capabilities of Australian institutions. To stimulate and encourage collaboration across Australia's RD&D ecosystem, institutional contact details are provided in Section 2.1.5. It should also be emphasised that this summary acts as a snapshot of currently active projects across the value chain and categories by 'process group' (see FIGURE 1). As such, it does not capture existing capability that could be readily transferred from one area of hydrogen research into another, nor knowledge and experience that may have been developed in a given institution over time.

Furthermore, hydrogen RD&D is expected to change rapidly over the coming years, as will capabilities that emerge with new projects and researchers. Ideally, this summary should be maintained regularly to hold an accurate picture of the Australian hydrogen RD&D landscape.

Not all information could be collated regarding the institutional activity in each hydrogen technology area, in part due to the wide range of active research being conducted at a given institution. While care has been taken to provide a comprehensive account of Australia's RD&D activity, it is likely that any given institution's active hydrogen research portfolio falls beyond the scope of any individual consulted for this project.

FIGURE 1: SNAPSHOT OF CURRENT HYDROGEN RD&D PROJECT ACTIVITY, BY CATEGORY AND NUMBER OF ACTIVE AUSTRALIAN INSTITUTIONS



2.1.1 Production

TABLE 1: AUSTRALIAN RESEARCH INSTITUTIONS WITH PRODUCTION RD&D CAPABILITY (BLUE = ACTIVE PROJECTS), LAST UPDATED 26/11/2019

Institution			CSIRO	University of Adelaide	University of NSW	Macquarie University	Monash University	University of Sydney	University of Technology Sydney	Curtin University	Swinburne University	University of Newcastle	Western Sydney University	University of Melbourne	Australian National University	University of WA	Griffith University	RMIT University	Victoria University	Future Fuels CRC	Deakin University	Queensland University of Technology	University of Queensland	Flinders University
Process	**Technology**	**Count**	**Production**																					
Biological hydrogen production	Biophotolysis (direct and indirect)	**2**		■																			■	
	Dark fermentation	**2**	■			■																		
	Hybrid light and dark fermentation	**0**																						
	Microbial electrolysis	**3**	■																			■	■	
	Photofermentation	**1**													■									
	Dark fermentation followed by anaerobic digestion of biomass	**5**	■													■	■		■			■		
Electrolysis	Anion exchange membrane (AEM) electrolysis	**5**	■	■			■														■	■		
	Alkaline electrolysis	**7**		■	■		■			■				■		■						■		
	Carbon and hydrocarbon-assisted water electrolysis	**4**	■									■	■								■			
	Polymer electrolyte membrane (PEM) electrolysis	**8**	■	■	■		■			■										■	■	■		
	Solid oxide electrolysis	**2**	■																		■			

Photochemical and photocatalytic processes	Photocatalytic water splitting	**13**	■	■	■					■		■	■	■	■		■			■		■	■	■
	Photoelectrochemical water splitting	**11**		■	■	■	■					■	■	■	■			■				■	■	
Biomass and waste conversion	Biogas reforming	**3**				■						■										■		
	Biomass and waste gasification	**8**	■	■			■			■		■			■							■	■	
	Hydrothermal liquefaction	**4**	■	■				■														■		
	Biomass and waste pyrolysis	**8**	■	■			■			■		■				■						■	■	
	Plasma-assisted biomass conversion	**3**										■				■						■		
	Plasma-assisted biogas reforming	**3**										■				■						■		
Fossil fuel conversion	Chemical looping water splitting	**6**	■	■			■					■			■								■	
	Coal gasification	**4**	■	■						■		■												
	Partial oxidation: thermal or catalytic	**4**	■	■								■			■									
	Coal and oil pyrolysis	**3**	■									■				■								
	Natural gas pyrolysis (methane cracking)	**6**	■	■								■				■				■			■	
	Concentrated solar-thermal methane reforming	**4**	■												■					■				■
	Steam methane reforming and carbon dioxide reforming	**5**	■		■			■				■											■	
	Autothermal reforming: dry or steam	**2**										■			■									
Thermal water splitting	Solar thermochemical water splitting (two-stage)	**5**	■	■	■										■									■
	Solar thermochemical water splitting (multi-stage)	**3**	■	■																				■
Direct hydrogen carrier production	Direct hydrogen carrier production	**4**	■	■			■		■															

2.1.2 Storage

TABLE 2: AUSTRALIAN RESEARCH INSTITUTIONS WITH STORAGE RD&D CAPABILITY (BLUE = ACTIVE PROJECTS), LAST UPDATED 26/11/2019

Institution			CSIRO	University of Adelaide	University of NSW	Macquarie University	Monash University	University of Sydney	University of Technology Sydney	Curtin University	Swinburne University	University of Newcastle	Western Sydney University	University of Melbourne	Australian National University	University of WA	Griffith University	RMIT University	Victoria University	Future Fuels CRC	Deakin University	Queensland University of Technology	University of Queensland	Flinders University
Process	**Technology**	**Count**	**Storage**																					
Compression and liquefaction	Compression: electrochemical	**1**	🟦																					
	Pipelines (gas networks)	**5**		🟦								🟦				🟦				🟦	🟦			
	Compression: Ionic liquids	**0**																						
	Compression: mechanical	**2**																		🟦	🟦			
	Compression: metal hydrides	**5**	🟦		🟦					🟦							🟦				🟦			
	Metal-composite pressurised vessels	**2**	🟦							🟦														
	Underground storage	**4**	🟦							🟦				🟦						🟦				
	Liquid hydrogen: cryogenic tanks	**6**	🟦		🟦		🟦	🟦								🟦						🟦		
	Liquid hydrogen: cryo-compression	**1**														🟦								
Chemical	Physisorption: metal-organic frameworks (MOFs)	**9**	🟦	🟦					🟦	🟦					🟦	🟦	🟦					🟦	🟦	
	Ammonia	**8**	🟦	🟦			🟦	🟦	🟦			🟦			🟦	🟦								
	Ammonia: dense metal membrane-based synthesis	**1**	🟦																					
	Ammonia: electrochemical synthesis	**5**	🟦	🟦			🟦		🟦													🟦		

	Ammonia: Haber-Bosch synthesis	**3**			■										■	■								
	Ammonia: hydration of metal nitrides	**2**					■									■								
	Ammonia: non-thermal plasma	**3**		■												■						■		
	Ammonia: enzymatic synthesis	**1**	■																					
	Ammonia: solid oxide electrolysis	**0**																						
	Ammonia: combined system synthesis	**0**																						
	Liquid organic hydrogen carrier (LOHC): toluene	**3**	■												■							■		
	Liquid organic hydrogen carrier (LOHC): dibenzyltoluene	**4**	■						■			■			■									
	Synthetic methane (compressed or liquid)	**7**	■	■					■			■		■		■				■				
	Synthetic methane: solid oxide electrolysis	**1**	■																					
	Synthetic methane: combined system synthesis	**0**																						
	Methanol	**6**	■	■	■			■						■		■								
	Methanol: solid oxide electrolysis	**1**	■																					
	Methanol: combined system synthesis	**1**		■																				
	Dimethyl ether (DME)	**1**													■									
	Hydrides: chemical	**3**			■			■		■														
	Hydrides: complex	**6**			■		■		■	■		■					■							
	Hydrides: metal	**8**	■		■				■	■					■		■				■		■	
	Electrochemical carbon-based storage: proton batteries	**3**							■									■			■			

2.1.3 Utilisation

TABLE 3: AUSTRALIAN RESEARCH INSTITUTIONS WITH UTILISATION RD&D CAPABILITY (BLUE = ACTIVE PROJECTS), LAST UPDATED 26/11/2019

Institution			CSIRO	University of Adelaide	University of NSW	Macquarie University	Monash University	University of Sydney	University of Technology Sydney	Curtin University	Swinburne University	University of Newcastle	Western Sydney University	University of Melbourne	Australian National University	University of WA	Griffith University	RMIT University	Victoria University	Future Fuels CRC	Deakin University	Queensland University of Technology	University of Queensland	Flinders University
Process	**Technology**	**Count**	**Utilisation**																					
Export	Export demonstration	**7**	🟦		🟦					🟦		🟦			🟦		🟦					🟦		
Gas blending	Pipeline materials	**4**		🟦										🟦						🟦	🟦			
	Appliance testing	**5**		🟦	🟦									🟦						🟦	🟦			
	Gas metering	**5**		🟦								🟦				🟦				🟦	🟦			
	Hydrogen gas separation	**5**										🟦		🟦		🟦				🟦			🟦	
Transport	Polymer electrolyte membrane fuel cell (PEMFC)	**8**	🟦	🟦	🟦			🟦										🟦	🟦		🟦	🟦		
	Refuelling station technologies	**1**																			🟦			
	Aviation and UAVs	**5**	🟦					🟦						🟦			🟦				🟦			
	Ammonia internal combustion engine	**4**	🟦											🟦		🟦					🟦			
	Hydrogen internal combustion engine	**3**			🟦									🟦						🟦				
	Steel embrittlement testing	**6**						🟦		🟦							🟦			🟦	🟦		🟦	
Electricity	Ammonia turbine	**1**																			🟦			
	Ammonia fuel cells	**1**	🟦																					
	Hydrogen gas turbine	**5**						🟦						🟦					🟦	🟦	🟦			

	Hydrogen fuel cells	**11**	🟦	🟦	🟦					🟦		🟦							🟦	🟦	🟦	🟦	🟦	🟦
	Alkaline anion exchange membrane fuel cell (AEMFC)	**3**	🟦	🟦						🟦														
	Microbial fuel cell	**3**			🟦							🟦											🟦	
	Solid oxide fuel cells	**4**	🟦							🟦		🟦											🟦	
	Unitised reversible fuel cell system	**1**																🟦						
	Polymer electrolyte membrane fuel cell (PEMFC)	**7**	🟦	🟦	🟦					🟦									🟦		🟦	🟦		
	Alkaline fuel cell (AFC)	**0**																						
	Molten carbonate fuel cell	**1**										🟦												
	Phosphoric acid fuel cell	**0**																						
	Direct methanol fuel cell	**1**	🟦																					
Industrial Processes	Steel processing	**5**	🟦	🟦							🟦	🟦			🟦									
	Combustion	**8**	🟦	🟦	🟦			🟦				🟦		🟦						🟦	🟦			
	Synthetic fuels	**10**	🟦	🟦	🟦			🟦	🟦			🟦		🟦		🟦				🟦				🟦
	Methanol production: carbon dioxide reduction	**4**	🟦	🟦										🟦										🟦
Heat storage	Thermal batteries based on metal hydrides	**2**			🟦					🟦														

2.1.4 Cross-Cutting RD&D

TABLE 4: AUSTRALIAN RESEARCH INSTITUTIONS WITH CROSS-CUTTING RD&D CAPABILITY (BLUE = ACTIVE PROJECTS), LAST UPDATED 26/11/2019

Institution			CSIRO	University of Adelaide	University of NSW	Macquarie University	Monash University	University of Sydney	University of Technology Sydney	Curtin University	Swinburne University	University of Newcastle	Western Sydney University	University of Melbourne	Australian National University	University of WA	Griffith University	RMIT University	Victoria University	Future Fuels CRC	Deakin University	Queensland University of Technology	University of Queensland	Flinders University
Process	**Technology**	**Count**	**Cross-cutting RD&D**																					
Environmental	Environmental	**5**	🟦		🟦				🟦						🟦						🟦			
Policy and regulation	Provenance	**6**	🟦				🟦		🟦						🟦					🟦	🟦			
Social licence, safety and standards	Social licence	**9**	🟦	🟦					🟦			🟦			🟦					🟦	🟦	🟦	🟦	
	General safety and standards	**7**		🟦		🟦		🟦	🟦			🟦								🟦	🟦			
	Combustion modelling	**4**		🟦	🟦									🟦						🟦				
Modelling	Modelling (various)	**14**	🟦	🟦	🟦			🟦	🟦			🟦		🟦	🟦		🟦		🟦	🟦	🟦	🟦	🟦	
	Technical/simulation	**12**	🟦	🟦		🟦		🟦	🟦			🟦		🟦			🟦		🟦	🟦		🟦	🟦	
	Pipelines (gas flow, technoeconomics, etc.)	**9**	🟦	🟦				🟦	🟦			🟦		🟦						🟦	🟦	🟦		
Ancillary technology and services	Specialised sensors, monitoring devices and other components	**7**	🟦	🟦					🟦		🟦			🟦						🟦	🟦			
	Technology integration and process improvement	**6**	🟦						🟦			🟦								🟦	🟦	🟦		
	Separation materials and technologies	**7**	🟦											🟦			🟦			🟦	🟦		🟦	🟦

2.1.5 Institutional contacts

TABLE 5: INSTUTIONAL CONTACT DETAILS

Institution	Listed contacts	Contact
The Australian National University	Igor Skryabin	iskryabin@gmail.com
CSIRO	Patrick Hartley	Patrick.Hartley@csiro.au
	Daniel Roberts	Daniel.Roberts@csiro.au
Curtin University	Refer to: https://www.curtin.edu.au/	
Deakin University	Refer to: https://www.deakin.edu.au/	
The Future Fuels Cooperative Research Centre	Klaas van Alphen	klaas.vanalphen@futurefuelscrc.com
Griffith University	Evan Gray	e.gray@griffith.edu.au
Macquarie University	Refer to: https://www.mq.edu.au/	
Monash University	Douglas MacFarlane	douglas.macfarlane@monash.edu
	Alexandr Simonov	alexandr.simonov@monash.edu
Queensland University of Technology	Ian MacKinnon	ian.mackinnon@qut.edu.au
RMIT University	John Andrews	john.andrews@rmit.edu.au
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	Eric May	eric.may@uwa.edu.au
The University of New South Wales	Kondo-Francois Aguey-Zinsou	f.aguey@unsw.edu.au
Victoria University	Refer to: https://www.vu.edu.au/	
Western Sydney University	Leigh Sheppard	L.Sheppard@westernsydney.edu.au

3 Australian demonstration projects and research infrastructure

A total of 23 hydrogen-specific demonstration projects and research facilities around Australia were found in this study, an increase from the 15 listed in the National Hydrogen Roadmap, published in 2018.[2] The summaries were created based on publicly available information and consultations conducted across Australia; and aim to provide an easily digestible overview of each project or facility. It is important to note that this sector rapidly evolving, and this list acts only as a snapshot of the current point in time.

This summary has been converted into a digital edition, available at: https://www.csiro.au/en/Showcase/Hydrogen.

TABLE 6: HYDROGEN DEMONSTRATION PROJECTS AND RESEARCH INFRASTRUCTURE

Project	State	Location	Organisation(s)	Summary
Clean Energy Innovation Hub[3]	WA	Jandakot	ATCO	Test bed for hybrid energy solutions, integrating natural gas, solar PV, battery storage and hydrogen production
Renewable Hydrogen for Ammonia production[4]	WA	Pilbara	Yara, Engie	The goal is to convert the Pilbara ammonia plant from one that relies completely on natural gas for its hydrogen to one where a significant share of its hydrogen comes from renewable power
Hazer Group Facility[5]	WA	Woodman Point	Hazer Group	Using the Hazer process of methane cracking, the facility will convert sewerage biogas into hydrogen and graphite
Australian Resources Research Centre[6]	WA	Perth	CSIRO & Curtin Uni	Research centre bringing together expertise across industrial and gas processing as well as mining.
Murchison Renewable Hydrogen Project	WA	Kalbarri	Siemens, Hydrogen Renewables Australia	5GW wind and solar project to produce green hydrogen for export to Asia.

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[2] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

[3] ATCO (2019). *Clean Energy Innovation Hub,* [Online] Available from: https://yourgas.com.au/energy-future/clean-energy-innovation-hub/ Accessed: 19/11/2019

[4] Yara (2019). *Yara and ENGIE to test green hydrogen technology in fertilizer production,* [Online] Available from: https://www.yara.com/news-and-media/news/archive/2019/yara-and-engie-to-test-green-hydrogen-technology-in-fertilizer-production/ Accessed: 19/11/2019

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[6] Australian Resources Research Centre (2019). *About ARC,* [Online] Available from: https://www.arrc.net.au/about-arrc/ Accessed: 19/11/2019

Crystal Brook Energy Park[7]	SA	Crystal Brook	Neoen	Neoen is investigating the construction of a renewable hydrogen production facility. The proposed 50MW Hydrogen Superhub would be the largest co-located wind, solar, battery and hydrogen production facility in the world, producing up to 25,000kg of hydrogen per day.
Hydrogen Park SA (HyP SA)[8]	SA	Adelaide	AGIG & Siemens	Electrolysis will be used to generate hydrogen using renewable electricity and injected into the natural gas network.
Port Lincoln Green Hydrogen Plant[9]	SA	Port Lincoln	Hydrogen Utility (H2U), Thyssenkrupp	A 30MW water electrolysis plant, as well as a facility for sustainable ammonia production.
Renewable Hydrogen Microgrid[10]	QLD	Daintree	Daintree Renewable Energy Inc	The proposed microgrid will store energy generated by new and existing solar panels by converting it to hydrogen for use in a fuel cell RAPS.
Gladstone Advanced Biofuels Pilot Plant[11]	QLD	Gladstone	Northern Oil & AFC Energy	Hydrogen will be produced from waste through the chemical looping process to support refining. Surplus hydrogen will be used to power a 200-400kw fuel cell.
Renewable Hydrogen Production and Refuelling Project[12]	QLD	Bulwer	BOC	A 220 KW electrolyser, 100 KW solar array for local hydrogen production and refuelling.
Redlands Research Centre[13]	QLD	Brisbane	Queensland University of Technology	Renewable hydrogen pilot plan to build knowledge and explore export opportunities.

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[7] Crystal Brook Energy Park (n.d.). *Neoen awarded funding to investigate hydrogen,* [Online] Available from: https://crystalbrookenergypark.com.au/neoen-awarded-funding-to-investigate-hydrogen/ Accessed: 19/11/2019

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[10] Maisch, M. (2019). *Australia's first solar to hydrogen-based microgrid gets nearly $1 million in federal funding, PV magazine,* [Online] Available from: https://www.pv-magazine-australia.com/2019/05/07/australias-first-solar-to-hydrogen-based-microgrid-gets-nearly-1-million-in-federal-funding/

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[13] Queensland Cabinet and Ministerial Directory (2019). *Media Statement – Queensland's hydrogen future closer to reality*, [Online] Available from: http://statements.qld.gov.au/Statement/2019/3/28/queenslands-hydrogen-future-closer-to-reality Accessed: 19/11/2019

Sir Samuel Griffith Centre renewable hydrogen microgrid	QLD	Brisbane	Griffith University	University building operating independent of the electricity grid by integrating PV, electrolysis and fuel cells.
Renewable ammonia plant[14]	QLD	Moranbah	Dyno Nobel	Assessing the feasibility of creating the world's largest ammonia plant using a 160MW electrolyser powered by a 210MW solar farm.
National Hydrogen Materials Reference Facility (NHMRF)[15]	QLD	Brisbane	Griffith University	Reference facility focused on characterising the performance of hydrogen storage materials. Capabilities include: measurement of hydrogen absorption, adsorption and desorption, lifetime testing, hydrogen storage testing systems.
Queensland Centre for Advanced Technology (QCAT)	QLD	Brisbane	CSIRO	Internationally-unique facility for studying the gasification behaviour of a range of feedstocks over a range of industrially relevant conditions.
ARC Training Centre for The Global Hydrogen Economy	NSW	Sydney	University of New South Wales	Centre to train and develop hydrogen engineering professionals to meet the demand for hydrogen production, storage and distribution skills.
Jemena's Power to Gas trial[16]	NSW	Western Sydney	Jemena	The trial will convert solar and wind power into hydrogen gas, via electrolysis, which will then be stored for use across the Jemena Gas Network.
Fire and Explosion Testing Services (FETS)[17]	NSW	Newcastle	University of Newcastle	A $15 million facility, FETS operates an integrated platform that combines a wide range of expertise at the University with one of the most comprehensive and state-of-the-art fire and explosion testing facilities in the country. Testing of

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[14] ARENAWire (2019). *Renewable future beckons for Queensland ammonia plants,* [Online] Available from: https://arena.gov.au/blog/renewable-future-beckons-for-queensland-ammonia-plants/ Accessed: 19/11/2019

[15] Griffith University (n.d.). *NATIONAL HYDROGEN MATERIALS REFERENCE FACILITY,* [Online] Available from: https://www.griffith.edu.au/queensland-micro-nanotechnology-centre/facilities/national-hydrogen-materials-reference-facility Accessed: 19/11/2019

[16] Jemena (n.d.). *Welcome to Jemena's Power to Gas Trial,* [Online] Available from: https://jemena.com.au/about/innovation/power-to-gas-trial Accessed: 19/11/2019

[17] Tunra Energy (2017). *Energy technology & safety solutions*, [Online] Available from: https://tunra.com.au/works/tunra-energy/ Accessed: 19/11/2019

				hydrogen is to be included. Comprises of a 30m and 100m detonation tube for explosion measurements and analysis.
Government Fleet and Refuelling station[18]	ACT	Canberra	ActewAGL, Neoen, Megawatt Capital, Hyundai	Public hydrogen refuelling station will open in Canberra to service 20 new FCEV's under order by the ACT government.
Hydrogen Energy Supply Chain (HESC)[19]	VIC	Latrobe valley	Kawasaki Heavy Industries (KHI), J-POWER, Iwatani Corporation, Marubeni Corporation, Shell & AGL	During the pilot phase, brown coal will be gasified in the Latrobe Valley to produce hydrogen-rich syngas which will subsequently be purified, then transported to the Port of Hastings to be liquefied and loaded onto a specialised tanker for transport to Japan.
Toyota Australia Hydrogen Centre[20]	VIC	Altona	Toyota Australia	To be built with an electrolyser, commercial refuelling station and education centre for live demonstrations.
Centre for Hybrid Energy Systems (CHES)[21]	VIC	Melbourne	CSIRO	Showcases expertise and capability in integrating energy storage, renewable energy, hydrogen and fuel cell technologies, fuel processing, systems design and construction.

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[18] Brewer, P. (2019). *Hydrogen to top up 20 new ACT fleet cars,* Canberra Times, [Online] Available from: https://www.canberratimes.com.au/story/6111531/hydrogen-to-top-up-20-new-act-fleet-cars/ Accessed: 19/11/2019

[19] https://hydrogenenergysupplychain.com/ Accessed: 19/11/2019

[20] Toyota (2019). *Toyota's Altona Site to Be Home to Victoria's First Hydrogen Refuelling Station,* [Online] Available from: https://www.toyota.com.au/news/toyotas-altona-site-to-be-home-to-victorias-first-hydrogen-refuelling-station Accessed: 19/11/2019

[21] CSIRO (2019). *Centre for Hybrid Energy Systems*, [Online] Available from: https://www.csiro.au/en/Do-business/Prototyping/CHES?ref=/CSIRO/Website/Research/EF/Areas/Facilities/CHES Accessed: 19/11/2019

4 Technology repository: Introduction

The following is a repository of hydrogen production and storage technologies collected during the *Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia* study. The technology summaries were created based on a combination of literature reviews, consultation with researchers, and reviews conducted by individuals with relevant expertise.

It is intended that this repository act as the foundation for a 'living document' which is updated over time as developments occur and research priorities change. This document is accompanied by a digital edition of the repository, referred to as the ‘hydrogen technology marketplace’, which allows navigation through the technical summaries for hydrogen production and storage, and aims to facilitate collaboration between institutions, industry, and government across various hydrogen research areas. This digital repository is available at: https://www.csiro.au/en/Showcase/Hydrogen.

The following technical summary chapters include:

- Production (Part 5): Technical summaries for various hydrogen production methods, organised by process type.
- Storage (Part 6): Technical summaries for various hydrogen production methods, organised by storage type.
- Utilisation (Part 7): Brief technical summaries for various hydrogen and hydrogen carrier utilisation technologies.

While not included in this repository, it should be noted that cross-cutting RD&D areas are equally important in developing a domestic and global hydrogen industry; and are covered in detail in *Hydrogen Research, Development and Demonstration: Priorities and Opportunities for Australia*.

The ‘characteristics’ box within each summary was created with the intention of providing high-level, strategically relevant information to aid in understanding and comparing technologies. The final edition of the technology repository will also include comparison tables which present these characteristics side-by-side for technologies within the same category.

Note also that while ‘direct hydrogen carrier synthesis’ is listed under the production taxonomy, the technologies that fall within this category are presented here under the Storage section.

Please note the following limitations of the repository:

- Not all information could be collected on each technology given the early stage of the research and the widely varying characteristics associated with exploratory work. Not all information can be presented with a high level of accuracy due to the wide variations possible within each technology, such as design, materials, conditions, or other factors. Additionally, the repository is not exhaustive of all technologies due to limitations of project scope, time, and availability of information. Further research could be conducted to provide more in-depth information on each technology and ensure a more comprehensive coverage of technologies across all categories.
- ‘Active institutions’ includes those institutions which have confirmed and approved their activity in current research projects in the given technology area. As mentioned, not all information could be collated regarding the institutional activity in each hydrogen technology area, in part due to the wide range of active research being conducted at a given institution. Note that the project team and individuals consulted have attempted to be as comprehensive as possible, however it is likely that in many cases an institution’s active hydrogen research portfolio falls beyond the scope of any individual consulted. Additionally, it should be noted that there will be some institutions with active

hydrogen research that have not been included in this summary, as they were unable to be consulted during the project.

- The repository acts a snapshot of the current state of the technologies included. These key characteristics and RD&D priorities are expected to change significantly in the future. We hope this repository will form part of a living document that is maintained and updated over time, in which case remaining gaps in knowledge could be addressed, and new developments added when they emerge.

5 Technology repository: Production

- Electrolysis
  - Alkaline electrolysis
  - Anion exchange membrane (AEM) electrolysis
  - Polymer electrolyte membrane (PEM) electrolysis
  - Solid oxide electrolysis
  - Carbon and hydrocarbon-assisted water electrolysis
- Fossil fuel conversion
  - Coal gasification
  - Coal and oil pyrolysis
  - Chemical looping reforming
  - Natural gas pyrolysis (methane cracking)
  - Steam reforming, carbon dioxide reforming
  - Chemical looping reforming
  - Autothermal reforming
  - Partial oxidation
- Biomass and waste conversion
  - Biogas reforming
  - Plasm-assisted biogas reforming
  - Biomass and waste gasification
  - Biomass and waste pyrolysis
  - Plasma-assisted biomass and waste conversion
- Direct chemical carrier production
  - Ammonia: electrochemical synthesis
  - Ammonia: enzymatic synthesis
  - Ammonia: solid oxide electrolysis
  - Methanol: photocatalytic synthesis
  - Methanol: solid oxide electrolysis
  - Methane: solid oxide electrolysis
- Thermal water splitting
  - Solar-thermochemical water splitting (two-stage)
  - Solar-thermochemical water splitting (multi-stage)
- Biological hydrogen production
  - Biophotolysis (direct and indirect)
  - Dark fermentation
  - Photofermentation
  - Microbial electrolysis
  - Hybrid light and dark fermentation
  - Two-stage anaerobic digestion
- Photochemical and photocatalytic processes
  - Photochemical water splitting
  - Photocatalytic water splitting

5.1 Electrolysis

5.1.1 Alkaline electrolysis

What is it?

Water is split into hydrogen and oxygen via the application of an electric current, using a porous diaphragm and an alkaline electrolyte.

Why is it important?

Alkaline electrolysis is an established technology which is already being employed at industrial scale.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Well established supply chain and manufacturing capacity • Large stack sizes available • Long-term stability • Low capital cost • Non-noble materials • Mature technology • Large stack sizes available (in MW range)[22]	• Improve operational flexibility • Enable higher temperature operation • Improve oxygen evolution • Achieve higher pressure operation
Limitations • High minimum load requirement (20%–40%) • Limited dynamic operation (requires stable load) • Corrosive liquid electrolyte[23] • Large footprint • Does not accommodate variability of power supply as well as other electrochemical methods • Crossover of gases leads to lower degree of purity, and reduced efficiency due to re-formation of water[24] • Low current density	**Active institutions (7)** • Curtin University • Monash University • Queensland University of Technology • The University of Adelaide • The University of Melbourne • The University of New South Wales • The University of Western Australia
Characteristics • Inputs: Water, electricity • By-products: Oxygen • Operating temperature: <100°C • Energy efficiency: ~69%	

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[22] Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). *A comprehensive review on PEM water electrolysis.* International Journal of Hydrogen Energy, 38(12), 4901-4934. doi:https://doi.org/10.1016/j.ijhydene.2013.01.151

[23] Ibid.

[24] Ibid.

5.1.2 Anion exchange membrane (AEM) electrolysis

What is it?

Water is split into hydrogen and oxygen via the application of an electric current, using a porous anion exchange membrane diaphragm and an alkaline electrolyte.

Why is it important?

More compact and safer than alkaline electrolysis and could make use of cheaper catalysts than in PEM electrolysis.

TRL[25]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Greater safety and efficiency compared to traditional alkaline electrolysis[26] • Potential long system lifetime[27] • Distilled water or a low concentration of alkaline solution can be used as electrolyte instead of concentrated KOH • Non-noble metal catalyst	• Improve OH- conductivity in polymeric membrane • Improve durability of membrane – degradation remains an issue • Improve conductivity of electrolyte/membrane
Limitations	**Active institutions (5)**
• Potentially higher capital cost compared to alkaline electrolysis • Unproven technology (membrane)	• CSIRO • Deakin University • Monash University • Queensland University of Technology • The University of Adelaide
Characteristics	
• Inputs: Water, electricity • By-products: Oxygen • Operating temperature: <100°C	

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[25] European Commission (2019). *New Anion Exchange Membrane Electrolysers*, Funding & tender opportunities, [Online] Available from: https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/fch-02-4-2019 Accessed: 19/11/2019

[26] Cho, M. K., Park, H.-Y., Lee, H. J., Kim, H.-J., Lim, A., Henkensmeier, D., Yoo, S.J., Kim, J.Y., Lee, S.Y., Park, H.S., Jang, J. H. (2018). *Alkaline anion exchange membrane water electrolysis: Effects of electrolyte feed method and electrode binder content.* Journal of Power Sources, 382, 22-29. doi:https://doi.org/10.1016/j.jpowsour.2018.02.025

[27] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). *Future cost and performance of water electrolysis: An expert elicitation study*. International Journal of Hydrogen Energy, 42(52), 30470-30492. doi:https://doi.org/10.1016/j.ijhydene.2017.10.045

5.1.3 Carbon and hydrocarbon-assisted water electrolysis

What is it?

A variation of an electrochemical system (AE, PEM, SOE) with a portion of the energy input being supplied by the chemical conversion of coal or other carbon sources such as biomass, alcohols or other hydrocarbons. Assisted electrolysis can be either high or low temperature.

Why is it important?

The electrical energy input required is reduced due to the energy supplied by the carbon source.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Requires 60% less electric input, due to chemical energy input in process[28]
- Produces a pure hydrogen stream
- Produces a separate CO2 stream, as opposed to in coal fired power plants[29]
- Cleaner and simpler process of extracting chemical energy from carbonaceous feedstocks
- Could use biomass carbon
- Could potentially achieve current densities similar to those achieved in PEM

RD&D priorities

- Improve carbon oxidation kinetics[30]
- Optimise anode catalyst[31]
- Optimise operating conditions[32]
- Improve conventional electrolyser technologies and renewables system integration[33]
- Develop materials to reduce degradation and improve long-term performance
- Improve current density[34]

Limitations

- Produces carbon dioxide or carbon monoxide (requires CCUS)
- Build-up of by-products on surfaces and in solution (by-products vary depending on feedstock and electrolysis type)

Active institutions (4)

- CSIRO
- Deakin University
- The University of Newcastle
- Western Sydney University

Characteristics

- Inputs: Carbon or hydrocarbon, water (as steam), electricity
- By-products: Carbon dioxide or carbon monoxide
- Operating temperature: PEM – Low (<100°C), SOE – High (>500°C)
- Energy efficiency: Varies depending on implementation with PEM or SOE systems

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[28] Giddey, S., Kulkarni, A., & Badwal, S. P. S. (2015). *Low emission hydrogen generation through carbon assisted electrolysis.* International Journal of Hydrogen Energy, 40(1), 70-74. doi:https://doi.org/10.1016/j.ijhydene.2014.11.033

[29] Ibid.

[30] Ibid.

[31] Ibid.

[32] Ibid.

[33] Ju, H., Badwal, S., & Giddey, S. (2018). *A comprehensive review of carbon and hydrocarbon assisted water electrolysis for hydrogen production.* Applied Energy, 231, 502-533. doi:https://doi.org/10.1016/j.apenergy.2018.09.125

[34] Giddey, S., Kulkarni, A., & Badwal, S. P. S. (2015). *Low emission hydrogen generation through carbon assisted electrolysis.* International Journal of Hydrogen Energy, 40(1), 70-74. doi:https://doi.org/10.1016/j.ijhydene.2014.11.033

5.1.4 Polymer electrolyte membrane (PEM) electrolysis

What is it?

Water is split into hydrogen and oxygen via the application of an electric current, using an acidic solid polymer electrolyte membrane.

Why is it important?

Is an established technology with a low footprint, and can accommodate a renewable energy supply.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Enables differential pressure operation – eliminates need for strict pressure controls, enables rapid changes in current for renewable integration, enables low pressure oxygen for safety and lower costs[35]
- Direct leveraging of PEM fuel cell advances[36]
- High current densities (low OPEX),[37] and voltage efficiency
- High operating pressure
- High purity hydrogen
- Small, flexible and modular
- Polymer membrane allows for thinner electrolyte than alkaline electrolysers[38]
- Low gas crossover leads to high gas purity and fast response times to changes in power supply[39]

RD&D priorities

- Improve durability of cell components
- Develop advanced catalysts to improve efficiency and reduce noble-metal use
- Develop alternatives to platinum-based components
- Achieve higher pressure operation, while preventing cross-permeation of gases[40]
- Develop low cost and corrosion resistant current collectors and separator plates[41]

Limitations

- High cost of membrane and noble metal catalyst
- Acidic corrosive environment[42]

Active institutions (8)

- CSIRO
- Curtin University
- Deakin University
- The Future Fuels Cooperative Research Centre
- Monash University
- Queensland University of Technology
- The University of Adelaide
- The University of New South Wales

Characteristics

- Inputs: Water, electricity
- By-products: Oxygen
- Operating temperature: <100°C

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[35] Ayers, K., (2011). *PEM Electrolysis R&D Webinar*, Proton Energy Systems, [Online] Available from: https://www.energy.gov/sites/prod/files/2014/03/f11/webinarslides052311_pemelectrolysis_ayers.pdf Accessed: 19/11/2019

[36] US DOE (2011). *HYDROGEN PRODUCTION BY PEM ELECTROLYSIS: SPOTLIGHT ON GINER AND PROTON,* [Online] Available from: https://www.energy.gov/sites/prod/files/2014/03/f12/webinarslides052311_pemelectrolysis_overview.pdf Accessed: 19/11/2019

[37] Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). *A comprehensive review on PEM water electrolysis.* International Journal of Hydrogen Energy, 38(12), 4901-4934. doi:https://doi.org/10.1016/j.ijhydene.2013.01.151

[38] Ibid.

[39] Ibid.

[40] Ibid.

[41] Ibid.

[42] Ibid.

5.1.5 Solid oxide electrolysis

What is it?

Solid oxide electrolysis uses thermal energy from heat in combination with electrical energy from an electric current to synthesise hydrogen, using a ceramic solid oxide electrolyte membrane.

Why is it important?

Solid oxide electrolysis makes use of heat to significantly reduce the required electrical energy input for hydrogen production.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Higher electrical efficiencies compared to AE/PEM can already be achieved and up to 10 kw systems have been demonstrated by R&D labs as well as commercial start-up companies • High energy efficiency • Non-noble materials • Low (projected) capital cost for MW scale system • Reversible operation as fuel cell is feasible • Can be used for the electrolysis of CO_2 to CO, or the co-electrolysis of CO_2 and H_2O to syngas (H_2 and CO)[43] • Reduced electrical input requirement due to use of thermal energy, which could be sourced from waste heat	• Improve electrode performance • Demonstrate integration with green energy sources at scale • Increase lifetime of ceramic materials for ongoing high temperature operation[44] • Understand fundamental reaction mechanism and degradation behaviour[45]
Limitations	**Active institutions (2)**
• High temperature operation – heat supplied must be of an appropriate quality (sufficiently high temperature) • Poor lifetime due to mechanically unstable electrodes (cracking), brittle ceramics and sealing issues • Limited flexibility: constant load recommended to achieve better efficiencies and avoid cell breakdown • Ceramic materials have low relatively durability[46] however SOFC system using same materials are now commercial and have been demonstrated to have sufficient stability for commercialisation and deployment	• CSIRO • Deakin University
Characteristics	
• Inputs: Water, heat, electricity, carbon dioxide (optional) • By-products: Oxygen, carbon monoxide (if carbon dioxide input) • Operating temperature: 700°–800°C[47] • Energy efficiency: (up to 82% system level efficiency claimed to date)	

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[43] Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). *A comprehensive review on PEM water electrolysis.* International Journal of Hydrogen Energy, 38(12), 4901-4934. doi:https://doi.org/10.1016/j.ijhydene.2013.01.151

[44] Ibid.

[45] Ibid.

[46] Ibid.

[47] US DOE (n.d.) *Hydrogen Production: Electrolysis*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis Accessed: 20/11/2019

5.2 Fossil fuel conversion

5.2.1 Autothermal reforming (dry or steam)

What is it?

A combination of SMR and combustion of the fuel (methane), where steam is added to the oxidation process. The heat from the oxidation component supplies the energy required for the steam reforming process.

Why is it important?

Steam methane reforming and partial oxidation are integrated into a single system, in which heat integration has been incorporated.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• High selectivity to syngas • Flexible H_2/CO ratio for syngas production, for subsequent production of synthetic fuels • Less clean-up required than pyrolysis options • Can use CO2 as a reagent • Lower process temperature than partial oxidation • Heat from fuel combustion is used to supplement the SMR component - lower parasitic heat load as a result • The SMR and combustion components are integrated into a single unit • Low carbon/soot formation which minimises pressure drop and reduces OPEX • Compact design, small footprint relative to other fossil fuel conversion methods • Rapid start-up time	• Improve appliance and plant design for greater flexibility in ramping up and ramping down • Develop and demonstrate effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions • Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process • Develop burner designs for optimal mixing and catalysts to cope with severe operating conditions
Limitations	**Active institutions (2)**
• Extensive control system required • Requires air or oxygen • Requires CCUS to achieve low carbon emissions	• The Australian National University • The University of Newcastle
Characteristics	
• Inputs: Hydrocarbons, oxygen, steam, heat • By-products: CO_2 • Operating temperature: >500°C • Energy efficiency: 60-75%[60]	

5.2.2 Chemical looping water splitting

What is it?

A chemical loop utilises a recyclable metal with water and hydrocarbon feedstocks to produce hydrogen, water and carbon dioxide. The metal is involved in a repeating cycle of reaction steps.[48]

Why is it important?

Hydrogen and carbon dioxide are obtained as separate high-purity gas streams, allowing easier integration of CCUS.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Multiple feedstock options: fuel gas (including alcohol, hydrocarbons [when combined with reforming], biogas, waste gas), heavy bio-crude, biomass, tar and coal
- Solid oxygen carrier eliminates need for air as oxygen supply – fuel is converted into a pure stream of CO_2 and H_2O, which is easily separated
- High purity hydrogen (99.95-99.999%) can be obtained as a separate gas stream
- High fuel conversion efficiency
- Heat from exothermic oxidation can be channelled to the exothermic reduction to reduce required heat input
- If using fluidised bed reactor: continuous operation, supply of pure separated CO_2, N_2 and H_2.- potentially a poly-generation application
- Can be incorporated with syngas conversion processes
- Carbon capture integration has been shown to be effective

RD&D priorities

- Optimise the composition or structure of the oxygen carrier to improve stability
- Evaluate fuel flexibility and investigate natural minerals as oxygen carriers to improve overall dynamic process characteristics
- Improve reactor design
- Improve process development and integration
- Improve process simulation
- Demonstrate prototypes and pilot plants (large scale, long term operation)
- Demonstrate use of oxygen carriers in industrial environment

Limitations

- Oxygen carriers require replacement over time – utilisation of low-cost natural minerals is important to reduce the cost

Active institutions (6)

- The Australian National University
- CSIRO
- Monash University
- The University of Adelaide
- The University of Newcastle
- The University of Queensland

Characteristics

- Inputs: Hydrocarbons / coal / tar. Optional: biomass
- By-products: CO_2, other hydrocarbons
- Operating temperature: 700 to 1000°C

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[48] Luo, M., Yi, Y., Wang, S., Wang, Z., Du, M., Pan, J., & Wang, Q. (2018). *Review of hydrogen production using chemical-looping technology.* Renewable and Sustainable Energy Reviews, 81, 3186-3214. doi:https://doi.org/10.1016/j.rser.2017.07.007

5.2.3 Coal gasification

What is it?

Coal is reacted with controlled amounts of oxygen and/or steam at high temperatures to produce syngas (hydrogen and carbon monoxide) which also contains carbon dioxide, methane and water vapour. Gasification involves four stages: drying, pyrolysis, combustion, and gasification reactions.

Why is it important?

This process is well understood and established at industrial scale.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Established industrial process • Other chemicals generated can be useful by-products • Higher hydrogen produced per unit of coal compared to coal pyrolysis • Cleaner hydrogen product than that obtained from coal pyrolysis	• Develop and demonstrate effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions • Develop alternatives to the cryogenic process used to separate oxygen feedstock from air • Improve appliance and plant design for greater flexibility in ramping up and ramping down • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process • Establish environmentally suitable treatment of waste by-products • Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications • Improve reactor design to accommodate highly exothermic or endothermic reactions (e.g. staged introduction of reagents, better designed heat transfer surfaces, process intensification, advanced materials, reaction monitoring/control, pre-treatment of waste streams)
Limitations	**Active institutions (3)**
• Impurities in syngas require further separation • Low thermal efficiency • Produces tar in product gas • Requires CCUS to achieve low carbon emissions • Remains a higher emitter of carbon dioxide than natural gas-based methods and renewable methods after CCUS is employed[49] • High water usage per kilogram hydrogen produced	• CSIRO • Curtin University • The University of Adelaide • The University of Newcastle
Characteristics • Inputs: Coal, water, heat • By-products: CO_2, carbon, other hydrocarbons (temperature dependent) • Operating temperature: >500°C • Energy efficiency: ~63%**Error! Bookmark not defined.**	

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[49] International Energy Agency (2019). *The Future of Hydrogen: Seizing Today's Opportunities.*

5.2.4 Coal and oil pyrolysis

What is it?

Coal or oil is heated in the absence of oxygen, in order to degrade it into char, pyrolysis oil and syngas.

Why is it important?

This process is well understood, established at industrial scale, and produces other useful by-products alongside hydrogen.

TRL	1	2	3	4	5	6	7	8	9

Benefits	RD&D priorities
• Toxic components are degraded by high temperatures • Established industrial process • A range of useful by-products • Can accept varied quality of feedstock • No water required	• Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications • Develop and demonstrate effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions • Improve appliance and plant design for greater flexibility in ramping up and ramping down • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process • Establish environmentally suitable treatment of waste by-products • Improve reactor design to accommodate highly exothermic or endothermic reactions (e.g. staged introduction of reagents, better designed heat transfer surfaces, process intensification, advanced materials, reaction monitoring/control, pre-treatment of waste streams)
Limitations	**Active institutions (3)**
• Produces lower quantities of hydrogen per unit coal than in coal gasification • High operational costs • Purification system required to treat flue gases from the process • By-products contain high heavy metal content • Requires CCUS to achieve low carbon emissions	• CSIRO • The University of Newcastle • The University of Western Australia
Characteristics	
• Inputs: Heat, coal or oil • By-products: CO_2, ethylene, acetylene, carbon • Operating temperature: >500°C	

5.2.5 Concentrated solar-thermal methane reforming

What is it?

Thermal energy from concentrated sunlight is used to react natural gas with steam to form syngas (a mixture of hydrogen and carbon dioxide).

Why is it important?

This process allows the use of sunlight to provide heat required for the reforming process. The conventional process (steam methane reforming) is well understood and established at industrial scale.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Well understood industrially, with a variety of technology suppliers available for the catalyst, reaction system and downstream processes, including ammonia production • Proven with demonstrations up to 600kWt • Operating temperature compatible with some thermal storage technologies • Easily hybridised	• Developing and demonstrating CCUS technology to minimise CO_2 emissions • Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications • Improve reactor design and materials to accommodate highly endothermic reactions and thermal cycling • Integrate thermal storage for continuous operation
Limitations	**Active institutions (4)**
• High carbon dioxide emissions (requires CCUS)	• The Australian National University • CSIRO • Flinders University • The Future Fuels Cooperative Research Centre
Characteristics	
• Inputs: Steam reforming - Water, sunlight (concentrated for thermal energy), natural gas • By-products: CO_2 (resulting from purification step to increase hydrogen production) • Operating temperature: 700 to 850°C	

5.2.6 Natural gas pyrolysis (methane cracking)

What is it?

In the absence of oxygen, methane is decomposed into hydrogen and elemental carbon at high temperatures, usually in the presence of a catalyst.

Why is it important?

Utilises natural gas to produce low-CO_2 hydrogen without the need for CCS whilst also producing a marketable by-product, elemental carbon powder.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- High purity carbon powder is produced as a by-product – these can include carbon black used in tyres and inks; activated carbon used in water purification and more exotic forms like graphene and nanotubes for use in electronics and composites
- Hydrogen gas easily separated from carbon powder[50]
- Zero-to-low CO_2 emissions if making use of heat from renewable or waste sources
- No water required

RD&D priorities

- Overcoming carbon deposition leading to clogging of reactor
- Demonstration at larger scale under industrially relevant reactor conditions
- Catalyst development
- Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process

Limitations

- During the extraction, processing and use of natural gas, methane can escape to the atmosphere[51]

Active institutions (6)

- CSIRO
- The Future Fuels Cooperative Research Centre
- The University of Adelaide
- The University of Newcastle
- The University of Queensland
- The University of Western Australia

Characteristics

- Inputs: Natural gas (methane) and heat
- By-products: High purity carbon (dependent on catalyst type)
- Operating temperature: >500°C
- Energy efficiency: Theoretically achievable value at commercial scale estimated at ~55%[52]
- The estimated median life cycle emissions of methane pyrolysis are 6.1kg CO_2e/kg H_2. This is lower than steam methane reforming and coal gasification estimates, but higher than electrolysis and biomass gasification methods [53]

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[50] EurekAlert! (2018) *Innovation award for climate-friendly methane cracking,* [Online] Available from: https://www.eurekalert.org/pub_releases/2018-12/kift-iaf120318.php Accessed: 19/11/2019

[51] Weger, L., Abánades, A., & Butler, T. (2017). *Methane cracking as a bridge technology to the hydrogen economy.* International Journal of Hydrogen Energy, 42(1), 720-731. doi:https://doi.org/10.1016/j.ijhydene.2016.11.029

[52] Ibid.

[53] Parkinson, B., Balcombe, P., Speirs, J. F., Hawkes, A. D., & Hellgardt, K. (2019). *Levelized cost of CO 2 mitigation from hydrogen production routes.* Energy Environ. Sci., 12(1), 19-40. doi:10.1039/c8ee02079e

5.2.7 Partial oxidation: thermal or catalytic

What is it?

A hydrocarbon fuel is partially combusted in a reformer in the presence of a limited amount of oxygen. Incomplete combustion occurs, leading to the formation of hydrogen gas and carbon monoxide. Can either be thermal (high temperature) or catalytic (lower temperature).

Why is it important?

Established industrial process with fast start-up time and yields a syngas ratio ideal for subsequent chemical synthesis.

TRL*	1	2	3	4	5	6	7	8	9

*The TRL for thermal partial oxidation is 9. Catalytic partial oxidation is a much less mature technology, with a TRL of 4-5.

Benefits

- Less clean-up required than gasification or pyrolysis options
- Exothermic reaction therefore does not require a heat exchanger and is more compact[54]
- Rapid start-up time[55]
- Yields ideal syngas ratio for subsequent chemical synthesis, e.g. methanol production

RD&D priorities

- Develop and demonstrate effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions
- Improve appliance and plant design for greater flexibility in ramping up and ramping down
- Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process
- Establish environmentally suitable treatment of waste by-products
- Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications
- Improve reactor design to accommodate highly exothermic or endothermic reactions (e.g. staged introduction of reagents, better designed heat transfer surfaces, process intensification, advanced materials, reaction monitoring/control, pre-treatment of waste streams)

Limitations

- Ideal syngas ration for subsequent chemical synthesis is produced at the expense of lower quantities of hydrogen
- Soot handling adds process complexity[56]
- Requires oxygen
- Requires CCUS to achieve low carbon emissions

Active institutions (3)

- The Australian National University
- CSIRO
- The University of Adelaide
- The University of Newcastle

Characteristics

- Inputs: Oxygen, heat (only required initially in the case of catalytic system), oil or natural gas
- By-products: CO_2
- Operating temperature: High for thermal system (however heat comes from combusting hydrocarbon feedstock), initially high temperature required for catalytic system (subsequently self-sustaining temperature during ongoing process)
- Energy efficiency: 60-75%[57]

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[54] Salameh, Z. (2014). *Chapter 4 - Energy Storage*. In Z. Salameh (Ed.), Renewable Energy System Design (pp. 201-298). Boston: Academic Press.

[55] Ibid.

[56] Holladay, J. D., Hu, J., King, D. L., & Wang, Y. (2009). *An overview of hydrogen production technologies*. Catalysis Today, 139(4), 244-260. doi:https://doi.org/10.1016/j.cattod.2008.08.039

[57] Nikolaidis, P., Poullikkas, A. (2017). *A comparative overview of hydrogen production processes*. Renewable and Sustainable Energy Reviews

5.2.8 Steam methane reforming and carbon dioxide reforming

What is it?

Natural gas is mixed with steam (and/or carbon dioxide) in the presence of a catalyst at high temperatures and moderate pressure to produce syngas.

Why is it important?

This process is well understood and established at industrial scale. Most hydrogen today is produced via this method.

TRL	1	2	3	4	5	6	7	8	9

Benefits	RD&D priorities
• Steam reforming - High selectivity to hydrogen in syngas product - higher H_2/CO ratio for H2 production than autothermal reforming or partial oxidation[58] • Less clean-up required than pyrolysis options • Carbon dioxide reforming - makes use of CO_2 as a reagent	• Developing and demonstrating CCUS technology to minimise CO_2 emissions • Developing new reactor membranes[59] • Improve appliance and plant design for greater flexibility in ramping up and ramping down • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process • Establish environmentally suitable treatment of waste by-products • Develop cheap and effective hydrogen separation systems to obtain appropriately pure hydrogen for specific applications • Improve reactor design to accommodate highly exothermic or endothermic reactions (e.g. staged introduction of reagents, better designed heat transfer surfaces, process intensification, advanced materials, reaction monitoring/control, pre-treatment of waste streams) • Develop catalysts more tolerant of impurities and wide temperature ranges
Limitations	**Active institutions (5)**
• High CO_2 emissions (requires CSS or further handling) • Steam reforming - High water usage per kilogram of hydrogen produced • CO_2 reforming: greater energy demand, lower quantities of hydrogen produced per unit of natural gas	• CSIRO • The University of Newcastle • The University of New South Wales • The University of Queensland • The University of Sydney
Characteristics	
• Inputs: Steam reforming - Water, heat, natural gas. Carbon dioxide reforming - CO_2, heat, natural gas • By-products: CO_2 (resulting from purification step to increase hydrogen production) • Operating temperature: ~750°C • Energy efficiency: 74-85%[60]	

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[58] Holladay, J. D., Hu, J., King, D. L., & Wang, Y. (2009). *An overview of hydrogen production technologies*. Catalysis Today, 139(4), 244-260. doi:https://doi.org/10.1016/j.cattod.2008.08.039

[59] Shafiee, A., Arab, M., Lai, Z., Liu, Z., & Abbas, A. (2016). *Modelling and sequential simulation of multi-tubular metallic membrane and techno-economics of a hydrogen production process employing thin-layer membrane reactor.* International Journal of Hydrogen Energy, 41(42), 19081-19097. doi:https://doi.org/10.1016/j.ijhydene.2016.08.172

[60] Nikolaidis, P., Poullikkas, A. (2017). *A comparative overview of hydrogen production processes*. Renewable and Sustainable Energy Reviews

5.3 Biomass and waste conversion

5.3.1 Biogas reforming

What is it?

Biogas is mixed with steam in the presence of a catalyst at high temperatures (~750°C) and moderate pressure to produce syngas. Biogas is obtained via the anaerobic digestion of biomass; therefore, this method is considered a composite of biological hydrogen production and biomass conversion.

Why is it important?

Biomass is plentiful, regenerative and removes carbon dioxide from the atmosphere, making this process carbon neutral. Coupling the process with CCUS has the potential to make it carbon negative.

TRL*	1	2	3	4	5	6	7	8	9

*The TRL for this method varies depending on process.

Benefits	**RD&D priorities**
• Makes use of biogas obtained from biomass • Makes use of similar reforming process as with steam methane reforming • Zero-to-low carbon emissions	• Develop CCUS technologies • Improve anaerobic digestion process • Develop methane/CO_2 separation technologies • Optimise operating parameters such as catalyst characteristics, temperature, throughput and concentration[61] • Improve reactor and process design for greater energy efficiency[62] • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process
Limitations	**Active institutions (3)**
• Operation of steam methane reforming systems to reform biogas is inefficient at small scale	• Macquarie University • Queensland University of Technology • The University of Newcastle
Characteristics	
• Inputs: Water, heat, biogas • By-products: CO_2 • Operating temperature: ~750°C	

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[61] Verma, P., & Samanta, S. K. (2016). *Overview of Biogas Reforming Technologies for Hydrogen Production: Advantages and Challenges*. Paper presented at the Proceedings of the First International Conference on Recent Advances in Bioenergy Research, New Delhi.

[62] Ibid.

5.3.2 Biomass and waste gasification

What is it?

Biomass gasification for hydrogen production involves the thermochemical conversion of biomass (such as crop and forest residues) with a controlled amount of steam and oxygen, to syngas at temperatures over ~700°C. This is followed by the water-gas shift reaction to increase the yield and concentration of hydrogen.

Why is it important?

Biomass is plentiful, regenerative and removes carbon dioxide from the atmosphere, making this process carbon neutral. Coupling the process with CCUS has the potential to make it carbon negative. Simultaneous treatment of municipal waste is also possible.

TRL	1	2	3	4	5	6	7	8	9

The TRL of this technology varies based on feedstock: TRL 9 for woody biomass, and TRL 6-7 for municipal solid waste.

Benefits	**RD&D priorities**
• Established industrial process • Utilises agricultural/forest waste products	• Address challenges in understanding characteristics of different biomass feedstocks and in process handling (due to high temperatures required) • Optimise systems for different biomass feedstocks • Improve gas purification • Intensify process (reduce number of steps) • Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process
Limitations	**Active institutions (8)**
• Slag and tar build up requires additional machinery to be integrated into conventional gasification processes • Releases carbon dioxide (CCS or further handling could be employed to make the process carbon negative) – otherwise carbon neutral	• The Australia National University • CSIRO • Curtin University • Monash University • Queensland University of Technology • The University of Adelaide • The University of Newcastle • The University of Queensland
Characteristics	
• Inputs: Biomass, air, oxygen and/or steam • By-products: Carbon dioxide • Operating temperature: 500 to 1400˚C • Energy efficiency: ~52%[63]	

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[63] Bakhtyari, A., Makarem, M., Rahimpour, M. (2018). *Hydrogen Production Through Pyrolysis*. Encyclopedia of Sustainability Science and Technology.

5.3.3 Biomass and waste pyrolysis

What is it?

Biomass pyrolysis is the thermal decomposition of biomass in a non-oxidising environment to produce predominantly bio-char, pyrolysis liquid, and syngas. The composition is dependent on operating conditions and feedstock type. Catalyst choice alters the hydrogen yield in the gas component at different temperatures. When biomass-derived liquid reforming is employed, addition of steam or oxidation results in steam reforming and produces a stream of syngas.

Why is it important?

Biomass is plentiful, regenerative and removes carbon dioxide from the atmosphere, making this process carbon neutral. Coupling the process with CCUS has the potential to make it carbon negative. Simultaneous treatment of municipal waste is also possible.

TRL*	1	2	3	4	5	6	7	8	9

*The TRL of this technology varies based on feedstock: TRL 7-8 for woody biomass, and TRL 5-7 for municipal solid waste.

Benefits

- With upgrading and stabilisation, the pyrolysis liquid can be used as a substitute for fossil fuels, or used for biomass-derived liquid reforming
- Lower temperature requirements
- Biochar can be used in biomass gasification, or used for fertilising agricultural soil

RD&D priorities

- Improve modelling and simulations of the heat, mass and momentum effects in conjunction with kinetics[64]
- Minimise pyrolysis oil formation and improve H_2 production
- Process miniaturisation and mobilisation (development of portable units)
- Integrate renewable energy sources. For example, concentrated solar power can act as a thermal energy source for the process

Limitations

- Low thermal efficiency due to high moisture content of biomass that must be dried[65]
- Produces a significant amount of tar in product gas
- Significant resource requirements to gather and transport biomass to plant for pyrolysis.[66]
- Produces carbon dioxide (CCUS required)

Active institutions (8)

- CSIRO
- Curtin University
- Monash University
- Queensland University of Technology
- The University of Adelaide
- The University of Newcastle
- The University of Queensland
- The University of Western Australia

Characteristics

- Inputs: Biomass, water
- By-products: Carbon dioxide, solid charcoal (biochar)
- Operating temperature: >500°C
- Energy efficiency: 35-50%[67]

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[64] Babu, B. (2008). Biomass pyrolysis: a state-of-the-art review, [Online] Available from: https://onlinelibrary.wiley.com/doi/epdf/10.1002/bbb.92

[65] Holladay, J. D., Hu, J., King, D. L., & Wang, Y. (2009). *An overview of hydrogen production technologies*. Catalysis Today, 139(4), 244-260. doi:https://doi.org/10.1016/j.cattod.2008.08.039

[66] Ibid.

[67] Bakhtyari, A., Makarem, M., Rahimpour, M. (2018). *Hydrogen Production Through Pyrolysis*. Encyclopedia of Sustainability Science and Technology.

5.3.4 Plasma-assisted biogas reforming

What is it?

Biogas is reacted with steam and/or CO_2 in a non-thermal plasma reactor integrating with a suitable catalyst to produce hydrogen rich syngas and/or liquid short chain oxygenates (e.g. MeOH). Biogas is obtained via the anaerobic digestion of biomass; therefore, this method is considered a composite of biological hydrogen production and biomass conversion.

Why is it important?

Biomass is plentiful and regenerative and removes carbon dioxide from the atmosphere, making this process carbon neutral. Coupling the process with CCS has the potential to make it carbon negative. Depending on the targeted product, CO_2 can be directly utilised and consumed in the reforming process. Liquid products can be easily transported from remote locations or exported.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Makes use of biogas obtained from biomass and waste streams
- Zero-to-low carbon emissions
- Operable at small and medium scales
- Operates at low temperature and atmospheric pressure
- Can eliminate tars and VOCs in the biogas as part of the reforming process
- Responsive and can be used with intermittent electricity sources
- Can produce liquid fuel/hydrogen carriers

RD&D priorities

- Develop and demonstrate effective means of integrating carbon capture, utilisation and storage (CCUS) to achieve zero-to-low carbon emissions
- Improve anaerobic digestion process
- Develop catalysts tailored for use in a plasma reactor
- Build fundamental understanding of synergistic plasma catalysis mechanisms
- Improve selectivity, yield, and energy efficiency of the plasma reactor

Limitations

- Carbon balance depends on electricity source
- Limited selectivity (depending on desired product)
- Low yield and energy efficiency
- CO_2 may be produced as a by-product (in the case of pure H_2 production)

Active institutions (3)

- Queensland University of Technology
- The University of Newcastle
- The University of Western Australia

Characteristics

- Inputs: Biogas, water, CO_2, electricity (to generate non-thermal plasma)
- By-products: CO_2
- Operating temperature: 200 to 300°C
- Energy efficiency: 1-20%

5.3.5 Plasma-assisted biomass conversion

What is it?

Gasification and pyrolysis processes are supported by thermal (gasification) or non-thermal (pyrolysis) plasma, which either provide energy or induce catalytic decomposition reactions for conversion of biomass or municipal waste into hydrogen and other hydrocarbons as value-added chemical materials.

In the gasification process, thermal plasma can be used to provide sufficient energy (at temperatures greater than 3000K) to break down complex hydrocarbons into simple gases, including CO and H_2.[68] In the pyrolysis process, input biomass or municipal waste can be converted into a range of output hydrocarbon gases and oils, in addition to solid char. This occurs at much lower temperatures (1000-2000K) than plasma gasification.

Why is it important?

Biomass is plentiful, regenerative and removes carbon dioxide from the atmosphere, making this process carbon neutral. Coupling the process with CCS has the potential to make it carbon negative. Simultaneous treatment of municipal waste is also possible.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Portable, small and low cost • Allows variable inputs - Can be used for the conversion of biomass or municipal solid waste • Highly selective catalyst • Safe elimination of toxic products[69]	• Develop catalysts and optimise their structures to promote H_2 formation • Investigate the effects of rapid heating on decomposition of feedstocks • Develop CCUS technologies
Limitations	**Active institutions (3)**
• Gasification – high energy requirement to create the plasma, reducing efficiency. Efficiency has been calculated to be 42% for plasma compared to 72% for conventional gasification.[70] • High capital cost	• Queensland University of Technology • The University of Newcastle • The University of Western Australia

Characteristics

- Inputs: Biomass or municipal solid waste, water, electricity
- By-products: Gasification = CO, pyrolysis = hydrocarbons, char
- Operating temperature: Gasification = >3000°C, pyrolysis = ~1000 to 2500°C
- Energy efficiency: ~42% for plasma gasification

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[68] Favas, J., Monteiro, E., & Rouboa, A. (2017). *Hydrogen production using plasma gasification with steam injection.* International Journal of Hydrogen Energy, 42(16), 10997-11005. doi:https://doi.org/10.1016/j.ijhydene.2017.03.109

[69] Ojha, A., Reuben, A. C., & Sharma, D. (2012). *Solid Waste Management in Developing Countries through Plasma Arc Gasification- An Alternative Approach*. APCBEE Procedia, 1, 193-198. doi:https://doi.org/10.1016/j.apcbee.2012.03.031

[70] Favas, J., Monteiro, E., & Rouboa, A. (2017). *Hydrogen production using plasma gasification with steam injection.* International Journal of Hydrogen Energy, 42(16), 10997-11005. doi:https://doi.org/10.1016/j.ijhydene.2017.03.109

5.4 Thermal water splitting

5.4.1 Solar thermochemical water splitting (two-stage)

What is it?

Concentrated sunlight is used to heat up transition metal oxides (e.g. cerium oxide), releasing oxygen. The metal oxides are then reacted with water, which splits to re-oxidise the metal oxide as well as produce hydrogen – the cycle then repeats.

Why is it important?

This process produces hydrogen using only water and sunlight and has the potential to be low-cost due to system simplicity.

TRL[71]	1	2	3	4	5	6	7	8	9

Benefits

- Less complex and fewer steps than hybrid thermochemical water splitting
- Does not require an electrolysis step (therefore no electricity input)[72]
- Zero CO_2 emissions
- Make use of concentrated sunlight as heat source

RD&D priorities

- Improve concentrated solar thermal technologies
- Improve thermal efficiency
- Improve long-term stability of reactor materials
- Conduct fundamental material investigations (e.g. understand mechanism of material melting and sticking)
- Develop overall large-scale system concepts

Limitations

- Requires very high operating temperatures
- Dependent on solar irradiation

Active institutions (5)

- The Australian National University
- CSIRO
- Flinders University
- The University of Adelaide
- The University of New South Wales

Characteristics

- Inputs: Water and sunlight
- By-products: Oxygen
- Operating temperature: ~900 to 1,500°C
- Energy efficiency: Theoretical greater than 30%. Demonstrated approximately 5%.

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[71] Binotti, M., Di Marcoberardino G, Biassoni M, Manzolini G (2017) *Solar Hydrogen Production with Cerium Oxides Thermochemical Cycle*

[72] US DOE (n.d.). *Hydrogen Production: Thermochemical Water Splitting*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting Accessed: 20/11/2019

5.4.2 Solar thermochemical water splitting (multi-stage)

What is it?

Concentrated solar is used to generate heat to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. In this 'hybrid' system, multiple steps are required, and electrical input is required for one of the reaction steps.[73]

Why is it important?

This multi-stage process has a lower required operating temperature than two-stage solar thermochemical water splitting. This is, however, at the cost of increased system complexity.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Can make use of concentrated sunlight as heat source
- Requires lower temperatures than 2-stage solar thermochemical water splitting

RD&D priorities

- Investigate efficiency and durability of materials for thermochemical cycling[74]
- Develop efficient and durable reactor designs for thermochemical cycling[75]
- Improve reactor and electrolyser performance
- Develop low-cost method for separation of O_2 from SO_2 prior to SO_2 electrolysis[76]
- Scale-up SO_2 electrolysis step from the 100-W to the hundreds of kW scale

Limitations

- Has an electrolysis step which requires electricity input alongside heat
- Heavy-metal processing required[77]
- Production of toxic or corrosive chemical intermediates[78]

Active institutions (3)

- CSIRO
- Flinders University
- The University of Adelaide

Characteristics

- Inputs: Sunlight, electricity, water
- By-products: Oxygen
- Operating temperature: Varies from medium to high (Hybrid sulphur at least 750°C, copper chloride lower at 300-400°C)

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[73] US DOE (n.d.). *Hydrogen Production: Thermochemical Water Splitting*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting Accessed: 20/11/2019

[74] Ibid.

[75] Ibid.

[76] Hinkley, J., Hayward, J., McNaughton, R., Edwards, J., Lovegrove, K. (2016). *Concentrating Solar Fuels Roadmap: Final Report*. Available at https://arena.gov.au/assets/2016/05/Concentrating-Solar-Fuels-Roadmap-Final-Report-CSIRO.pdf

[77] Rao, C., & Dey, S. (2017). *Solar thermochemical splitting of water to generate hydrogen*. Proceedings of the National Academy of Sciences of the United States of America, 114(51), 13385-13393.

[78] Ibid.

5.5 Biological hydrogen production

5.5.1 Biophotolysis (direct and indirect)

What is it?

Microorganisms such as green algae and blue-green algae (cyanobacteria) split water into hydrogen and oxygen via direct or indirect bio-photolysis. In direct biophotolysis, hydrogenase in green algae drives hydrogen evolution. In indirect biophotolysis, nitrogenase in blue-green algae drives nitrogen fixation.

Why is it important?

Biophotolysis could be used for producing hydrogen from wastewater with sunlight as an energy source.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Low-to-net zero carbon • Could be used in wastewater or water which cannot be used for drinking or agriculture • Biocatalysts are inexpensive and biodegradable	• Improve production rates and conversion efficiency, both of which are currently low[79,80] • Reduce cost of photobioreactors[84] • Develop oxygen resistant hydrogenase[81] • Continue materials development,[84] including characteristics such as increased durability[82] • Investigate immobilisation of microorganism cultures to achieve improvement[83] • Technology development while sustaining high rate of biohydrogen production
Limitations	**Active institutions (2)**
• In the case of direct biophotolysis: Oxygen produced inhibits the hydrogen production reaction.[79] Oxygen that is evolved destroys the hydrogen enzyme. Separate streams of high purity H_2 and O_2 are not obtainable[84] • Indirect biophotolysis: hydrogenase enzyme provides low hydrogen yield and produces carbon dioxide • Requires large surface area[84] • Need to cope with the intermittent nature of solar irradiation supply for the process	• The University of Adelaide • The University of Queensland
Characteristics	
• Inputs: Direct: Water, sunlight. Indirect: Carbon monoxide, water, sunlight • By-products: Direct: oxygen. Indirect: carbon dioxide • Operating temperature: Ambient	

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[79] US DOE (n.d.). *Hydrogen Production: Photobiological*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-photobiological Accessed: 20/11/2019

[80] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

[81] Ibid.

[82] Ibid.

[83] Ibid.

[84] Ibid.

5.5.2 Dark fermentation

What is it?

In the absence of light, microorganisms such as bacteria break down organic matter to produce hydrogen gas through dark fermentation. Bacteria can be engineered in order to increase metabolic activity for a higher hydrogen production rate.

Why is it important?

Dark fermentation allows the production of hydrogen using biomass as a feedstock, without requiring exposure to sunlight. System tanks and cells could be transported for on-site hydrogen generation.

TRL[85]	1	2	3	4	5	6	7	8	9

The TRL of this technology is 7 for conventional dark fermentation, however lower (TRL 5-6) when incorporating metabolic engineering as part of the system design.

Benefits	**RD&D priorities**
• Smaller footprint than light-dependent methods • Can use a variety of waste resources[86] • No light required for process to occur[87] • Simple reactor design[88] • Functions without requiring strict anaerobic conditions • Biocatalysts are inexpensive and biodegradable • Process occurs at ambient temperature and pressure • Can transport systems for on-site hydrogen generation	• Improve hydrogen yield[89] • Improve production rate • Metabolic engineering of bacteria to improve performance,[90] or suppress activity of hydrogen-consuming bacteria • Condition optimisation and robustness testing
Limitations	**Active institutions (2)**
• Bacteria must be kept within survivable conditions • Increasing yield requires very low hydrogen partial pressure to overcome thermodynamic restrictions • Hydrogen consuming microbes must be effectively suppressed to ensure harvestable yield of hydrogen can be realised	• CSIRO • Macquarie University
Characteristics	
• Inputs: Water, organic matter (biomass) • By-products: Carbon dioxide • Operating temperature: Ambient	

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[85] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[86] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

[87] Ibid.

[88] Ibid.

[89] Lee, H., Vermaas, W., & Rittmann, B. (2010*). Biological hydrogen production: Prospects and challenges.* Trends in Biotechnology, 28(5), 262-271.

[90] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

5.5.3 Hybrid light and dark fermentation

What is it?

Dark fermentation and photofermentation processes occur sequentially in a series of reactors.

Why is it important?

Hybrid fermentation allows extraction of additional hydrogen from the effluents of the typical dark fermentation process.

TRL[91]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Maximises hydrogen yield from source material[92] • Makes use of untreated dark-fermentation effluents (which would otherwise require further handling or present an environmental hazard)[93] • Biocatalysts are inexpensive and biodegradable • Could use organic waste as substrate	• Improve substrate conversion efficiency[94] • Improve reactor design
Limitations	**Active institutions (0)**
• Large surface area required for photo-fermentation • Operation variability depending on solar irradiation supply for the photofermentation step	• (No active institutions found in study)
Characteristics	
• Inputs: Organic matter (biomass), water, light for photo-fermentation step • By-products: Carbon dioxide • Operating temperature: Ambient	

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[91] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[92] Das, D., & Veziroglu, T. N. (2008). *Advances in biological hydrogen production processes.* International Journal of Hydrogen Energy, 33(21), 6046-6057. doi:https://doi.org/10.1016/j.ijhydene.2008.07.098

[93] Tao, Y., Chen, Y., Wu, Y., He, Y., & Zhou, Z. (2007). *High hydrogen yield from a two-step process of dark- and photo-fermentation of sucrose.* International Journal of Hydrogen Energy, 32(2), 200-206. doi:https://doi.org/10.1016/j.ijhydene.2006.06.034

[94] Ibid.

5.5.4 Microbial electrolysis

What is it?

Electrical energy produced by microbes via breakdown of organic matter are augmented with a small additional current to facilitate proton reduction, forming hydrogen gas. A microbial electrolysis cell (MEC) can have a membrane or be membraneless and operates under anaerobic conditions.[95]

Why is it important?

Microbial electrolysis presents the opportunity to use breakdown or organic matter to reduce the electrical input required for hydrogen production in an electrochemical cell.

TRL[96]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Hydrogenase enzymes function with high catalytic rates at thermodynamic equilibrium[97] • Could be used in wastewater or water which cannot be used for drinking or agriculture • No light required for process to occur • Reduced electrical input required compared to electrolytic methods • Glucose or glucose-rich substrates such as cellulose can also be converted into hydrogen[98] • Rates of hydrogen production and organic waste destruction/ conversion can be controlled and monitored via electrical means • Australia has plentiful supply of renewable energy in the form of wind and solar radiation. Microbial electrolysis can potentially be a platform technology for converting surplus electrical energy generated from the established wind-turbines and photovoltaic technologies into a storable energy form as hydrogen, while also accomplishing waste treatment	• Develop inexpensive cathodes such as Nickel and stainless steel[99] • Engineer cells with lower internal resistance[100] • Improve anode geometry, eliminating 'short circuit' metabolic reactions (H2 cycling)[101] • Improve production rates and yields • Increase current densities[102] • Develop effective measures to prevent further conversion of hydrogen into other compounds such as methane gas
Limitations	**Active institutions (3)**
• Expensive precious metal cathodes required (Pt)[103] • Energy losses at several point during MECs process[104]	• CSIRO • Queensland University of Technology • The University of Queensland

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[95] Show, K. Y., Yan, Y. G., & Lee, D.-J. (2019). *Chapter 16 - Biohydrogen Production: Status and Perspectives.* In A. Pandey, S. V. Mohan, J.-S. Chang, P. C. Hallenbeck, & C. Larroche (Eds.), Biohydrogen (Second Edition) (pp. 391-411): Elsevier.

[96] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[97] Caserta, G., Roy, S., Atta, M., Artero, V., & Fontecave, M. (2015). *Artificial hydrogenases: biohybrid and supramolecular systems for catalytic hydrogen production or uptake*. Current Opinion in Chemical Biology, 25, 36-47. doi:https://doi.org/10.1016/j.cbpa.2014.12.018

[98] Ditzig, J., Liu, H., & Logan, B. E. (2007). *Production of hydrogen from domestic wastewater using a bioelectrochemically assisted microbial reactor (BEAMR).* International Journal of Hydrogen Energy, 32(13), 2296-2304. doi:https://doi.org/10.1016/j.ijhydene.2007.02.035

[99] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

[100] Ibid.

[101] Ibid.

[102] Ibid.

[103] Show, K. Y., Yan, Y. G., & Lee, D.-J. (2019). *Chapter 16 - Biohydrogen Production: Status and Perspectives.* In A. Pandey, S. V. Mohan, J.-S. Chang, P. C. Hallenbeck, & C. Larroche (Eds.), Biohydrogen (Second Edition) (pp. 391-411): Elsevier.

[104] Lee, H., Vermaas, W., & Rittmann, B. (2010*). Biological hydrogen production: Prospects and challenges.* Trends in Biotechnology, 28(5), 262-271.

<table>
<tr><td>• Process efficiencies may vary, depending on the microbial activities
• The use of membrane separating the anode and the cathode in a MEC may result in pH splitting problems
• Effective management of pH condition within the MEC may be required to ensure stable microbial activity</td><td></td></tr>
<tr><td colspan="2">Characteristics
• Inputs: Water, organic matter; electricity; a suitable source of electrochemically active microbes
• By-products: Carbon dioxide; valuable chemicals (depending on the type of substrates and the biodegradation pathways taking place)
• Operating temperature: Near ambient, up to 40°C commonly tested[105]</td></tr>
</table>

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[105] Cotterill, S., Heidrich, E., & Curtis, T. (2016). *9 - Microbial electrolysis cells for hydrogen production.* In K. Scott & E. H. Yu (Eds.), Microbial Electrochemical and Fuel Cells (pp. 287-319). Boston: Woodhead Publishing.

5.5.5 Photofermentation

What is it?

Photosynthetic microbes use sunlight to break down organic matter via fermentation.

Why is it important?

Photo-fermentation could be used for producing hydrogen from wastewater or other organic waste with sunlight as an energy source.

TRL[106]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Low-to-net zero carbon[107] • Could be used in wastewater or water which cannot be used for drinking or agriculture[108] • Converts organic substrate • Nearly complete substrate conversion into biohydrogen[109] • Can extract additional hydrogen from dark fermentation effluents	• Develop inexpensive photobioreactors • Strain improvement through metabolic engineering[110] • Investigate replacement of nitrogenase with hydrogenase enzyme • Overcome low hydrogen production rate[111] • Overcome low solar-to-hydrogen efficiency[112] • Reduce cost of photobioreactors
Limitations	**Active institutions (1)**
• Large surface areas required[113] • Oxygen inhibits hydrogen production[114] • Operation variability depending on solar irradiation supply • Less flexible than dark fermentation regarding the type of substrate.[115] • It is usually necessary to convert complex substrates into a mixture of carboxylic acids and alcohols prior to H2 production by photofermentation.[116]	• The Australian National University
Characteristics	
• Inputs: Organic matter (hydrocarbons), water, sunlight • By-products: Carbon dioxide • Operating temperature: Ambient • Energy efficiency: <10%[117]	

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[106] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[107] US DOE (n.d.). *Hydrogen Production: Photobiological*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-photobiological Accessed: 20/11/2019

[108] Ibid.

[109] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

[110] Ibid.

[111] US DOE (n.d.). *Hydrogen Production: Photobiological*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-photobiological Accessed: 20/11/2019

[112] Ibid.

[113] Hallenbeck, P. C., Abo-Hashesh, M., & Ghosh, D. (2012). *Strategies for improving biological hydrogen production.* Bioresource Technology, 110, 1-9. doi:https://doi.org/10.1016/j.biortech.2012.01.103

[114] Ibid.

[115] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[116] Ibid.

[117] Ibid.

5.5.6 Dark fermentation followed by anaerobic digestion of biomass

What is it?

Biomass is processed via dark fermentation, followed by anaerobic digestion, which leads to the production of hydrogen and methane.[118] Methane can then be processed to produce further hydrogen, if required, via processes such as reforming or pyrolysis.

Why is it important?

Two-stage anaerobic digestion of biomass presents an opportunity to produce additional methane and hydrogen from biomass following dark fermentation.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Low-to-net zero carbon • Can be carried out at high organic loading rates[119] • Higher theoretical energy yield achievable compared to one-stage dark fermentation • More effective for treatment of slurry than pyrolysis	• Utilise biochar from biomass to enhance yield. Biochar can act as a buffer to maintain optimal pH conditions, and supply carbon, nutrients and minerals that support high bacterial growth[120] • Optimise operating temperature and pH of the system • Optimise biomass pre-treatment
Limitations	**Active institutions (5)**
• Bacteria must be kept within survivable conditions	• CSIRO • Griffith University • Queensland University of Technology • The University of Western Australia • Victoria University
Characteristics	
• Inputs: Biomass, water • By-products: Methane, carbon dioxide • Operating temperature: Ambient, or elevated to approximately 50 to 70°C if thermophilic microbes are used	

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[118] Moscoviz, R., Trably, E., Bernet, N., & Carrère, H. (2018). *The environmental biorefinery: state-of-the-art on the production of hydrogen and value-added biomolecules in mixed-culture fermentation.* Green Chemistry, 20(14), 3159-3179. doi:10.1039/C8GC00572A

[119] Ibid.

[120] Jang, H. M., Choi, Y.-K., & Kan, E. (2018). *Effects of dairy manure-derived biochar on psychrophilic, mesophilic and thermophilic anaerobic digestions of dairy manure*. Bioresource Technology, 250, 927-931. doi:https://doi.org/10.1016/j.biortech.2017.11.074

5.6 Photochemical and photocatalytic processes

5.6.1 Photocatalytic water splitting

What is it?

Makes use of photocatalyst materials, usually as single particles or nanostructured sheets, which uses sunlight to split water to produce hydrogen and oxygen gas. These types of systems do not have any external wiring or additional components.

Why is it important?

No membrane or electrical input is required to produce hydrogen.

TRL	1	2	3	4	5	6	7	8	9

<table>
<tr><th>Benefits</th><th>RD&D priorities</th></tr>
<tr><td>• Technically very simple and therefore inexpensive to operate
• No membrane required (depending on system configuration)
• Low capital cost compared to thermochemical and photobiological methods[121]
• Flexible reactor size
• In some cases, could be used for simultaneous treatment of wastewater[122]</td><td>• Develop photocatalyst materials[123]
• Develop co-catalyst materials (cheaper alternatives)
• Develop photocatalysts for one-step excitation, Z-scheme, and two-step excitation
• Improve surface engineering approaches for cocatalyst loading, surface morphology control, surface modification, and surface phase junction strategies
• Improve system design for large scale hydrogen production including reactor design and particle immobilisation schemes</td></tr>
<tr><th>Limitations</th><th>Active institutions (13)</th></tr>
<tr><td>• Need additional effort to separate hydrogen from oxygen[124]</td><td>• The Australian National University
• CSIRO
• Curtin University
• Flinders University
• The Future Fuels Cooperative Research Centre
• Griffith University
• Queensland University of Technology
• The University of Adelaide
• The University of Melbourne
• The University of Newcastle
• The University of New South Wales
• The University of Queensland
• Western Sydney University</td></tr>
<tr><th colspan="2">Characteristics</th></tr>
<tr><td colspan="2">• Inputs: Water (in some cases could be low purity), sunlight
• By-products: Oxygen
• Operating temperature: Ambient</td></tr>
</table>

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[121] Jafari, T., Moharreri, E., Amin, A., Miao, R., Song, W., & Suib, S. (2016). *Photocatalytic Water Splitting-The Untamed Dream: A Review of Recent Advances.* Molecules, 21(7), 900.

[122] Kim, J., & Choi, W. (2010). *Hydrogen producing water treatment through solar photocatalysis.* Energy & Environmental Science, 3(8), 1042-1045.

[123] Ahmad, H., Kamarudin, S. K., Minggu, L. J., & Kassim, M. (2015). *Hydrogen from photo-catalytic water splitting process: A review. Renewable and Sustainable Energy Reviews*, 43, 599-610. doi:https://doi.org/10.1016/j.rser.2014.10.101

[124] Kim, J., Hansora, D., Sharma, P., Jang, J., & Lee, J. (2019). *Toward practical solar hydrogen production an artificial photosynthetic leaf-to-farm challenge.* Chemical Society Reviews, 48(7), 1908-1971.

5.6.2 Photoelectrochemical water splitting

What is it?

Sunlight irradiates one or more photovoltaic components, which can generate electricity. One or more photovoltaic components can be integrated with catalysts to create photoelectrodes or can be electrically connected to standard catalyst-coated electrodes. Hydrogen and oxygen are produced at different (photo)electrodes, separated by a membrane.

Why is it important?

Photoelectrochemical water splitting makes use of sunlight to convert water to hydrogen, with the option of supplementing the process with some electrical energy.

TRL	1	2	3	4	5	6	7	8	9

Benefits	RD&D priorities
• Integrated solar capture and hydrogen production • Uses sunlight as primary energy source • In some designs, additional electrical energy input can be applied • Separation of H_2 and O_2 • Zero-to-low carbon emissions • Can leverage existing solar cell and electrocatalyst technologies	• Continue materials development[125] • Develop low-cost, stable catalyst and co-catalysts materials[126] • Develop low-cost, high-efficiency photoelectrode materials[127] • Improve long term stability of photoelectrodes • Improve system integration and design[128] • Improve membrane and electrode durability • Conduct technoeconomic analysis of PEC based solar hydrogen systems versus PV-electrolysis systems[129]
Limitations	**Active institutions (11)**
• Photoelectrodes absorb a limited range of sunlight[130]	• The Australian National University • Macquarie University • Monash University • Queensland University of Technology • RMIT University • The University of Adelaide • The University of Melbourne • The University of New South Wales • The University of Newcastle • The University of Queensland • Western Sydney University
Characteristics	
• Inputs: Water, sunlight, electricity (optional in some designs) • By-products: Oxygen	

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[125] Alfaifi, B., Ullah, H., Alfaifi, S., Tahir, A., & Mallick, T. (2018*). Photoelectrochemical solar water splitting: From basic principles to advanced devices.* Veruscript Functional Nanomaterials, 2, BDJOC3. doi:10.22261/FNAN.BDJOC3

[126] Montoya, J. H., Seitz, L. C., Chakthranont, P., Vojvodic, A., Jaramillo, T. F., & Nørskov, J. K. (2017). *Materials for solar fuels and chemicals*. Nature Materials, 16(1), 70-81. doi:10.1038/nmat4778

[127] Montoya, J. H., Seitz, L. C., Chakthranont, P., Vojvodic, A., Jaramillo, T. F., & Nørskov, J. K. (2017). *Materials for solar fuels and chemicals*. Nature Materials, 16(1), 70-81. doi:10.1038/nmat4778

[128] Beck, F. J. (2019). *Rational Integration of Photovoltaics for Solar Hydrogen Generation.* ACS Applied Energy Materials, 2(9), 6395-6403. doi:10.1021/acsaem.9b01030

[129] Shaner, M., Atwater, H., Lewis, N., & McFarland, E. (2016). *A comparative technoeconomic analysis of renewable hydrogen production using solar energy.* Energy & Environmental Science, 7, 2354-2371. doi: 10.1039/c5ee02573g

[130] Ahmed, M., & Dincer, I. (2019). *A review on photoelectrochemical hydrogen production systems: Challenges and future directions*. International Journal of Hydrogen Energy, 44(5), 2474-2507. doi:https://doi.org/10.1016/j.ijhydene.2018.12.037

- Operating temperature: Ambient
- Energy efficiency: Low (however uses direct sunlight). Efficiencies of 10-30% have been demonstrated for stand-alone (no added electricity) lab-based systems. DOE have set target STH > 20%[131] using low cost materials

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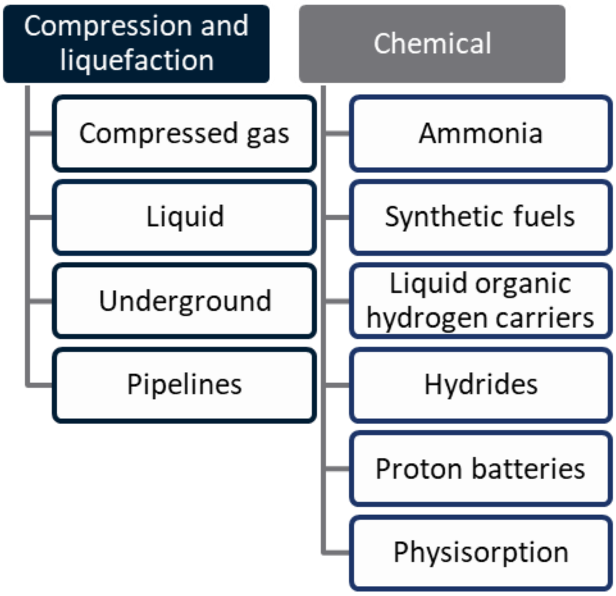
[131] US DOE (n.d.). *DOE Technical Targets for Hydrogen Production from Photoelectrochemical Water Splitting*, [Online] Available from: https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-production-photoelectrochemical-water-splitting Accessed: 21/11/2019

6 Technology repository: Storage



6.1 Compression and liquefaction

6.1.1 Compression: Electrochemical

What is it?

A compressor in which hydrogen is supplied at the anode and then driven through a polymer exchange membrane to the cathode via the application of an electric current, where it is collected in a compressed form on the other side.

Why is it important?

Electrochemical compression has the potential to displace mechanical compression by operating at higher efficiencies (70-80%), with a smaller footprint and the benefit of no moving parts. This can result in lower maintenance costs, reduce stack costs, and noiseless operation.

TRL[132]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Hydrogen product easily extracted • Solid state membrane • No moving parts – lower maintenance costs and noiseless operation • Higher efficiencies than traditional mechanical compression • Output compressed hydrogen pressures of approximately 1000 bar have so far been reached with this technology. • Can operate from very low pressure	• Improve compressor reliability • Fabricate new membranes • Reduce electro-osmotic drag (EOD) • Maintain stack seals at higher operating pressures • Reduce stack costs
Limitations	**Active institutions (1)**
• High capital cost • Lifetime and sensitivity to impurities such as reactive gas species • Reverse permeability leads to movement of hydrogen gas back into non-pressurised side of system	• CSIRO
Characteristics	
• Gravimetric hydrogen density: N/A • Storage conditions: High pressure (up to 1000 bar) • Compression efficiency: 70-80%	

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[132] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

6.1.2 Compression: Metal hydrides

What is it?

Hydrogen is absorbed at low pressure into the metal hydride material, and subsequently released as a high-pressure gas via the application of heat.

Why is it important?

Metal hydride compressors present the possibility to use waste heat in place of electricity to drive compression.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Simple design and operation[133] • Minimal ongoing maintenance required[134] • Potential to use waste heat in place of electricity to drive compression	• Optimise hydride-forming alloys • Enable long-term reliable operation • Improve kinetics of hydrogen absorption/release at high efficiency • Improve stability to hydrogen impurities (e.g. water, CO_2) • Improve system design and thermal management
Limitations	**Active institutions (5)**
• Requires elevated temperatures to release hydrogen from metal hydride material • Low efficiency • High capital cost	• CSIRO • Curtin University • Deakin University • Griffith University • The University of New South Wales
Characteristics	
• Gravimetric hydrogen density: N/A • Storage conditions: High pressure (approaching 700 bar depending on application), ambient pressure storage, high temperatures required for hydrogen release	

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[133] Lototskyy, M. V., Yartys, V. A., Pollet, B. G., & Bowman, R. C. (2014). *Metal hydride hydrogen compressors: A review*. International Journal of Hydrogen Energy, 39(11), 5818-5851. doi:https://doi.org/10.1016/j.ijhydene.2014.01.158

[134] Ibid.

6.1.3 Compression: Ionic liquids

What is it?

Ionic compressors make use of ionic liquids instead of a piston to compress hydrogen gas. Ionic compressors are currently in use in several hydrogen refuelling stations to reach the required pressures for hydrogen FCEVs.

Why is it important?

Potentially lower-cost compression. As with other mechanical compressors, could be effective for large-scale compression of hydrogen.

TRL	1	2	3	4	5	6	7	8	9

Benefits	RD&D priorities
• Potential to yield energy saving of 40% over standard mechanical compressors • Do not require bearings and seals, which are the most common sources of failure in mechanical compressors[135]	• Develop low-cost ionic liquids • Develop high performance ionic liquids (lower viscosity, improved operating temperature range)
Limitations	**Active institutions (0)**
• Low volumetric energy density • Energy intensive process • High cost of ionic liquids	• (No active institutions found in study)
Characteristics	
• Gravimetric hydrogen density: N/A • Storage conditions: Up to 1000 bar pressure demonstrated[136]	

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[135] US DOE (n.d.). *Gaseous Hydrogen Compression,* [Online] Available from: https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-compression Accessed: 21/11/2019

[136] The Linde Group (n.d.) *Hydrogen technologies. The ionic compressor IC90 (90MPa) – Datasheet.* [Online] Available from: https://www.boconline.co.uk/en/images/Datasheet_Ionic%20Fueler%20IC90_tcm410-410855.pdf Accessed: 21/11/2019

6.1.4 Liquid hydrogen: Cryo-compression

What is it?

Hydrogen is cooled to cryogenic temperatures and compressed to pressures approaching 300 bar into a supercritical fluid. The cryo-compressed hydrogen can be further compressed to pressures up to 700 bar.

Why is it important?

More financially viable where high density hydrogen storage is required under limited space, or where a larger roundtrip distance is involved.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Higher volumetric storage capacity than compressed gas
- Fewer evaporation losses (boil off losses) than in typical compression mechanisms or liquid hydrogen[137]
- Cryo-compressed can be denser than liquid hydrogen[138] – cryo-compressed hydrogen can be in liquid or gaseous state.
- The dormancy is greatly extended as the allowable pressure inside the vessel increases

RD&D priorities

- Reduce boil-off (i.e. vaporisation) rates
- Improve engineering, insulation, heat exchangers, and coolants
- Create larger and better insulated storage tanks
- Increase loss-free dormancy time (time before hydrogen will need to be vented from the tank)
- Reduce material costs and improve durability for increased lifetime

Limitations

- Requires advanced and more expensive storage material

Active institutions (1)

- The University of Western Australia

Characteristics

- Volumetric hydrogen density: 49.6 kg H_2/m^3 at 700 bar, 50.9 kg H_2/m^3 at 350 bar[139]
- Gravimetric hydrogen density: 7.0% at 700 bar, 10.0% at 350 bar[140]
- Storage conditions: Commonly 250 to 350 bar, 23 to 35K. 78K at 700 bar, 66K at 350 bar also recorded[141]
- Well-to-tank efficiency range: 40-45%. The energy required to liquify the hydrogen is 6- 8 kW/kg H_2. Well-to-tank efficiency includes from the feedstock natural gas consumed to the low heating value of H_2 delivered to tank.

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[137] Petitpas, G., Bénard, P., Klebanoff, L. E., Xiao, J., & Aceves, S. (2014). *A comparative analysis of the cryo-compression and cryo-adsorption hydrogen storage methods.* International Journal of Hydrogen Energy, 39(20), 10564-10584. doi:https://doi.org/10.1016/j.ijhydene.2014.04.200

[138] Barthelemy, H., Weber, M., & Barbier, F. (2017). *Hydrogen storage: Recent improvements and industrial perspectives*. International Journal of Hydrogen Energy, 42(11), 7254-7262. doi:https://doi.org/10.1016/j.ijhydene.2016.03.178

[139] Ahluwalia, R. K., Peng, J. K., Roh, H. S., Hua, T. Q., Houchins, C., & James, B. D. (2018). *Supercritical cryo-compressed hydrogen storage for fuel cell electric buses.* International Journal of Hydrogen Energy, 43(22), 10215-10231. doi:https://doi.org/10.1016/j.ijhydene.2018.04.113

[140] Ibid.

[141] Ibid.

6.1.5 Liquid hydrogen: Cryogenic tanks

What is it?

Hydrogen is liquefied and stored at -253°C, at ambient-moderate pressures, in cryogenic tanks through a multi-stage process of compression and cooling.

Why is it important?

More financially viable where high density hydrogen storage is required under limited space, or where a larger roundtrip distance is involved.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Higher volumetric storage capacity than compressed gas • Fewer evaporation losses than typical compression mechanisms	• Reduce boil-off (i.e. vaporisation) rates • Improve engineering, insulation, heat exchangers and coolants • Improve insulation material construction techniques to achieve larger scale and better insulated tanks • Improve hydrogen compression technology • Study and analyse the effects of vessel shape designs, stratification, and thermal overfill • Conduct thermal-fluid dynamical analysis on the effects of flashing during the transport of liquid hydrogen from bulk storage to atmospheric on-site storage • Develop low cost catalysts for improved ortho-para conversion, and ortho-para ratio measurement capability, to reduce boil off rate[142] • Conduct studies of impurity freeze-out in H_2 production[143]
Limitations	**Active institutions (6)**
• Requires advanced and more expensive storage material • Liquefaction requires complex technical plant[144] • Liquefied hydrogen incurs boil-off losses • To be liquefied, up to 40% of energy content of hydrogen is required[145]	• CSIRO • Monash University • Queensland University of Technology • The University of New South Wales • The University of Sydney • The University of Western Australia

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[142] May, E.F., Johns, M.L., Stajduhar, J., Al Ghafri, S.Z.S, Metaxas, P.J., Connolly, P.R.J., Sampson, C.C. (2019). *Research & Development Needs for Australia's H2 Export Industry*, University of Western Australia.

[143] Ibid.

[144] Hydrogen Europe (2017). *Hydrogen Storage,* [Online] Available from: https://hydrogeneurope.eu/hydrogen-storage Accessed: 21/11/2019

[145] Dagdougui, H., Sacile, R., Bersani, C., & Ouammi, A. (2018). *Chapter 4 - Hydrogen Storage and Distribution: Implementation Scenarios*. In H. Dagdougui, R. Sacile, C. Bersani, & A. Ouammi (Eds.), Hydrogen Infrastructure for Energy Applications (pp. 37-52): Academic Press.

Characteristics

- Volumetric hydrogen density: 70.85 kg H_2/m^3 [146] at 1 bar
- Storage conditions: 2- 10 bar, 20K
- Well-to-tank efficiency range: 20-25%. The energy required to liquify the hydrogen is 6- 8 kW/kg H_2. Well-to-tank efficiency includes from the feedstock natural gas consumed to the low heating value of H_2 delivered to tank.

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[146] NIST (2018). Saturation Properties for Hydrogen — Pressure Increments, [Online] Available from: https://webbook.nist.gov/cgi/fluid.cgi?Action=Load&ID=C1333740&Type=SatT&Digits=5&PLow=.5&PHigh=1.5&PInc=.1&RefState=DEF&TUnit=K&PUnit=atm&DUnit=kg/m3&HUnit=kJ/mol&WUnit=m/s&VisUnit=uPa*s&STUnit=N/m Accessed: 21/11/2019

6.1.6 Metal-composite pressurised vessels

What is it?

Hydrogen is stored at high pressures (approaching 800 bar) in steel or carbon fibre composite tanks via mechanical compression.

Why is it important?

Well established and commonly used storage technology; currently the standard storage method.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Established technology • Simple compression process • Ambient temperature storage	• Develop higher efficiency compression technologies
Limitations	**Active institutions (2)**
• Energy intensive process • Low volumetric hydrogen density	• CSIRO • Curtin University
Characteristics	
• Storage conditions: High pressure (350-800 bar), ambient temperature	

6.1.7 Underground storage

What is it?

Hydrogen gas is compressed and injected via wells into subsurface formations. Apart from pure hydrogen, there are also options to store natural gas that is lean in hydrogen, or rich hydrogen mixtures with methane, carbon dioxide and carbon monoxide (syngas or town gas). This parallels the underground storage of natural gas, which is used extensively around the world, including in Australia. The options for subsurface storage include salt caverns (which are excavated and shaped by injecting fresh water into existing rock salt formations), depleted gas or oil fields, or saline aquifers. The hydrogen is then extracted back from the formation via the wells when required.

Why is it important?

The underground storage approach allows large volumes of hydrogen to be stored and therefore potentially cope with seasonal variation in demand, not just peak load cycling. Subsurface storage will have much lower costs per mass of hydrogen stored than options at the surface, as it makes use of existing formations and is much safer.

TRL	1	2	3	4	5	6	7	8	9

The TRL of hydrogen storage in underground formations varies depending on the local geology. Pure hydrogen storage in salt cavern storage is already commercial but not widespread (TRL 8). Storage in depleted fields and saline aquifers has been done for some hydrogen mixtures but needs development (TRL 5).

Benefits	**RD&D priorities**
• High volume at lower pressure and cost • Allows seasonal storage as well as peak load • Very large feasible scale of storage	• Develop methodology for assessing sites • Develop simulation technology for subsurface mixtures of hydrogen and other gases. • Identify candidate sites for storage near hydrogen production • Investigate potential interactions of hydrogen with rocks, fluid and subsurface bacteria
Limitations	**Active institutions (4)**
• Cannot be used for transport of hydrogen • Specific geological requirements	• CSIRO (related CO_2 and natural gas storage research) • Curtin University • The Future Fuels Cooperative Research Centre • The University of Melbourne
Characteristics	
• Gravimetric hydrogen density: ~100% (not taking into account underground cavern mass) • Storage conditions: High pressure (~50-200 bar) and moderate temperature (30-80°C)	

6.2 Chemical storage

6.2.1 Ammonia

What is it?

Ammonia is synthesised from hydrogen and nitrogen via one of a variety of methods. Ammonia can then be transported, and the hydrogen extracted again at the point of use via a thermal decomposition and separation process.

Why is it important?

Ammonia can be transported under mild conditions and be utilised directly or converted back into hydrogen for use.

TRL*	1	2	3	4	5	6	7	8	9

*Various ammonia technologies in development cover the whole TRL scale.

Benefits	**RD&D priorities**
• Cracking leads to formation of nitrogen gas, which is innocuous and can be released back into the atmosphere • Can be stored at mild temperature and pressure for transport • Can leverage existing ammonia handling and transport infrastructure • High Gravimetric hydrogen density: 17.8% by mass[147] • High Volumetric hydrogen density -10.7kg H_2 / 100L at 10 bar and 25°C[148]	• Develop higher efficiency and lower cost synthesis methods
Limitations	**Active institutions (8)**
• Requires cracking at point of use to extract hydrogen • See limitations for each synthesis method • High toxicity of ammonia vapours[149]	• The Australian National University • CSIRO • Monash University • The University of Adelaide • The University of Newcastle • The University of Sydney • The University of Technology Sydney • The University of Western Australia
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C[150]) • Gravimetric hydrogen density: High (17.8 % by mass[151]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[147] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: http://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[148] Ibid.

[149] Thomas, G., Parks, G. (2006). *Potential roles of ammonia in a hydrogen economy.* U.S. Department of Energy. [Online] Available from: https://www.energy.gov/sites/prod/files/2015/01/f19/fcto_nh3_h2_storage_white_paper_2006.pdf

[150] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: http://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[151] Ibid.

- Energy efficiency: Varies depending on synthesis approach. See Haber-Bosch synthesis method for conventional synthesis

6.2.2 Ammonia: Dense-metal membrane-based synthesis

What is it?

Membrane based ammonia synthesis is a method in which hydrogen gas is supplied on one side of a dense metallic membrane and nitrogen gas on the other. The structure of the membrane allows individual hydrogen atoms to pass through to the nitrogen gas side and react to form ammonia.

Why is it important?

Membrane based ammonia synthesis offers a near-term opportunity to achieve significant reductions in operating costs and carbon emissions compared to the traditional Haber-Bosch process.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Low pressure ammonia synthesis – allows direct coupling of reactor to electrolyser and air separation unit • Less capital intensive than Haber-Bosch synthesis • Highest non-Haber-Bosch synthesis rate achieved • Fast switch-on/off times can accommodate intermittent energy sources • Centralised or decentralised ammonia production possible	• Improve conversion efficiency to ~15% (from ~4%) • Demonstrate use of lower-cost membranes • Improve production rate • Utilise lower-cost catalysts
Limitations	**Active institutions (1)**
• Does not allow direct synthesis of ammonia from nitrogen and water	• CSIRO
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C.[152]) • Gravimetric hydrogen density: High (17.8 % by mass[153]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[152] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: http://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[153] Ibid.

6.2.3 Ammonia: Electrochemical synthesis

What is it?

Electrochemical ammonia synthesis describes a group of methods that can make use of either a hydrogen gas or water feedstock to produce ammonia with nitrogen.

Why is it important?

Electrochemical ammonia synthesis presents a long-term opportunity to create ammonia for export directly if water and nitrogen are used as the feedstocks, skipping the hydrogen feedstock production step which is currently required. This could facilitate reductions in operating costs and balance of plant compared to the traditional Haber-Bosch process.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Synthesis of ammonia directly from water (instead of hydrogen gas) is possible • Operates at milder conditions than traditional Haber-Bosch synthesis (temperatures below 100°C possible) • Could potentially make use of waste water, sea water, or alcohol inputs • Lower operating costs and balance of plant than traditional Haber-Bosch process • Could theoretically yield energy savings from bypassing the hydrogen production step	• Improve cost competitive ammonia production rate (highest achieved so far is two orders of magnitude lower than required) and conversion efficiency • Improve high ratio of ammonia to hydrogen generation • Optimise reactor materials and reaction conditions
Limitations	**Active institutions (5)**
• Low temperature kinetics • Energy intensive hydrogen generation	• CSIRO • Monash University • Queensland University of Technology • The University of Adelaide • The University of Technology Sydney
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C.[154]) • Gravimetric hydrogen density: High (17.8 % by mass[155]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[154] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: http://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[155] Ibid.

6.2.4 Ammonia: Enzymatic synthesis

What is it?

An electric current is supplied to isolated nitrogenase enzymes, which reduce nitrogen gas (N_2) and water to form ammonia, whilst also producing hydrogen.

Why is it important?

Ammonia can be synthesised under ambient conditions via the application of an electric current.

TRL	1	2	3	4	5	6	7	8	9

<table>
<tr><td>Benefits
• Occurs at ambient temperature and pressure[156]
• Less energy intensive than Haber-Bosch
• Occurs at neutral pH[157]</td><td>RD&D priorities
• Develop alternative redox mediator to methyl viologen (which is highly poisonous)
• Improve transport of electrons from solar panels
• Test carrier protein as a means of electron transport
• Stabilise enzyme using MOFs
• Conduct pilot scale experiments
• Develop an isolated anaerobic environment to prevent exposure of enzyme to oxygen</td></tr>
<tr><td>Limitations
• Separation of ammonia and hydrogen required after production
• Biological system is difficult to control
• Metallo-protein is oxygen sensitive and usually negated by biology</td><td>Active institutions (1)
• CSIRO</td></tr>
<tr><td colspan="2">Characteristics
• Volumetric hydrogen density: High (107kg H_2/m^3 at 10 bar and 25°C.[158])
• Gravimetric hydrogen density: High (17.8 % by mass[159])
• Storage conditions: Liquid at ambient temperature, 10-11 bar pressure</td></tr>
</table>

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[156] Milton, R., Abdellaoui, S., Khadka, N., Dean, D., Leech, D., Seefeldt, L., & Minteer, S. (2016). *Nitrogenase bioelectrocatalysis: Heterogeneous ammonia and hydrogen production by MoFe protein*. Energy & Environmental Science, 9(8), 2550-2554.

[157] Ibid.

[158] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: http://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[159] Ibid.

6.2.5 Ammonia: Haber-Bosch synthesis

What is it?

Ammonia is synthesised by reacting hydrogen with nitrogen gas at high temperatures and pressures.

Why is it important?

Haber-Bosch synthesis is a well-established industrial process that has been optimised for hydrogen production.

TRL	1	2	3	4	5	6	7	8	9

<table>
<tr><td>Benefits
• Established industrial process</td><td>RD&D priorities
• Improve catalyst development
• Integrate with renewable sources of hydrogen</td></tr>
<tr><td>Limitations
• High operating temperature and pressures, highly energy-intensive
• Generates large amounts of carbon dioxide
• Diminishing returns expected from improvements to this synthesis method[160]</td><td>Active institutions (3)
• The Australian National University
• The University of New South Wales
• The University of Western Australia</td></tr>
<tr><td colspan="2">Characteristics
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C[161])
• Gravimetric hydrogen density: High (17.8 % by mass[162])
• Storage conditions: Liquid at ambient temperature, 10-11 bar pressure
• Synthesis energy efficiency: Production of hydrogen via SMR paired with Haber-Bosch synthesis has an overall energy efficiency of approximately 61-66%[163]</td></tr>
</table>

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[160] Brown, T. (2018). *Innovations in Ammonia*. Presentation at US Department of Energy H2@Scale R&D Consortium Kick-Off Meeting. Chicago IL

[161] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[162] Ibid.

[163] Soloveichik, G., (2017). *FUTURE OF AMMONIA PRODUCTION: IMPROVEMENT OF HABER-BOSCH PROCESS OR ELECTROCHEMICAL SYNTHESIS?,* US DOE, [Online] Available from: http://nh3fuelassociation.org/wp-content/uploads/2017/11/NH3-Energy-2017-Grigorii-Soloveichik.pdf

6.2.6 Ammonia: Hydration of metal nitrides

What is it?

Ammonia is synthesised via the hydration (hydrolysis) of a metal nitride (a metal bonded with nitrogen). Water is reacted with the metal nitride to produce ammonia at ambient to moderate (200+°C) temperatures.[164]

Why is it important?

Ammonia can be synthesised directly from water, without requiring formation of hydrogen.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Direct ammonia synthesis from water • Can make use of waste or solar heat to generate required temperature	• Improve efficient regeneration of metal nitride for reuse • Improve long term stability of metal nitride catalysts[165]
Limitations	**Active institutions (2)**
• Metal nitride needs to be regenerated to complete chemical loop	• Monash University • The University of Western Australia
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C.[166]) • Gravimetric hydrogen density: High (17.8 % by mass[167]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[164] Jain, A., Miyaoka, H., Kumar, S., Ichikawa, T., & Kojima, Y. (2017). *A new synthesis route of ammonia production through hydrolysis of metal – Nitrides*. International Journal of Hydrogen Energy, 42(39), 24897-24903.

[165] Michalsky, R., Avram, A. M., Peterson, B. A., Pfromm, P. H., & Peterson, A. A. (2015). *Chemical looping of metal nitride catalysts: Low-pressure ammonia synthesis for energy storage.* Chemical Science, 6(7), 3965-3974.

[166] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[167] Ibid.

6.2.7 Ammonia: Non-thermal plasma synthesis

What is it?

Hydrogen and nitrogen are reacted via the use of non-thermal plasma, which provides sufficient energy for reaction and conversion to ammonia.

Why is it important?

Non-thermal plasma could facilitate the synthesis of ammonia at temperature and pressure ranges much lower than those required for the traditional Haber-Bosch process.

Furthermore, plasma processes are likely to be suitable for small-scale on-site ammonia production.[168]

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Low temperature and pressure ammonia synthesis • Fast switch-on/off times can accommodate intermittent energy sources • Decentralised ammonia production possible[169]	• Develop cheaper catalyst alternatives • Increase production rate • Develop improved understanding of fundamental interactions and reaction mechanism • Increase process efficiency[170]
Limitations	**Active institutions (3)**
• Does not allow direct synthesis of ammonia • High-cost ruthenium catalyst	• Queensland University of Technology • The University of Adelaide • The University of Western Australia
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C.[171]) • Gravimetric hydrogen density: High (17.8 % by mass[172]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure • Synthesis efficiency: Assumed efficiency ~10 times lower than Haber-Bosch process	

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[168] Hong, J. B., Murphy, A., & Prawer, S. (2018). *Plasma Catalysis as an Alternative Route for Ammonia Production: Status, Mechanisms, and Prospects for Progress*. ACS Sustainable Chemistry and Engineering, 6(1), 15-31

[169] Ibid.

[170] Ibid.

[171] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[172] Ibid.

6.2.8 Ammonia: combined system synthesis

What is it?

Hydrogen is produced via solid oxide electrolysis, then fed into a second reactor in which it is used as an input for ammonia synthesis. The heat from the ammonia production step is then fed back to the solid oxide electrolysis cell for further hydrogen production.

Why is it important?

Integrated hydrogen production and ammonia synthesis presents an opportunity to make use of the heat generated from ammonia synthesis step, reducing the amount of input energy required for the solid oxide electrolysis step.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Downstream process well established • Heat integration makes use of heat from exothermic downstream reaction, supplies it back to hydrogen generation reaction • No air separation unit required to provide a nitrogen input for ammonia synthesis •	• Develop means to economically manufacture and implement cells at scale • Prevent degradation of solid oxide electrolysers • Develop system integration concepts to engineer a complete integrated system • Reduce system capital cost
Limitations	**Active institutions (0)**
• Limitations largely dependent on type of ammonia synthesis method employed. Conventional synthesis is carried out via the Haber-Bosch process, which would necessitate an intermediate compression of hydrogen between steps	• (No active institutions found in study)
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C[173]) • Gravimetric hydrogen density: High (17.8 % by mass[174]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[173] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[174] Ibid.

6.2.9 Ammonia: solid oxide electrolysis

What is it?

Ammonia is synthesised directly from steam and nitrogen in a solid oxide electrolysis cell at elevated temperatures.

Why is it important?

Ammonia can be synthesised directly from water and nitrogen, without requiring a precursory hydrogen production step. This reduces system complexity and could yield energy savings.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Single reactor means reduced system complexity and lower associated capital costs • Allows integration of waste heat streams, reducing the required energy input • Makes use of carbon dioxide as a process input	• Improve catalyst selectivity • Develop cell designs and electrolytes capable of operating at thermodynamically favourable conditions • Understand fundamental reaction mechanisms
Limitations	**Active institutions (0)**
• Balancing reactor temperature is a challenge. Ammonia product decomposition occurs at typical solid oxide cell operating temperature	• (No active institutions found in study)
Characteristics	
• Volumetric hydrogen density: High (107 kg H_2/m^3 at 10 bar and 25°C[175]) • Gravimetric hydrogen density: High (17.8 % by mass[176]) • Storage conditions: Liquid at ambient temperature, 10-11 bar pressure	

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[175] Kojima, Y. (2014). *Liquid Ammonia for Hydrogen Storage,* NH3 Fuel Association, [Online] Available from: https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/ Accessed: 21/11/2019

[176] Ibid.

6.2.10 Dimethyl ether (DME)

What is it?

DME is the simplest of the ethers and the dehydration product of methanol. A gas at room temperature, it has physical properties very similar to LPG and can be easily compressed to a liquid. As for methanol, renewable DME can be synthesised from syngas derived from a renewable source or by the direct hydrogenation of CO_2. Also like methanol, DME can be converted back into hydrogen when needed or utilised directly in a number of applications. DME can be synthesised directly from CO_2 or produced via methanol. The direct synthesis of DME is more efficient than the synthesis of methanol.

Why is it important?

DME can be blended with LPG and used without changes to storage and transportation infrastructure or end use technologies when blended up to 10%. With minor modification to seals and elastomers, DME can completely replace LPG. DME is a better fuel for compression ignition engines than diesel, with a higher cetane rating and producing very low particulate and Sox emissions on combustion. Ironically, a major initiative in Japan to develop DME as a replacement for diesel in the 1990s was apparently halted due to the “success” of the diesel particle filter.

TRL*	1	2	3	4	5	6	7	8	9

*The TRL for DME is dependent on the feedstock employed for its synthesis. For natural gas, coal or biomass the TRL is very high (8-9), whereas from CO_2 it is somewhat lower (5-6). The direct synthesis of DME from CO_2 (not via methanol) is lower again (3-4).

Benefits	**RD&D priorities**
• Very low toxicity • Does not pollute ground water or marine environments • Excellent fuel for CI or SI engines • Compatible with existing LPG storage and distribution infrastructure • Better chemical/hydrocarbon fuel intermediate than methanol • More efficient production than methanol	• Develop direct synthesis from CO_2: ○ Process development ○ Catalyst development ○ Reactor development • Develop reforming process to produce H_2 from DME • Develop DME compression ignition engine • Modify compression ignition engine for DME use
Limitations	**Active institutions (1)**
• Approximately half the energy density of diesel • Diesel engines require modification for use (not a drop-in fuel for CI engines) • Minor modifications required for use in LPG infrastructure if to be used at high concentrations	• The Australian National University
Characteristics	
• Volumetric hydrogen density: ~95 kg H_2/m^3 (liquid at -25°C) • Gravimetric hydrogen density: ~13 % by mass • Storage conditions: Liquid at ambient temperature and 4 bar pressure.	

6.2.11 Electrochemical carbon-based storage: proton batteries

What is it?

Proton battery – A proton battery is a reversible PEM fuel cell, or a hybrid between a fuel cell and battery-based system, that allows solid-state storage and extraction of hydrogen in atomic form.[177] During charging, protons produced by water splitting on the oxygen-side electrode of the reversible cell pass through the membrane and are neutralised by excess electrons on the solid negatively-charged storage electrode. A metallic electrode was first used, in which case hydrogen is stored as a metal hydride[178]. Later work employed a porous activated carbon electrode, with the hydrogen stored by a weak bond to the carbon surfaces within pores[179]. During discharging, protons are directly released back into the membrane as electrons flow in the external circuit, with the usual water formation reaction on the oxygen-side electrode driving the electricity-generation process.

Why is it important?

Proton batteries allow the solid-state storage of atomic hydrogen, without requiring the formation or splitting of hydrogen gas, thus potentially increasing the roundtrip energy efficiency of the standard electrolyser–hydrogen gas storage–fuel cell system.

TRL	1	2	3	4	5	6	7	8	9

Benefits[180]

- Hydrogen atoms are generated directly from water and stored in atomic form, avoiding energy losses in hydrogen gas formation, compression, and H_2 splitting in fuel-cell mode
- High roundtrip energy efficiency
- Near atmospheric pressure operation
- High level of safety, since no high-pressure flammable hydrogen gas
- Carbon is abundant and lightweight, and therefore storage electrodes are cheap and have high internal surface area
- Can be recharged directly with electricity

RD&D priorities

- Select and test hydrogen storage electrodes specially synthesised for this application from layered graphene and carbon-nitride materials
- Increase current densities during charging and discharging
- Test multiple cycles
- Understand reactions between hydronium/protons and carbon surfaces
- Increase volumetric and gravimetric energy densities to nearer theoretical maximum

Limitations

- Does not store hydrogen gas; makes use of water feedstock only.[181] Cannot be used to produce a gaseous hydrogen output

Active institutions (3)

- Deakin University
- RMIT University
- The University of Technology Sydney

Characteristics

- Volumetric energy density:[182]
    - Theoretical upper ranges
        - electrode material: 0.9 – 1.9 kWhe/L (assuming 0.7 nm spacing between graphene layers, and 1 H stored per 2C or 1C)
        - system density – to be determined
- Gravimetric energy density:
    - Theoretical upper ranges

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[177] Heidari, S., Seif Mohammadi, S., Oberoi, A., & Andrews, J. (2018). T*echnical feasibility of a proton battery with an activated carbon electrode.* International Journal of Hydrogen Energy, 43(12), 6197-6209.

[178] Andrews, J., & Seif Mohammadi, S. (2014). *Towards a 'proton flow battery': Investigation of a reversible PEM fuel cell with integrated metal-hydride hydrogen storage*. International Journal of Hydrogen Energy, 39(4), 1740-1751.

[179] Heidari, S., Seif Mohammadi, S., Oberoi, A., & Andrews, J. (2018). *Technical feasibility of a proton battery with an activated carbon electrode.* International Journal of Hydrogen Energy, 43(12), 6197-6209.

[180] Ibid.

[181] Ibid.

[182] Sourced from research consultation - Assumes an efficiency in fuel-cell (electricity supply) mode of 50%.

    - electrode material: 4.0 -7.7 wt%H, or 0.8 -1.5 kWhe/kg[1] (corresponding to 1 H stored per 2C or 1C atoms)
    - system density – to be determined
- Storage conditions: ambient temperature and pressure
- Roundtrip Energy efficiency: similar in theory to that of a lithium-ion battery

6.2.12 Hydrides: chemical

What is it?

Chemical hydrides, or chemical hydrogen, refers to hydrogen bonded to a compound in solid or liquid form. These compounds generally have high hydrogen densities.[183] The hydrogen can be extracted via reaction with water or application of heat. Examples include Ammonia borane, sodium borohydride, and alane compounds.

Why is it important?

Chemical hydrides have high hydrogen densities and can be transported at ambient temperatures.

TRL*	1	2	3	4	5	6	7	8	9

*The TRL for 'on-off' utilisation of chemical hydrides that cannot be regenerated is 5-7.

Benefits

- Some chemical hydrides offer high volumetric hydrogen density, depending on system configuration[184]
- Typically lighter weight than metal hydrides[185]
- Can transport at ambient temperatures

RD&D priorities

- Improve overall 'wells-to-power plant' efficiency[186]
- Improve carrier chemical regeneration efficiency[187]

Limitations

- Regeneration of the chemical required to be able to use it again for hydrogen storage.[188] This considerably increases the well-to-powerplant fuel cost[189]
- Need to utilise or return carrier chemical if transported[190]
- Some liquids can solidify while hydrogen is not bonded, requiring further handling[191]

Active institutions (3)

- Curtin University
- The University of New South Wales
- The University of Sydney

Characteristics

- Volumetric hydrogen density: ~90 to 150 kg H_2/m^3 [192]
- Gravimetric hydrogen density: 7.5 to 25 % by mass
- Storage conditions: Ambient
- Extraction conditions - ~25-200°C[193] if not hydrolysed. Hydrolysis allows release at ambient conditions
- Roundtrip Energy efficiency: N/A – system is irreversible

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[183] US DOE (n.d.). *Chemical Hydrogen Storage Materials*, [Online] Available from: https://www.energy.gov/eere/fuelcells/chemical-hydrogen-storage-materials Accessed: 21/11/2019

[184] Kojima, Y., Miyaoka, H., & Ichikawa, T. (2013) Hydrogen storage materials. In Suib, S.L. (Ed.), *New and Future Developments in Catalysis Batteries, Hydrogen Storage and Fuel Cells,* Elsevier B.V.

[185] Smythe, N. C., & Gordon, J. (2010). *Ammonia borane as a hydrogen carrier: Dehydrogenation and regeneration*. European Journal of Inorganic Chemistry, 2010(4), 509-521.

[186] US DOE (n.d.). *Hydrogen Storage Engineering Center of Excellence*, [Online] Available from: https://www.energy.gov/eere/fuelcells/hydrogen-storage-engineering-center-excellence#graphs Accessed: 21/11/2019

[187] Hua, T. Q., & Ahluwalia, R. K. (2012). *Off-board regeneration of ammonia borane for use as a hydrogen carrier for automotive fuel cells.* International Journal of Hydrogen Energy, 37(19), 14382-14392. doi:https://doi.org/10.1016/j.ijhydene.2012.07.013

[188] Kojima, Y., Miyaoka, H., & Ichikawa, T. (2013) Hydrogen storage materials. In Suib, S.L. (Ed.), *New and Future Developments in Catalysis Batteries, Hydrogen Storage and Fuel Cells,* Elsevier B.V.

[189] US DOE (n.d.). *Chemical Hydrogen Storage Materials*, [Online] Available from: https://www.energy.gov/eere/fuelcells/chemical-hydrogen-storage-materials Accessed: 21/11/2019

[190] Ibid.

[191] Ibid.

[192] Moller, K. T., Jensen, T. R., Akiba, E., Li, H. (2017) *Hydrogen – A sustainable energy carrier*, Progress in Natural Science, 27(1), doi:10.1016/j.pnsc.2016.12.014

[193] US DOE (n.d.). *Chemical Hydrogen Storage Materials*, [Online] Available from: https://www.energy.gov/eere/fuelcells/chemical-hydrogen-storage-materials Accessed: 21/11/2019

6.2.13 Hydrides: complex

What is it?

Complex metal hydrides are salts in which the anion contains hydrides (negatively charged hydrogen atoms). Hydrogen chemically bonds with complex molecules such as $LiBH_4$ and $LiAlH_4$, allowing the complex hydride to act as a storage mechanism for the hydrogen. When the hydrogen is required after transport, the hydrogen can be released via application of heat.

Why is it important?

Complex hydrides offer storage at moderate pressure, retrieval at safe temperatures, and a higher hydrogen storage density than pressurised or liquefied hydrogen. Shipping and handling a powdered solid-state complex hydride is advantageous compared to liquids and gases.

TRL[194]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Typically have higher gravimetric capacities and volumetric densities than metallic or alloy hydrides[195] • Higher hydrogen-storage density than pressurised or liquefied hydrogen[200] • Solid state powders for ease of transport • Hydrogen release is endothermic and self-regulated, reducing risk of accidental explosion • Lower pressures than pressurised gas and more moderate temperatures than liquefied hydrogen, leading to increased safety [196] • Negligible self-discharge	• Develop new catalysts to improve kinetics for storage/retrieval of hydrogen • Develop fundamental understanding of the reaction of complex hydrides with hydrogen and hydrogen diffusion in complex hydrides • Develop novel approaches to control the thermodynamics for hydrogen release/uptake to achieve full hydrogen reversibly under moderate conditions of temperature and pressure • Develop understanding of the integration/translation of the hydrides into full vessels/tanks delivering hydrogen against delivery/uptake targets • Achieve long cycling life > 10,000 hydrogen uptake and release cycles • Improve off-board regeneration of complex hydrides (re-hydrogenation)
Limitations	**Active institutions (6)**
• Kinetics and thermodynamics of complex metal hydrides mean that hydrogen storage and release must occur at elevated temperatures, ranging from 100°C to 800°C[197] • Hydrogen release is often not reversible under moderate conditions • Developing a cost-effective complex hydride system is challenging • Achieving the reversible uptake and release of hydrogen with high efficiency close to the ambient and under moderate hydrogen pressure is challenging • Sensitive to air	• Curtin University • Griffith University • Monash University • The University of Newcastle • The University of New South Wales • The University of Technology Sydney

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[194] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

[195] Abdin, Z., & Khalilpour, K. R. (2019). *Chapter 4 - Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems.* In K. R. Khalilpour (Ed.), Polygeneration with Polystorage for Chemical and Energy Hubs (pp. 77-131): Academic Press.

[196] Sakintuna, B., Lamari-Darkrim, F., & Hirscher, M. (2007). *Metal hydride materials for solid hydrogen storage: A review.* International Journal of Hydrogen Energy, 32(9), 1121-1140. doi:https://doi.org/10.1016/j.ijhydene.2006.11.022

[197] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

Characteristics

- Volumetric hydrogen density: 80 to 150 kg H_2/m^3
- Gravimetric hydrogen density: 8 to 18.5 % by mass
- Hydrogenation conditions: 100°C to 800°C
- Storage conditions: Room temperature, sealed container due to air sensitivity. Pressure at ~1-100 bar[198]
- Extraction conditions: 100°C to 800°C
- Roundtrip energy efficiency: Varies widely depending on complex hydride material and if the system is reversible (i.e. temperature and pressure needed to achieve reversible hydrogen cycling)

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[198] Lai, Q., Sun, Y., Wang, T., Modi, P., Cazorla, C., Demirci, U., Fernandez, J., Leardini, F., Aguey-Zinsou, K. (2019). *How to Design Hydrogen Storage Materials?* Fundamentals, Synthesis, and Storage Tanks. Advanced Sustainable Systems, 3(9), N/a.

6.2.14 Hydrides: metal

What is it?

Metals, such as magnesium, chemically bond with hydrogen gas to be transported as a metal hydride. When the hydrogen is required, heat is applied to release it from the metal. Intermetallic hydrides are a variation in which transition metals are present instead of main group metals.

Why is it important?

Metal hydrides offer storage at moderate pressure, retrieval at safe temperatures, and a higher hydrogen storage density than pressurised or liquefied hydrogen.

TRL*[199]	1	2	3	4	5	6	7	8	9

*Hydrides of very high hydrogen storage capacity (e.g. aluminium hydride, AlH_3) are low TRL as they are not reversible for hydrogen storage. Room temperature hydrides of lower hydrogen capacity (< 2 wt% H_2) are high TRL.

Benefits	**RD&D priorities**
• Hydrogen release is endothermic and self-regulated, reducing risk of accidental explosion • Lower pressures than pressurised gas and more moderate temperatures than liquefied hydrogen, leading to increased safety[200] • Higher hydrogen-storage density than pressurised or liquefied hydrogen[201] • Low temperature hydrides have near-ambient operating pressure and temperature • For room temperature hydrides, extremely long cycle life, up to 20,000 cycles in some cases • Negligible self-discharge • 90% round trip efficiency for room temperature hydrides • Can be readily scaled to very large capacities for grid storage • Suitable for hydrogen transport to fuelling stations	• For high temperature hydrides, improve hydrogen sorption kinetics for fast and effective dissociation of hydrogen molecules[202] • Improve energy density, cycle life and operating temperature[203] • Improve gravimetric hydrogen density
Limitations	**Active institutions (8)**
• For high temperature hydrides, hydrogenation and hydrogen release occur at elevated temperatures, ranging from ~100-500°C.[204] Light metal simple hydrides require high temperatures for rapid hydrogen release	• The Australian National University • CSIRO • Curtin University • Deakin University

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[199] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

[200] Sakintuna, B., Lamari-Darkrim, F., & Hirscher, M. (2007). *Metal hydride materials for solid hydrogen storage: A review*. International Journal of Hydrogen Energy, 32(9), 1121-1140. doi:https://doi.org/10.1016/j.ijhydene.2006.11.022

[201] Ibid.

[202] Ibid.

[203] Niaz, S., Manzoor, T., & Pandith, A. H. (2015). *Hydrogen storage: Materials, methods and perspectives.* Renewable and Sustainable Energy Reviews, 50, 457-469. doi:https://doi.org/10.1016/j.rser.2015.05.011

[204] US DOE (n.d.). *Materials-Based Hydrogen Storage*, [Online] Available from: https://www.energy.gov/eere/fuelcells/materials-based-hydrogen-storage Accessed: 21/11/2019

• High temperature hydrides require higher operating temperatures and are not reversible in some cases • Low temperature metal hydrides not reversible in some cases • Low gravimetric hydrogen density[205] for current generation of low temperature metal hydrides. Many intermetallics with favourable thermodynamics have low gravimetric capacities and/or poor cycling capacity • Sensitive to air and humidity	• Griffith University • The University of New South Wales • The University of Queensland • The University of Technology Sydney
Characteristics – high temperature hydrides • Volumetric hydrogen density: >100 kg H_2/m^3 • Gravimetric hydrogen density: Moderate to high (7 to 10 % by mass) • Hydrogenation and extraction conditions: ~100 to 500°C, or above to achieve hydrogen reversibility • Storage conditions: Reversibility in some cases occurs only under high temperature and pressure conditions, e.g. Mg/MgH_2 is 20 bar and 300°C but AlH_3 is >100 C and > 1000 bar H_2 pressure • Hydrogenation/dehydrogenation energy efficiency: 80%[206] **Characteristics – low temperature hydrides** • Volumetric hydrogen density: >100 kg H_2/m^3 • Gravimetric hydrogen density: Low (< 2 % by mass) • Hydrogenation and extraction conditions: -10 to 50°C • Storage conditions: Reversible at room temperature and reasonable hydrogen pressure conditions (e.g. TiFe and $LaNi_5$ can absorb hydrogen at 30 bar and 25°C) • Hydrogenation/dehydrogenation energy efficiency: 90%	

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[205] Abdin, Z., & Khalilpour, K. R. (2019). *Chapter 4 - Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems.* In K. R. Khalilpour (Ed.), Polygeneration with Polystorage for Chemical and Energy Hubs (pp. 77-131): Academic Press.

[206] Lototskyy, M., Nyallang Nyamsi, S., Pasupathi, S., Wærnhus, I., Vik, A., Ilea, C., & Yartys, V. (2018). *A concept of combined cooling, heating and power system utilising solar power and based on reversible solid oxide fuel cell and metal hydrides.* International Journal of Hydrogen Energy, 43(40), 18650-18663. doi:https://doi.org/10.1016/j.ijhydene.2018.05.075

6.2.15 Liquid organic hydrogen carrier: Dibenzyl toluene

What is it?

Hydrogen is reacted with dibenzyltoluene (DBT), resulting in a hydrogenated form of the DBT, a compound that can be transported at ambient temperature and pressure. The hydrogen can be extracted after transport via the application of heat or catalysis.

Why is it important?

Hydrogenated DBT can carry hydrogen in liquid form at ambient temperature and pressure.

TRL[207]	1	2	3	4	5	6	7	8	9

Benefits

- Safer and easier to handle than toluene/methylcyclohexane,[208] however, toluene is often a significant component in petrol
- Lower temperature requirement for hydrogenation than toluene
- Can utilize existing oil and chemical infrastructure for storage and transportation[209]
- Stays in liquid state under ambient temperature and pressure

RD&D priorities

- Develop catalysts for improved conversion efficiency
- Improve process efficiency through heat and pressure management
- Demonstrate hydrogen release at mild reaction conditions[210]
- Demonstrate system durability over long-term use

Limitations

- Need to return carrier if exported
- High temperature required for both hydrogenation and dehydrogenation[211]

Active institutions (4)

- The Australian National University
- CSIRO
- The University of Newcastle
- The University of Technology Sydney

Characteristics

- Volumetric hydrogen density: 58 kg H_2/m^3[212]
- Gravimetric hydrogen density: 6.2 % by mass[213]
- Storage conditions: Ambient storage, should be kept below 30°C. Container should be carefully sealed to prevent exposure to sunlight, heat and humidity
- Roundtrip Energy efficiency: ~43%

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[207] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

[208] Hydrogenious Technologies (2018). *Hydrogen – stored as an oil*, [Online] Available from: http://www.energiewende-erlangen.de/wp-content/uploads/2018/02/0_HydrogeniousTechnologies.pdf

[209] Kurosaki, D., (2018). Introduction of Liquid Organic Hydrogen Carrier and the Global Hydrogen Supply Chain Project, Chiyoda Corporation, [Online] Available from: https://www.energy.gov/sites/prod/files/2018/10/f56/fcto-infrastructure-workshop-2018-32-kurosaki.pdf

[210] Aakko-Saksa, P. T., Cook, C., Kiviaho, J., & Repo, T. (2018). *Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion*. Journal of Power Sources, 396, 803-823. doi:https://doi.org/10.1016/j.jpowsour.2018.04.011

[211] Hydrogenious Technologies (2018). *Hydrogen – stored as an oil*, [Online] Available from: http://www.energiewende-erlangen.de/wp-content/uploads/2018/02/0_HydrogeniousTechnologies.pdf

[212] Preuster, P., Alekseev, A., & Wasserscheid, P. (2017*). Hydrogen Storage Technologies for Future Energy Systems*. Annual Review of Chemical and Biomolecular Engineering, 8(1), 445-471. doi:10.1146/annurev-chembioeng-060816-101334

[213] Ibid.

6.2.16 Liquid organic hydrogen carrier: Toluene/methylcyclohexane

What is it?

Hydrogen is reacted with toluene to form methylcyclohexane (MCH), a compound that can be transported at ambient temperature and pressure. The hydrogen can be extracted after transport via the application of heat or catalysis.

Why is it important?

Hydrogenated toluene can carry hydrogen in liquid form at ambient temperature and pressure.

TRL[214]	1	2	3	4	5	6	7	8	9

Benefits

- Stays in liquid state under ambient temperature and pressure[215]
- Minor loss over long-term storage and transport[216]
- Can utilize existing oil and chemical infrastructure for storage and transportation[217]

RD&D priorities

- Lower the hydrogenation and dehydrogenation temperature and pressure
- Develop catalysts using cheap elements and with improved efficiency

Limitations

- Both toluene and MCH are toxic substances
- Purification requirements
- Need to return carrier if exported
- High temperature required for both hydrogenation and dehydrogenation

Active institutions (3)

- CSIRO
- Queensland University of Technology
- The University of Western Australia

Characteristics

- Volumetric hydrogen density: 47 kg H_2/m^3 [218]
- Gravimetric hydrogen density: 6.1 % by mass[219]
- Storage conditions: Ambient storage, should be kept below 30°C. Container should be carefully sealed to prevent exposure to sunlight, heat and humidity
- Roundtrip Energy efficiency: <50%

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[214] Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., Hartley, P. (2018). *National Hydrogen Roadmap,* CSIRO.

[215] Kurosaki, D., (2018). Introduction of Liquid Organic Hydrogen Carrier and the Global Hydrogen Supply Chain Project, Chiyoda Corporation, [Online] Available from: https://www.energy.gov/sites/prod/files/2018/10/f56/fcto-infrastructure-workshop-2018-32-kurosaki.pdf

[216] Ibid.

[217] Ibid.

[218] Preuster, P., Alekseev, A., & Wasserscheid, P. (2017*). Hydrogen Storage Technologies for Future Energy Systems*. Annual Review of Chemical and Biomolecular Engineering, 8(1), 445-471. doi:10.1146/annurev-chembioeng-060816-101334

[219] Ibid.

6.2.17 Methanol

What is it?

Methanol is conventionally synthesised at large scale from synthesis gas (or syngas), a mixture of hydrogen and carbon monoxide typically at an H_2/CO ratio of ~1.8-2.2, derived through steam reforming of natural gas or steam gasification of coal. Renewable methanol can also be synthesised from syngas derived from a renewable source such as biomass or direct hydrogenation of CO_2.[220] Methanol can be converted back into hydrogen when needed or utilised directly in a number of applications.

Why is it important?

Methanol can be stored and transported in liquid form at ambient temperatures. It can be converted to yield high purity hydrogen or utilised directly in a number of applications in the energy and chemical sectors.

TRL[221]	1	2	3	4	5	6	7	8	9

The TRL for this technology varies based on the synthesis method. Conventional synthesis from syngas has a TRL of 9. Direct hydrogenation of CO_2 has a TRL of 6-7.[222] Integrated biomass pyrolysis with methanol synthesis has a TRL of 3. Photocatalytic conversion of CO_2 and water into methanol has a TRL of 2-4.[223] Methanol produced via solid oxide electrolysis has a TRL of 1.

Benefits	**RD&D priorities**
• Greater volumetric energy density than hydrogen gas • In CO_2 hydrogenation method - Makes use of CO_2 as a feedstock. This can be sourced from waste streams or direct air capture • Can leverage existing methanol handling and transport infrastructure • Liquid under ambient conditions[224] • Flexibility in its production, storage, transport and end uses. It can be dissociated to yield high purity hydrogen or used directly as a fuel for methanol fuel cells, conventional liquid transport fuel for internal combustion engines and as an intermediate for chemical manufacturing and other purposes	• Improve methanol synthesis via hydrogenation of CO_2 with hydrogen (this method is less mature than the incumbent syngas conversion process) • Develop catalysts and test • Process intensification and miniaturisation of conventional methanol synthesis to match distributed nature of renewable biomass resources • Improve energy efficient extraction of hydrogen from methanol after transport
Limitations	**Active institutions (6)**
• Poisonous to humans, requires similar precautions as petrol and diesel[225] • If converted back into hydrogen, releases CO_2	• CSIRO • The University of Adelaide • The University of Melbourne • The University of New South Wales • The University of Sydney • The University of Western Australia

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[220] Badwal, S., Giddey, S., & Munnings, C. (2018). *Emerging technologies, markets and commercialization of solid-electrolytic hydrogen production.* Wiley Interdisciplinary Reviews: Energy and Environment, 7(3).

[221] Jarvis, S. M., & Samsatli, S. (2018). *Technologies and infrastructures underpinning future CO2 value chains: A comprehensive review and comparative analysis*. Renewable and Sustainable Energy Reviews, 85, 46-68. doi:https://doi.org/10.1016/j.rser.2018.01.007

[222] Ibid.

[223] Ibid.

[224] Plass L., Bertau M., Linicus M., Heyde R., Weingart E. (2014) *Methanol as a Hydrogen and Energy Carrier*. In: Bertau M., Offermanns H., Plass L., Schmidt F., Wernicke HJ. (eds) Methanol: The Basic Chemical and Energy Feedstock of the Future. Springer, Berlin, Heidelberg

[225] Danish Technological Institute (n.d.) *Methanol and hydrogen*, [Online] Available from: https://www.dti.dk/_/media/41868_Methanol%20and%20hydrogen%20UK.pdf

Characteristics

- Volumetric hydrogen density: 100 kg H_2/m^3 at ambient conditions[226]
- Gravimetric hydrogen density: 12.5% by mass[227]
- Storage conditions: Liquid at ambient conditions

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[226] Makepeace, J. W., He, T., Weidenthaler, C., Jensen, T. R., Chang, F., Vegge, T., Peter, N., Kojima, Y., Jongh, P, Chen, P., David, W. I. F. (2019). *Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress.* International Journal of Hydrogen Energy, 44(15), 7746-7767. doi:https://doi.org/10.1016/j.ijhydene.2019.01.144

[227] Taylor, C. E., Howard, B. H., & Myers, C. R. (2007). *Methanol Conversion for the Production of Hydrogen.* Industrial & Engineering Chemistry Research, 46(26), 8906-8909. doi:10.1021/ie061307v

6.2.18 Methanol: combined system synthesis

What is it?

Hydrogen is produced via solid oxide electrolysis, then fed into a second reactor in which it is combined with carbon dioxide to produced methanol. The heat from the methanol production step is then fed back to the solid oxide electrolysis cell for further hydrogen production.

Why is it important?

Integrated hydrogen production and methanol synthesis presents an opportunity to make use of the heat generated from methanol synthesis step, reducing the amount of input energy required for the solid oxide electrolysis step.

TRL	1	2	3	4	5	6	7	8	9

Benefits

- Downstream process well established
- Heat integration makes use of heat from exothermic downstream reaction, supplies it back to hydrogen generation reaction
- Makes use of carbon dioxide as a process input

RD&D priorities

- Develop means to economically manufacture and implement cells at scale
- Prevent degradation of solid oxide electrolysers
- Develop system integration concepts to engineer a complete integrated system
- Reduce system capital cost

Limitations

- If converted back into hydrogen, releases CO_2
- Higher system complexity than solid oxide electrolysis method

Active institutions (1)

- The University of Adelaide

Characteristics

- Volumetric hydrogen density: 100kg H_2/m^3 at ambient conditions[228]
- Gravimetric hydrogen density: 12.5% by mass[229]
- Storage conditions: Liquid at ambient conditions

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[228] Makepeace, J. W., He, T., Weidenthaler, C., Jensen, T. R., Chang, F., Vegge, T., Peter, N., Kojima, Y., Jongh, P, Chen, P., David, W. I. F. (2019). *Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress.* International Journal of Hydrogen Energy, 44(15), 7746-7767. doi:https://doi.org/10.1016/j.ijhydene.2019.01.144

[229] Taylor, C. E., Howard, B. H., & Myers, C. R. (2007). *Methanol Conversion for the Production of Hydrogen*. Industrial & Engineering Chemistry Research, 46(26), 8906-8909. doi:10.1021/ie061307v

6.2.19 Methanol: solid oxide electrolysis

What is it?

Methanol is synthesised directly from steam and carbon dioxide gas in a solid oxide electrolysis cell at elevated temperatures.

Why is it important?

Methanol can be synthesised directly from water and carbon dioxide, without requiring a precursory hydrogen production step. This reduces system complexity and could yield energy savings.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Single reactor means reduced system complexity and lower associated capital costs • Allows integration of waste heat streams, reducing the required energy input • Makes use of carbon dioxide as a process input	• Improve catalyst selectivity • Develop cell designs and electrolytes capable of operating at thermodynamically favourable conditions • Understand fundamental reaction mechanisms • Validate proof of concept
Limitations	**Active institutions (1)**
• Balancing reactor temperature is a challenge. Methanol product decomposition occurs at typical solid oxide cell operating temperature	• CSIRO
Characteristics	
• Volumetric hydrogen density: 100kg H_2/m^3 at ambient conditions[230] • Gravimetric hydrogen density: 12.5% by mass[231] • Storage conditions: Liquid at ambient conditions	

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[230] Makepeace, J. W., He, T., Weidenthaler, C., Jensen, T. R., Chang, F., Vegge, T., Peter, N., Kojima, Y., Jongh, P, Chen, P., David, W. I. F. (2019). *Reversible ammonia-based and liquid organic hydrogen carriers for high-density hydrogen storage: Recent progress.* International Journal of Hydrogen Energy, 44(15), 7746-7767. doi:https://doi.org/10.1016/j.ijhydene.2019.01.144

[231] Taylor, C. E., Howard, B. H., & Myers, C. R. (2007). *Methanol Conversion for the Production of Hydrogen*. Industrial & Engineering Chemistry Research, 46(26), 8906-8909. doi:10.1021/ie061307v

6.2.20 Physisorption: Metal organic frameworks (MOFs)

What is it?

Hydrogen physisorption involves hydrogen physically adsorbing to either the surface of a molecule or within pores. Metal organic frameworks are composed of inorganic metal clusters and organic linkers that act as highly selective networks of pores and channels providing a high surface area. Physisorption is driven by forces acting between the hydrogen molecules and the surface of the adsorbent material.**Error! Bookmark not defined.**

Why is it important?

Physisorption presents a lightweight, safe and fully reversible route for storage and transport of hydrogen.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Lightweight materials[232] • Release of hydrogen is endothermic, negating risk of ignition • Hydrogen can be adsorbed and released quickly • Fully reversible process	• Demonstrate tank prototypes that can operate at reduced by not cryogenic conditions. • Enhance the binding energy between the H_2 molecules and adsorbents to increase hydrogen uptake • Investigate the effects of dopants, catalysts, and substitution to improve hydrogen uptake
Limitations • Requires low temperature or high pressure • Weak interaction with H_2 limits applicability	**Active institutions (9)** • The Australian National University • CSIRO • Curtin University • Griffith University • Queensland University of Technology • The University of Adelaide • The University of Queensland • The University of Technology Sydney • The University of Western Australia
Characteristics • Volumetric hydrogen density: ~40-50 kg H_2/m^3 demonstrated[233] • Gravimetric hydrogen density: varies widely, ~2-20% by weight demonstrated[234] • Storage conditions: Low temperatures (~-196°C)	

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[232] Gregorie Padro, C. E., Putsche, V., (1999). *Survey of the Economics of Hydrogen Technologies*, NREL, [Online] Available from: https://www.nrel.gov/docs/fy99osti/27079.pdf

[233] Lai, Q., Paskevicius, M., Sheppard, D., Buckley, C., Thornton, A., Hill, M., Gu, Q., Mao, J., Huang, Z., Liu, H., Guo, Z., Banerjee, A., Chakraborty, S., Ahuja, R., Aguey-Zinsou, K. (2015). *Hydrogen Storage Materials for Mobile and Stationary Applications: Current State of the Art.* ChemSusChem, 8(17), 2789-2825.

[234] Ibid.

6.2.21 Synthetic methane (compressed gas or liquid)

What is it?

Carbon dioxide (from waste or from direct air capture) is reacted with clean or renewable hydrogen to produce methane, which is then liquefied for transport (note that this should not include hydrogen sourced from methane, as this would involve unnecessary conversions). Given the synthetic production routes (i.e. thermal catalysis, electrocatalysis or photocatalysis), methane produced may sometimes be referred to as synthetic natural gas (as opposed to fossil natural gas). Hydrogen can then be extracted from the synthetic methane at the point of use via cracking or steam reforming combined with CCUS. If CO_2 is sourced from direct air capture, methane combustion becomes carbon-neutral.

Why is it important?

Synthetic methane presents an opportunity to make use of carbon dioxide (from direct air capture or waste streams) with hydrogen to produce methane, which can be used as either a fuel, hydrogen transport carrier, or fed into existing gas pipelines.

TRL[235]	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Can be mixed with traditional LNG – existing infrastructure can be leveraged • Existing methane market for which synthetic methane could be supplied • Carbon dioxide can be sourced from carbon emitting processes, enabling reductions in life cycle emissions**Error! Bookmark not defined.** • It can accommodate emerging direct CO_2 air capture technologies to utilise CO_2 • Volumetric energy density approximately 3 times that of hydrogen[236] • Can be synthesised at lower pressures than conventional methanol synthesis • Existing HSE practices and standards • Reaction is exothermic, presenting an opportunity for heat released to be used for other chemical process or plant energy integration	• Improve catalyst and reactor technologies for both thermocatalytic and electrocatalytic processes to reduce costs of synthetic methane production chain • Develop carbon capture from the atmosphere,[237] to be integrated as a reactant • Energy integration to use the “exothermicity” of the reaction to drive other aspects of the chemical process (energy integration/management) • Integrate renewable H_2 production • Integrate renewable energy sources to drive the process where required • Develop mechanisms/technologies to cope with the intermittent nature of renewable energy which may drive such processes
Limitations	**Active institutions (7)**
• Source of hydrogen cannot be steam methane reforming, in order to avoid unnecessary chemical conversions • Heat management required, given the highly exothermic nature of the reaction • Needs high temperatures (approximately 300°C) to start up process, and the system requires subsequent cooling down due to exothermicity	

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[235] Blanco, H., Nijs, W., Ruf, J., & Faaij, A. (2018). *Potential of Power-to-Methane in the EU energy transition to a low carbon system using cost optimization*. Applied Energy, 232, 323-340. doi:https://doi.org/10.1016/j.apenergy.2018.08.027

[236] Plass L., Bertau M., Linicus M., Heyde R., Weingart E. (2014) *Methanol as a Hydrogen and Energy Carrier*. In: Bertau M., Offermanns H., Plass L., Schmidt F., Wernicke HJ. (eds) Methanol: The Basic Chemical and Energy Feedstock of the Future. Springer, Berlin, Heidelberg

[237] ARENA (2019). *Methane Fuel Carrier Research and Development*, [Online] Available from: https://arena.gov.au/projects/methane-fuel-carrier/ Accessed: 21/11/2019

- Half of the input hydrogen used is converted to water instead of methane	- CSIRO - The Future Fuels Cooperative Research Centre - The University of Adelaide - The University of Melbourne - The University of Newcastle - The University of Technology Sydney - The University of Western Australia

Characteristics

- Volumetric hydrogen density: Liquid state = ~100 kg H_2/m^3. At standard temperature and pressure = 0.7946g/100L
- Gravimetric hydrogen density: ~25% H_2 by weight[238]
- Storage conditions: 90 to 120 bar

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[238] Møller, K., Jensen, T., Akiba, E., & Hai-Wen, L. (2017). *Hydrogen - A sustainable energy carrier.* Progress in Natural Science: Materials International, 27. doi:10.1016/j.pnsc.2016.12.014

6.2.22 Synthetic methane: combined system synthesis

What is it?

Hydrogen is produced via solid oxide electrolysis, then fed into a second reactor in which it is combined with carbon dioxide to produced methane. The heat from the methane production step is then fed back to the solid oxide electrolysis cell for further hydrogen production.

Why is it important?

Integrated hydrogen production and methane synthesis presents an opportunity to make use of the heat generated from methane synthesis step, reducing the amount of input energy required for the solid oxide electrolysis step.

TRL	1	2	3	4	5	6	7	8	9

Benefits • Downstream process well established • Heat integration makes use of heat from exothermic downstream reaction, supplies it back to hydrogen generation reaction	**RD&D priorities** • Develop means to economically manufacture and implement cells at scale • Prevent degradation of solid oxide electrolysers • Develop system integration concepts to engineer a complete integrated system • Reduce system capital cost
Limitations • Higher system complexity than solid oxide electrolysis method	**Active institutions (0)** • (No active institutions found in study)
Characteristics • Volumetric hydrogen density: Liquid state = ~100 kg H_2/m^3. At standard temperature and pressure = 0.7946g/100L • Gravimetric hydrogen density: ~25% H_2 by weight[239] • Storage conditions: 90 to 120 bar	

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[239] Møller, K., Jensen, T., Akiba, E., & Hai-Wen, L. (2017). *Hydrogen - A sustainable energy carrier.* Progress in Natural Science: Materials International, 27. doi:10.1016/j.pnsc.2016.12.014

6.2.23 Synthetic methane: solid oxide electrolysis

What is it?

Methane is synthesised directly from steam and carbon dioxide gas in a solid oxide electrolysis cell at elevated temperatures.

Why is it important?

Methane can be synthesised directly from water and carbon dioxide, without requiring a precursory hydrogen production step. This reduces system complexity and could yield energy savings.

TRL	1	2	3	4	5	6	7	8	9

Benefits	**RD&D priorities**
• Single reactor means reduced system complexity and lower associated capital costs • Allows integration of waste heat streams, reducing the required energy input • Makes use of carbon dioxide as a process input	• Improve catalyst selectivity • Develop cell designs and electrolytes capable of operating at thermodynamically favourable conditions • Understand fundamental reaction mechanisms
Limitations	**Active institutions (1)**
• Balancing reactor temperature is a challenge • Methane product decomposition occurs at typical solid oxide cell operating temperature	• CSIRO

Characteristics

- Volumetric hydrogen density: Liquid state = ~100 kg H_2/m^3. At standard temperature and pressure = 0.7946g/100L
- Gravimetric hydrogen density: ~25% H_2 by weight[240]
- Storage conditions: 90 to 120 bar

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[240] Møller, K., Jensen, T., Akiba, E., & Hai-Wen, L. (2017). *Hydrogen - A sustainable energy carrier.* Progress in Natural Science: Materials International, 27. doi:10.1016/j.pnsc.2016.12.014

7 Technology repository: Utilisation

This section differs in format in depth from the hydrogen production and hydrogen storage and distribution sections. It should be noted that this section does not comprehensively cover all hydrogen and hydrogen carrier utilisation technologies. Further work could be conducted to cover this area in greater detail, including the variations of each technology which exist.

TABLE 7: EMERGING FUEL CELL AND TURBINE TECHNOLOGIES

Technology	Description	TRL	Potential for disruption
Hydrogen gas turbines[241]	Likely to be used in IGCC power plants. These are turbines that can run off hydrogen or a hydrogen-rich syngas mixture. There are technical challenges associated with the high combustion temperature of hydrogen[242]. Burning gas mixtures with hydrogen concentrations of up 5-60% is possible in certain gas turbines, depending on the degree to which they have been modified.	6-7	A carbon free turbine technology with potential for larger scale electricity production as compared with fuel cells.
Ammonia turbines	Involves the combustion of ammonia, a methane mixture or ammonia mixed with hydrogen. NOx emissions from the combustion of ammonia need to be removed which creates additional costs[243]. Still in early development.	3	Possible to utilise domestic ammonia production to burn green ammonia resulting in carbon-free power generation. Development of the turbine could open up additional demand for ammonia.
Alkaline Anion Exchange Membrane FC (AEMFC)	Similar design to a PEM FC, but AEMFC's membrane is solid alkaline instead of acidic. Instead of protons, OH^- anions are transported from anode to cathode providing certain advantages, such as the potential for non-precious metal catalysts [244].	4	Offers the potential for cheaper catalysts and polymers. Can also accept a wider range of fuels but has low oxidation reaction rates and unstable conducting materials.
Direct ammonia FC[245]	A number of ammonia fuel cell types exist, including low-temperature direct ammonia fuel cells, solid oxide	NA	Possible to utilise ammonia directly in fuel cells, without requiring conversion to hydrogen gas. Development of the fuel cell could create additional demand for ammonia.

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[241] Mitsubishi Hitachi Power Systems (2018). *Insight of Large-scale hydrogen gas turbine Developer*, [Online] Available from: https://www.mhps.com/special/hydrogen/article_1/index.html Accessed: 18/11/2019

[242] Kraftwerk Forshung (2016). *Hydrogen gas turbines*. [Online] Available from: http://kraftwerkforschung.info/en/hydrogen-gas-turbines/

[243] Valera-Medina, A., Marsh, R., Runyon, J., Pugh, D., Beasley, P., Hughes, T., & Bowen, P. (2017). *Ammonia–methane combustion in tangential swirl burners for gas turbine power generation*. Applied Energy, 185, 1362-1371. doi:https://doi.org/10.1016/j.apenergy.2016.02.073

[244] Dekel, D. R. (2018). *Review of cell performance in anion exchange membrane fuel cells*. Journal of Power Sources, 375, 158-169. doi:https://doi.org/10.1016/j.jpowsour.2017.07.117

[245] Adli, N., Zhang, H., Mukherjee, S., & Wu, G. (2018). *Review-Ammonia Oxidation Electrocatalysis for Hydrogen Generation and Fuel Cells*. Journal Of The Electrochemical Society, 165(15), J3130-J3147.

	fuel cells, and protonic ceramic fuel cells.[246]		
Microbial FC	Microorganisms are used to oxidize fuel, such as glucose or biomass, and transfer acquired electrons to the anode. This oxidation has at extremely low rates, limiting application. Wastewater as a fuel is also being explored	3-4[247]	Fuel is cheap, safe and plentiful but these systems currently have a low power density
Unitised Regenerative Fuel Cell System	A fuel cell, capable of producing hydrogen and oxygen when in regenerative mode and delivering electricity when in fuel cell mode. Providing a system with operating conditions optimal for both modes is an engineering challenge, for example one reaction is exothermic and the other, endothermic. PEM and solid oxide are two reversible technologies under development currently.	2-5	Opportunity to combine the electrolysis and fuel cell process into a single system
Direct dimethyl ether fuel cell (DDMEFCs)[248]	In the fuel cell, dimethyl ether (CH_3OCH_3) is oxidised to produce proton, electrons, and CO_2. In some cases, Nafion is utilised as an electrolyte, with Pt anodes and cathodes. There is currently minimal recent literature exploring DDMEFCs.	NA	DDMEFCs are often compared to DMFCs. Dimethyl ether has a higher density than methanol and is non-toxic. One molecule if DME releases 12 electrons in the reaction, leading reduced theoretical fuel consumption compared to Direct Methanol FCs.
Direct formic acid fuel cell (DFAFCs)[249]	Formic acid oxidation takes place at the anode on a catalyst layer, where CO_2 is formed. Protons pass through polymer membrane to react with O_2 on a catalyst coated cathode.	NA	Similar to DDMEFCs, DFAFCs are seen as a potential competitor to DMFCs in portable applications due to lower toxicity and high energy density.

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[246] Zhao, Y., Setzler, B.P., Wang, J., Nash, J., Wang, T., Xu, B., & Yan, Y. (2019). *An Efficient Direct Ammonia Fuel Cell for Affordable Carbon-Neutral Transportation*. Joule, 3(10), 2472-2484.

[247] Tender, L. M. (2014). *Microbial Fuel Cells for Powering Navy Devices*, Naval Research Laboratory.

[248] Mench, M., Chance, H., & Wang, C. (2004). *Direct dimethyl ether polymer electrolyte fuel cells for portable applications*. Journal of the Electrochemical Society, 151(1), A144-A150.

[249] El-Nagar, G., Hassan, M., Lauermann, I., & Roth, C. (2017). *Efficient Direct Formic Acid Fuel Cells (DFAFCs) Anode Derived from Seafood waste: Migration Mechanism.* Sci Rep, 7(1), 17818.

TABLE 8: MATURE FUEL CELLS (TRL 9)

TECHNOLOGY	DESCRIPTION[250]	ADVANTAGES AND DISADVANTAGES	TYPICAL STACK SIZE[251]	USES[252]
Polymer electrolyte membrane (PEM) FC	Also known as a proton exchange membrane fuel cell. Hydrogen is catalytically split into protons which permeate through the membrane from the anode to the cathode to create an electrical current.	+ Low operating temperature + Low noise + High power density + Quick start-up + Small size - Expensive catalyst - Sensitive to impurities	<1-100kW	Backup power, portable power, distributed generation, transportation and specialty vehicles
Alkaline FC (AFC)	Uses a liquid potassium hydroxide electrolyte and can utilise non-precious catalysts. Suitable for small scale (<100 kW) applications. It has a low cost, low temperature and short start up time.	+ Low temperature + Quick start up + Lower cost components - Sensitive to CO_2 in fuel and air	1-100kW	Military, space, back- up power, transportation
Solid oxide FC (SOFC)	Fuel cell that uses a solid oxide or ceramic electrolyte and high temperatures (up to 1000°C), negating the need for a catalyst. It is suitable for both industrial and residential applications and can run using fuels other than hydrogen (i.e. syngas, ammonia). However, it has a long start time and therefore needs to be run continuously.	+ High efficiency + Fuel flexibility + Suitable for Combined heat and power - High operating temperatures - Corrosion - Long start-up time - Limited number of shutdowns	1-2000kW	Auxiliary power, electric utility, distributed generation
Molten carbonate FC	Use a molten carbonate electrolyte and runs at high temperatures, so non-precious catalysts can be used. It does not require hydrogen or a reformer (i.e.it can run off natural gas and CO_2). It is suitable for industrial and grid scale applications (i.e. tens of MW). It is also relatively low cost but has a short lifespan and low power density.	+ High efficiency + Fuel flexibility + Suitable for CHP - High operating temperatures - Low durability, susceptible to corrosion - Long start-up time - Low power density	300-3000kW (300kW modules)	Electric utility, distributed generation
Phosphoric acid FC	Uses a liquid phosphoric acid electrolyte and has typically been applied in commercial, combined-heat power systems. It requires a temperature of between 150-200°C to operate, has a long start time and relies on expensive catalysts.	+ Increased tolerance to fuel impurities + Suitable for CHP - Expensive catalysts - Long start-up time Sulphur sensitivity	5-400kW	Distributed generation
Direct methanol FC	Instead of methanol being reformed within the system, methanol is fed directly to the anode. DMFCs suffer from low efficiency and power density and are most likely to be used for small portable applications. Runs at operating temperatures of 50-120°C.	+ Fuel is cheap and easy to transport - Expensive catalysts - Low efficiency - Low power density - Toxic vapours - Produces CO_2	<1kW	Small scale portable power[253]

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[250] Kirubakaran, A., Jain, S., & Nema, R. (2009). *A review on fuel cell technologies and power electronic interface*. Renewable and Sustainable Energy Reviews, 13(9), 2430-2440.

[251] US DOE (2016). *Comparison of Fuel Cell Technologies*, [Online] Available from: https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

[252] Ibid.

[253] Kamarudin, S., Achmad, F., & Daud, W. (2009). *Overview on the application of direct methanol fuel cell (DMFC) for portable electronic devices.* International Journal of Hydrogen Energy, 34(16), 6902-6916.

8 Publications search strategy

8.1 Bibliometric Methodology

The bibliometric analysis presented within this report was conducted according to the following methodology.

8.2 Data Sources

Data was drawn from the following two related data sources.

8.2.1 Web of Science (WoS)

The *Web of Science* (WoS) is the publication and citation index from Clarivate. It indexes around 20,000 peer reviewed journals each year as well as a selection of conference proceedings, datasets and books. The journals are divided into four indices – the core journals in the Science (SCI), Social Science (SSCI) and Arts & Humanities (AHCI), along with the Emerging Sources Citation Index (ESCI). This latest index includes newer journals that have yet to establish a reputation. This index was excluded from the analysis.

Publication metadata is indexed at an article level, making it possible to analyse publication and citation counts by a range of fields, such as subject area, institution, publication type, author, country and year.

WoS is divided into 250 subject areas, allowing for highly granular reporting. Allocation to subject areas takes place at a journal, rather than publication, level. A journal may appear in multiple WoS categories; this means that when WoS subjects are compared, publications can be counted multiple times. In some subjects – such as Veterinary Sciences, Energy & Fuels and Plant Sciences – this level is still arguably insufficiently granular. No single subject encapsulated hydrogen research.

Limited-scale tests have shown that WoS has a good level of data quality and a reliable citation matching algorithm. Coverage is highly variable by subject area, with fields such as Medicine including over 80% of global published materials and Social Sciences less than 50%. While this is clearly far from ideal, the subjects in which CSIRO publishes heavily tend to be very well covered. The inclusion of the Conference Proceedings Citation Index allows some Business Units, such as Data61, which publishes a higher proportion of conference papers, to have a more representative analysis of their publication output.

8.2.2 InCites

InCites aggregates WoS data into an online reporting tool and is primarily used for organisation benchmarking, country and world-level reporting. Advantages of InCites include the obviation of data collection and processing; detailed analysis of national peer performance; and the option to analyse data at a range of levels. The data available in InCites differs slightly to WoS in that the Book Citation Index is not included in InCites, and indexation into InCites lags that going into WoS by 1-2 months. Therefore, publication counts between InCites and WoS should not be directly compared, but comparisons of data from a single data source have been shown to be valid.

8.3 Dataset Filters

Both datasets were filtered to the following publication types for all analyses:

Articles, Reviews, and Proceedings Papers.

8.4 Publication Metrics

The following metrics were used in the analysis.

8.4.1 Publication Count

This is a measure of output volume and represents the number of publications in the given data source for the stated organisation or country in the stated year range. The criteria by which the publication count and all associated citation statistics were acquired are usually stated in figure headings or a note under the table, as appropriate. Please note that most bibliometric analyses look only at articles, reviews and, where the necessary citation data exist for them, conference proceedings, and omit smaller documents that do not tend to contain research output, such as book reviews and editorials.

8.4.2 Normalised Citation Impact (NCI)

This is a measure of citation impact relative to a world average of 1.00; a result of 1.2 indicates 20% more citation than the global average and 0.8 indicates 20% less citation. Each publication has a baseline, calculated from the average citations received by publications from the same subject area(s), year and type. The number of citations the publication actually receives is divided by this baseline, to give a measure of relative citation. This takes account of any fluctuations in the annual number of publications produced either by the unit of analysis or globally and removes from comparison any skew based on the age of a publication, its subject area or its type.

This is one of the most robust metrics available and is used by ERA, the UK's REF, the global Snowball Metrics Project and leading bibliometric institutions like the CWTS in Leiden and the Karolinska Institute. However, it is not without issues. Article-level ratios might undervalue particularly strong publications – for example, the benefit of an article receiving 200 citations against a baseline of 50 would be eliminated by three publications from the most recent year receiving 0 citations against a baseline of 1. More importantly, it is important to understand that the most recent 1-2 years can provide misleading results; this is because articles that are cited rapidly (i.e. within the first year or two after publication) are not necessarily the ones that ultimately are cited most. The most recent five-year window thus combines two elements – high citation (strong research) and rapid citation ("hot" research). From CSIRO's perspective, both of these attributes are desirable and there is therefore no issue with using the metric.

The baselines used also rely on the mean citation counts for a year and subject; this makes them (and indeed the ratios used for calculation) very prone to outliers, given the highly skewed nature of citation distributions. Broadly, this means one should never calculate the NCI for fewer than 50 publications and should be cautious with means based on samples of up to 100 publications. Within this analysis, 200 publications have been required for robust rankings. NCI for organisations with 100-200 publications have been reported but recommended to be treated with caution. NCI for organisations with < 100 publications has not been reported.

2014-2018 NCI for Top 20 Countries

Production	
Country	NCI
Singapore	3.12
Saudi Arabia	2.42
Australia	2.13
Hong Kong	2.01
Switzerland	1.97
Denmark	1.93
China	1.91
USA	1.70
Greece	1.65
England	1.61

Storage	
Country	NCI
Australia	1.58
USA	1.56
Germany	1.52
China	1.39
England	1.35
Canada	1.31
Italy	1.27
South Korea	1.25
Iran	1.22
Japan	1.13

Utilisation	
Country	NCI
Australia	2.04
Saudi Arabia	1.95
Switzerland	1.55
USA	1.54
China	1.44
Sweden	1.36
Germany	1.32
Italy	1.30
England	1.23
Denmark	1.21

Overall	
Country	NCI
Singapore	2.88
Saudi Arabia	2.23
Australia	2.01
Hong Kong	1.98
Israel	1.97
Switzerland	1.83
China	1.70
USA	1.64
Denmark	1.48
Scotland	1.44

8.5 Search Strategy

A search strategy was developed to determine the publications to include within the analysis of hydrogen research. The strategy consisted generally of a list of topic keyword combinations to include and exclude, as well as a list of WoS subject areas to exclude that were clearly irrelevant. Topic keywords are matched against article title, abstract text, author provided keywords, and Keywords Plus (keywords determined by Clarivate by an algorithm). A keyword-based strategy was required as there was no clear WoS subject area definition that included hydrogen and only hydrogen research.

The search strategy began with lists of keywords developed by subject matter experts on hydrogen production, hydrogen storage, and hydrogen utilisation. These keywords were queried against the WoS database and the returned articles were spot checked manually to determine whether the results were relevant to the topic. When irrelevant papers were found, other keywords were determined to exclude them, and then searches were performed to ensure these exclusions did not remove any important publications. An example of this was hydrogen peroxide production research appearing within the hydrogen production set. This wasn’t relevant to hydrogen fuel production, so “hydrogen peroxide” was added to the excluded keywords. This process was iterative and is no way expected to be perfect, but the numbers of false positives and false negatives were minimised as much as was practical.

Finally, the overlap between the production, storage and utilisation sets was determined, and the keywords were modified to try and reduce this overlap. This was particularly difficult as the end-use (utilisation) is often mentioned within the abstract of production and storage publications. While the separation of publications into each of the three categories may not have been performed perfectly by the final search strategies, the three categories were also combined and analysed as a whole, which should be reasonably representative.

The final search strategies are outlined in the table below.

KEY: TS = Topic; WC = WoS Subject Area

Topic	Search String
Production	TS=(Hydrogen AND produc* AND ("water split*" OR ("water oxid*" AND catal*) OR WOC or WOCs OR electrolysis OR biomass OR photo* OR biological OR alkaline OR gasif* OR "balance of plant" OR stack OR "chemical looping" OR "methane crack*" OR "concentrating solar" OR "power to gas" OR reform OR biogas OR fermentation OR "solid oxid*" OR "proton exchange" OR thermo* OR autothermal OR pyrolysis OR "steam methane" OR "partial oxid*" OR PEC OR CCS OR “Carbon captur*” OR “Hydrogen evolution reaction*” OR “oxygen evolution reaction*” OR “water reduc*” OR “techno-economic” OR model* OR "dry reform*") NOT ("fuel cell*" OR wine OR "alcoholic ferm*" OR drug OR "hydrogen bond*" OR "hydrogen peroxide" OR shale OR angiogen* OR "hydrogen sulfide" OR "hydrogen sulphide" OR deuterium) OR (("hydrogen sulfide" OR "hydrogen sulphide") AND produc* AND biogas)) NOT WC=(Astronomy Astrophysics OR Toxicology OR Oceanography OR Agronomy OR Medicine Research Experimental OR Genetics Heredity OR Agriculture Dairy Animal Science OR Gastroenterology OR Hepatology OR Quantum Science Technology OR Pharmacology Pharmacy Or Radiology Nuclear Medicine Medical Imaging OR Endocrinology Metabolism OR Veterinary Sciences OR Chemistry Medicinal OR Telecommunications OR Nutrition Dietetics OR Forestry OR Food Science Technology)
Storage	TS=(Hydrogen AND stor* AND (ammonia OR hydride OR liquef* OR compres* OR "liquid organic" OR "line pack*" OR cryo* OR distribution OR electrochem* OR physisorption OR "physical adsorption" OR "thermal energ*" OR "proton batter*" OR "synthetic methane" OR underground

Topic	Search String
	OR cavern OR reservoir OR tank OR "ammonia crack*" OR embrittlement OR bioalcohol* OR bioacid* OR absorption OR “nitrogen reduc*” OR “techno-economic” OR model*) NOT ("fuel cell*" OR wine OR "alcoholic ferm*" OR drug OR "hydrogen bond*" OR "hydrogen peroxide" OR shale OR angiogen* OR "hydrogen sulfide" OR "hydrogen sulphide")) NOT WC=(Astronomy Astrophysics OR Toxicology OR Oceanography OR Agronomy OR Medicine Research Experimental OR Genetics Heredity OR Agriculture Dairy Animal Science OR Gastroenterology OR Hepatology OR Quantum Science Technology OR Pharmacology Pharmacy Or Radiology Nuclear Medicine Medical Imaging OR Endocrinology Metabolism OR Veterinary Sciences OR Chemistry Medicinal OR Telecommunications OR Nutrition Dietetics OR Forestry OR Food Science Technology)
Utilisation	TS=(Hydrogen AND ("fuel cell*" OR turbine* OR vehicle* OR regenerative OR reversible OR dispens* OR "synthetic fuel produc*" OR "direct reduction" OR refuel* OR refuell* OR biofuel* OR biocrude OR steelmak* OR hydrocrack* OR "grid firm*" OR "remote area power" OR "material* hand*" OR hydrotreat* OR "stationary power" OR export OR "residential heat*" OR appliance* OR "commercial heat*" OR PEM OR ammonia OR fertiliser OR syngas) NOT (electrolysis OR wine OR "alcoholic ferm*" OR drug OR "hydrogen bond*" OR "hydrogen peroxide" OR shale OR croplands OR angiogen* OR "hydrogen sulfide" OR "hydrogen sulphide" OR "plant grow*" OR "ammonia crack*" OR (produc* AND (syngas OR "Carbon captur*" OR "Hydrogen evolution reaction*" OR “oxygen evolution reaction*” OR "dry reform*"))) OR (("hydrogen sulfide" OR "hydrogen sulphide") AND ("fuel cell*" OR syngas)) OR (hydrogen AND "plant grow*" AND (biofuel OR "fuel cell*" OR biogas))) NOT WC=(Astronomy Astrophysics OR Toxicology OR Oceanography OR Agronomy OR Medicine Research Experimental OR Genetics Heredity OR Agriculture Dairy Animal Science OR Gastroenterology OR Hepatology OR Quantum Science Technology OR Pharmacology Pharmacy Or Radiology Nuclear Medicine Medical Imaging OR Endocrinology Metabolism OR Veterinary Sciences OR Chemistry Medicinal OR Telecommunications OR Nutrition Dietetics OR Forestry OR Food Science Technology)

8.6 Publication Data

2014-2018 Australia's most frequent collaborator countries

Production	
Country	Publications
China	302
USA	98
England	50
Germany	35
Japan	31
India	25
Malaysia	19
Switzerland	18
Hong Kong	17
France	16

Storage	
Country	Publications
China	108
USA	36
Germany	22
Denmark	17
England	14
Japan	12
India	12
South Korea	10
France	9
Singapore	8

Utilisation	
Country	Publications
China	199
USA	41
Germany	23
England	20
Malaysia	17
India	16
Japan	15
Singapore	10
Saudi Arabia	9
Iran	9

Overall	
Country	Publications
China	534
USA	153
England	75
Germany	72
Japan	52
India	43
Malaysia	38
Switzerland	30
France	28
Denmark	27

9 Patent landscape search

9.1 Details of relevant IPCs and / or CPCs covered by the search strategy

9.1.1 Production

C01 INORGANIC CHEMISTRY
C01B NON-METALLIC ELEMENTS; COMPOUNDS THEREOF …
C01B3/00 Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures …
C01B2203/00 Integrated processes for the production of hydrogen or synthesis gas …

C25 ELECTROLYTIC OR ELECTROPHORETIC PROCESSES; APPARATUS THEREFOR
C25B ELECTROLYTIC OR ELECTROPHORETIC PROCESSES FOR THE PRODUCTION OF COMPOUNDS OR NON-METALS; APPARATUS THEREFOR (anodic or cathodic protection C23F13/00; single-crystal growth C30B)
C25B1/00 Electrolytic production of inorganic compounds or non-metals
C25B1/02 • of hydrogen or oxygen
C25B1/04 • • by electrolysis of water
C25B1/06 • • • in cells with flat or platelike electrodes
C25B1/08 • • • • of the filter-press type
C25B1/10 • • • in diaphragm cells
C25B1/12 • • • in pressure cells

C25B9/00 Cells or assemblies of cells; Constructional parts of cells …
C25B11/00 Electrodes; Manufacture thereof not otherwise provided for
C25B13/00 Diaphragms; Spacing elements

Y02 TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE
Y02E REDUCTION OF GREENHOUSE GAS [GHG] EMISSIONS, RELATED TO ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION
Y02E60/00 Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E60/30 • Hydrogen technology
Y02E60/36 • • Hydrogen production from non-carbon containing sources
Y02E60/362 • • • by chemical reaction with metal hydrides, e.g. hydrolysis of metal borohydrides
Y02E60/364 • • • by decomposition of inorganic compounds, e.g. splitting of water other than electrolysis, ammonia borane, ammonia
Y02E60/366 • • • by electrolysis of water
Y02E60/368 • • • • by photo-electrolysis

9.1.2 Storage

C01 INORGANIC CHEMISTRY
C01B NON-METALLIC ELEMENTS; COMPOUNDS THEREOF …
C01B3/00 Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures …

C01C AMMONIA; CYANOGEN; COMPOUNDS
C01C1/00 Ammonia; Compounds thereof { (C01C3/08, C01C3/14, C01C3/16, C01C3/20 take precedence)}
C01C1/02 • Preparation, {purification} or separation of ammonia
C01C1/04 • • Preparation of ammonia by synthesis …

C01C1/0405 • • • {from N2 and H2 in presence of a catalyst}
C01C1/0411 • • • • {characterised by the catalyst}
C01C1/0417 • • • • {characterised by the synthesis reactor …

F17 STORING OR DISTRIBUTING GASES OR LIQUIDS
F17B GAS-HOLDERS OF VARIABLE CAPACITY …
F17C VESSELS FOR CONTAINING OR STORING COMPRESSED, LIQUEFIED OR SOLIDIFIED GASES …
F17D PIPE-LINE SYSTEMS; PIPE-LINES

F25 REFRIGERATION OR COOLING; COMBINED HEATING AND REFRIGERATION SYSTEMS; HEAT PUMP SYSTEMS; MANUFACTURE OR STORAGE OF ICE; LIQUEFACTION SOLIDIFICATION OF GASES
F25J LIQUEFACTION, SOLIDIFICATION OR SEPARATION OF GASES OR GASEOUS {OR LIQUEFIED GASEOUS} MIXTURES BY PRESSURE AND COLD TREATMENT …
F25J1/00 Processes or apparatus for liquefying or solidifying gases or gaseous mixtures

Y02 TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE
Y02E REDUCTION OF GREENHOUSE GAS [GHG] EMISSIONS, RELATED TO ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION
Y02E60/00 Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation
Y02E60/30 • Hydrogen technology
Y02E60/32 • • hydrogen storage
Y02E60/321 • • • Storage of liquefied, solidified, or compressed hydrogen in containers
Y02E60/322 • • • Storage in caverns
Y02E60/324 • • • Reversible uptake of hydrogen by an appropriate medium
Y02E60/325 • • • • the medium being carbon
Y02E60/327 • • • • the medium being a metal or rare earth metal, an intermetallic compound or a metal alloy
Y02E60/328 • • • • the medium being an organic compound or a solution thereof

9.1.3 Utilisation

B60 VEHICLES IN GENERAL
B61 RAILWAYS
B62 LAND VEHICLES FOR TRAVELLING OTHERWISE THAN ON RAILS

C10 PETROLEUM, GAS OR COKE INDUSTRIES; TECHNICAL GASES CONTAINING CARBON MONOXIDE; FUELS; LUBRICANTS; PEAT
C10G CRACKING HYDROCARBON OILS; PRODUCTION OF LIQUID HYDROCARBON MIXTURES …
C10G45/00 Refining of hydrocarbon oils using hydrogen or hydrogen-generating compounds
C10G47/00 Cracking of hydrocarbon oils in the presence of hydrogen or hydrogen generating compounds, to obtain lower boiling fractions …
C10G49/00 Treatment of hydrocarbon oils in the presence of hydrogen or hydrogen-generating compounds …
C10G50/00 Production of liquid hydrocarbon mixtures from lower carbon number hydrocarbons …

C21 METALLURGY OF IRON
C21C PROCESSING OF PIG-IRON, e.g. REFINING, MANUFACTURE OF WROUGHT-IRON OR STEEL …

F02 COMBUSTION ENGINES; HOT-GAS OR COMBUSTION-PRODUCT ENGINE PLANTS
F02C GAS-TURBINE PLANTS …

H02 GENERATION; CONVERSION OR DISTRIBUTION OF ELECTRIC POWER
H02J CIRCUIT ARRANGEMENTS OR SYSTEMS FOR SUPPLYING OR DISTRIBUTING ELECTRIC POWER …

H01 BASIC ELECTRIC ELEMENTS
H01M PROCESSES OR MEANS …
H01M8/00 Fuel cells; Manufacture thereof

H01M8/22 • Fuel cells in which the fuel is based on materials comprising carbon or oxygen or hydrogen …

Y02 TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE
Y02E REDUCTION OF GREENHOUSE GAS [GHG] EMISSIONS, RELATED TO ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION
Y02E50/00 Technologies for the production of fuel of non-fossil origin
Y02E50/10 • Biofuels

Y02E60/00 Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation

Y02E60/50 • Fuel cells

9.2 Search strategy

Orbit FAMPAT Database; TI/AB = Title and Abstract.

Search Step	Result(s)	Query
1	5414	(((HYDROGEN OR H2) 30D (PRODUC+ OR MANUFACTUR+ OR GENERAT+)) 30D (ELECTROCHEMIC+ OR (ELECTRO+ W CHEMIC+) OR ((ELECTROLYSIS+ OR ELECTROLYTIC+ OR ELECTROLYSER+ OR ELECTROLYZER+) 3D (WATER OR H2O OR STEAM+)) OR (ALKALIN+ W ELECTROL+) OR (PROTON+ W EXCH+ W MEMBRANE+ W ELECTROL+) OR (PEM W ELECTROL+) OR (POLYMER+ W ELECTROL+ W MEMBRANE+) OR ((HIGH+ W TEMP+) 3D ELECTROL+) OR (SOLID+ W OXID+ W ELECTROL+) OR (ELECTROL+ W STACK+)))/TI/AB
2	3014	(((HYDROGEN OR H2) 30D (PRODUC+ OR MANUFACTUR+ OR GENERAT+)) 30D (THERMOCHEMIC+ OR (THERMO+ W CHEMIC+) OR ((METHANE OR CH4) 3D REFORM+) OR ((COAL+ OR BIOMAS+) 3D GASIFICAT+) OR BIOGAS+ OR AUTOTHERMAL+ OR (AUTO+ W THERMAL+) OR PYROLYSIS+ OR (PARTIAL+ W OXID+) OR (CHEMIC+ W LOOP+)))/TI/AB
3	603	(((HYDROGEN OR H2) 30D (PRODUC+ OR MANUFACTUR+ OR GENERAT+)) 30D (PHOTOCHEMIC+ OR (PHOTO+ W CHEMIC+) OR PHOTOSYNTH+ OR (PHOTO+ W SYNTH+) OR PHOTOBIOLOG+ OR (PHOTO+ W BIOLOG+) OR (BIOLOGY+ 3D ALGAE+) OR (FERMENT+ 3D CONVER+) OR BIOHYDROGEN+ OR (BIO+ HYDROGEN+) OR (BIO+ W H2)))/TI/AB
4	924	(((HYDROGEN OR H2) 30D (PRODUC+ OR MANUFACTUR+ OR GENERAT+)) 30D ((METHAN+ 3D CRACK+) OR (CH4 3D CRACK+) OR (POWER 3D GAS+) OR (CONCENTRAT+ 3D SOLAR+) OR (CONCENTRAT+ 3D SUN+) OR (BALANC+ 3D PLANT+)))/TI/AB
5	19502	(((HYDROGEN OR H2) 30D (PRODUC+ OR MANUFACTUR+ OR GENERAT+))/TI/AB) AND (C01B-003+/IPC/CPC)
6	11609	(C01B-2203+)/CPC
7	515	((((HYDROGEN OR H2) AND ((ALKALIN+ W ELECTROL+) OR (PROTON+ W EXCH+ W MEMBRANE+ W ELECTROL+) OR (PEM W ELECTROL+) OR (POLYMER+ W ELECTROL+ W MEMBRANE+) OR ((HIGH+ W TEMP+) 3D ELECTROL+) OR (SOLID+ W OXID+ W ELECTROL+) OR (ELECTROL+ W STACK+)))/TI/AB) AND (C25B-001/02 OR C25B-001/04 OR C25B-001/06 OR C25B-001/08 OR C25B-001/10 OR C25B-001/12 OR C25B-009+ OR C25B-011+ OR C25B-013+)/IPC/CPC)

8	15388	(PRODUC+ OR MANUFACTUR+ OR GENERAT+)/TI/AB AND (Y02E-060/3+)/CPC
9	15660	(Y02E-060/36+)/CPC
10	44200	1 OR 2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9
11	15505	((((HYDROGEN OR H2) 30D (STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+)) 30D (COMPRESS+ OR LIQUEF+ OR SOLIDIF+ OR (REVERS+ 3D UPTAK+) OR SYNTHES+ OR AMMONIA OR NH3 OR PHYSISORP+ OR (PHYSI+ W SORP+) OR (METAL+ 3D HYDRID+) OR (ORGANIC+ 3D COMPOUND+) OR (ORGANIC+ 3D SOLUTION+) OR (ORGANIC+ 3D LIQUID+) OR METHANE+ OR CH4 OR (PROTON+ W BATTER+))))/TI/AB
12	7517	((((HYDROGEN OR H2) 30D (STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+)) 30D (EMBRITTL+ OR (LINE+ W PACK+) OR UNDERGROUND+ OR (UNDER+ W GROUND+) OR CAVERN+ OR CANISTER+ OR TANK+ OR CYLINDER+)))/TI/AB
13	11715	(((HYDROGEN OR H2) 30D (STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+))/TI/AB) AND (C01B-003+/IPC/CPC)
14	335	(((HYDROGEN OR H2) 30D (STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+)))/TI/AB AND (C01C-001/04+)/IPC/CPC
15	4555	(HYDROGEN OR H2)/TI/AB AND (F17B+ OR F17C+ OR F17D+)/IPC/CPC
16	171	(((HYDROGEN OR H2) 30D (STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+)))/TI/AB AND (F25J-001+)/IPC/CPC
17	12291	(STORE+ OR STORING OR STORAG+ OR HOLD+ OR HELD+ OR CONTAIN+)/TI/AB AND (Y02E-060/3+)/CPC
18	9124	(Y02E-060/32+)/CPC
19	39482	11 OR 12 OR 13 OR 14 OR 15 OR 16 OR 17 OR 18
20	14749	((HYDROGEN OR H2) 30D (FUEL+ 3D CELL+))/TI/AB
21	2770	((HYDROGEN OR H2) 30D (FUEL+ 30D (TRANSPORT+ OR VEHICLE+ OR CAR OR CARS OR TRUCK+ OR TRAIN+)))/TI/AB
22	1136	((HYDROGEN OR H2) 30D ((SYNTHETIC+ 3D FUEL+) OR BIOFUEL+ OR (BIO+ W FUEL+) OR SYNGAS+ OR BIOCRUDE+ OR (BIO+ W CRUDE+)))/TI/AB
23	5784	((HYDROGEN OR H2) 30D (((INDUST+ OR COMMERCIAL+ OR DOMESTIC+) 30D ELECTR+) OR ((INDUST+ OR COMMERCIAL+ OR DOMESTIC+) 30D (HEAT+ OR AIRCONDITION+ OR (AIR W CONDITION+))) OR (ELECTR+ 3D GRID+ 3D (STABILITY OR STABLE)) OR (REMOTE+ 3D AREA+ 3D (POWER+ OR ELECTR+)) OR ((POWER+ OR FUEL+) 3D TURBINE+) OR (INDUST+ 3D (FEEDSTOCK+ OR (FEED+ W STOCK+))) OR (STEEL+ 3D (MAK+ OR MANUFACTUR+ OR PRODUCT+)) OR HYDROTREAT+ OR (HYDRO+ W TREAT+) OR HYDROCRACK+ OR (HYDRO+ W CRACK+)))/TI/AB
24	23420	(HYDROGEN OR H2)/TI/AB AND (H01M-008+ OR Y02E-060/50+)/IPC/CPC

25	7199	(HYDROGEN OR H2)/TI/AB AND (B60+ OR B61+ OR B62+)/IPC/CPC
26	2897	(HYDROGEN OR H2)/TI/AB AND (Y02E-050+)/CPC
27	1324	(HYDROGEN OR H2)/TI/AB AND (F02C+)/IPC/CPC
28	1867	(HYDROGEN OR H2)/TI/AB AND (H02J+)/IPC/CPC
29	7711	(HYDROGEN OR H2)/TI/AB AND (C10G-045+ OR C10G-047+ OR C10G-049+ OR C10G-050+)/IPC/CPC
30	1232	(HYDROGEN OR H2)/TI/AB AND (C21C+)/IPC/CPC
31	49430	20 OR 21 OR 22 OR 23 OR 24 OR 25 OR 26 OR 27 OR 28 OR 29 OR 30
32	24548450	PD >= 2010
33	**25598**	**10 AND 32**
34	**19785**	**19 AND 32**
35	**25220**	**31 AND 32**
36	**52871**	**33 OR 34 OR 35**
37	**335528**	**(AU)/PR**
38	**280**	**36 AND 37**

Results of **Search Steps 33 to 36 and 38** were analysed.

9.3 Copyright, search limitations and disclaimers

Copyright

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There are several limitations relating to patent searching that make it impossible to conduct an exhaustive patent search and hence guarantee that all relevant patents have been located. The following are three examples of these limitations:

- A patent search strategy will include the use of keywords and/or patent classifications. It is not possible to conceive and use every possible keyword variation in the search strategy. It is also not possible to guarantee that all relevant classifications will be discovered and searched or that patents will be correctly classified.
- The search strategy will be implemented in an appropriate database. Each database has respective limitations as to its patent coverage and the level of information available for patent records. There is no single database that has complete coverage of all patent data. The same key word search in one particular database will not necessarily provide the same results in another database.
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