Australia's National
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The State of Energy Transition Technologies

Low Carbon Fuels

TECHNICAL APPENDIX

December 2025

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Acknowledgement

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Accessibility

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Unit conversions

UNITS	
GJ	Gigajoule (1 000 000 000 joules)
PJ	Petajoules (1 000 000 gigajoules)
GW	Gigawatt (1 000 megawatts)
GWh	Gigawatt hour (a gigawatt of power used in an hour)
kL	Kilolitres (1 000 litres)
Km	kilometre (1 000 metres)
kW	Kilowatt (1000 watts of electrical power)
MJ	Megajoule (1 000 000 joules)
Mwe	Megawatt electric (1 000 000 watts of electrical energy)
MWh	Megawatt hour (1 000 000 watts of power used in an hour)
MWth	Megawatt thermal (1 000 000 watts of thermal energy)
TWh	Terawatt hour (1 000 000 megawatt hours)

1 Executive summary

Low Carbon Fuels

RD&D to support the development of sustainable and low-cost hydrogen, biofuels, and synthetic fuels will underpin the deployment of many low-emission technologies across demand sectors.

Challenge

Australia's economy is highly reliant on carbon-based gaseous and liquid fuels for domestic use. This makes low carbon fuels (LCFs) a critical component of the energy transition and key to providing a decarbonisation option for sectors that rely on energy-dense fuels, such as long-distance transport, aviation, mining and construction. Despite its importance, the transition to greater LCF adoption poses technical, economic and infrastructure challenges. While biofuels, synthetic fuels and hydrogen are critical low-carbon alternatives to conventional fossil fuels, their adoption is hindered by high costs and will require investment in new production, storage and end-use infrastructure and technologies.

Scope of analysis

This analysis highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts of large-scale hydrogen production and hydrogen storage solutions, as well as across the biofuels and synthetic fuels sub-sectors:

- **Hydrogen production** analyses low emissions technologies that will best service Australia's growing hydrogen industry by enabling large scale domestic hydrogen production (greater than 50 tonnes of hydrogen per day) at a commercially viable scale. Three technologies were explored in more detail to identify RD&D opportunities.
- **Hydrogen storage** analyses hydrogen storage technologies across three storage profiles; each reflecting a characteristic use case for short, medium and long duration storage. These technologies include the storage of hydrogen in its gaseous and liquid chemical state, as well as its storage via hydrogen carriers. Five technologies were explored in more detail to identify RD&D opportunities.
- **Synfuels** and **Biofuels** explores high-level RD&D opportunities across several production pathways for these LCFs. Transport and Industry identify RD&D opportunities associated with three biofuel technologies (Aviation), and two technologies that utilise synfuels (Aviation and Shipping). These chapters do not apply the methodology to filter technologies.

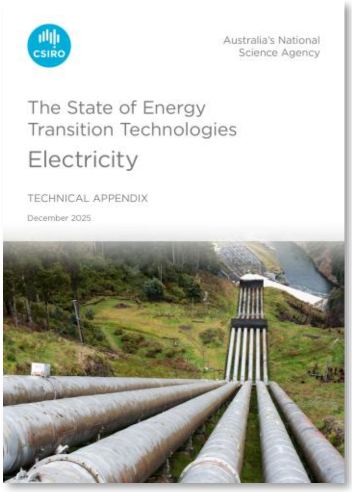
2 Low Carbon Fuels overview

Research, development and demonstration (RD&D) will be pivotal in informing and driving the change required to achieve the energy transition and Australia's net zero ambitions. However, with limited resources and a broad array of emerging low emissions technologies, Australia faces the important task of strategically and collaboratively optimising its RD&D efforts to maximise national benefit.

This study, *The State of the Energy Transition Technologies*, highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. It is not intended to prescribe research strategies for Australia or any individual organisation. Rather, it serves as a resource to support constructive dialogue and help navigate the energy transition by leveraging the nation's RD&D strengths.

2.1 This report

The *State of the Energy Transition* consists of a Synthesis report and five technical appendices spanning a range of Australian energy supply and demand related sectors. This report, focused on the supply of low carbon liquid fuels, is to be considered alongside the other reports, and aims to evaluate a diverse range of technologies to help explore opportunities for RD&D across the vast and rapidly growing low emissions technology landscape. It leverages global literature and CSIRO expertise, designing and applying a technology analysis framework to explore RD&D opportunities.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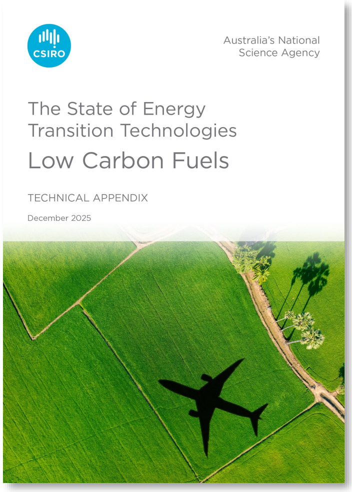
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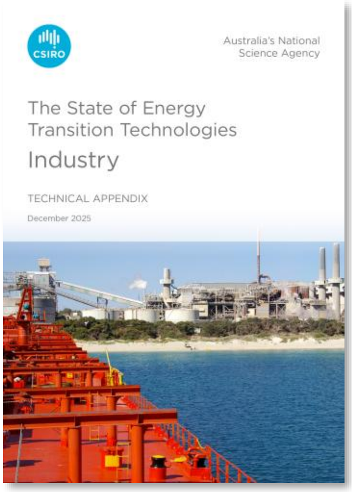
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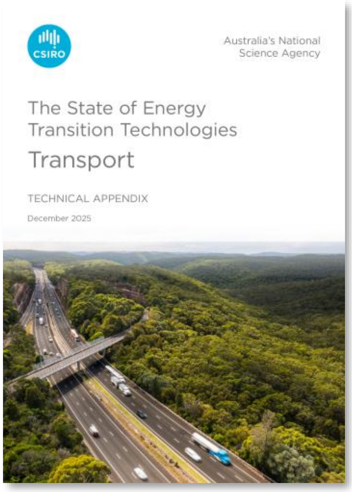
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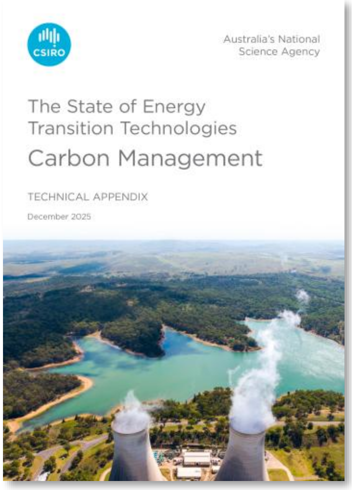
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2.2 Australia’s low carbon fuel needs

Australia’s economy is highly reliant on carbon-based gaseous and liquid fuels for domestic use. In 2022-23, Australian industries and households used 2,170PJ of petroleum and petroleum-based products and a further 726PJ of natural gas. Combined, this equated to 71% of energy consumed, compared to 991PJ (or 24%) of electricity.[1]

Low carbon fuels (LCFs) are a critical component of the energy transition, providing a decarbonisation option for sectors that rely on energy-dense fuels, such as long-distance transport, aviation, mining and construction. LCFs include biofuels (hydrocarbon fuels produced from biogenic feedstocks via biochemical or thermochemical conversion); synthetic fuels, or synfuels, (hydrocarbon fuels produced from renewable energy and non-fossil feedstocks, like captured CO_2); and hydrogen and its derivatives (e.g., ammonia). In transport, biofuels can help the aviation sector transition away from petroleum-based fuels, renewable diesel can replace petroleum fuels in heavy road freight, while synfuels can provide alternatives for shipping and long-haul applications. Within industry (e.g., steel, chemicals), LCFs can help shift conventional coal and natural gas processes to low emissions alternatives, while continuing to meet high energy and temperature needs.

Fuel storage buffers play an important role in ensuring energy security, managing supply disruptions, and stabilising domestic markets**.** Storage acts as a safeguard against extreme weather, supply chain failures, demand fluctuations and other disruptions. Chemical fuel storage is of particular importance, allowing energy to be stored in molecular forms, enabling high-density, long-duration storage that is not subject to self-discharge like electrical energy storage systems. Expanding domestic LCF capabilities can help ensure sovereign energy supply by harnessing Australia’s valuable renewable energy and biogenic resources. In 2023, the two remaining large-scale refineries in Australia produced less than 15 billion litres of fuel, or 24% of domestic petroleum product sales.[2] In the same year, Australia imported over 52 billion litres of refined petroleum products, with diesel accounting for ~60% of imports as Australia’s largest single source of energy demand.[3]

Despite its importance in decarbonising complex applications and industries, the transition to greater LCF adoption poses technical, economic and infrastructure challenges. While biofuels, synthetic fuels and hydrogen are critical low carbon alternatives to conventional fossil fuels, their integration into existing energy systems require substantial investment in new production, storage and end-use technologies. Current supply chains and industrial processes are optimised for fossil fuels, necessitating modifications to existing fuel production and distribution infrastructure. These fuels are also challenged by their economic viability. Hydrogen and synthetic fuels require high electricity inputs which may necessitate grid network upgrades and scaled renewable generation capacity to meet demands. Meanwhile, biofuels are highly sensitive to feedstock prices which are in turn influenced by the availability and access to suitable resources.

Ultimately, off-takers require energy dense fuels that are cost effective, accessible and affordable. Accelerating low emissions and cost-effective technologies will be essential to meeting these needs. Biofuels, synfuels and hydrogen fuels industries are interrelated industries, where strategic investment in biofuels can be designed to establish market conditions for green hydrogen production and synfuels. This interdependency supports the development of an integrated LCF ecosystem capable of delivering sufficient supply of market ready low carbon fuel options.

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[1] Australian Bureau of Statistics (2024) Energy Account, Australia. Reference period 2022-23 financial year. <https://www.abs.gov.au/statistics/industry/energy/energy-account-australia/latest-release> (accessed 28 March 2025)

[2] Petroleum products include regular fuel, premium fuel, ethanol-blended, diesel oil, aviation turbine fuel, LPG (automotive and non-automotive), aviation gasoline, fuel oil, lubricating oils & greases, and other products, as defined by Australian Petroleum Statistics 2024. As from CSIRO (2025) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia.

[3] DCCEEW (2024) Australian Petroleum Statistics 2024. <https://www.energy.gov.au/publications/australian-petroleum-statistics-2024> (accessed 25 March 2025)

2.3 Scope of this report

The scope of this report is structured around three categories of LCFs: hydrogen (and its derivatives), biofuels, and synthetic fuels. Exploration of the use of these fuels from an end-user perspective has been conducted within the demand-side reports, where their potential for adoption across industry and transport has been assessed. Building upon the application-specific details and analysis in these reports, this report centres on the broader production, storage and distribution considerations of these fuels and their respective RD&D opportunities.

For hydrogen, the methodology framework outlined in *Section 3*, has been applied to highlight low emissions and cost-effective production and storage technologies that can help to advance Australia's decarbonisation efforts. This formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

For biofuels and synthetic fuels, RD&D opportunities are discussed more holistically in this report without highlighting explicit technological pathways. Many of these production technologies, such as the Fischer-Tropsch synthesis for power-to-liquid synfuels and the Haber-Bosch process for ammonia, are well-established in conventional fuel production. Similarly, many fuels such as e-methanol/ammonia and renewable diesel are chemically equivalent to their fossil fuel counterparts, and so conventional storage methods can be readily adopted.

In this sense, the primary innovation challenge for these fuels lies in RD&D across feedstock, processing and supply chain development. It also lies in establishing important process inputs, which are discussed for hydrogen (refer to *Section's 4* and *5*), electricity (refer to the *Electricity* technical appendix), and carbon-feedstocks (refer to the *Carbon Management* technical appendix).

Overview of hydrogen production analysis

This report chapter highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts through large scale hydrogen production.

Large scale hydrogen production refers to the centralised production facilities with the capacity to produce greater than 50 tonnes of hydrogen per day. Large scale production of hydrogen is necessary for meeting offtaker demands across key industries, including transport applications; industrial processes, such as chemical refining and manufacturing and steel production; and export markets. As hydrogen demand grows across domestic and international markets, identifying and deploying scalable low emissions production technologies will play a fundamental role in accommodating diverse sector-specific needs, including its role as a fuel, chemical feedstock. For industries and applications that are not able to electrify their operations and rely on energy-dense liquid and gaseous fuels, large-scale hydrogen production enables an alternative decarbonisation pathway.

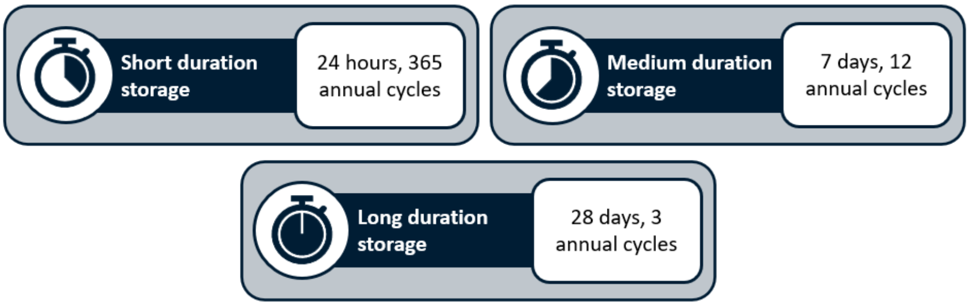
Overview of hydrogen storage analysis

This report chapter highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions hydrogen storage technologies, across three storage durations: short, medium and long.

These technologies include the storage of hydrogen in its gaseous and liquid chemical state, as well as its storage via hydrogen carriers (which considers both the conversion of hydrogen into the carrier molecule and its reconversion back to hydrogen for use).

Unlike electricity storage technologies, chemical energy carriers, including hydrogen, do not face substantial self-discharge unless there is a leak or chemical degradation of the storage media, allowing for extended periods of energy storage with minimal energy loss if carefully managed. As such, the short, medium and long duration storage profiles (Figure 1) represent increasing levels of hydrogen storage capacity. The short duration use case operates on a daily cycle, with operational profiles for medium and long duration storage adapted to reflect longer drawdown periods for industries requiring multi-week or seasonal hydrogen demand (i.e., fertiliser and/or chemical industries, or seasonal grid balancing).

Figure 1: Use case characteristics of short, medium and long duration hydrogen storage technologies



Hydrogen storage solutions are highly variable across the scale of storage, duration and number of annual cycles required. There are also a number of interdependencies among the technologies and processes for hydrogen production, storage and distribution; for example, the approach chosen for distribution (gaseous, liquid, or carrier) will affect the availability of storage options, cost and efficiency. As such, the use case durations and cycles are intended to be viewed as examples, with operational profiles aligned with representative applications. These provide a useful proxy for analysing the cost competitiveness of various energy storage solutions.

3 General methodology

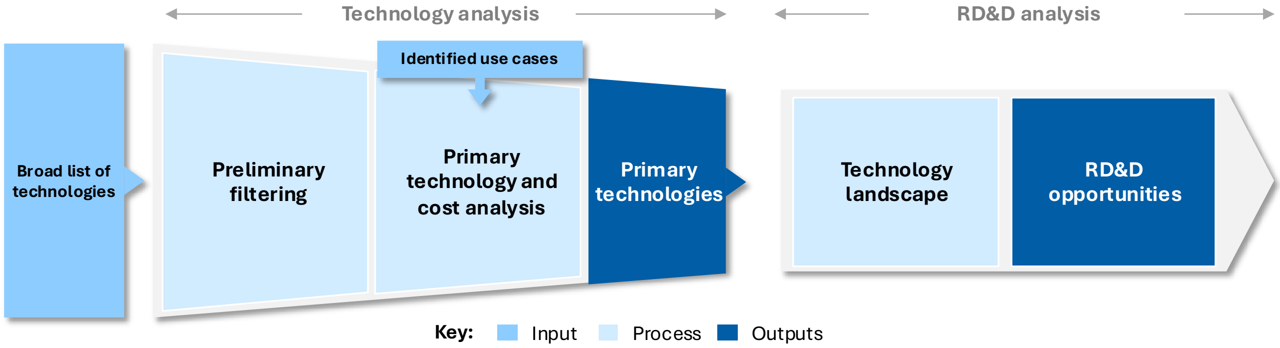
The State of Energy Transition Technologies report methodology was designed to highlight RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. The methodology adopts a multi-stage approach (see Figure 2), where prospective technology solutions were identified from a broad list through a technology analysis framework. This formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

The framework uses a structured approach to consistently filter technologies, while retaining flexibility to adapt criteria to a broad range of sectors and sub-sectors. This helps ensure technologies are fit-for-purpose and can meet the expected requirements for indicative energy- and emissions-intensive Australian use cases, while capturing a diverse range of technologies and RD&D opportunities to support Australia's sectoral and economy-wide 2050 net zero objectives.

The analysis derives technology specific RD&D opportunities that could address the technical, economic, and operational requirements of different sector applications. While extremely important, non-technical RD&D is outside of the scope of this study. This includes research related to policy and regulation, social licence and participation, communication and engagement and governance to support the energy transition.

The following is a high-level summary of the methodology and framework applied in this report.

Figure 2: Summary of framework



Inputs

The broad list of technologies was compiled from most recent Australian and global literature and assigned to key (sub)sectors (see *Appendix A.3* for sources). As the level of detail varied across sources, only technologies that directly contribute to emissions reduction efforts were considered as inputs to the framework.

Use cases were defined based on energy and emissions intensive applications identified for the sector/subsector. These use cases were developed to ensure technologies were fit-for-purpose for the specific (sub)sector, and focus on opportunities with the highest abatement impact. These use cases aim to capture a diverse range of applications where possible to ensure the technologies explored provide a portfolio of solutions that align with Australia's sectoral and economy-wide decarbonisation needs.

Technology analysis

The technology broad list was filtered through a two-stage process to explore their suitability for the chosen use case(s). Filtering has been conducted on a knock-out basis, ensuring that only technologies meeting all relevant conditions progressed through the analysis. The order of filters is not indicative of a relative importance of criteria.

- **Preliminary filtering**: Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:
  1. Relevance to Australia;
  2. Technology maturity; and
  3. Abatement potential.[4]

Primary technology and cost analysis: Specific criteria were applied to determine each technology's suitability for use case applications, followed by levelised cost analysis to provide a relative comparison of the long-term feasibility of technology options and to support RD&D opportunity analysis.

1. The specific criteria used to evaluate suitability differed by subsector. For more detail on the criteria used across each (sub)sector in the *State of Energy Transition Technologies* reports, please refer to *Appendix A.3*.
2. Levelised cost analysis was conducted for each use case to identify technologies that are relatively more cost competitive and therefore likely to play a role in advancing Australia's decarbonisation efforts. Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis*.

At each filter, technologies were assigned one of three ratings (see Figure 3) based on their ability to meet the criteria. Where conditions or limitations were identified but deemed surmountable for a given technology, a 'meets criteria with caveats' rating was applied.

The subset of technologies that met all filtering criteria are described as *Primary technologies*, and inform the technology landscape development and RD&D opportunity analysis.

Figure 3: Technology assessment rating criteria

🟦 Meets filter criteria ◻ Meets criteria with caveats ■ Does not meet criteria ▨ Not assessed further

Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the exploration of RD&D opportunities. The identified *Primary technologies* cannot exist in isolation and form one part of a broader technology landscape that must be developed in parallel. This landscape includes technologies essential for the deployment or enhanced performance of the primary technologies, described in *The State of Energy Transition Technologies* reports as *Auxiliary technologies* (see Figure 4).

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[4] Considers Scope 1 emissions arising from the direct use of a technology, as well as Scope 2 (indirect) emissions generated from the production of key energy inputs. Some Scope 3 emissions are considered on a case-by-case basis. See the relevant section for further detail.

Figure 4: Technology landscape components

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

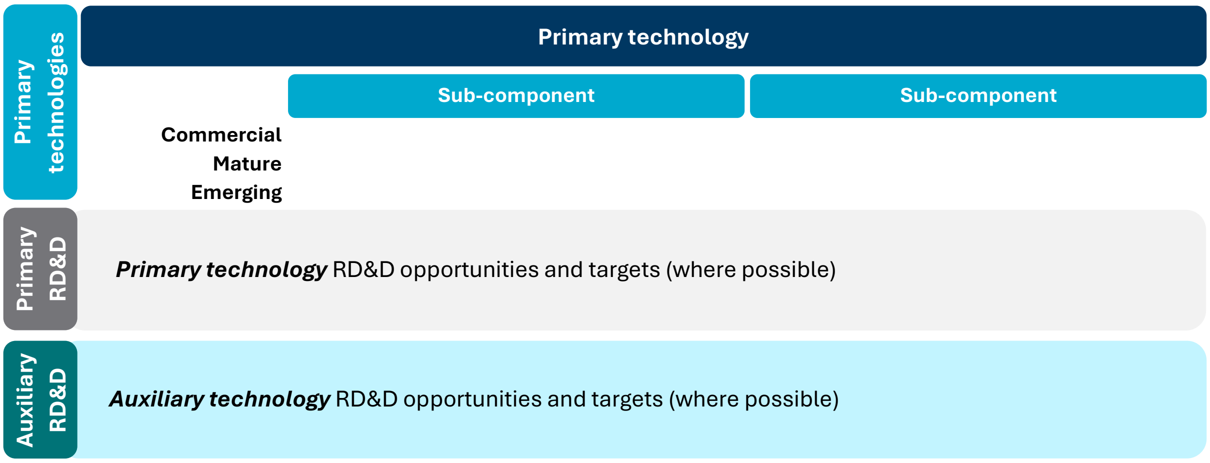
RD&D opportunity analysis

Following the development of the technology landscape, RD&D opportunities were explored. These RD&D opportunities reflect broad workstreams that are likely to help scale-up, de-risk and accelerate the deployment of low emissions technologies.

The analysis is designed to inform constructive dialogue around the role of RD&D in navigating Australia's energy transition. As such, the identified opportunities are not exhaustive of all RD&D areas for the technologies explored. Where possible, cost projections or quantitative targets for technology development were also identified, informed by model cost projections, literature reviews, and the input of subject matter experts. Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of the explored low emission technologies.

Primary technologies were categorised based on their technological maturity and disaggregated into their key components where relevant. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9). Literature and stakeholder experts were consulted to determine detailed RD&D opportunities related to the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies (Figure 5).

Figure 5: Technology RD&D opportunity overview



4 Hydrogen production

4.1 Executive summary

Large-scale (50t/day) deployment of natural, electrolytic or biomass-derived hydrogen production requires RD&D efforts to address the technical and economic challenges facing these pathways.

Technology landscape: Large-scale (50t/day) hydrogen production

Electrolytic production, natural hydrogen, and biomass and waste conversion with carbon capture and storage (CCS) represent potential pathways for large-scale, low-emission hydrogen production in Australia, each with distinct auxiliary technologies, technical and economic considerations.

Electrolysis	Natural hydrogen production	Biomass and waste conversion
• Low emissions electricity generation • Transmission and storage • Diagnostic systems	• Exploration activities • Proximity modelling • Surface processing infrastructure	• Feedstock pre-treatments • Gas separation

RD&D Opportunities

Electrolysis	• RD&D opportunities for electrolytic hydrogen production can support efforts to meet the required performance and cost targets set for commercially viable operations. Achieving these targets will be dependent on RD&D to reduce capital costs by minimising the costs of system-specific components, optimising cell designs and improving stack durability to extend system lifespan. • Bespoke electrolyser systems, including those that make use of alternate water sources or waste heat, require investment to scale-up and RD&D to overcome lower efficiencies and higher operational costs. These systems may present significant cost reduction potential in particular applications.
Natural hydrogen production	• RD&D is required to improve current understanding of the kinetics of natural hydrogen production and develop exploration methodologies to evaluate natural hydrogen deposits and understand its domestic potential. • Similarly, RD&D will be required to optimise extraction and purification of natural hydrogen resources, and support field development planning.
Biomass and waste conversion	• Catalyst designs across the thermochemical pathways and water-gas shift reaction need to be improved to optimise both cost-efficiency and conversion rates for the effective production of hydrogen. • RD&D can facilitate the advancement of resistive materials, ensuring the preservation of reactor integrity and extending operational lifespan.

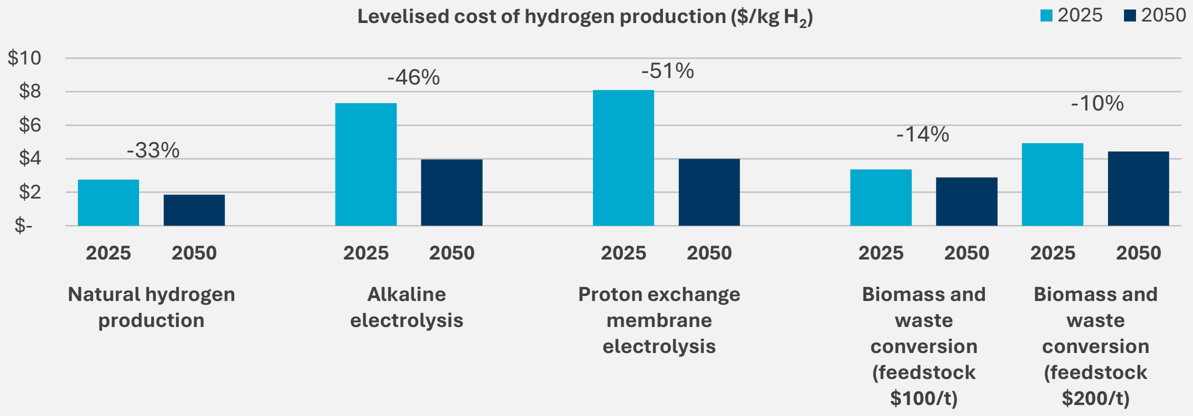
Auxiliary

- Integrating renewable energy generation into electrolytic hydrogen production will require RD&D to manage flexible operation patterns.
- Realising natural hydrogen production on a large-scale requires further RD&D to develop exploration methodologies specific to the geological conditions under which natural hydrogen may accumulate alongside reservoir characterisation and field development planning, including impurity management.

Levelised cost analysis

Large-scale hydrogen production (>50t/day)

Natural hydrogen is projected to be the lowest cost hydrogen production technology in 2050. Biomass and waste conversion, alkaline electrolysers (AE) and proton exchange membrane (PEM) electrolysers are projected to become the next most cost-effective abatement technologies by 2050 relative to other assessed technologies, driven by improvements in electrolyser efficiency and an anticipated decline in electricity prices.



See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

4.2 Introduction

The large-scale production of low emissions hydrogen plays a fundamental role in decarbonising sectors where emissions are hard-to-abate, offering a pathway to replace fossil-based hydrogen with low emissions alternatives and supporting long-term adoption in transport and other energy-intensive industries.

Global hydrogen demand reached 97Mt in 2023, an increase of 2.5% compared with 2022, responsible for 1080Mt of CO_2e in direct emissions.[5] However, only 1Mt low emissions hydrogen was produced in 2023. Like global trends, hydrogen in Australia is primarily produced from natural gas via steam methane reforming (SMR) and is largely consumed by associated ammonia synthesis and crude oil refining.[6] This process produces CO_2, which is typically vented to the atmosphere.

Australia's natural endowment of renewable energy resources and land availability presents a comparative advantage. In leveraging these advantages, Australia can further efforts to decarbonise sectors reliant on energy-dense fuels, bolster domestic energy security and capture economic opportunities associated with the global energy transition.[7] Australian hydrogen can be exported as an energy carrier to countries less able to generate renewable electricity. It can also be exported through low emissions products that have been manufactured locally using hydrogen as a chemical or heat input to the production of green metals, ammonia and low-carbon liquid fuels.

Australia has the largest pipeline of hydrogen projects globally, with over 100 projects valued at more than $225 billion[8] announced since 2019.[9] These projects focus on mature electricity-based production routes, such as electrolysis, aligning with Australia's extensive wind and solar resources. Diversifying hydrogen production pathways is essential given the scale of hydrogen required and the impact on production inputs such as water, electricity and biomass. Although long-term cost reductions are expected for hydrogen produced from renewable resources, there are a number of projects under development that employ fossil fuel-pathways with integrated carbon capture and storage (CCS), both in Australia and globally.[10]

While large scale production is the focus of this chapter, small-scale production methods will be important to progressing decarbonisation objectives, and may complement large-scale initiatives by supporting distributed production, facilitating storage, and advancing scalable innovative and scalable solutions.

Despite recent industry advancements, the scale up of hydrogen production continues to face high upfront investment costs, and ambiguity regarding the timing, scale and use of hydrogen, highlighting the need for continued RD&D to de-risk hydrogen solutions. Scale up is also dependent on the supporting networks and systems required for operation, in particular shoring up hydrogen storage capacity (refer to the *Section 5 Hydrogen storage)* for buffering and distribution, and renewable electricity generation and storage networks to ensure the reliable supply of key process inputs (refer to the *Electricity* report). Policy mechanisms will also play a role in aligning supply and demand.

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[6] Advisian (2021) Australian market study: Sector analysis summary. Prepared for the Clean Energy Finance Corporation. <https://www.cefc.com.au/media/nhnhwlxu/australian-hydrogen-market-study.pdf> (accessed March 2025).

[7] DCCEEW (2024) National Hydrogen Strategy 2024, Department of Climate Change, Energy, the Environment and Water, Canberra. CC BY 4.0. <https://www.dcceew.gov.au/sites/default/files/documents/national-hydrogen-strategy-2024.pdf>

[8] DISR 2023, Resources and energy major projects 2023. www.industry.gov.au/publications/resources-and-energy-major-projects-2023 Note a revised valuation methodology was used, compared with previous years, that excluded projects that were at an 'Advanced Feasibility' stage. The preceding report from 2022 valued the pipeline at $230 to $303 billion.

[9] DCCEEW (2024) National Hydrogen Strategy 2024, Department of Climate Change, Energy, the Environment and Water, Canberra. CC BY 4.0. <https://www.dcceew.gov.au/sites/default/files/documents/national-hydrogen-strategy-2024.pdf>

[10] IEA (2025) Hydrogen. <https://www.iea.org/energy-system/low-emission-fuels/hydrogen> (accessed March 2025);

4.2.1 Hydrogen production use case(s)

To explore low emissions technologies in the hydrogen production subsector, a single use case has been defined, reflecting large-scale production (see Table 1). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

This use case refers to the centralised production of hydrogen with a capacity capable of exceeding 50 tonnes of hydrogen per day. Large-scale production of hydrogen is necessary for supporting offtaker demands in decarbonising sectors, including transportation, industry (i.e., chemical refining, steel production, and chemical manufacturing), and in export markets.

This use case is illustrative and presents requirements that technologies must be able to meet in order to service high-demand hydrogen offtakers. Small-scale solutions, though not evaluated here, are acknowledged for their role in enabling distributed production models and accelerating progress towards scalable solutions as the hydrogen industry develops.

In reality, hydrogen production facilities in Australia are likely to span a range of scales, from centralised hubs to decentralised systems. Production technologies must also work in concert with storage and distribution (molecules vs electrons) networks to support different regions and customers, creating additional complexities.

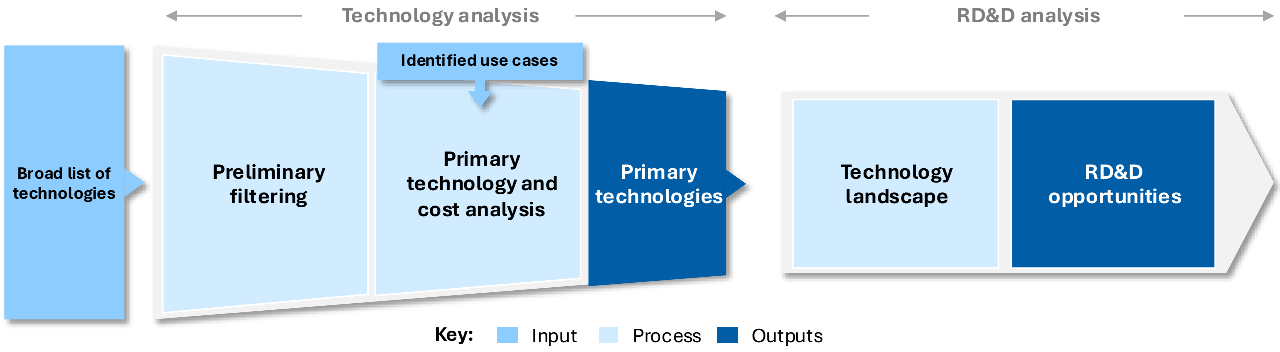
Table 1: Use case(s) – Hydrogen production

Use case(s)	Large-scale production
Description:	A centralised large-scale hydrogen production facility, capable of exceeding a daily production capacity of over 50 tonnes per day.

4.3 Methodology: Hydrogen production inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to contribute to the decarbonisation of hydrogen production. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 6).

Figure 6: Technology and RD&D analysis framework for hydrogen production



4.3.1 Broad technology list

A broad technology list comprised of eight technologies was developed (Table 2). These technologies were then passed through three preliminary filters: relevance to Australia, technological maturity and abatement potential. The technologies that satisfied the preliminary filters were then assessed against the filters for the relevant use case.

Table 2: Technology category definitions – Hydrogen production

Technology	Definition
Aluminium oxidation	A chemical reaction of aluminium with water, producing hydrogen gas. To be considered a carbon neutral pathway, synthesis must utilise recovered aluminium.
Biological hydrogen production	Utilises microorganisms, such as bacteria and algae, to generate hydrogen through metabolic processes under specific conditions.
Biomass and waste conversion (/with CCS)	Involves thermochemical processing of organic materials, often via gasification and pyrolysis processes. These processes may be coupled with carbon capture and storage (CCS) to capture direct process emissions.
Electrolysis *Electrolysis: Proton exchange membrane (PEM)*	Uses electrical energy to split water into hydrogen and oxygen, conducted in an electrolyser. Utilises an acidic solid polymer electrolyte membrane.
Electrolysis: Alkaline electrolysis (AE)	Uses electrical energy to split water into hydrogen and oxygen, conducted in an electrolyser. Utilises a porous diaphragm and an alkaline electrolyte.
Electrolysis: Solid oxide electrolysis (SOE)	Uses electrical energy to split water into hydrogen and oxygen, conducted in an electrolyser. Utilises a solid oxide (or ceramic) electrolyte. It operates at high temperatures which can be obtained via integration with industrial processes, consequently increasing energy efficiencies.
Electrolysis: Other	Uses electrical energy to split water into hydrogen and oxygen, conducted in an electrolyser. **Anion exchange membrane** utilises a porous anion exchange membrane diaphragm and an alkaline electrolyte. **Alkaline capillary-fed electrolysis** utilises capillaries to transport water along a porous inter-electrode separator, leading to inherently bubble-free operation at the electrodes. **Seawater electrolysis** utilises untreated seawater directly as the electrolyte. **Wastewater electrolysis** utilises wastewater and its organic contaminants as reactants within the electrolyte.
Fossil fuel conversion with CCS[11]	Extracts hydrogen from fossil fuels (typically via conventional gasification, pyrolysis and reforming processes), while capturing and storing process emissions.
Natural hydrogen production	Extracts hydrogen from naturally occurring sources, such as underground deposits and geological processes.
Photochemical & photocatalytic processes	Harnesses sunlight to drive chemical reactions that split water into hydrogen and oxygen using specialised photoelectrodes or catalysts.
CST thermochemical water splitting	Utilises high temperatures, obtained through CST, to drive chemical cycles that decompose water into hydrogen and oxygen.[12]

4.3.2 Primary technology filters

Technology assessment involved evaluating the technologies identified through preliminary filtering against two filters for large-scale hydrogen production (Table 3): scalability and cost. These represent two core operating requirements that will be instrumental in establishing the large-scale production facilities for this use case.

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[11] Includes autothermal reforming; chemical looping with water splitting; coal gasification; coal and oil pyrolysis; concentrated solar-thermal methane reforming; natural gas pyrolysis; steam methane reforming; thermal and catalytic oxidation; and underground methane reforming.

[12] Thermochemical water splitting can also adopt nuclear energy to generate the high temperatures required for hydrogen production.

The threshold for scale has been informed by subject matter experts and was deemed to reflect the scale of production required to meet the demands of high utilisation sectors. The lowest cost mitigation technologies able to meet the scale of generation required were progressed for further RD&D opportunity analysis. Further details on the selected filters are provided in *Section 4.4.2 Primary technology* analysis.

Table 3: Technology filtering criteria – Hydrogen production

Subsector	Hydrogen production
Use case(s)	**Large-scale production**
Preliminary filtering criteria	**Relevance to Australia** *Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.* *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources.*
	Technology maturity *Technology has a TRL greater than 3. The TRL index can be found in Appendix A.2.*
	Abatement potential *Technology options have been compared against a 'zero-emissions' benchmark. This was established to reflect the anticipated availability of zero emissions technology solutions with significant abatement potential by 2050, and in accordance with long term decarbonisation targets which acknowledge supply-side technology impacts on downstream emissions.*
Primary technology analysis	**Scalability** *Technology can produce greater than 50t H_2 per day.*
	Levelised Cost of Hydrogen ($LCOH_2$) in 2050 *Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in $LCOH_2$ relative to other assessed technologies (in \$/kg of H_2).*

4.4 Technology analysis

This chapter outlines the process of identifying primary technologies that can service Australia's domestic large-scale hydrogen production requirements. Following the technology analysis framework process, **electrolysis, natural hydrogen production and biomass and waste conversion with CCS, emerged as primary technologies for further RD&D analysis.** These technologies were able to service the designated use cases and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in hydrogen production, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. The results of the technology analysis for the hydrogen production subsector are provided in Table 4.

Hydrogen production may be referred to using a simplistic colour-naming convention, as outlined in Box 1. This nomenclatue was not adopted in this report, largely as it does not account for technology variations or nuances within each of these categories. However, the 'zero-emission' or 'low-emission' hydrogen technologies considered in this report can be broadly mapped to 'green', 'white' and 'blue' hydrogen classifications.

Table 4: Technology analysis results – Hydrogen production[13]

🟦 Meets criteria ▢ Meets with caveats ⬜ Does not meet ★ Primary technology ▨ Not assessed further

1. Preliminary filtering

2. Primary technology analysis

				Large scale production		
Technologies	**Relevance to Australia**	**Maturity**	**Abatement threshold**	**Scalability**	**2050 LCOH$_2$**	
Threshold		*TRL >3*	*Zero or negative emissions*	*>50t/day*		
Aluminium oxidation	🟦	TRL 4	Zero	kg per day, resource constraints	▨	▨
Biological hydrogen production	🟦	TRL 4-6	Zero or negative	kg per day, resource constraints	▨	▨
Biomass and waste conversion	🟦	TRL 6	Positive (3.7$kgCO_2e/kgH_2$)	▨	▨	▨
Biomass and waste conversion with CCS	Geo-dependent (CCS)	TRL 4-5	Negative (-17.5$kgCO_2e/kgH_2$)	Residual biomass constraints	\$2.89/kg @ \$100/$t_{biomass}$ \$4.44/kg @ \$200/$t_{biomass}$	★
Electrolysis: Proton exchange membrane (PEM)	🟦	TRL 9	Zero	Contingent on network upgrades and water availability	\$3.99/kg	★
Electrolysis: Alkaline electrolysis (AE)	🟦	TRL 9	Zero	As above	\$3.95/kg	★
Electrolysis: Solid oxide electrolysis (SOE)	🟦	TRL 7-8	Zero	As above	Cost potential for heat-generating industries	★
Electrolysis: Other	🟦	TRL 2-7[14]	Zero	As above	Cost potential through efficiency gains or for water constrained regions	★
Fossil fuel conversion with CCS (SMR or coal gasification)	Geo-dependent (CCS)	TRL 4-9	Positive (1.5-3.7$kgCO_2e/kgH_2$)	▨	▨	▨
Natural hydrogen production	Subject to discovery of geological deposits	TRL 5	Near zero (<1$kgCO_2e/kgH_2$)	Subject to capacity of geological deposits	\$1.85/kg	★
Photochemical & photocatalytic water splitting	🟦	TRL 4-5	Zero	kg per day	▨	▨
CST thermochemical water splitting	🟦	TRL 4	Zero	Subject to land availability for solar installations	\$4.29/kg	▨

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[13] Details for these figures, including sources/assumptions, are found in Table 7 (abatement potentials), '*Scalability*' and '*Levelised cost analysis*' (LCOH$_2$, see also *Technical Appendix: Levelised cost analysis*).

[14] Anion Exchange Membrane (AEM; TRL 7), Seawater (TRL 5), wastewater (TRL 4), and alkaline capillary-fed electrolysis (TRL 5-6) meet the criteria. Carbon and hydrocarbon-assisted electrolysis does not meet the criteria (TRL 2-3).

Box 1: Hydrogen nomenclature

Hydrogen can be produced through several different processes, classified by either the material source, or the type of energy used to drive the production process. This nomenclature is described in Table 5. For hydrogen production pathways to be considered in this report, they are required to produce ‘zero-emission’ or ‘low-emission’ hydrogen.

This includes hydrogen that is produced via processes that utilise renewable energy sources (i.e., renewable electricity or heat from solar) and renewable material inputs (i.e., H_2O); hydrogen that is produced when conventional fossil-based pathways are coupled with carbon capture systems with high capture rates (i.e., >90%) to sequester process emissions; and hydrogen that is naturally occurring (geogenic) and able to be extracted from geological deposits with minimal atmospheric impact.

Table 5: Hydrogen terminology[15]

🟦 Generally considered ‘low-emission’ or ‘zero-emission’

Terminology	Process	Process energy	Material source	GHG emissions ($kgCO_2/kgH_2$)
Green*	Electrolysis	Electricity (renewable)	H_2O	Zero (~2.21 when considering embedded emissions)
Pink		Electricity (nuclear)	H_2O	0.47–0.96
Yellow		Electricity (grid, mixed origin)	H_2O	Variable (22.7 using 100% Combined Cycle Gas Turbine, and 44.5 using 100% coal fired generation)[16]
White	Natural hydrogen production	*NA*	Naturally occurring	Zero/minimal
Blue*	Steam methane reforming w/ CCS Gasification w/ CCS	Thermal	Natural gas; coal; biomass	-17.5 to -11.7 (Biomass + CCS) 3.0 to 9.2 (SMR/ATR + CCS)
Turquoise	Pyrolysis	Thermal	Natural gas	4.2 to 9.1 (solid carbon)[17]
Grey	Steam methane reforming	Thermal	Natural gas	10.1 to 17.2
Brown*	Gasification	Thermal	Coal; biomass	14.7 to 30.9 (coal) Variable (biomass). Generally, 2-4$kgCO_2/kgH_2$, but estimates up to 8.6 have been cited

*Biomass-based pathways can fall under a number of the above classifications depending on the biofeedstock employed, production practices, and the process in which the feedstock is used. Biomass can be used in conventional gasification processes; although fewer emissions are produced when used as a replacement for coal, emissions can still be significant (i.e., ‘brown’ hydrogen).[18] Emissions are highly variable and depend on the feedstocks used, transportation required, and, though not captured here, emissions associated with indirect land use change (ILUC). When used as a direct replacement for fossil fuel inputs *and* coupled with CCS, ‘blue’ hydrogen is produced. When employed in electrolysis systems, ‘green’ hydrogen can be produced.

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[15] https://pubs.rsc.org/en/content/articlelanding/2019/ee/c8ee02079e. Adapted from Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: a review. Geological Society, London, Special Publications 528, 73–86. https://doi.org/10.1144/SP528-2022-88

[16] Emissions intensities taken as 414gCO_2/kWh (CCGT) and 809gCO_2/kWh (Coal-fired generation). Figures assume emissions from combustion and fugitives, and are sourced from ACIL Allen Consulting (2016) AEMO Emissions Factors. Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/ntndp/2016/data_sources/acil-allen---aemo-emissions-factors-20160511-pdf-document.pdf?la=en&hash=AB233ACCECC78768D7C236E307433C10>. A 55kWh/kgH_2 electrical efficiency was assumed.

[17] Regarding emissions intensity calculations, if not utilised, the environmental impacts and carbon within the co-produced solid carbon is attributed to the hydrogen produced. Therefore, it is necessary that there are industrial offtakers and uses for the solid carbon (i.e., tires, rubber plastics, paints

4.4.1 Preliminary filtering

Key information – Preliminary filtering

Three criteria were employed to ensure that the technologies offer marked emissions reductions in the Australian context:

- Relevance to Australia: Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- Technology maturity: Technology has a TRL greater than 3.
- Abatement potential: Technology demonstrates the potential to meet a nominated abatement threshold. The threshold for this sector is distinguished in the relevant filtering section, below.

Relevance to Australia

Most technologies listed in Table 2 were found to meet this criterion as they can be reasonably deployed in the Australian context. There were, however, some exceptions which meet the criteria with certain caveats: Natural hydrogen production and CCS-coupled production routes.

Natural hydrogen production

The extent of natural hydrogen production in Australia is reliant on the presence and identification of deposits in Australia. While there have been reports of high concentrations of hydrogen found in Australian gas samples, the extent of geological deposition is not yet well understood.[19] Some states have amended exploration licenses in the oil & gas industry to incorporate natural hydrogen, to further identify occurrences.

Biomass and waste conversion or fossil fuel conversion with CCS

CCS-coupled pathways rely on point-source carbon capture along the production route, which is then permanently stored in deep, geological formations. This requires the identification of subsurface structures that possess acceptable injectivity, capacity and seal (safety) characteristics for permanent CO_2 storage. For further detail, please refer to the *Carbon Management* technical appendix.

Technological maturity

All technologies were found to meet this criterion, possessing a TRL greater than 3 (Table 6). Maturity ratings are informed by the IEA Clean Energy Technology Guide.[20] Many forms of electrolysis are mature and have reached high maturity, however, less mature systems (e.g., carbon and hydrocarbon-assisted water electrolysis, TRL 2-3), were not considered.[21]

While many technology groups fall within the 'emerging technology' range (TRL 4-6), presenting opportunities for long-term zero emissions hydrogen production, near-term production targets will be reliant on established production routes such as electrolysis.

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etc.) which is generated at a rate three times that of hydrogen: Diab J, Fulcheri L, Hessel V, Rohani V, Frenklach M (2022) Why turquoise hydrogen will be a game changer for the energy transition. International Journal of Hydrogen Energy 47(61), 25831–25848. https://doi.org/10.1016/j.ijhydene.2022.05.299

[18] Incer-Valverde J, Korayem A, Tsatsaronis G, Morosuk T (2023) "Colors" of hydrogen: Definitions and carbon intensity. Energy Conversion and Management 291, 117294. https://doi.org/10.1016/j.enconman.2023.117294; Marín Arcos JM, Santos DMF (2023) The Hydrogen Color Spectrum: Techno-Economic Analysis of the Available Technologies for Hydrogen Production. Gases 3(1), 25–46. https://doi.org/10.3390/gases3010002

[19] Geoscience Australia (2023) Australia's Hydrogen Production Potential. https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen/australias-hydrogen-production-potential (accessed 11 December 2024).

[20] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology>

[21] Higher TRL systems include: Proton exchange membrane electrolysis (TRL 9), AE (TRL 9), solid oxide electrolysis (TRL 8), anion exchange membrane (TRL 6), seawater electrolysis (TRL 5), wastewater electrolysis (TRL 4).

Table 6: Technology maturities – Hydrogen production

Technology	TRL
Aluminium oxidation	- TRL 4
Biological hydrogen production	- TRL 4-6 - **Bio photolysis (direct and indirect):** TRL 4 - **Dark fermentation:** TRL 4 - **Hybrid light and dark fermentation:** TRL 5-6 - **Microbial electrolysis:** TRL 4 - **Photo fermentation**: TRL 6
Biomass and waste conversion	- TRL 9[22] - **Gasification**: TRL 9 - **Pyrolysis:** TRL 9 - **Steam reforming**: TRL 9
Biomass and waste conversion with CCS	- TRL 4-5 - **Biomass waste gasification with CCS:** TRL 4-5
Electrolysis: *Proton exchange membrane (PEM)*	- TRL 9
Electrolysis: *Alkaline electrolysis (AE)*	- TRL 9
Electrolysis: *Solid oxide electrolysis (SOE)*	- TRL 7-8
Electrolysis: *Other*	- TRL 2-7 - **Anion exchange membrane:** TRL 7 - **Seawater:** TRL5 - **Alkaline capillary-fed electrolysis:** TRL 5-6 - **Wastewater:** TRL 4 - **Carbon and hydrocarbon-assisted electrolysis**: TRL 2-3
Fossil fuel conversion with CCS (SMR or coal gasification)	- TRL 4-9 - **Coal gasification:** High capture rate, TRL 5 | Partial capture rate, TRL 9/CRI 2 - **Steam methane reforming:** Electric powered, TRL 4 | Sorption enhanced with CCS, TRL 4 - **Chemical looping:** TRL 4
Natural hydrogen production	- TRL 5
Photochemical & photocatalytic water splitting	- TRL 4-5 - **Photocatalytic water splitting**: TRL 4-5 - **Photoelectrochemical:** TRL 4
CST thermochemical water splitting	- TRL 4

Abatement potential

Key information – Abatement potential

The abatement potential criterion identifies technologies that are meet or exceed a nominated abatement threshold. Emissions estimates reflect full fuel cycle emissions, including:

- Scope 1 (direct) emissions: arising from the direct use of a technology from the combustion or use of its fuel, including fugitives in some instances.
- Scope 2 (indirect) emissions: arising the production of a given energy input.
- Some Scope 3 emissions: For biofuels, indirect land-use change (ILUC) have been included for completeness; however, other Scope 3 emissions, such as embodied emissions have been excluded due to a lack of available data and low likelihood of impacting the relative results of the filtering criteria.

For more details, please refer to the *Appendix A.4.*

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[22] See, e.g., table 6: Lanjekar PR, Panwar NL (2024) A Review on Hydrogen Production from Biomass and Commercialization Assessment Through Technology Readiness Levels (TRLs). BioEnergy Research 17:912–931. https://doi.org/10.1007/s12155-023-10697-1

Globally, almost all hydrogen production is synthesised via steam methane reforming (SMR) ('grey' hydrogen). Global estimates of life cycle emissions for the SMR production route from natural gas range between 10-13kg CO_2e/kgH_2.[23]

In Australia, current demand and utilisation of hydrogen is limited, but expected to grow as road and industry offtakers continue to decarbonise their operations. In line with this, the assessment did not compare incoming technologies to conventional fossil-based production systems like SMR. Instead, the technologies were compared against a 'zero emissions' threshold, reflecting the availability of zero emissions technology solutions with significant abatement potential by 2050. This approach aligns with that taken in other supply-side assessments where an absolute threshold is applied in accordance with long term decarbonisation targets, acknowledging that supply-side technology choices largely determine the emissions intensity of downstream energy use. Emissions estimates, in CO_2 equivalents, draw on analysis from the International Energy Association (IEA),[24] which applies the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) methodology. Direct emissions refer to the emissions occurring in the production of hydrogen, and indirect (upstream and midstream) emissions refer to those arising from the production, conversion and transport of required input fuels, such as natural gas or electricity. These results are reported in Table 7, and include the global warming impacts of carbon dioxide, methane and some N_2O impacts.

Upstream N_2O emissions from coal and gas production are understood to be 'relatively small' and 'uncertain' by the source material, leading to their exclusion. Additionally, while literature shows that atmospheric chemical reactions involving leaked hydrogen can change the abundance of certain greenhouse gases, this has not been accounted for in the IEA analysis.[25] This highlights the need to manage hydrogen leaks throughout the entire production pathway (for more detail see Section 4.6).

Under the IPHE methodology, renewable energy from wind, solar PV and hydropower is assumed to produce zero upstream and direct emissions.[26] Therefore, hydrogen production pathways drawing on these inputs were deemed to meet the criteria.

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[23] IEA (2021) Comparison of the emissions intensity of different hydrogen production routes. International Energy Agency. https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021 (accessed 11 December 2024).

[24] IEA (2023) Comparison of the emissions intensity of different hydrogen production routes, 2021. International Energy Agency. https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021 (accessed 11 December 2024); IEA (2023) Towards hydrogen definitions based on their emissions intensity. International Energy Agency. https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf (accessed 11 December 2024).

[25] Sand M, Skeie RB, Sandstad M, Krishnan S, Myhre G, Bryant H, Derwent R, Hauglustaine D, Paulot F, Prather M, Stevenson D (2023) A multi-model assessment of the Global Warming Potential of hydrogen. Communications Earth & Environment 4(1), Article 203. <https://www.nature.com/articles/s43247-023-00857-8.pdf>

[26] IPHE (2023) Hydrogen Production and Delivery: Challenges and Opportunities. International Partnership for Hydrogen and the Fuel Cell, USA. <https://www.iphe.net/_files/ugd/45185a_8f9608847cbe46c88c319a75bb85f436.pdf> (accessed 11 December 2024).

Table 7: Abatement potential (full fuel cycle) – Hydrogen production

■ Meets filter criteria ▨ Meets with caveats □ Does not meet

Technology	Direct	Upstream & midstream			Total	Abatement potential	Source/assumption
		CO$_2$	*CH$_4$*	**Total**			
	gCO$_2$e/kgH$_2$	*gCO$_2$e/kgH$_2$*	*gCO$_2$e/kgH$_2$*		*gCO$_2$e/kgH$_2$*	*Threshold: zero emissions*	
Conventional SMR (Best available)	***9.0***	*0.8*	*1.6*	***2.4***	***13.8***		***IEA (2023)***
Aluminium oxidation	*Assumed zero*				**0.0**	Zero	Assumed recycled Aluminium
Biological hydrogen production	*Assumed zero or negative*				**≤0.0**	Zero or negative	Assumed renewable energy & sustainable feedstocks
Biomass and waste conversion	**0.0**	3.6	0.1	**3.7**	**3.7**	Positive	IEA (2023); forestry residues
Biomass and waste conversion with CCS	**-21.7**	4.1	0.1	**4.2**	**-17.5**	Zero or negative	IEA (2023); forestry residues, 95% CCS capture rate
Electrolysis	**0.0**	0.0	0.0	**0.0**	**0.0**	Zero	Assumed to operate at 60% utilisation to align with 100% VRE generation.[27]
Fossil fuel conversion with CCS 1. SMR (best available) 2. SMR (global median) 3. Coal gasification (best available) 4. Coal gasification (global median)	 **1. 0.7** **2. 0.7** **3. 1.4** **4. 1.4**	 1. 0.7 2. 2.2 3. 0.4 4. 0.4	 1. 0.1 2. 0.8 3. 0.8 4. 1.3	 **1. 0.8** **2. 3.0** **3. 1.2** **4. 1.7**	 **1. 1.5** **2. 3.7** **3. 2.6** **4. 3.1**	Positive	IEA (2023); 93% CCS capture rate
Natural hydrogen production	*Lifecycle emissions are site specific but assumed to be low/negligible*				**<1**	Near zero	IEA (2023)
Photochemical & photocatalytic processes	*Assumed zero*				**0.0**	Zero	Assumed renewable energy
CST thermochemical water splitting	*Assumed zero*				**0.0**	Zero	Assumed renewable energy

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[27] As per Table 5, emissions can be high where renewable electricity is not assumed. For example, 22.7kgCO2/kgH$_2$ from 100% CCGT electricity generation (414gCO$_2$/kWh) and 44.5kgCO$_2$/kgH$_2$ from 100% coal-fired generation (809gCO$_2$/kWh), assuming an 55kWh/kgH$_2$ electrical efficiency. Derived from ACIL Allen Consulting (2016) AEMO Emissions Factors. Australian Energy Market Operator (AEMO). <https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/ntndp/2016/data_sources/acil-allen---aemo-emissions-factors-20160511-pdf-document.pdf?la=en&hash=AB233ACCECC78768D7C236E307433C10>.

Biological hydrogen production

Emissions estimates of biological hydrogen production can be highly variable, largely dictated by biomass sourcing (e.g., feedstock type and cultivation practice), conversion technology, and energy supply.[28]

Algal-based bio-hydrogen production (such as bio photolysis) generally produces net negative life cycle emissions when accounting for the absorption of CO_2 related to algal growth.[29] Bacterial production systems, such as dark fermentation, can achieve carbon neutrality or even negative emissions when utilising waste biomass under anaerobic conditions, effectively diverting organic waste landfill. For systems that require an electricity source (i.e., microbial fermentation production or hydrogen compression systems), life cycle emissions are dependent on the emissions intensity of the energy source. Here, renewable electricity is assumed.

Biomass and waste conversion (/with CCS)

Biomass and waste conversion can meet the criteria only in conjunction with CCS.

The emissions potential of biomass-based hydrogen is highly variable and dependent on the process employed. For biomass and waste conversion processes, conventional gasification and pyrolysis production methods are adapted to draw on biomass feedstocks as an alternative to fossil fuel inputs, such as coal. When biomass is sustainably sourced, the emissions from these processes will be less than their fossil fuel counterpart, as CO_2 absorbed by the biomass feedstock earlier in the carbon cycle offset process emissions. However, these processes are energetically intense and when biomass is not sustainably sources, overall emissions can be large.[30]

Biomass and waste conversion processes can be carbon neutral or net-negative when coupled with CCS, by removing captured biogenic carbon in the biomass from the natural carbon cycle. Novel systems, such as reforming systems that employ electrolytic principles are also being investigated for carbon neutral hydrogen production.[31]

Fossil fuel conversion with CCS

Fossil fuel conversion pathways with CCS do not meet the abatement criteria.

Technology pathways that generate hydrogen from fossil fuel materials (i.e., coal/oil gasification, natural gas pyrolysis, steam methane reforming, autothermal reforming etc) were considered when coupled with CCS. CCS systems are unable to capture the totality of direct emissions for a given process, and therefore these pathways are not considered net-zero. For reference, standalone high capture rate systems (i.e., >90%) are at TRL 5, and partial capture rate systems (i.e., 60%) at TRL 9.[32]

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[28] Borole AP, Greig AL (2019) Chapter 20 - Life-Cycle Assessment and Systems Analysis of Hydrogen Production. In: Biohydrogen (Second Edition): Biomass, Biofuels, Biochemicals, 485–512. https://doi.org/10.1016/B978-0-444-64203-5.00020; Song G, Zhao Q, Shao B, Zhao H, Wang H, Tan W (2023) Life Cycle Assessment of Greenhouse Gas (GHG) and NOx Emissions of Power-to-H2-to-Power Technology Integrated with Hydrogen-Fueled Gas Turbine. Energies 16(2), 977. https://doi.org/10.3390/en16020977

[29] Borole AP, Greig AL (2019) Chapter 20 - Life-Cycle Assessment and Systems Analysis of Hydrogen Production. In: Biohydrogen (Second Edition): Biomass, Biofuels, Biochemicals, 485–512. https://doi.org/10.1016/B978-0-444-64203-5.00020

[30] Royal Society (2018) Green Hydrogen. Royal Society, London. <https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf> (accessed 11 December 2024).

[31] ARENA (2023) Waste Biomass to Renewable Hydrogen. Australian Renewable Energy Agency. <https://arena.gov.au/projects/waste-biomass-to-renewable-hydrogen/> (accessed 11 December 2024).

[32] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

4.4.2 Primary technology analysis

Key information – Primary technology analysis

Two criteria were employed to ensure the suitability and feasibility of each technology for the use case applications determined.

- **Scalability:** Technologies that are able to meet a production capacity of 50t of hydrogen per day.
- **Levelised cost of hydrogen:** Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Scalability

Technologies were assessed based on their suitability for large-scale (>50t/day) hydrogen production by 2050 This scale is reflective of the scale required to meet the demands of high utilisation sectors, through which centralised large-scale production systems will be required to meet commercial needs of transport and heavy industries (such as heavy-duty vehicle refuelling, chemicals production and minerals refining).

While not assessed here, small-scale solutions should be acknowledged for the role that they may play in less demanding applications (including small-scale industry cases or integration with microgrids), distributed production models, and in accelerating progress towards scalable solutions as the hydrogen industry develops. All technologies were deemed to satisfy small-scale production needs (5t/day).

Aluminium oxidation

Aluminium oxidation production does not meet the scalability criteria, given its batch-style production process is unlikely to be suitable for large-scale hydrogen production. In the literature, only small production yields have been achieved of ~5kg per day.[33] Moreover, for this production method to yield carbon neutral hydrogen, synthesis must utilise recovered aluminium which may be subject to supply constraints, particularly at scale. Some sources suggest 8kg of Aluminium is required to produce 1kg of hydrogen.[34]

Biological hydrogen production

Biological hydrogen production does not meet the scalability criteria.

Biological hydrogen production is constrained by process-specific dependencies. Many pathways depend on intricate biological and biochemical mechanisms that require specific microbial strains, targeted feedstocks and precise environmental conditions. These factors introduce complexities that restrict flexibility and increase scalability challenges (such as non-linear scaling patterns). While results are highly variable depending on bioreactor type, feedstock, organisms and process optimisation, small pilot tests have yielded production rates of ~5kgH_2/day (equivalent to 166kWh).[35] Higher production yields have been obtained in

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[33] Amrani MA, Haddad Y, Obeidat F, Ghaleb AM, Mejjaouli S, Rahoma I, Galil MSA, Shameeri M, Alsofi AA, Saif A (2022) Productive and sustainable H2 production from waste aluminum using copper oxides-based graphene nanocatalysts: A techno-economic analysis. Sustainability 14(22), 15256. https://doi.org/10.3390/su142215256

[34] Amrani MA, Haddad Y, Obeidat F, Ghaleb AM, Mejjaouli S, Rahoma I, Galil MSA, Shameeri M, Alsofi AA, Saif A (2022) Productive and sustainable H2 production from waste aluminum using copper oxides-based graphene nanocatalysts: A techno-economic analysis. Sustainability 14(22), 15256. https://doi.org/10.3390/su142215256

[35] Based on a 11m^3 reactor system comprised of sequential ark and photo fermentation hydrogen production from corn stover. Source reports a production rate of 59.7m^3H_2/day, which is converted to kg/day under Normal Temperature and Pressure (NTP) conditions. Zhang Q, Zhange Z, Wang Y, Lee D, Li G, Zhou X, Jiang D, Hu B, Lu C, Li Y, Ge X (2018) Sequential dark and photo fermentation hydrogen production from hydrolyzed corn stover: A pilot test using 11m3 reactor. Bioresource Technology. https://doi.org/10.1016/j.biortech.2018.01.017

laboratories, however, these remain constrained to controlled environments.[36] These trials do not address the broader feasibility of adapting biological processes to meet the designated scalability threshold.

In addition, these pathways rely on biomass material which is considered a supply-limited source, where cost, availability and access will be a factor in deployment. For large scale production, the geographically dispersed nature and variability of resources could make the collection and transport of critical mass challenging.

Biomass and waste conversion with CCS

Biomass and waste conversion processes meet the criteria with caveats.

Like biological production, these pathways rely on biomass material which is supply limited. Though feasible at large scale if sufficient biogenic material is sourced, it should be noted that this pathway does not make the most efficient use of biomass material. Given the carbon content in the feedstock, co-production of carbon-based fuels and chemicals, such as methanol and Fischer-Tropsch products, is generally preferred to make effective use of biogenic carbon content while adding economic value.

Electrolysis

Electrolysis pathways meet the scalability criteria with caveats. Electrolysis pathways require large amounts of electricity to operate. In the near term, the scale of the large-scale (>50t/day) hydrogen production use case may necessitate grid network upgrades and scaled renewable generation capacity to meet hydrogen production demands, however, off-grid hydrogen production may prove more cost competitive in the long-term.[37] Meanwhile, water availability could pose a challenge in arid and water-constrained regions of Australia, whereby regional-specific area studies are required to determine the feasibility of electrolysis developments.

Natural hydrogen production

The scalability of natural hydrogen production meets the criteria with caveats, given it is subject to the discovery and total capacity of geogenic hydrogen deposits.[38] Research estimates by Geoscience Australia suggest that onshore Australia has an estimated natural hydrogen potential ranging from 0.13-4.86 kt of hydrogen per year, at depths up to 1km.[39] However, despite the identification of hydrogen seepage in natural gas samples, no deposits have been confirmed to date. This is primarily attributed to limited and/or restricted exploration efforts.[40]

Photochemical and photocatalytic water splitting

This technology does not meet the criteria. The practicality and feasibility of large-scale photochemical and photocatalytic hydrogen production is not well understood. Current photochemical and catalyst mechanisms

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[36] Ramprakash B, Lindblad P, Eaton-Rye JJ, Incharoensakdi A (2022) Current strategies and future perspectives in biological hydrogen production: A review. Renewable and Sustainable Energy Reviews 168, 112773. https://doi.org/10.1016/j.rser.2022.112773; Sivaranjani R, Veerathai S, Jenifer KJ, Sowmiya K, Rupesh KJ, Sudalai S, Arumugam A (2023) A comprehensive review on biohydrogen production pilot scale reactor technologies: Sustainable development and future prospects. International Journal of Hydrogen Energy 48(62), 23785–23820. https://doi.org/10.1016/j.ijhydene.2023.03.161.

[37] White LV, Fazeli R, Beck FJ, Baldwin KGH, Li C (2023) Implications for cost-competitiveness of misalignment in hydrogen certification: a case study of exports from Australia to the EU. International Journal of Hydrogen Energy 48(73), 27694–27708. <https://doi.org/10.1016/j.ijhydene.2023.04.208>

[38] Boreham CJ, Edwards DS, Czado K, Rollet N, Wang L, van der Wielen S, Champion D, Blewett R, Feitz A, Henson PA (2021) Hydrogen in Australian natural gas: Occurrences, sources and resources. The APPEA Journal 61(1), 163–191. https://doi.org/10.1071/AJ20044

[39] Source reports a production rate of 1.6 to 58 million m^3 H_2 per year, which is converted to tonnes/year under Normal Temperature and Pressure (NTP) conditions.

[40] Boreham CJ, Edwards DS, Czado K, Rollet N, Wang L, van der Wielen S, Champion D, Blewett R, Feitz A, Henson PA (2021) Hydrogen in Australian natural gas: Occurrences, sources and resources. The APPEA Journal 61, 163–191. https://doi.org/10.1071/AJ20044.

produce less than a kilogram of hydrogen per day. While RD&D efforts have the potential to significantly change this[41], current production capacities fail to meet the scalability threshold of over 50tH_2 per day.[42]

CST thermochemical water splitting

Thermochemical hydrogen production is highly scalable and meets the scalability criteria with caveats given its dependency on sufficient land availability for solar installations. The Clean Hydrogen Joint Undertaking (JU) Strategic Research and Innovation Agenda (SRIA) of the European Union suggests current hydrogen production rates of 1.13kg/day/m^2 for a location with direct normal irradiation of 2500kWh/m^2/year.[43] Production rates of 4.11kgH_2/day/m^2 are being targeted.[44]

Broadly, estimates from literature suggest production capacities of up to 100t/day for thermochemical hydrogen production where energy is supplied via CST.[45]

Levelised cost analysis

Key information – Levelised cost analysis

The levelised cost of hydrogen (LCOH_2) was estimated to determine the viability of each technology considered. LCOH_2 is defined as the cost per unit of produced hydrogen ($/kg) over the lifetime of the production facility.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis*.

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from levelised cost analysis are outlined in Figure 7. **Electrolysis, natural hydrogen production and biomass and waste conversion with CCS are projected to be the most cost competitive**, distinguished by a cost differential in LCOH_2 relative to other assessed technologies. Though the levelised costs of high-temperature electrolysis and other (e.g., seawater, wastewater) electrolysis systems were inconclusive due

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[41] Sharma A, Longden T, Catchpole K, Beck FJ (2023) Comparative techno-economic analysis of different PV-assisted direct solar hydrogen generation systems. Energy & Environmental Science 16(10), 4486–4501. <https://pubs.rsc.org/en/content/articlehtml/2023/ee/d3ee01697h>.

[42] Kumar M, Singh NK, Kumar RS, Singh R (2024) Production of green hydrogen through photocatalysis. In Towards Sustainable and Green Hydrogen Production by Photocatalysis: Insights into Design and Development of Efficient Materials (Volume 2). ACS Symposium Series Vol. 1468, Chapter 1, 1–24. https://doi.org/10.1021/bk-2024-1468.ch001

[43] Clean Hydrogen Joint Undertaking (2024) Strategic Research and Innovation Agenda (SRIA): Key performance indicators (KPIs). <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 December 2024).

[44] Clean Hydrogen Joint Undertaking (2024) Strategic Research and Innovation Agenda (SRIA): Key performance indicators (KPIs). <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 December 2024).

[45] Gabriel KS, El-Emam RS, Zamfirescu C (2022) Technoeconomics of large-scale clean hydrogen production – A review. International Journal of Hydrogen Energy 47(72), 30788–30798. https://doi.org/10.1016/j.ijhydene.2021.10.081; Oruc O, Dincer I (2021) Assessing the potential of thermo-chemical water splitting cycles: A bridge towards clean and sustainable hydrogen generation. Fuel 286(Part 2), 119325. https://doi.org/10.1016/j.fuel.2020.119325; Li X, Sun X, Song Q, Yang Z, Wang H, Duan Y (2022) A critical review on integrated system design of solar thermochemical water-splitting cycle for hydrogen production. International Journal of Hydrogen Energy 47(79), 33619–33642. https://doi.org/10.1016/j.ijhydene.2022.07.249; Lee JE, Shafiq I, Hussain M, Lam SS, Rhee GH, Park Y-K (2022) A review on integrated thermochemical hydrogen production from water. International Journal of Hydrogen Energy 47(7), 4346–4356. https://doi.org/10.1016/j.ijhydene.2021.11.065

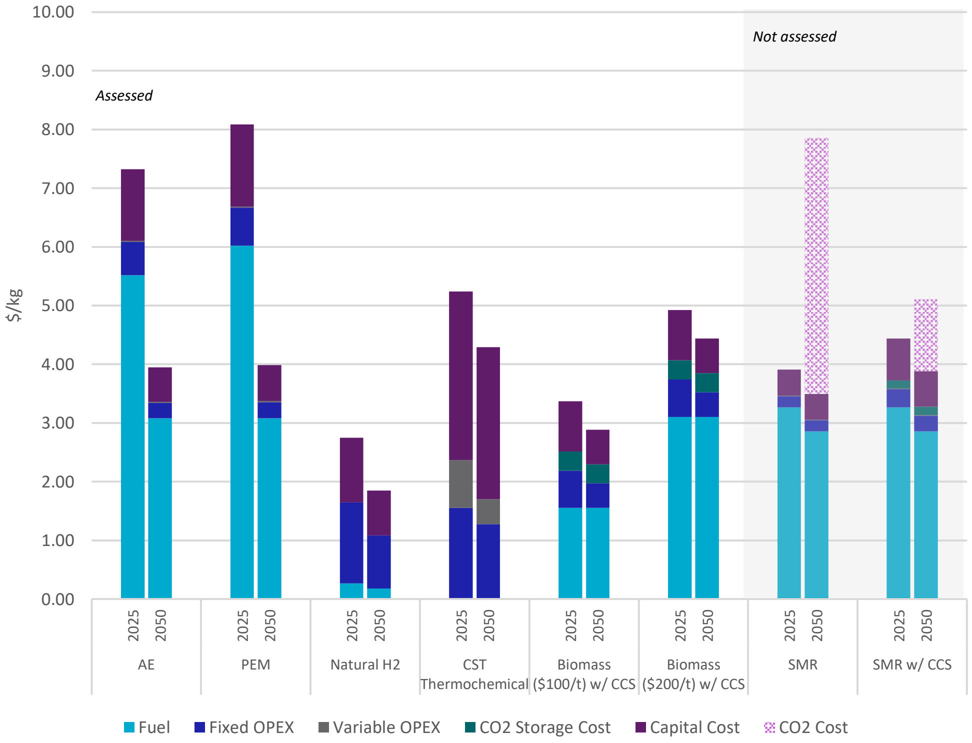
to insufficient data for $LCOH_2$ modelling, these solutions could present cost reduction potential in specific applications. Thermochemical water splitting was not projected to be cost competitive.

As noted above, a CO_2 emission cost is applied to each tonne of emissions produced by a particular technology and contributes to the levelised cost of that technology in the long-term.[46] Further analysis was conducted to quantify the impact of applying the CO_2 emission price as a rebate for negative emissions and is outlined in Box 2. A CO_2 storage cost has also been applied where CCS systems are coupled to the production process.

Refer to the *Technical Appendix: Levelised cost analysis* for detailed cost assumptions. The levelised cost analysis does not consider the pressure of the produced hydrogen, which varies between processes.

Additional technologies included for completeness include SMR (/with CCS). These technologies did not meet the earlier filtering criteria, respectively, with cost analysis conducted for reference only. SMR is included for reference though it is not assessed, given its role as a conventional means of hydrogen production. SMR with CCS did not meet the earlier abatement threshold and also presents high costs relative to alternative low emissions technologies in the long term, once accounting for a carbon price.

Figure 7: Levelised cost of hydrogen ($/kg H_2) – Hydrogen production



Natural hydrogen production

Natural hydrogen is estimated to have the lowest $LCOH_2$ of all assessed technologies, in both 2025 and 2050.

Compared to other production methods, natural hydrogen is subject to high levels of impurities; with other components present in the subsurface gaseous mixture. This analysis is based on the identification of a 650km^2 reservoir with 82%mol hydrogen composition. The remainder of the gaseous mixture is comprised of N_2 (12%), CO_2 (2%) and minor methane, hydrogen sulphide and helium constituents. Levelised costs

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[46] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

include separation membranes and surface processing facilities in order to achieve hydrogen of 99.99% purity.[47]

This solution is location-specific and subject to favourable geological conditions. Further exploration is required to determine its feasibility as a solution in Australia.[48]

Low-temperature electrolysis (PEM, AE)

Low-temperature electrolysis systems present a reliable means of hydrogen production, given the uncertainty surrounding natural hydrogen deposits, and are the next most competitive production solution relative to other assessed technologies.

For low-temperature electrolysis systems, high fuel costs in 2025 make a large contribution to the overall cost of AE and PEM. By 2050, there is a large cost reduction, driven by improvements in electrolyser efficiency and a decrease in electricity prices. Here, electrical efficiencies are assumed to fall from 51kWh/kgH$_2$ (AE) and 56 kWh/kgH$_2$ (PEM) in 2025, to 43 kWh/kgH$_2$ in 2050. Please see *Technical Appendix: Levelised cost analysis* for the assumptions used, including electricity input costs.

Thermochemical water splitting

Thermochemical systems were estimated to have a much higher levelised cost compared to natural hydrogen, biomass and electrolysis, rendering it less competitive than these technologies. This technology does not incur fuel costs, given the hydrogen is produced directly using CST systems. This results in lower estimated costs in the near term compared with electrolysis. However, it is projected to be higher cost than the assessed alternatives in 2050 due to a high capital cost requirement and ongoing costs related to equipment replacement and reaction materials.

Other electrolysis

High-temperature (e.g., SOE) and other (e.g., seawater, wastewater) electrolysis systems were unable to be assessed due to a lack of available information and so cost-competitiveness remains inconclusive. However, these systems present significant cost reduction potential in particular applications through the utilisation of waste streams (e.g., heat, water etc.) and as such, meet the criteria with caveats. Spillover effects from technological advancements in low-temperature electrolysis will likely benefit the development of these other systems. With these factors coalescing, it is likely that these systems could present a pathway for cost-effective hydrogen production in niche applications.

Biomass and waste conversion with CCS

Given the projected cost competitiveness of biomass and waste conversion technologies is highly subject to the cost of biogenic feedstocks, which is in turn influenced by availability and competition, the technology meets the cost criteria with caveats. The overall levelised cost of biomass with CCS is primarily driven by the cost of biomass feedstock, with the technology estimated to be competitive with electrolysis at the $100/tonne price point. The modelled levelised cost of hydrogen production via biomass gasification does not include any credits for the net removal of carbon dioxide that this process could deliver as a co-benefit, which was included as a sensitivity (see Box 2). In a case where feedstock prices are doubled to $200/tonne, production may be less cost effective; though still more viable than conventional SMR production where a carbon price is incorporated.

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[47] Assumptions draw on Musa M, Hosseini T, Sander R, Frery E, Sayyafzadeh M, Haque N, Kinaev N (2024) Techno-economic Assessment of Natural Hydrogen Produced from Subsurface Geologic Accumulations. International Journal of Hydrogen Energy. doi.org/10.1016/j.ijhydene.2024.11.009

[48] Musa M, Hosseini T, Sander R, Frery E, Sayyafzadeh M, Haque N, Kinaev N (2024) Techno-economic Assessment of Natural Hydrogen Produced from Subsurface Geologic Accumulations. International Journal of Hydrogen Energy. doi.org/10.1016/j.ijhydene.2024.11.009

The impacts of carbon removals on hydrogen generation, biomass and waste conversion with CCS is provided in Box 2.

Box 2: Impact of carbon removals on hydrogen generation, biomass and waste conversion with CCS

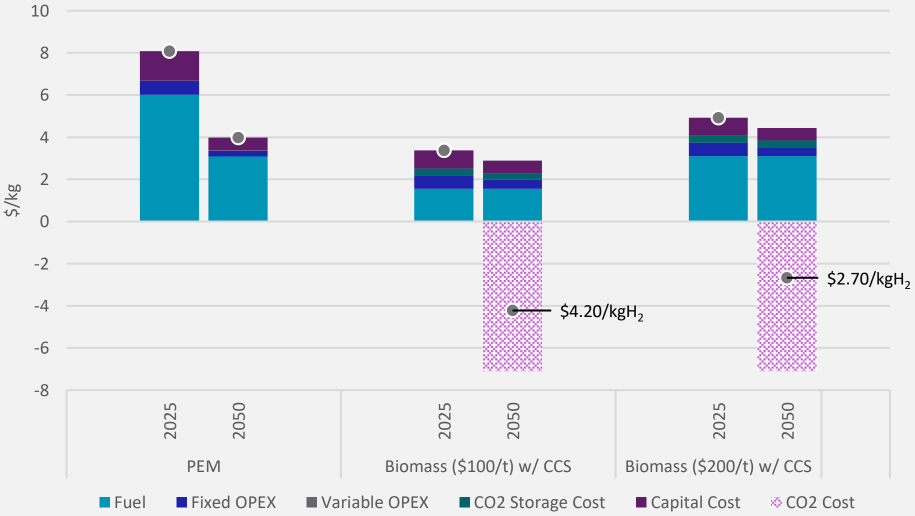
Carbon credits could improve the economics of hydrogen production processes that remove CO_2 from the atmosphere and durably store it. In some cases, this can lead to a negative levelised cost, whereby suppliers could be paid to produce hydrogen.

For example, in a case where hydrogen is produced via biomass gasification with CCS, assuming a **CO_2 price of \$435/tCO_2**[49] and biomass price of \$100/tonne, this would lead to suppliers being paid \$4.20/kgH_2 (see Figure 8). The value of the CO_2 rebate reflects the CO_2 cost that has been applied elsewhere in this analysis for fossil-based, carbon emitting processes.

Note that this outcome is highly sensitive the assumed carbon price and availability and cost of biogenic feedstock, both of which are **highly uncertain**. In a case where the biomass price is \$200/tonne the price paid to hydrogen suppliers would be around \$2.70/kgH_2.

It is likely that the biomass would be better served for use in fuels and chemical applications rather than for production for H_2 alone to maximise use of carbon content.

Figure 8: Levelised cost of hydrogen for biomass with CCS with a carbon credit



4.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

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[49] The CO_2 emissions cost is adapted from the IEA to align with CSIRO modelling specifications: IEA (2023) World Energy Outlook 2023. <https://www.iea.org/reports/world-energy-outlook-2023> (accessed 10 December 2024).

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

The technology analysis framework identified electrolysis, natural hydrogen production and biomass and waste conversion as *Primary technologies* for a large-scale hydrogen production use case (Figure 9).

Although not explored further, the other low emissions technologies evaluated in this report (Table 2) could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the hydrogen production subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

Figure 9: Technology landscape identification – Hydrogen production

Electrolysis	Natural hydrogen production	Biomass and waste conversion
• Low emissions electricity generation • Transmission and storage • Diagnostic systems	• Exploration activities • Proximity modelling • Surface processing infrastructure	• Feedstock pre-treatments • Gas separation

The associated auxiliary technologies and energy efficiency solutions identified for analysis are outlined in Table 8 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

Electrolysis and natural hydrogen production cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 8.

Table 8: Auxiliary technologies – Hydrogen production

Primary Technology	Auxiliary Technology	Description
Electrolysis	**Low emissions electricity generation, transmission and storage**	Systems and networks required for low emissions electricity generation, transmission and storage.
	Diagnostic systems	Systems required for the reliable, efficient and flexible operation of large-scale electrolysis.
Natural hydrogen production	**Exploration techniques and technologies (pre-extraction)**	The various systems and techniques that allow for the monitoring natural hydrogen reservoirs, assisting site analysis and operation.
	Monitoring techniques and technologies	The various systems and techniques that allow for the monitoring natural hydrogen reservoirs, assisting site analysis and operational performance and safety.
	Surface processing facilities (post-extraction)	Systems that assist in the processing and purification of hydrogen gas.
Biomass and waste conversion with CCS	**Feedstock pre-treatments**	Pre-processing of biomass and waste feedstocks to remove inorganic materials and prepare them for thermochemical processing.

	Gas separation	Used to separate out high-purity hydrogen from a gas or syngas mixture.

Energy efficiency solutions

No explicit energy efficiency technologies were identified for hydrogen production; rather, incremental energy efficiency improvements will be a core focus of RD&D efforts across primary and auxiliary technologies.

4.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the identified technology landscape, spanning primary, auxiliary and energy efficiency technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include **non-technical RD&D opportunities.** Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 9. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system.

Table 9: Summary of RD&D opportunities – Hydrogen production[50]

		Electrolysis		Natural hydrogen production
		Electrolysis system		Hydrogen extraction
		Low temperature (LT)	High temperature (HT)	Rotary and percussion drilling methods[51]
Primary technologies	**Commercial**	Proton exchange membrane electrolysis (PEM), alkaline electrolysis (AE), anion exchange membrane (AEM)	-	-
	Mature	-	Solid oxide electrolysis (SOE)	-
	Emerging	Seawater electrolysis, wastewater electrolysis, alkaline capillary-fed	-	
Primary RD&D[52]		• Reduce cost of electrolysis **(LCOH$_2$ forecast: \$3.95/kgH$_2$, cf. \$7.32 (AE), \$8.09 (PEM))** through: - E.g. System cost reductions **(LT: \$360/kW @ 72% efficiency | HT: \$300/kW @ 79% efficiency)** - E.g. Improving system efficiencies **(LT: 72% cf. 61% | HT: 79% cf. 71%)** - E.g. Improving stack durability **(80,000hrs, cf. LT: 40,000hrs | HT: 20,000hrs)**[53] - E.g. System-specific componentry improvements • Validation and scale-up of emerging electrolyser systems		• Explore and evaluate new prospects through: - E.g. Developing exploration strategies, tools and detection techniques (i.e., seepage sensing, geochemical analysis) - E.g. Building understanding of hydrogen-generating conditions and migration pathways • Enhance field appraisal for resource planning and infrastructure development through: - E.g. Developing methods to determine resource life (i.e., subsurface mapping) - E.g. Developing continuous monitoring technologies to detect changes over time and support early identification of risks. - E.g. Modelling proximity and accessibility of end-use applications to hydrogen deposits. • Enhance separation and purification techniques for surface processing and quantify additional revenue that could be captured from co-extracted gases.
Auxiliary RD&D		• Advanced diagnostics to predict and prevent system failures and optimise performance • Establish sufficient low emissions electricity generation, transmission and storage infrastructure (Refer to the *Electricity* technical appendix)		

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cf. – Compare

[50] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

[51] Drilling techniques and gas/hydrogen processing facilities are well-established in operational environments and at commercial readiness, however, the TRL of natural hydrogen extraction remains lower (TRL5) as further exploration and field testing is required to progress to higher maturity.

[52] Target sources: System cost reductions from Graham P, Hayward J, Foster J (2024) GenCost 2023-24: Final report. CSIRO, Australia; Electrical efficiencies converted from kWh/kgH$_2$ using the Lower Heating Value of hydrogen (33.33kWh/kgH$_2$). Electrical efficiencies and durability targets obtained from US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office and European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en; Electrical efficiencies for reference: 46kWh/kgH2, cf. 55 (LT) | 42kWh/kgH2, cf. 47 (HT).

[53] End-of-life is based on 10% voltage loss from beginning-of-life operations, measured at the same current density. Targets are consistent with the following degradation rates: ***High temperature:*** Target assumes 1.6mV/kH (c.f., 6.4mV/kH). ***PEM electrolysis:*** Target assumes 2.0mV/kH (c.f., 4.8mV/kH); ***Alkaline electrolysis:*** Target assumes 2.1mV/kH (c.f., 3.2mV/kH).

Biomass and waste conversion with CCS

Primary technologies

	Thermochemical pathways	Water-gas shift reaction	CCS
Commercial	-	Water-gas shift reaction	Refer to the *Carbon Management* technical appendix
Mature	Gasification, pyrolysis, steam reforming	-	
Emerging	-	-	

Primary RD&D[54]

- Improve catalysts to be cost- and conversion-efficient for efficient hydrogen production
- Innovate on materials to improve technology performance and longevity
  - E.g. Seeking favourable properties such as high thermal stability, oxidation resistance, and creep resistance to prevent deformations from mechanical stress
- Further information on CCS can be found in the *Carbon Management* technical appendix

Auxiliary RD&D

- Reduce cost of feedstocks through improvements in feedstock pre-treatments, e.g.,
  - E.g. Lowering the energy intensity of the treatments (all)
  - E.g. Minimising the necessity for their continuous processing (drying)
  - E.g. Addressing operational drawbacks in continuous reactor systems (carbonisation)
- Enhance the cost-effectiveness, efficiency and performance of gas separation techniques

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[54] Target sources: System cost reductions from Graham P, Hayward J, Foster J (2024) GenCost 2023-24: Final report. CSIRO, Australia; Electrical efficiencies converted from kWh/kgH_2 using the Lower Heating Value of hydrogen (33.33kWh/kgH_2). Electrical efficiencies and durability targets obtained from US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office and European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en; Electrical efficiencies for reference: 46kWh/kgH2, cf. 55 (LT) | 42kWh/kgH2, cf. 47 (HT).

In March 2020, the Energy and Emissions Reduction Minister announced the 'H_2 under $2' stretch target; seeking to produce hydrogen under $2 per kilogram by 2030.[55] More recent levelised cost analysis (2023)[56] estimates electrolysis falling to $1.70-3.33/kg, falling from $5.40-$9.20 for AE and from $6.90-11.10 for PEM. RD&D is required to achieve this cost ambition, while also meeting performance targets.

4.6.1 Electrolysis

Electrolysis is a direct water splitting process where electricity is passed through an electrolyte solution to stimulate the splitting of water into its hydrogen and oxygen constituents. These systems can support small-scale distributed hydrogen production to large-scale centralised production facilities. This modularity can decrease initial installation costs, while allowing large-scale production to take advantage of economies of scale.

Primary technologies

RD&D is essential for the development of cost-effective electrolysis systems that can affordably produce hydrogen by contributing to efforts to reduce system and input costs.

Cost reductions forecasting $3.95 per kg of hydrogen (c.f., $7.32 for AE and $8.09 for PEM) have been calculated for electrolysis, significantly improving the economics for offtakers. Electrolysis costs are largely driven by the cost of electricity, which can be addressed by innovations in electricity generation (see the *Electricity* technical appendix), and to a lesser extent, the cost of the electrolysis unit.

Cost targets for electrolyser units have been identified from the US Department of Energy (DOE) aligning to the efficiency targets set out in Table 11. These targets should be viewed as aspirational targets to achieve cost-competitiveness, reflective of high-volume manufacturing, rather than a cost forecast. However, it is useful in indicating the scale of cost reductions needed. These are:[57]

I. $230/kW for low-temperature systems, at 72% efficiency target (low heating value (LHV)), and

II. $300/kW for high temperature systems, at 79% efficiency target (LHV)

Cost reductions could be achieved by improving technical performance characteristics; namely, system and electrical efficiencies and componentry improvements.

There are several strategies that can contribute toward reducing capital and operational cost, including minimising the costs of system-specific components and improving stack durability to extend system lifespan. A number of notable system-specific componentry improvements have been identified by the DOE, to reduce costs and improve performance for low-temperature electrolysis. These are provided in Table 10.[58]

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[55] Department of Industry, Science, and Resources (2020) Technology Investment Roadmap: Discussion Paper. Australian Government. <https://storage.googleapis.com/converlens-au-industry/industry/p/prj1a47c947e19c97e172db4/public_assets/technology-investment-roadmap-discussion-paper.pdf> (accessed 11 December 2024).

[56] Unpublished CSIRO analysis. Whereby cost curves were generated for AE and PEM electrolysis by calculating $LCOH_2$ values in 1-year increments over the period 2025–2050. It does not include tax, depreciation, profit or other financial parameters.
U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office (2024) Hydrogen Production Multi-Year Program Plan. U.S. Department of Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-hydrogen-production.pdf> (accessed 11 December 2024). Cost targets are converted from USD to AUD with a conversion rate of 1AUD=0.6591USD, representing the annual average exchange rate from Feb 2023-Feb 2024.

[58] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office (2024) Hydrogen Production Multi-Year Program Plan. U.S. Department of Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-hydrogen-production.pdf> (accessed 11 December 2024); U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (n.d.) Technical Targets for Proton Exchange Membrane Electrolysis. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis> (accessed 11 December 2024); Vincent I, Bessarabov D (2018) Low cost hydrogen production by anion exchange membrane electrolysis: A review. Renewable and Sustainable Energy Reviews 81(2), 1690–1704. https://doi.org/10.1016/j.rser.2017.05.258; Khan MA, Al-Attas T, Roy S, Rahman MM, Ghaffour N, Thangadurai V, Larter S, Hu J, Ajayan PM, Kibria MG (2021) Seawater electrolysis for hydrogen production: a solution looking for a problem? Energy & Environmental Science 9, 1234–1250. https://doi.org/10.1039/D1EE00870F

Table 10: Example system-specific componentry improvements for low-temperature electrolysis

System-specific componentry improvements	Targeted electrolyser system
Optimising membrane systems that are low-cost, robust and more amenable to scalable manufacturing processes	PEM, AEM
Reducing dependence on platinum group metals (PGMs) by developing advanced catalysts and electrode materials, while maintaining high activity. The US DOE has set a Platinum group metal content target of 0.125mg/cm^2 across both electrodes.[59]	PEM, AEM, AE
Improving ion conductivity and enhance membrane-electrode assemblies to minimise degradation and improve efficiency	PEM, AEM
Optimising cell designs and dynamic operation performance	AE, PEM
Addressing long-term component stability by mitigating contaminants and impurities such as salt precipitation and particulate contamination	Seawater and wastewater electrolysis

Componentry advancements could also support efficiency improvements. For example, obtaining higher current densities at lower cell voltages can reduce electrical energy requirements and lower electricity consumption and OPEX costs, allowing for more hydrogen to be produced from the electrolyser stack (increasing hydrogen output per unit of capital).[60] Electrical efficiency targets have been identified for low and high temperature systems, from the US DOE's Hydrogen and Fuel Cell Technologies Office Multi Year Program Plan. These have been converted to system efficiencies using both the LHV and higher heating value (HHV) of hydrogen, Table 11.

Table 11: Electrolysis efficiency targets – Hydrogen production

	Electrical efficiencies *kWh/kgH$_2$*	**Efficiency (LHV)**[61]	**Efficiency (HHV)**[62]
Low temperature			
Target	**46**	**72%**	**86%**
Current	*55*	*61%*	*72%*
High temperature			
Target	***42***	***79%***	***94%***
Current	*47*	*71%*	*84%*

RD&D could assist in evaluating and realising the potential of bespoke, emerging electrolysis systems for efficient hydrogen production in specialised applications.

Beyond established electrolysis systems, several emerging technologies remain at lower maturity,[63] with RD&D focused on scaling up, improving efficiencies and reducing operational costs.

Some novel systems are being designed to operate with alternate water sources, offering potential advantages in water-stressed environments. These approaches face technical challenges related to feedstock variability, corrosion and membrane fouling, demonstrating need for continued research into selective membranes, pretreatment processes and system durability. High-temperature electrolysers, such as SOE, can achieve higher efficiencies by utilising waste heat to reduce electrical energy demand. While their

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[59] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office (2024) Hydrogen Production Multi-Year Program Plan. U.S. Department of Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-hydrogen-production.pdf> (accessed 11 December 2024).

[60] U.S. Department of Energy, Vehicle Technologies Office (2024) U.S. DRIVE Hydrogen Production Technical Team Roadmap. U.S. Department of Energy. <https://www.energy.gov/eere/vehicles/articles/us-drive-hydrogen-production-technical-team-roadmap> (accessed 10 January 2025).

[61] 33.33 kWh/kgH$_2$

[62] 39.39 kWh/kgH$_2$

[63] Wastewater electrolysis, TRL 4, and seawater electrolysis, TRL 5.

compatibility industrial processes could be advantageous, current operating temperatures (500-900°C) limit integration with lower-grade heat sources and present material durability challenges under thermal cycling. Similarly, RD&D centring on reducing operating temperatures, improving thermal integration and load cycling with intermittent electricity generation,[64] and developing robust, heat-resistant materials to improve lifetime duration could improve these outcomes.[65]

Auxiliary technologies

Advanced diagnostics and operational flexibility can support more responsive, resilient electrolyser systems that are able to integrate variable renewable energy (VRE) electricity generation.

Advanced diagnostic and monitoring tools can improve electrolyser performance, reliability and maintenance planning. Areas of interest may include enabling flexible operation strategies to align with variability of renewable energy sources, and developing advanced diagnostics to predict and prevent system failures. These tools can support fault detection, optimise efficiency under dynamic load, and extend system lifetimes.

The feasibility and viability of electrolysis hydrogen production will be heavily influenced by the availability of low-cost electricity (including generation, transmission and storage).

The cost of electricity is the highest cost component for electrolysis hydrogen production, and as such, innovations that reduce electricity costs will also contribute to lower hydrogen costs. For detailed targets and RD&D opportunities related to the electricity system, refer to the *Electricity* technical appendix.

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[64] International Energy Agency (2024) ETP Clean Energy Technology Guide. International Energy Agency. <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide> (accessed 10 January 2025); U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office (2024) Hydrogen Production Multi-Year Program Plan. U.S. Department of Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-hydrogen-production.pdf> (accessed 10 January 2025).

[65] For example, Ni-coarsening and Cr-poisoning degradation mechanisms.

4.6.2 Natural hydrogen production

Natural hydrogen, or geogenic hydrogen, can be found in underground deposits. Accumulations of natural hydrogen has been discovered in several locations around the world including in Mali, Russia, France, Brazil and the United States.[66] The most advanced case of natural hydrogen production in Mali (Africa), was discovered in 1987 during water drilling. The site has been supplying hydrogen to generate electricity for a nearby village since 2012.[67] These discoveries have identified that natural hydrogen fields can form through geological processes, however, the potential mechanisms that lead to their formation are still being investigated.

Australia's endowment in mineral and natural gas reserves provides an advantage and foundation for abiogenic hydrogen potential in geological reservoirs. In Australia, seeps of natural hydrogen were identified in the Northern Territory in 2021.[68] In addition, hydrogen concentrations analysed in natural gas samples are at low to trace levels (<0.01 mol%); however, a few samples with very high hydrogen contents have been found (>10 mol%).[69] Recognising this, some Australian states have amended their petroleum exploration licences to include natural hydrogen.[70]

Primary technologies

Extraction methods are technically feasible. Instead, natural hydrogen production requires RD&D efforts to improve our understanding of natural hydrogen prospectivity and explore new approaches to field development (see Auxiliary technologies).

Natural hydrogen extraction draws on well-established techniques from the oil and gas industry, and benefits from long-standing extraction experience at the Bourakebougou hydrogen field in Mali. Extraction is achieved by modifying conventional drilling rigs to penetrate rock layers, with hydrogen transported through pipelines installed in the perforated rock, using reservoir pressure.[71]

While the extraction process itself is considered technically mature, the maturity of natural hydrogen is considered much lower (TRL 5), primarily due to limited geological data and a lack of confirmed deposits for further demonstration. In Australia, this is challenged by absent or prohibitive regulation for further exploration and extraction (i.e., regulatory barriers, cost etc). RD&D that could assist in improving the identification, characterisation and long-term monitoring of natural hydrogen reserves are discussed as Auxiliary technologies, below.

Auxiliary technologies

The development of new exploration tools, detection techniques, and understanding of hydrogen-generating conditions can support the evaluation of new prospects.

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[66] Gaucher E, et al. (2023) The place of natural hydrogen in the energy transition: A position paper. European Geologist, 5–9. 10.5281/zenodo.8108239

[67] Maiga O, Deville E, Laval J, Prinzhofer A, Diallo AB (2023) Characterization of the spontaneously recharging natural hydrogen reservoirs of Bourakebougou in Mali. Scientific Reports 13, 11876. https://doi.org/10.1038/s41598-023-38977-y

[68] Frery E, Langhi L, Maison M, Moretti I (2021) Natural hydrogen seeps identified in the North Perth Basin, Western Australia. International Journal of Hydrogen Energy 46(61), 31158–31173. https://doi.org/10.1016/j.ijhydene.2021.07.023

[69] The period of time extending from about 4.6 billion years ago (the point at which Earth began to form) to the beginning of the Cambrian Period, 541 million years ago. Boreham CJ, Edwards DS, Czado K, Rollet N, Wang L, van der Wielen S, Champion D, Blewett R, Feitz A, Henson PA (2021) Hydrogen in Australian natural gas: Occurrences, sources and resources. The APPEA Journal 61(1), 163–191. https://doi.org/10.1071/AJ20044

[70] Geoscience Australia (2024) Australia's hydrogen production potential. <https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen/australias-hydrogen-production-potential> (accessed 13 December 2024).

[71] Blay-Roger R, Bach W, Bobadilla LF, Ramirez Reina T, Odriozola JA, Amils R, Blay V (2024) Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. Renewable and Sustainable Energy Reviews 189(A), 113888. https://doi.org/10.1016/j.rser.2023.113888

Although natural hydrogen extraction itself does not pose signification technical challenges, successful field discovery could be assisted by developing a range of auxiliary systems required for exploration and characterisation. RD&D could advance exploration strategies that account for subsurface migration pathways and trapping mechanisms unique to hydrogen, as well as to improve detection methods such as seepage sensing and geochemical analysis. These efforts would be further supported by deeper understanding of the geochemical geological conditions that favour hydrogen generation and accumulation, and the mechanics and kinetics of production.

Undertaking efforts to understand the sustainability of deposits and their proximity to end use applications is important for effective for resource planning and infrastructure development.

Where accumulations are identified, assessing the field size and potential lifetime is essential for informing field development strategies. There are opportunities to develop methods to determine the operational life of geogenic deposits (i.e., subsurface mapping). Complementary to this is the development of continuous monitoring technologies - such as in-situ gas sampling, pressure management systems, and multi-gas sensors - which can improve reservoir characterisation, detect compositional changes over time, and support early identification of geochemical or operational risks.

In parallel, systems modelling or other tools could be adopted to evaluate proximity and accessibility to end use applications to guide infrastructure planning and optimise integration with downstream hydrogen demand.

RD&D could enhance separation and purification technologies for natural hydrogen, helping to address efficiency losses and unlock potential value from co-extracted gases.

Natural hydrogen contains a number of impurities, such as nitrogen, methane, unreacted CO_2, and moisture which may introduce further contaminants or lead to additional geological side reactions. Unlike methods that produce hydrogen with low levels of impurities (i.e., electrolysis), surface processing facilities are required to purify the gas stream. While commercial hydrogen purification systems exist, energy and cost inefficiencies are amplified for large scale production. This creates imperative to improve process performance by increasing energy efficiency, reliability and scalability outcomes.[72]

Technoeconomic studies can also help identify potential value streams from co-extracted gases, improving the commercial viability of natural hydrogen projects.[73] Further detail regarding large-scale purification is provided in *Underground hydrogen storage* (UHS).

4.6.3 Biomass and waste conversion with CCS

Biomass and waste conversion involves the thermochemical processing of organic materials. Biomass (agricultural residues, wood chips, and algae) and waste feedstocks (municipal solid waste, industrial by-products) are typically pre-processed to remove inorganics. Once pre-processed, these solid feedstocks can be converted into gaseous products through various thermochemical pathways, including gasification, pyrolysis, and steam reforming.[74] Impurities are removed as necessary, and the hydrogen content is increased using the water-gas shift reaction or additional reforming. High-purity hydrogen is then separated

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[72] Yousefi Rizi HA, Shin D (2022) Green Hydrogen Production Technologies from Ammonia Cracking. Energies 15(21), 8246. https://doi.org/10.3390/en15218246

[73] Blay-Roger R, Bach W, Bobadilla LF, Ramirez Reina T, Odriozola JA, Amils R, Blay V (2024) Natural hydrogen in the energy transition: Fundamentals, promise, and enigmas. Renewable and Sustainable Energy Reviews 189(A), 113888. https://doi.org/10.1016/j.rser.2023.113888

[74] Huang S, Duan W, Jin Z, Yi S, Lv Q, Jiang X (2025) Progress in carbon capture and impurities removal for high purity hydrogen production from biomass thermochemical conversion. Carbon Capture Science & Technology 14:100345. https://doi.org/10.1016/j.ccst.2024.100345

from the gas or syngas using techniques like pressure swing adsorption or membrane separation.[75] These processes are coupled with CCS, to capture direct process emissions; further information on CCS can be found in the *Carbon Management* technical appendix.

Primary technologies

Improving the efficiency of thermochemical conversion pathways and the water-gas shift reaction can improve the economics of hydrogen production.

Catalysts play a crucial role in various thermochemical conversion pathways, such as gasification and pyrolysis. Current catalysts, such as those using nickel or noble metals, can be expensive, inefficient, and/or experience carbon deposition and sintering, producing byproducts like tar and char that affect durability and performance by reducing the active surface area.[76] To address these challenges, RD&D endeavours are exploring catalyst composition that facilitate a high dispersion state of metal particles. These efforts incorporate the use of supporting and promoting components to reduce byproduct formation and enhance regeneration capabilities, optimising yield potential and advancing hydrogen conversion processes. Promising catalysts include coal bottom ash for biomass steam gasification,[77] and biochar for biomass pyrolysis-catalytic steam reforming.[78]

Enhancing catalyst efficiency and durability are also crucial to optimising and reducing the costs of the water-gas shift reaction. RD&D efforts for water-gas shift reaction catalysts largely aim to improve their resistance to sintering and carbon deposition, while refining the environmental conditions required for catalytic and non-catalytic processes.[79]

Materials innovations and other cross-cutting RD&D can improve technical performance characteristics and durability across all biomass and waste conversion pathways.

Most pathways require extreme, variable conditions that can be corrosive. For example, gasification, pyrolysis and steam reforming all operate at high temperatures (often exceeding 700°C), but differ in specific thermal and chemical environments.[80] These processes can involve the production of abrasive ashes and tars, and are generally more corrosive than other forms of hydrogen production (e.g. electrolysis).[81] Conventional materials can deteriorate rapidly under these combined thermal, mechanical, and chemical stresses. RD&D can assist in identifying and developing materials for the reactor, catalyst, oxygen carrier, heat carrier, and other apparatuses to preserve technology efficiency over extended periods of life. Favourable properties for these materials include high thermal stability, oxidation resistance, and creep resistance to prevent

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[75] Huang, S.et al (2025) Progress in carbon capture and impurities removal for high purity hydrogen production from biomass thermochemical conversion. *Carbon Capture Science & Technology*, 14, 100345. https://doi.org/10.1016/j.ccst.2024.100345; Dai F, Zhang S, Luo Y, Wang K, Liu Y, Ji X (2023) Recent progress on hydrogen-rich syngas production from coal gasification. Processes 11(6):1765. https://doi.org/10.3390/pr11061765

[76] Aziz M, Darmawan A, Juangsa FB (2021) Hydrogen production from biomasses and wastes: A technological review. International Journal of Hydrogen Energy 46(68):33756-33781. https://doi.org/10.1016/j.ijhydene.2021.07.189; Sher F, Hameed S, Smječanin Omerbegović N, Chupin A, Ul Hai I, Wang B, Teoh YH, Yildiz MJ (2025) Cutting-edge biomass gasification technologies for renewable energy generation and achieving net zero emissions. Energy Conversion and Management 323:119213. https://doi.org/10.1016/j.enconman.2024.119213

[77] Shahbaz M, Yusup S, Inayat A, Patrick DO, Ammar M (2017) The influence of catalysts in biomass steam gasification and catalytic potential of coal bottom ash in biomass steam gasification: A review. Renewable and Sustainable Energy Reviews 73:468-476. https://doi.org/10.1016/j.rser.2017.01.153

[78] Li Y, Williams PT (2025) Catalytic conversion of biomass components and waste biomass for hydrogen/syngas production using biochar catalysts. Biomass and Bioenergy 194:107675. https://doi.org/10.1016/j.biombioe.2025.107675

[79] Aziz M et al. (2021) Hydrogen production from biomasses and wastes: A technological review. International Journal of Hydrogen Energy 46(68):33756-33781. https://doi.org/10.1016/j.ijhydene.2021.07.189; Chen WH, Chen CY (2020) Water gas shift reaction for hydrogen production and carbon dioxide capture: A review. Applied Energy 258:114078. https://doi.org/10.1016/j.apenergy.2019.114078

[80] Zhao X, Zhou H, Sikarwar VS, Zhao M, Park AHA, Fennell PS, Shen L, Fan LS (2017) Biomass-based chemical looping technologies: the good, the bad and the future. Energy & Environmental Science 10(9):1929-1955. https://doi.org/10.1039/C6EE03718F

[81] They have acidification potentials of greater than 25g SO_2/kg H_2 basis. See, e.g., figure 3 in: Dincer I, Acar C (2015) Review and evaluation of hydrogen production methods for better sustainability. International Journal of Hydrogen Energy 40(34):11094-11111. https://doi.org/10.1016/j.ijhydene.2014.12.035

deformations from mechanical stress.[82] Please also refer to the RD&D discussion on *Biomass combustion* for Medium-temperature steam in the *Industry* technical appendix.

Auxiliary technologies

The sustainable supply of cost-effective biomass sources will be a crucial factor in driving the adoption of biomass and waste conversion for hydrogen production.

According to the cost analysis in this report (refer to *Levelised cost analysis*), the production of hydrogen using biomass and waste conversion in 2050 is forecasted to range between $2.81 and $4.32 per kilogram of hydrogen produced, corresponding to feedstocks priced at $100 and $200 per tonne, respectively.[83] While feedstock costs are impacted by market availability and competition, improvements in feedstock pre-treatments, such as drying, shredding and carbonisation, can help reduce costs (see also *Section 7 Biofuels*). Undertaking these treatments can increase energy density and remove moisture from feedstocks, ensuring optimal reactor temperature and enhancing conversion efficiency. RD&D is investigating, for instance, lowering the energy intensity of the treatments (all), minimising the necessity for their continuous processing (drying),[84] and addressing operational drawbacks in continuous reactor systems (carbonisation).[85]

RD&D could enhance the cost-effectiveness, efficiency and performance of gas separation processes to facilitate the production of high-purity hydrogen using biomass and waste conversion.

These processes involve the separation of high-purity hydrogen from gas or syngas generated during biomass and waste conversion, employing techniques such as pressure swing adsorption and membrane separation. Given the energy-intensive nature of these methods, technological advancements are imperative to address operational challenges and optimise functionality.[86] RD&D efforts are concentrating on improving the efficiency of adsorbents, introducing innovations in adsorber design, and refining reaction conditions, including flow rates, purge methodologies, depressurisation, and equalisation. Optimising cycle times is also crucial to achieving greater cost-efficiency and enhancing performance.[87]

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[82] Aziz M et al. (2021) Hydrogen production from biomasses and wastes: A technological review. International Journal of Hydrogen Energy 46(68):33756-33781. https://doi.org/10.1016/j.ijhydene.2021.07.189; Chen WH et al. (2020) Water gas shift reaction for hydrogen production and carbon dioxide capture: A review. Applied Energy 258:114078. https://doi.org/10.1016/j.apenergy.2019.114078

[83] Modelled using forestry residues for biomass gasification.

[84] Liu Y, Aziz M, Fushimi C, Kansha Y, Mochidzuki K, Kaneko S, Tsutsumi A, Yokohama K, Myoyo K, Oura K, Matsuo K, Sawa S, Shinoda K (2012) Exergy Analysis of Biomass Drying Based on Self-Heat Recuperation Technology and Its Application to Industry: a Simulation and Experimental Study. Industrial & Engineering Chemistry Research 51(30):9997-10007. https://doi.org/10.1021/ie2027298

[85] Lohri CR, Rajabu HM, Sweeney DJ, Zurbrügg C (2016) Char fuel production in developing countries – A review of urban biowaste carbonization. Renewable and Sustainable Energy Reviews 59:1514-1530. https://doi.org/10.1016/j.rser.2016.01.088

[86] Huang, S et al. (2025) Progress in carbon capture and impurities removal for high purity hydrogen production from biomass thermochemical conversion. *Carbon Capture Science & Technology*, 14, 100345. https://doi.org/10.1016/j.ccst.2024.100345. Dai F et al. (2023) Recent progress on hydrogen-rich syngas production from coal gasification. Processes 11(6):1765. https://doi.org/10.3390/pr11061765

[87] Sharma SD (2009) FUELS – HYDROGEN PRODUCTION | Gas Cleaning: Pressure Swing Adsorption. In: Encyclopedia of Electrochemical Power Sources, pp 335-349. https://doi.org/10.1016/B978-044452745-5.00307-5; Motola V, Scarlat N, Hurtig O, Buffi M, Georgakaki A, Letout S, Mountraki A, Salvucci R, Schmitz A (2023) *Clean Energy Technology Observatory: Bioenergy in the European Union – 2023 Status Report on Technology Development, Trends, Value Chains and Markets*. Publications Office of the European Union, Luxembourg. <https://publications.jrc.ec.europa.eu/repository/handle/JRC135079> (accessed 12 June 2025).

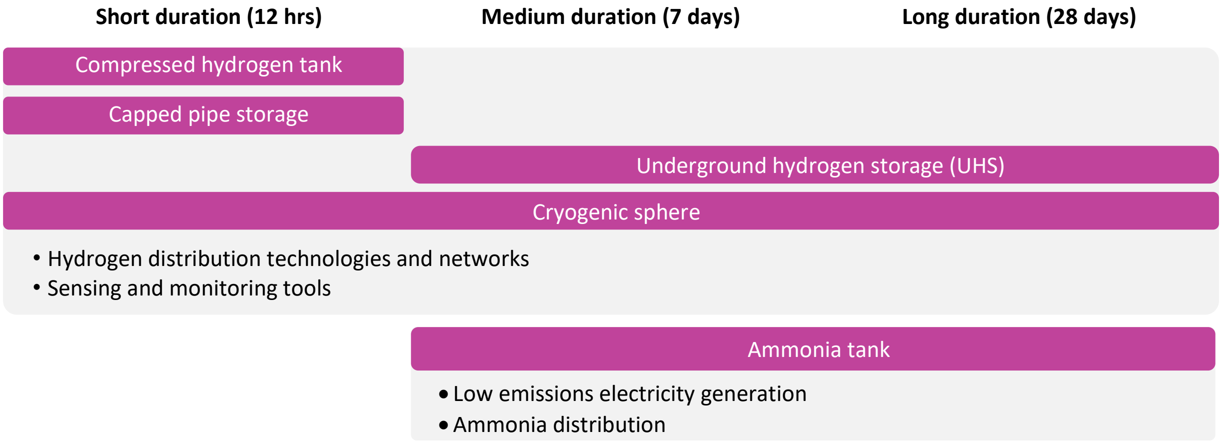
5 Hydrogen storage

5.1 Executive summary

The suitability of hydrogen storage technologies depends on operational parameters and derivative feedstock costs, but targeted RD&D can reduce costs and improve performance across the five explored technologies.

Technology Landscape: Short, medium and long duration hydrogen storage

Hydrogen storage technologies are highly dependent on the required storage duration, number of fill/discharge cycles, and additional costs associated with producing the feedstock or hydrogen derivative. This therefore necessitates a diverse suite of hydrogen storage technologies to accommodate various applications.



Note: Use case durations describe the amount of storage provided, as opposed to duration of storage.

RD&D Opportunities

Compressed hydrogen tank, Capped pipe	• Improvements to the reliability and energy efficiency of compression technologies is a common requirement across gaseous storage systems. • Material and system innovations can be used to extend asset lifetimes and improve safety, increase storage capacity and minimise storage losses.
Underground hydrogen storage	• Further exploration and reservoir characterisation is required alongside the development of sustainable and safe facilities, supported by the development of more appropriate reservoir modelling tools and purification facilities.
Cryogenic sphere	• Cryogenic hydrogen (and ammonia storage) involves an energy intensive hydrogen conditioning process. RD&D to increase storage system efficiencies by improving material durability under cryogenic conditions and minimising hydrogen losses, could improve cost competitiveness and safety performance.
Ammonia tank	• For ammonia tanks and hydrogen derivatives more broadly, there is a need for RD&D to develop and optimise catalysts and reactors for improved synthesis and cracking performance and reduce the raw materials needed in hydrogenation and dehydrogenation reactions.

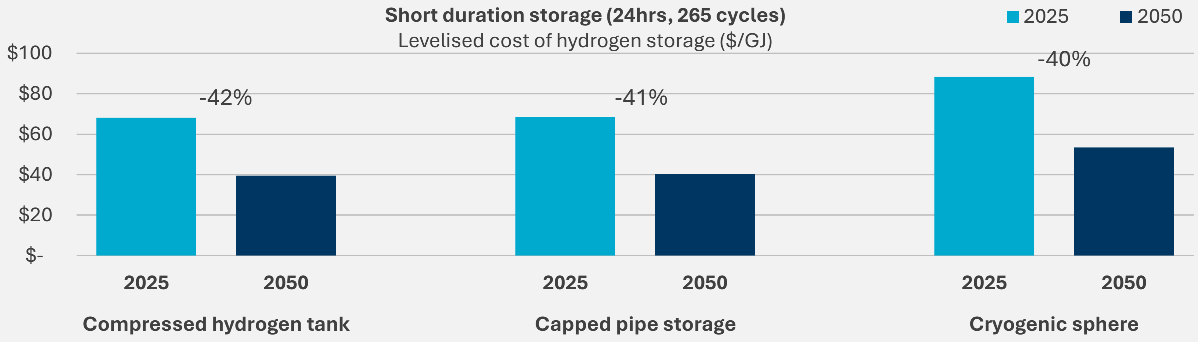
Auxiliary

- To support these technologies, RD&D is required to improve the structural integrity of hydrogen distribution infrastructure, including both gaseous tube trailers and pipelines or liquid trailers or tankers suitable for manoeuvring hydrogen or its derivatives. The use of existing pipelines may warrant blending, which will necessitate developing higher efficiency and lower cost downstream separation technologies.
- Ensuring safe operations and distribution will require the development of real-time, sensitive hydrogen sensors and measurement tools (ppb-level sensitivity).

Levelised cost analysis

Short duration: 24hrs, 265 cycles

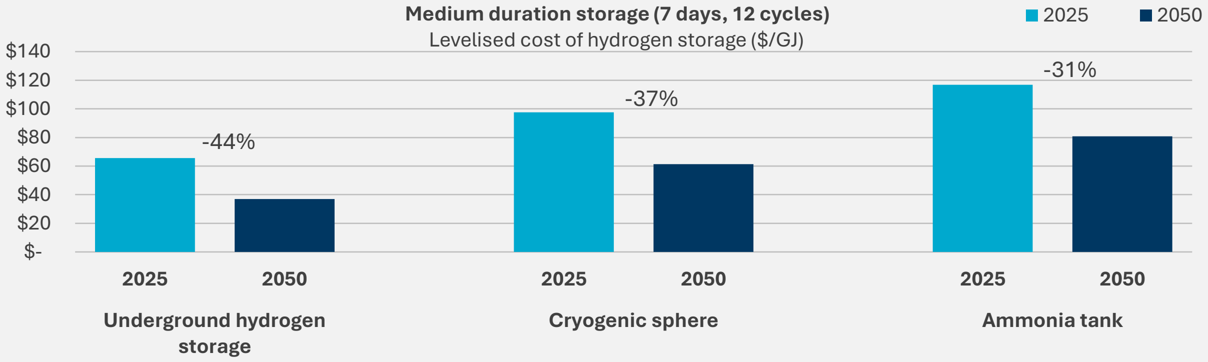
For the specific use case analysed, gaseous storage (compressed hydrogen tanks and capped pipe storage) were estimated to have a lower levelised cost of hydrogen storage when compared with cryogenic spheres, which are impacted by the additional cost of hydrogen liquefaction.



See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

Medium duration: 7 days, 12 cycles

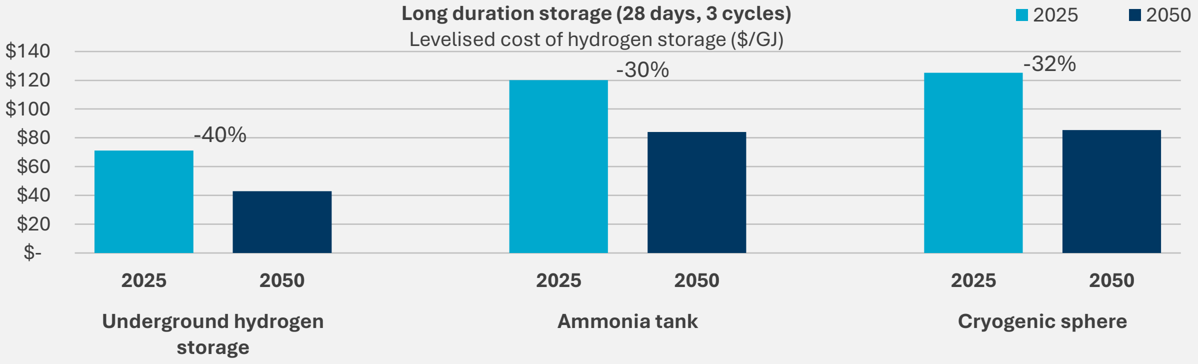
For the specific use case analysed, as a result of lower feedstock and componentry costs, UHS is projected to have the lowest cost of hydrogen storage, when compared with cryogenic spheres and ammonia tanks.



See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

Long duration: 28 days, 3 cycles

For the specific use case analysed, as a result of lower feedstock and componentry costs, UHS is projected to have the lowest cost of hydrogen storage, when compared with ammonia tanks and cryogenic spheres. The energy capital costs of cryogenic hydrogen storage increase with capacity, rendering it less competitive than ammonia tanks for this use case.



See *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions.

5.2 Introduction

Storage infrastructure is essential to enable hydrogen to be produced and stored during periods of low energy demand, then distributed to offtakers during periods of high energy consumption. Hydrogen is today mostly produced and consumed in the same location, without the need for transport infrastructure. As demand increases, the production of low emissions hydrogen in regions with abundant renewable energy resources will become more economically attractive, leading to an increase in transport and storage needs to connect production sites with areas of demand.[88]

While large-scale, stationary storage is the focus of this chapter to align with large scale production systems, small-scale storage systems are also under development, most notably in end use mobility applications such as road transportation.

Hydrogen possesses inherent chemical properties that make its storage challenging. Hydrogen has a low volumetric density at ambient temperatures, necessitating the development of advanced physical storage methods to increase density, often through additional process steps, higher pressures (generally 350-700bar), or cryogenic temperatures (252.8°C).[89] It can also be stored using chemical storage systems, either on the surface of solids (adsorption) or within solids (absorption).[90] In gaseous form, its high diffusivity also introduces embrittlement challenges which limits storage capacity and presents safety concerns.[91]

Regardless of storage mechanism, whether above- or below-ground or gaseous, liquid or carrier form, the largest common challenge is reducing the cost of storage. Research is underway to produce materials that are safe, reliable and cost effective for targeted applications.

Storage solutions are also highly variable and the most cost effective and suitable technology will be dependent on its operational profile (i.e., storage capacity, duration and cycle frequency) in addition to commercial, site, region, and deployment specific factors. Solutions are also highly dependent on other technologies within the hydrogen value chain, and these interdependencies mean that hydrogen storage solutions must be assessed within an integrated supply chain framework, considering factors such as compression, liquefaction, conversion losses, and re-conversion efficiency. These factors lend themselves to the conclusion that a portfolio of storage solutions will be required to create a stable hydrogen industry.

This chapter presents an analysis of low emissions technologies to identify technically feasible and cost competitive solutions that could support Australia's hydrogen storage needs. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

5.2.1 Hydrogen storage use case(s)

To explore low emissions technologies in the hydrogen production subsector, three use cases have been defined, reflecting short, medium and long duration use cases (see Table 12). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with these use cases.

Chemical storage systems can be stored for long durations, with minimal losses if carefully managed. Therefore, the short, medium and long duration use cases are considered a function of storage capacity,

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[88] IEA (2025) Hydrogen. <https://www.iea.org/energy-system/low-emission-fuels/hydrogen> (accessed March 2025)

[89] Office of Energy Efficiency and Renewable Energy (2023) Hydrogen Storage. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-storage> (accessed 10 November 2023).

[90] Office of Energy Efficiency and Renewable Energy (2023) Hydrogen Storage. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-storage> (accessed 10 November 2023).

[91] Meda U, Bhat N, Pandey A, Subramanya K, Raj M (2023) Challenges associated with hydrogen storage systems due to the hydrogen embrittlement of high strength steel. https://doi.org/10.1016/j.ijhydene.2023.01.292

whereby a common daily consumption rate is required to be stored across the three timescales. The storage capacity for each of the three use cases were modelled on the consumption of a moderately-sized ammonia production plant, where 32,000GJ (up to 270t$H_{2\,LHV}$)[92] of hydrogen is required per day (the fill/discharge rate). The short duration use case operates on a daily cycle, with operational profiles for medium and long duration storage adapted to reflect longer drawdown periods for industries requiring multi-week or seasonal hydrogen demand (i.e., fertiliser and/or chemical industries, or seasonal grid balancing).

These use cases are illustrative and presents requirements that technologies must be able to meet in order to service Australia's hydrogen storage subsector. The context in which energy storage is applied will ultimately determine the most competitive and appropriate forms of storage technologies to consider. For example, stakeholders must consider their individual energy needs, alongside technological, commercial, and site, region, and deployment specific factors. In the case of hydrogen (and derivative) storage, the energy stored may serve a dual purpose depending on application, for example both as an energy source and as a chemical feedstock. As such, the selected use cases aim to identify a range of storage technologies suitable for Australia to consider, rather than identifying a single storage technology for a given application.

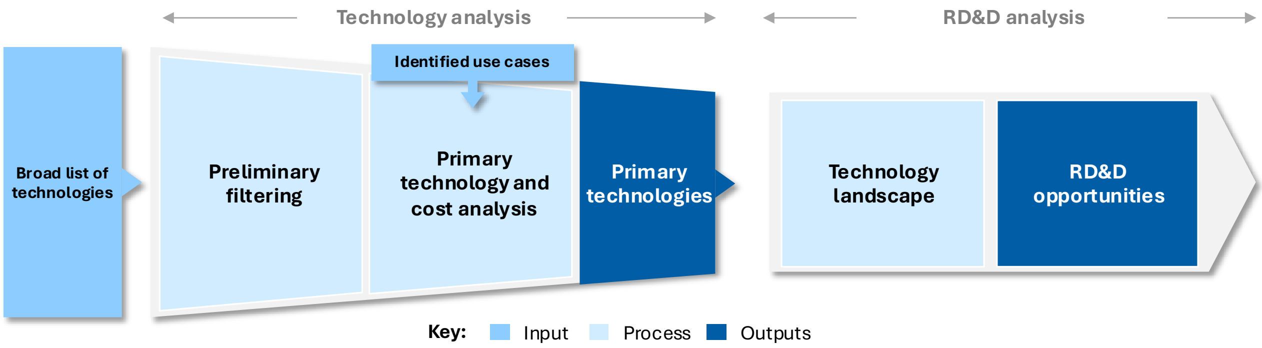
Table 12: Use case(s) – Hydrogen storage

Use case(s)	Short duration (12hours, 365 cycles)	Medium duration (7 days, 12 cycles)	Long duration (28 days, 3 cycles)
Description:	**12hrs of energy storage, discharged 365 times per year.** H_2 is produced at twice the fill/discharge rate. Half of the produced H_2 is immediately discharged for use and the remaining half stored. The stored H_2 is then consumed until the reserve is depleted over next 12hrs, marking one full cycle.	**7 days of energy storage, discharged 12 times per year.** The storage system is filled over a seven-day period. H_2 is depleted as needed over the following three weeks until replenishment is required.	**28 days of energy storage, discharged 3 times per year.** The storage system is filled over a 28-day period. H_2 is depleted as needed over the following three months until replenishment is required.

5.3 Methodology: Hydrogen storage inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to contribute to the decarbonisation of hydrogen (and derivative) storage. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 10).

Figure 10: Technology and RD&D analysis framework for hydrogen storage



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[92] 32,000GJ is equivalent to between 267tH_2 (calculated using the Lower Heating Value) and 226tH_2 (calculated using the Higher Heating Value)

5.3.1 Broad technology list

A broad technology list comprised of 10 technologies was developed (Table 13). These technologies were then passed through two preliminary filters: relevance to Australia and technological maturity. The third common preliminary filter (i.e., abatement potential), was not applied as the storage technologies do not produce direct greenhouse gas emissions; emissions associated with the energy inputs are captured under *Section 4 Hydrogen production*. Lifecycle emissions associated with their manufacture, maintenance and disposal have been excluded from the analysis.

The technologies that satisfied the preliminary filters were then assessed against the filters for the relevant use case(s).

Table 13: Technology category definitions – Hydrogen storage

Technology category	Definition
Compressed hydrogen tank	Hydrogen is compressed at high pressure (up to 800 bar) in steel or carbon fibre tanks.
Underground hydrogen storage (UHS)	Hydrogen is compressed and injected into geological or engineered subsurface structures, including salt caverns, depleted gas fields, aquifers or excavated caverns. Filtering and end-use assessment is based on salt cavern storage.
Capped pipe storage	Pipelines with sealed ends are laid underground and then filled with compressed hydrogen (up to 100 bar). Please note, while a valuable shared hydrogen storage and distribution asset, line packing is identified as an auxiliary technology and therefore has not been assessed as a primary technology system.
Cryogenic sphere	Hydrogen is liquefied and stored in cryogenic spheres at extremely low temperatures (below -253°C) and pressures (2-10 bar), through a multi-stage process of compression and cooling.
Ammonia tank[93]	Hydrogen is stored as liquid e-ammonia in conventional ammonia storage tanks. Various tank types can be adopted depending on storage volume and conditions; most commonly, pressure storage (<1500t NH_3), semi-refrigerated (<3000t NH_3) or low-temperature storage (<50,000t NH_3).
Methanol tank[94]	Hydrogen is stored as liquid e-methanol (CH_3OH) in conventional storage tanks, conventionally constructed from carbon steel or austenitic stainless steel.
Solid hydride	The absorption and desorption of hydrogen by hydride-forming material.
Liquid organic hydrogen carriers (LOHC)	Organic materials that can be reversibly converted between hydrogenated (hydrogen-rich) and dehydrogenated (hydrogen-lean) forms to store and release hydrogen; and are characterised by their liquid state in both forms. LOHCs can be transported and stored at ambient temperature and pressure and hydrogen can be extracted via the application of heat or catalysis.
Proton batteries	A reversible PEM fuel cell that allows solid-state storage and extraction of hydrogen.
Absorbents	The physical adsorption of hydrogen to the surface of a molecule or within pores.

5.3.2 Primary technology filters

Technology assessment involved evaluating the technologies were assessed against two to three filters for hydrogen storage across the three timescales (Table 14). These filters were deemed to be core operational requirements that will enable or limit technology uptake.

The thresholds for these filters were largely dictated by the storage operating profile. For discharge frequency, at least one charging/discharging cycle is required in a 24hr period to meet the daily cycling needs

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[93] Considers the storage of e-ammonia. E-ammonia is produced via electrolytic hydrogen and nitrogen, most commonly via the Haber-Bosch process. Hydrogen is then extracted for use via thermal decomposition and separation process.

[94] Considers the storage of e-methanol. E-methanol is synthesised by the hydrogenation of CO_2 (carbon neutral if obtained from direct air capture (DAC)) with renewable hydrogen. Hydrogen can then be extracted for use via cracking or SMR with CCS.

of the short duration use case. For storage capacity, the scale of energy storage was also dictated by the 32,000GJ/day charging rate and the number of days over which it charged. A land constraint was also imposed for this assessment, aiming to reflect potential land available for hydrogen storage in industrial applications for each storage duration profile.

The lowest cost mitigation technologies able to meet the scale and discharge frequency of storage required, were progressed for further RD&D opportunity analysis. Further details on the selected filters are provided in *Section 5.4.2 Primary technology analysis.*

Table 14: Technology filtering criteria – Hydrogen storage

Subsector	Hydrogen storage		
Use case(s)	**Short duration** **(12hours, 365 cycles)**	**Medium duration** **(7 days, 12 cycles)**	**Long duration** **(28 days, 3 cycles)**
Preliminary filtering criteria	**Relevance to Australia** *Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.* *The criterion identifies constraining factors that may limit or prohibit technology adoption in the Australian context, including geographical constraints, legislation, or incompatibility with key domestic resources.*		
	Technology maturity *Technology has a TRL greater than 3. The TRL index can be found in Appendix A.2.*		
Primary technology analysis	**Storage capacity** *Technologies can store the required amount of energy within a defined surface area. Storage requirements are equivalent to 32,000GJ/day for 0.5, 7 and 28 days, respectively.*		
	Discharge frequency *Technology can meet rapid energy cycling needs (i.e., >1 cycle per 24hrs).*	*Excluded in medium- and long-duration use cases due to their reduced cycle frequency.*	
	Levelised Cost of Storage (LCOS) in 2050 *Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOS relative to other assessed technologies (in $/GJ).*		

5.4 Technology analysis

This chapter outlines the process of identifying primary technologies for hydrogen storage. Following the technology analysis, **compressed hydrogen tanks, underground hydrogen storage (UHS), capped pipe storage, cryogenic spheres and ammonia tanks emerged as primary technologies for further RD&D exploration.** These technologies able to service the designated use cases and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in hydrogen storage, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. The results of the technology analysis for the Hydrogen storage subsector are provided in Table 15.

Table 15: Technology analysis results – Hydrogen storage[95]

■ Meets criteria ▣ Meets with caveats □ Does not meet ★ Primary technology ▨ Not assessed further

	1. Preliminary filtering		2. Primary technology analysis									
			Short duration, cyclical daily draw down (12 hours, 365 annual cycles)				Medium duration (1 week, 12 annual cycles)			Long duration (1 month, 3 annual cycles)		
	Relevance to Australia	Maturity	Storage capacity[96]	Discharge frequency	LCOS (2050)		Storage capacity	LCOS (2050)		Storage capacity	LCOS (2050)	
Pass threshold		*TRL >3*	*System can store up to 133t of H_2 over ≤3,000m^2*	*High cycling frequency[97]*			*System can store up to 1884t of H_2 over ≤5,000m^2*			*System can store 7551t of H_2 over ≤20,000m^2*		
Compressed hydrogen tank	■	■ CRI 6	■	■	■ $40/GJ	★	□	□ $151/GJ	▨	□	□ $494/GJ	▨
Underground hydrogen storage (UHS)	▣ Geo-dependent	▣ TRL 3-9	▣ Geo-dependent	▣ Structural and operational limitations	□ $35/GJ	▨	▣ Geo-dependent	■ $37/GJ	★	▣ Geo-dependent	■ $43/GJ	★
Capped pipe storage	■	■ TRL 9	▣ With vertical storage	■	■ $40/GJ	★	□	□ $247/GJ	▨	□	□ $889/GJ	▨
Cryogenic sphere	■	■ TRL 8-9	■	■	▣ $53/GJ	★	■	▣ $61/GJ	★	□	▣ $85/GJ	★
Ammonia tank (e-ammonia)	■	■ CRI 6	■	▣ Tank optimisation required	□ $80/GJ	▨	■	▣ $81/GJ	★	■	▣ $84/GJ	★
Methanol tank (e-methanol)	■	■ CRI 6	▣	▣ Tank optimisation required	□ $89/GJ	▨	■	□ $93/GJ	▨	■	□ $94/GJ	▨
Solid hydride	■	▣ TRL 1-9	■	■	□ Insufficient data	▨	□	▨	▨	□	▨	▨
Liquid organic hydrogen carriers (LOHC)	■	■ TRL 6-7	■	■	□ Insufficient data	▨	□	▨	▨	□	▨	▨
Proton batteries	■	■ TRL 4	□ Insufficient data	▨	▨	▨	□ Insufficient data	▨	▨	□ Insufficient data	▨	▨
Absorbents	■	□ TRL 2-3	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

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[95] Details for these figures, including sources/assumptions, are found in Table 16 (maturities) and under '*Levelised cost analysis'* and in *Technical Appendix: Levelised cost analysis* (LCOS).

[96] This filter evaluates the ability of each technology to meet the storage capacity of the use cases. The number of units required, and their associated surface area was calculated for each technology option.

[97] Assesses the suitability of hydrogen storage technologies for applications requiring frequent energy cycling on a daily basis (i.e., >1 cycle per 24 hours)

5.4.1 Preliminary filtering

Key information – Preliminary filtering

Two criteria were employed to ensure that the technologies are mature and able to be employed in the Australian context:

- **Relevance to Australia:** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.
- **Technology maturity:** Technology has a TRL greater than 3.

Relevance to Australia

All technologies assessed satisfy this criterion across the designated use cases, as they can be reasonably deployed in the Australian context.

CCS-coupled pathways rely on point-source carbon capture along the production route, which is then permanently stored in deep, geological formations. This requires the identification of subsurface structures that possess acceptable injectivity, capacity and seal (safety) characteristics for permanent CO_2 storage. For further detail, please refer to the *Carbon Management* technical appendix.

Technological maturity

All evaluated technologies were found to meet this criterion, possessing technology types with a TRL greater than 3 (Table 16). Absorbent materials do not meet the criteria (at TRL 2-3), nor do some forms of UHS and hydride storage systems.

Table 16: Technology maturities – Hydrogen storage

Technology	TRL
Compressed hydrogen tank	• CRI 6
Underground hydrogen storage (UHS)	• TRL 3-9 - **Salt cavern:** TRL 8-9 - **Hard rock lined cavern:** TRL 5 - **Depleted hydrocarbon fields:** TRL 4 - **Aquifers:** TRL 3
Capped pipe storage	• TRL 9
Cryogenic sphere	• TRL 8-9
Ammonia tank (e-ammonia)	• CRI 6
Methanol tank (e-methanol)	• CRI 6
Solid hydride	• TRL 1-9 - **Metal hydrides:** TRL 8-9 - **Chemical hydrides:** TRL 5-6 - **Complex hydrides:** TRL 1-3
Liquid organic hydrogen carriers (LOHC)	• TRL 6-7
Proton batteries	• TRL 4
Absorbents	• TRL 2-3

5.4.2 Primary technology analysis

Key information – Primary technology analysis

Three criteria were employed to ensure the suitability and feasibility of each technology across the use case applications:

- **Storage capacity:** Technologies can store the required amount of energy within a defined surface area. Storage requirements are equivalent to 32,000GJ/day for 0.5, 7 and 28 days, respectively.
- **Discharge frequency:** Technologies can meet rapid energy cycling needs (i.e., >1 cycle per 24hrs). Note: applied to the short duration use case only.
- **Levelised cost of storage (LCOS):** Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive.

Storage capacity

This filter evaluates the ability of each technology to meet the storage capacity of each end-use case. The number of units and associated surface area was calculated for each technology option.

The threshold for each use case was determined using a daily storage rate of approximately 32,000GJ/day (270t$H_{2\ LHV}$), representative of demand for a moderately sized ammonia plant. This was scaled to reflect each of the energy storage durations (12hrs, 7 days and 28 days), to give a storage capacity requirement of 16,000GJ (up to 133tH_2), 226,000GJ (up to 1884tH_2) and 906,000GJ (up to 7551tH_2) for short, medium and long duration use cases, respectively. Informed by stakeholder consultation, a land constraint was also applied to each use case, aiming to reflect potential land available for hydrogen/energy storage in industrial applications for each storage duration profile. This resulted in the following thresholds (Table 17).

Table 17: Thresholds – Hydrogen storage, storage capacity

	Threshold[98]
Short	Technology can store up to 133tH_2 over ≤3,000m^2
Medium	Technology can store up to 1884tH_2 over ≤5,000m^2
Long	Technology can store up to 7551tH_2 over ≤15,000m^2

To determine the storage capacity of the technology systems, a 4-step process was used.

1. The unit size of a singular storage was assumed, drawing on literature to identify an upper volume for large-scale hydrogen storage. This was used to calculate the amount of hydrogen energy stored per unit, excluding chemical loss.

$$Energy_{before\ loss}\ (MJ) = ((working\ volume_{unit} \times \rho_{grav.} \times \rho_{vol.})$$

2. The amount of annual chemical losses (such as boil-off and leakage) was accounted for and distributed across the relevant number of cycles to derive a total hydrogen energy storage capacity. Losses of 3% were assumed for UHS systems,[99] and 27.4% for cryogenic sphere (i.e., 0.075% per day).[100] Losses were assumed to be minimal across all other technology types.

$$Energy_{total}\ (MJ) = Energy_{before\ loss} - \frac{Energy_{before\ loss} \times \%\ annual\ loss}{\#\ annual\ cycles}$$

3. Once the total amount of energy per unit of storage was determined, the number of units required to fulfill the storage capacity requirement of each use case was calculated.

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[98] **Short:** 16,000GJ is equivalent to between 113tH_2 (calculated using the Higher Heating Value) and 133tH_2 (calculated using the Lower Heating value). **Medium:** 226,000GJ is equivalent to between 1594tH_2 and 1883tH_2. **Long:** 906,000GJ is equivalent to between 6390tH_2 and 7551tH_2.

[99] Ennis-King J, Michael K, Strand J, Sander R, Green C (2021) Underground storage of hydrogen: Mapping out the options for Australia. Future Fuels CRC. <https://www.futurefuelscrc.com/wp-content/uploads/FutureFuelsCRC_UndergroundHydrogenStorage2021.pdf> (accessed 13 December 2024).

[100] Krenn A, Desenberg D (2019) Return to service of a liquid hydrogen storage sphere. NASA Technical Reports Server (NTRS). <https://ntrs.nasa.gov/api/citations/20190028305/downloads/20190028305.pdf> (accessed 13 December 2024).

$$\#units = \frac{Storage\ capacity\ requirement}{Energy_{total}}$$

4. Once the number of units was determined, the dimensions of the unit was used to calculate the minimum geographical footprint required for storage, excluding buffer room and safety zones. Two equations were used depending on the shape or orientation of the storage vessel.

$$Surface\ area_{vertical}\ (m^2) = \#\ units\ \times Diameter\ (m)^2$$

$$Surface\ area_{horizontal}\ (m^2) = \#\ units\ \times Length\ (m) \times Diameter\ or\ Width\ (m)$$

For the above equations:

- $\boldsymbol{v_{unit}}$ is the assumed maximum volume of a singular containment unit in m^3
- $\boldsymbol{working\ capacity}$ is the relative volume available for hydrogen containment, accounting for, for example, vapour room or cushion gas requirements
- $\boldsymbol{\rho_{grav.}}$ is the gravimetric hydrogen density (i.e., the amount of energy in the hydrogen component of the chemical storage system), in MJ/kg_{H2}
- $\boldsymbol{\rho_{vol.}}$ is the volumetric hydrogen density under temperature and pressure conditions (i.e., the amount of hydrogen per cubic meter of storage), in kg_{H2}/m^3
- $\%\ \boldsymbol{annual\ loss}$ is the amount of hydrogen loss assumed over the course of a year, as a percentage
- $\#\ \boldsymbol{annual\ cycles}$ is the number of annual cycles per use case, to distribute losses on a per cycle basis
- $\boldsymbol{Storage\ capacity\ req.}$ is the amount of energy capacity that is required per each use case.

Assumptions and final figures are provided in Table 18.

Table 18: Hydrogen storage capacity assumptions[101]

■ Meets criteria ▢ Meets with caveats ⬜ Does not meet ▨ Not assessed

	Storage unit assumptions		Energy characteristics		Unit capacity				Short duration	Medium duration	Long duration
	Dimensions	Total volume	Working capacity[102]	Working volume	Energy density	Volumetric energy density		Unit storage capacity	*Can store 133tH_2 over ≤3,000m^2*	*Can store 1884tH_2 of H_2 over ≤5,000m^2*	*Can store 7551tH_2 over ≤15,000m^2*
	m	*m^3*	*%*	*m^3*	*MJ/kgH_2*	*kgH_2/m^3*	*GJ*	*tH_2*			
Compressed hydrogen tank[a]	D=3; L=14.15 (horizontal)	100	100%	100	119.8	23.32 @ 350bar, 25°C	279	2.3	**2,500m^2** (58 units)	**34,400m^2** (811 units)	**137,700m^2** (3244 units)
Underground hydrogen storage[b]	NA	1,000,000	63%	630,730	119.8	9.10 @ 120bar, 25°C	Short: 666,827 Med: 665,215 Long: 661,880	Short: 5,557 Med: 5,544 Long: 5,516	**Minimal m^2 footprint** (15,000m^3, 0.02 units)	**Minimal m^2 footprint** (208,000m^3, 0.3 units)	**Minimal m^2 footprint** (831,000m^3, 1.4 units)
Capped pipe storage[c]	D= 2; L=1000 (horizontal)	3,140	91%	2,860	119.8	2.40 @ 30bar, 25°C 7.67 @ 100bar, 25°C	821	6.8 (30bar) 21.9 (100bar)	**39,400m^2** (20km) **12,300m^2** (6.1km) [**Vertical: <3000m^2**]	**551,700m^2** (275km) **172,400m^2** (86km)	**2,206,900m^2** (1,100km) **689,700m^2** (345km)
Cryogenic sphere[d]	D=21.6; H=21.6	5,300	10%	4,770	119.8	70.85 @ 1 bar, 253°C	Short: 29,382 Med: 28,733 Long: 27,391	Short: 244.8 Med: 239.4 Long: 228.3	**300m^2** (0.6 units)	**3,600m^2** (8 units)	**15,500m^2** (33 units)
Solid hydride[e]	L=2.12; W=1.41; H=1.5	4.5	100%	4.5	119.8	80-160	43-86	0.36-0.72	**1,100m^2** (375 units)	**15,800m^2** (5252 units)	**63,000m^2** (21,006 units)

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[101] Annual losses (i.e., boil-off, leakage) are distributed across number of cycles, and therefore vary across use cases. Chemical losses per year assumed 3% for UHS and 27.4% for cryogenic sphere (0.075% per day). See table endnotes for sources and other assumptions.

[102] Reflects the amount of available 'working room' for hydrogen storage once taking into account vapour room and cushion gas requirements.

Proton batteries			2.23wt%						*Too uncertain (laboratory-scale only)*		
LOHC:[f] Toluene/MCH	D=50.3; H=50.3 (vertical)	100,000	95%	95,000	7.4	47.4	33,253	277.1	**1,200m^2** (0.5 units)	**17,200m^2** (7 units)	**69,000m^2** (27 units)
LOHC: Naphthalene/decalin			97%	97,000	8.7	63.4	53,667	447.3			
LOHC: Benzene/cyclohexane			95%	95,000	8.6	56.1	45,960	383.0			
LOHC: DBT/PDBT			97%	97,000	7.4	56.5	40,690	339.1			
Ammonia tank[g]	D=50; H=40.5 (vertical)	73,300	85%	62,000	21.30	120.92 @ 1 bar, -33.3°C	160,529	1338	**300m^2** (0.1 units)	**3,500m^2** (1.4 units)	**14,100m^2** (5.6units)
Methanol tank[h]	D=52.4; H=86.4 (vertical)	200,000	80%	48,000	15.10	99.54 @ 1 bar, 20°C	240,439	2004	**200m^2** (0.1 units)	**2,600m^2** (0.9 units)	**10,300m^2** (3.8 units)

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[a] **Compressed hydrogen tank:** Tank dimensions align with those employed in cost analysis. Chemical losses from leakage assumed to be negligible.

[b] **UHS.** Total storage volume: Muhammed N S, Haq B, Al Shehri D, Al-Ahmed A, Rahman M M, Zaman E (2022) A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. *Energy Reports* 8, 461-499. https://doi.org/10.1016/j.egyr.2021.12.002; Geoscience Australia (2023) Salt Storage Basins. Geoscience Australia. https://www.entx.com.au/wp-content/uploads/2023/05/Geoscience-Australia-Salt-Storage-Basins.pdf (accessed 10 January 2025). Working capacity: HyUnder Consortium (2016) Overview of All Known Underground Storage Technologies. HyUnder Consortium. <https://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf> (accessed 10 January 2025). Annual losses (i.e., boil-off, leakage) are distributed across number of cycles, and therefore vary across use cases. Chemical losses per year assumed 3% for UHS, Ennis-King et al. (2021) Underground storage of hydrogen: Mapping out the options for Australia. Future Fuels CRC. <https://www.futurefuelscrc.com/wpcontent/uploads/FutureFuelsCRC_UndergroundHydrogenStorage2021.pdf> (accessed 10 January 2025).

[c] **Capped pipe storage:** Total volume was calculated on a per km basis, assuming a 2m pipe diameter. Working capacity: HyUnder Consortium (2016) Overview of All Known Underground Storage Technologies. HyUnder Consortium. <https://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf> (accessed 10 January 2025).

[d] **Cryogenic sphere:** Unit volume and dimensions informed by: NASA (2021) 2021 CEC Virtual Big Tank LH2 DAA Draft. <https://ntrs.nasa.gov/api/citations/20210018293/downloads/2021%20CEC%20Virtual%20Big%20Tank%20LH2%20DAA%20draft%2007JUl2021.docx.pdf> (accessed 10 January 2025); ARENA (2024) Mega-Scale Liquid H2 Storage with Super-Insulated Full Containment and Zero Boil-Off. ARENA. <https://arena.gov.au/projects/mega-scale-liquid-h2-storage-with-super-insulated-full-containment-and-zero-boil-off/> (accessed 10 January 2025). Chemical losses from boil-off are distributed across number of cycles, and therefore vary across use cases. Assumed to be 27.4% for cryogenic sphere or 0.075% per day. Krenn A & Desenberg D (2019) Return to service of a liquid hydrogen storage sphere, Kennedy Space Center. <https://ntrs.nasa.gov/api/citations/20190028305/downloads/20190028305.pdf> (accessed 10 January 2025).

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[e] **Solid hydride:** Unit volume: Oxford Institute for Energy Studies (2023) Hydrogen Storage for a Net-Zero Carbon Future. Oxford Institute for Energy Studies. <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/04/ET23-Hydrogen-storage-for-a-net-zero-carbon-future.pdf> (accessed 10 January 2025). Dimensions calculated by assuming a height of 1.5m and that the W/L ratio is 1.5.

[f] **LOHC:** Unit volume: Oxford Institute for Energy Studies (2023) Hydrogen Storage for a Net-Zero Carbon Future. Oxford Institute for Energy Studies. <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/04/ET23-Hydrogen-storage-for-a-net-zero-carbon-future.pdf> (accessed 10 January 2025); Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM (2021) Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems, and policy options. *Energy Research & Social Science* 80, 102208. https://doi.org/10.1016/j.erss.2021.102208. Highly volatile 'Toluene/MCH' & 'Benzene/cyclohexane' couplets assume a floating roof tank with a 95% working capacity. Less volatile 'Naphthalene/decalin' and 'DBT/PDBT' couplets assume a fixed roof with vapour control, with 97% working capacity. A vertical tank was assumed with a H/D ratio of 1. U.S. Environmental Protection Agency (2006) Chapter 7: Liquid Storage Tanks. *Compilation of Air Pollutant Emission Factors (AP-42)*. U.S. Environmental Protection Agency. <https://www3.epa.gov/ttnchie1/ap42/ch07/final/ch07s01.pdf> (accessed 10 January 2025).

[g] **Ammonia tank:** Unit volume/dimensions: Calculated based on a 50,000t ammonia storage tank, assuming typical storage conditions (ambient pressure, -33°C). International PtX Hub (2024) Ammonia Transport and Storage. International PtX Hub. <https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-transport-and-storage.pdf> (accessed 10 January 2025); McDermott (n.d.) QAFCO Ammonia Storage Tanks. McDermott. <https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks> (accessed 10 January 2025); Oil and Gas Advancement (n.d.) QAFCO Ammonia Storage Tanks Project. Oil and Gas Advancement. <https://www.oilandgasadvancement.com/projects/qafco-ammonia-storage-tanks> (accessed 10 January 2025).

[h] **Methanol tank:** Unit volume: Adheres to API 650 specification, no restrictions to size so long as appropriate engineering principles are adhered to. Large LNG tanks of ~200,000m3 have been constructed. For dimensions, see U.S. Department of Energy (2002) Hydrogen, Fuel Cells, and Infrastructure Technologies Program: Multi-Year Research, Development and Demonstration Plan. U.S. Department of Energy. <http://large.stanford.edu/publications/coal/references/docs/add10896.pdf> (accessed 10 January 2025). For working volume, see Politecnico di Torino (2022) Prediction of Flammable Conditions of a Methanol Storage Tank Using Neural Networks. Politecnico di Torino. <https://webthesis.biblio.polito.it/19882/1/tesi.pdf> (accessed 10 January 2025); AXA XL (2023) Ammonia Hazards: PRC Guideline 7212. AXA XL. <https://axaxl.com/-/media/axaxl/files/pdfs/prc-guidelines/prc-7/prc7212ammoniahazardsv1.pdf?sc_lang=en&hash=F04D14512E8D4A92A3DCE9598CFAFBF8> (accessed 10 January 2025).

Compressed hydrogen tank

The storage capacity of compressed hydrogen tanks heavily depends on the volume and pressure of storage. These parameters make compressed hydrogen tanks a suitable solution for short duration storage where energy requirements are reduced. While a type I vessel can reach up to 500 bar maximum pressure,[103] for industrial applications operating pressures are lower at 200-350 bar. For this reason, a pressure of 350 bar was selected for a storage cylinder with a volume of 100m.[3]

Our analysis determined that 58, 811, and 3244 tanks would be required to fulfill the energy storage requirements of short, medium and long duration storage. For the short duration, the geographical footprint of deploying a storage system of this size falls within the land constrain imposed. Moreover, future advancements in tank materials may allow for higher stationary storage pressures, further reducing surface area requirements.

While storage configurations can be optimised to minimise space requirements, for medium to long duration hydrogen storage, the large geographical footprint required for a storage system of this scale is a constraining factor. For example, at 350 bar, the long-duration use case requires nearly 3250 tanks of standard dimensions, this requires nearly 14Ha of land.[104] Some suppliers are investigating vertical storage solutions to minimise space requirements, which would see surface area requirements fall to 3Ha; however horizontal storage is the industry norm and threshold requirements could still not be met in this example.[105]

Capped pipe storage

Hydrogen pipe storage, in which underground pipes are capped and filled, meets the storage capacity criteria for the short duration use case. The above analysis is performed on a per km basis. A diameter of 2m was used, based on the larger diameter used in natural gas pipe storage projects and in which distribution aspects, such as optimising flow rates, is less imperative.[106]

While pipe storage is an underground storage solution, it was still considered on a surface area basis due to the significant earthworks and soil displacement that would be required to bury the pipe system. Both at 30 and 100 bar for medium and large duration storage, the size of the system is extensive and deemed unfeasible in these applications and unable to meet the criteria. Line packing would be a more suitable approach for the given storage capacity and has been identified as an important auxiliary technology for storage and distribution of hydrogen.

For short duration storage, at 30 bar, 20km of pipe is required (39,000m^2). This falls to 6km (12,300m^2) when the pressure is increased to 100bar. While in both instances the footprint required is greater than the established threshold, land disturbance can be further minimised by efforts to also store the pipes vertically which could make this a practical solution for short duration in the future, depending on application requirements.

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[103] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

[104] 19Ha if accounting for a 35% allowance between tanks.

[105] Calculated assuming a cylindrical storage vessel with a 3m diameter and 14.15m length. Further information on vertical storage solutions can be found here: Wang Y, Kowal J, Leuthold M, Sauer D (2012) Storage system of renewable energy generated hydrogen for chemical industry. Energy Procedia, 29. https://doi.org/10.1016/j.egypro.2012.09.076

[106] HyUnder Consortium (2016) Overview of All Known Underground Storage Technologies. HyUnder Consortium. <https://hyunder.eu/wp-content/uploads/2016/01/D3.1_Overview-of-all-known-underground-storage-technologies.pdf> (accessed 3 January 2025).

Cryogenic sphere

Cryogenic spheres can be scaled to store very large quantities of liquefied hydrogen in a single unit. Due to the higher volumetric energy density of liquefied hydrogen, they enable greater storage capacities with a smaller geographical footprint, compared to aboveground gaseous storage systems. Cryogenic spheres meet the storage capacity criteria for the short and medium duration use cases.

However, at significantly large scales, such as those required for seasonal, long duration storage, the surface area required exceeded the imposed threshold for this filter. Consequently, cryogenic sphere did not meet the criteria for the long duration use case. Beyond this analysis, if sufficient surface area were available for a given application, cryogenic sphere could present a possible technology option.

Liquid organic hydrogen carrier (LOHC)

As the energy output of this storage assessment captures the energy of hydrogen stored, the energy densities used to calculate the total geographical footprint refer to the hydrogen density within the carrier molecule rather than the total density of the molecule itself. This reflects that a significant portion of the working volume within a storage unit will be filled by the other molecular constituents of the LOHC.

Due to this, while LOHCs typically have a relatively high volumetric energy density compared to gaseous hydrogen systems, they are generally less dense than cryogenic hydrogen storage or molecules with a relatively higher portion of hydrogen in their molecular structure (i.e., ammonia and methanol).

These factors align with the results obtained. LOHCs meet the storage capacity criteria for short duration storage, requiring less surface area than gaseous hydrogen storage systems. However, for longer duration storage with higher storage capacity requirements, the resulting surface areas do not fall below the designated threshold.

Solid hydrides

Solid hydrides generally possess a high volumetric hydrogen density; however, unit volumes are small (generally storing between 0.1-20kgH_2).[107] This storage capacity is dependent on the material used, operating conditions and cycling frequency.[108] Consequently, the number of units required for each use case was higher than for other storage systems.

The dimensions of the solid hydride system assumed a simple rectangular prism, with a height of 1.5m[109] and a length to width ratio of 1.5:1. This resulted in a footprint of 1,100m^2, 15,800m^2 and 63,000m^2 across the use cases. Only in the short duration use case did this satisfy the threshold. In the other instances, their small unit volumes limit the feasibility of scaling metal hydride solutions to meet the capacity and duration needs.

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[107] Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM (2021) Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems, and policy options. Energy Research & Social Science 80, 102208. https://doi.org/10.1016/j.erss.2021.102208

[108] Klopčič N, Grimmer I, Winkler F, Sartory M, Trattner A (2023) A review on metal hydride materials for hydrogen storage. Journal of Energy Storage 72, Part B, 108456. https://doi.org/10.1016/j.est.2023.108456; Klopčič N, Grimmer I, Winkler F, Sartory M, Trattner A (2023) A review on metal hydride materials for hydrogen storage. Journal of Energy Storage 72, Part B, 108456. https://doi.org/10.1016/j.est.2023.108456

[109] Similar to the LAVO system, standing 1.68 meters high. Lavo Hydrogen Energy Storage System. Lavo. <https://www.lavo.com.au/> (accessed 3 January 2025).

Proton batteries

Recent developments in proton batteries have seen storage capacities increase to 2.23wt% (i.e., 22.3g H_2 per kg of storage material), which is modest compared to other hydrogen storage solutions.[110] However, only lab scale prototypes, with cells measuring 5cmx5cmx2cm, have been achieved.[111]

Due to this high uncertainty around feasible dimensions and system size requirements, proton batteries were not able to be assessed. Large scale storage needs, across short-, medium- and long- durations, will likely rely on more established solutions; however, proton batteries may be promising for storage of small absolute volumes in the future.

Discharge frequency

A discharge frequency filter was introduced for the short duration use case, due to its rapid cycling operational profile. The filter assesses the suitability of hydrogen storage technologies for applications requiring frequent energy cycling on a daily basis (i.e., >1 cycle per 24hrs). This filter is excluded from the medium- and long-duration end-use cases due to their reduced cycle frequency, at 12 and three annual cycles, respectively. Capped pipe storage, cryogenic spheres, solid hydride and LOHC were found to be functional with high rapid cycling applications.

Pass or pass with caveats criterion was used to indicate that rapid daily cycling needs can be met. Does not meet criterion was used where rapid cycling was expected to be unsuitable for a technology.

UHS

UHS systems, such as salt caverns do not meet the criteria due to both structural and operational limitations. Rapid cycling and frequent filling cycles can induce mechanical stress and fatigue in cavern walls, leading to potential faults and failures over time.[112]

The frequency of daily charging/discharging cycles also presents operational challenges, whereby there is a lack of sufficient downtime to repressurise and recharge the storage system. These processes require longer intervals to maintain cavern integrity and stability.

Ammonia/methanol tank

Ammonia and methanol tank storage meet the criteria with caveats. These storage vessels are typically optimised for long-duration, low-frequency cycling where energy is stored and discharged over extended periods and therefore require optimisation of current designs to be effectively utilised for this storage duration. While possible, higher operational costs, risk of leakage and efficiency losses are exacerbated at higher discharge frequencies and should be addressed before adoption in high-frequency cycling applications.

Levelised cost analysis

Key information – Levelised cost analysis

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[110] Rezaei Niya SM, Heidari S, Andrews J (2022) Enhancement of the performance of a proton battery. *Journal of Power Sources* 543, 231808. https://doi.org/10.1016/j.jpowsour.2022.231808; Huang C, Zhang W, Zheng W (2023) Proton batteries shape the next energy storage. Energy Storage Materials 61, 102913. https://doi.org/10.1016/j.ensm.2023.102913; CSIRO (n.d.) Hydrogen Ion Batteries with High Power and Energy Densities. <https://research.csiro.au/hyresearch/hydrogen-ion-batteries-with-high-power-and-energy-densities/> (accessed 3 January 2025).

[111] Australian Renewable Energy Agency (ARENA) (2022) Proton Flow Reactor System: End of Activity Report. ARENA. <https://arena.gov.au/assets/2022/01/proton-flow-reactor-system-end-of-activity-report.pdf> (accessed 3 January 2025).

[112] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: A review. Geological Society, London, Special Publications 528, 73-86. https://doi.org/10.1144/SP528-2022-88; Masoudi M, Hassanpouryouzband A, Hellevang H, Haszeldine RS (2024) Lined rock caverns: A hydrogen storage solution. Journal of Energy Storage 84, Part B, 110927. https://doi.org/10.1016/j.est.2024.110927

The Levelised Cost of Storage (LCOS) is estimated to determine the viability of each technology considered. LCOS is defined as the per-unit cost of storing hydrogen over the lifetime of the storage system and is measured in terms of the $/GJ of hydrogen output.

Explicit thresholds were not applied for this filter. Technologies were assessed based on cost differentials that distinguish those that are projected to be more cost competitive. Given the difference in methodology and assumptions across technologies, the levelised cost results were used to gauge the relative cost of technologies under specified assumptions, rather than the absolute cost of a particular technology. For more detail on the levelised cost analysis methodology, please refer to the assumptions provided in *Technical Appendix: Levelised cost analysis.*

For reference:

- Some technologies that did not meet earlier filtering criteria have been included for completeness, where information was available – however, these were not assessed.
- Costs are estimated using the projected fuel, operational, capital and integration costs in 2025 and 2050 to understand the potential for shorter-term and longer-term solutions.
- A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, contributing to the levelised cost of that technology in the long-term. No CO_2 emission cost has been assumed for 2025.

Results from levelised cost analysis are outlined in Figure 11 (short duration), Figure 12 (medium duration), and Figure 13 (long duration). The following technologies were projected to be the most cost competitive, distinguished by a cost differential in LCOS, and suggesting areas of promise for further RD&D activity:

- **Short duration:** Compressed hydrogen tanks and capped pipe storage, owing to low costs and optimisation for frequent cycling. While marginally higher cost, cryogenic spheres offer denser energy storage for space constrained areas.
- **Medium duration:** UHS can service longer duration needs through increased storage capacity, and ammonia tanks and cryogenic spheres through increased volumetric density.
- **Long duration:** At longer durations, UHS, ammonia tanks and cryogenic spheres become vastly more competitive relative to other solutions.

For levelised cost analysis, the total capex cost has been broken down into energy capital cost (dependent on the amount of energy stored) and power capital cost (dependent on the rate of energy discharge).

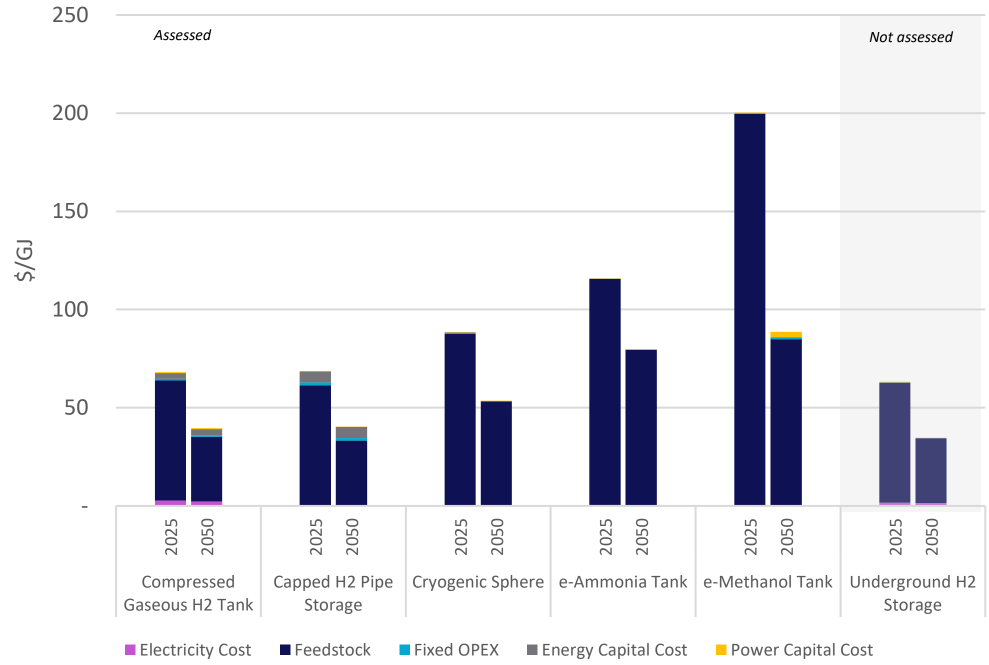
For storage systems that do not use hydrogen as an input, the feedstock cost incorporates the cost of converting hydrogen into these other mediums, such as e-methanol and e-ammonia, and reconversion to hydrogen for use. Hydrogen production costs assume PEM production, ammonia via Haber-Bosch synthesis, and methanol with DAC and renewable hydrogen.

As this assessment considers ammonia and methanol as hydrogen carriers, it does not capture that e-methanol and e-ammonia are higher value products compared to hydrogen, and as such higher costs of production and storage may be tolerated.

Short duration hydrogen storage, cyclical daily draw down

The levelised cost of short duration hydrogen storage is modelled based on a 12-hour storage duration and 365 charging cycles per year (Table 14). The levelised costs of technologies that are considered practical for the short duration use case are shown in Figure 11. While UHS does not meet the discharge frequency criteria for short duration hydrogen storage, it is included for completeness.

Figure 11: Levelised cost of hydrogen storage – Short duration[113]



Gaseous storage (compressed hydrogen tanks and capped pipe storage)

Gaseous storage in compressed hydrogen tanks and capped pipe storage are modelled to have the lowest levelised cost of short duration hydrogen storage in both 2025 and 2050, whilst still meeting storage capacity and discharge frequency requirements. The feedstock cost (i.e. the hydrogen/hydrogen carrier production cost) is the dominant factor in the overall levelised cost for the short-duration end-use case.

Cryogenic spheres

Cryogenic spheres are relatively less cost competitive than the gaseous hydrogen storage counterparts due to the cost of hydrogen liquefaction driving up feedstock costs, but can offer a competitive solution where larger volumes of storage are required. Compared to other storage methods designed to increase storage density, the liquefaction costs are estimated to be lower than the feedstock cost of e-ammonia and e-methanol. As such, cryogenic spheres are projected to be more cost competitive than the hydrogen carrier options at slightly higher cost than small-scale gaseous solutions.

Ammonia and methanol tanks

Ammonia tanks storing e-ammonia are estimated to have a lower levelised cost than methanol tanks storing e-methanol due to the lower cost of ammonia cracking and Haber-Bosch synthesis. Both are significantly more costly than pure gaseous and liquid hydrogen storage and do not meet the cost filter.

Medium duration hydrogen storage

The levelised cost of medium duration hydrogen storage is modelled based on a one-week storage duration and 12 charging cycles per year (Table 14). The levelised costs of technologies that are considered practical for the medium duration use case are shown in Figure 12. While gaseous storage in compressed hydrogen

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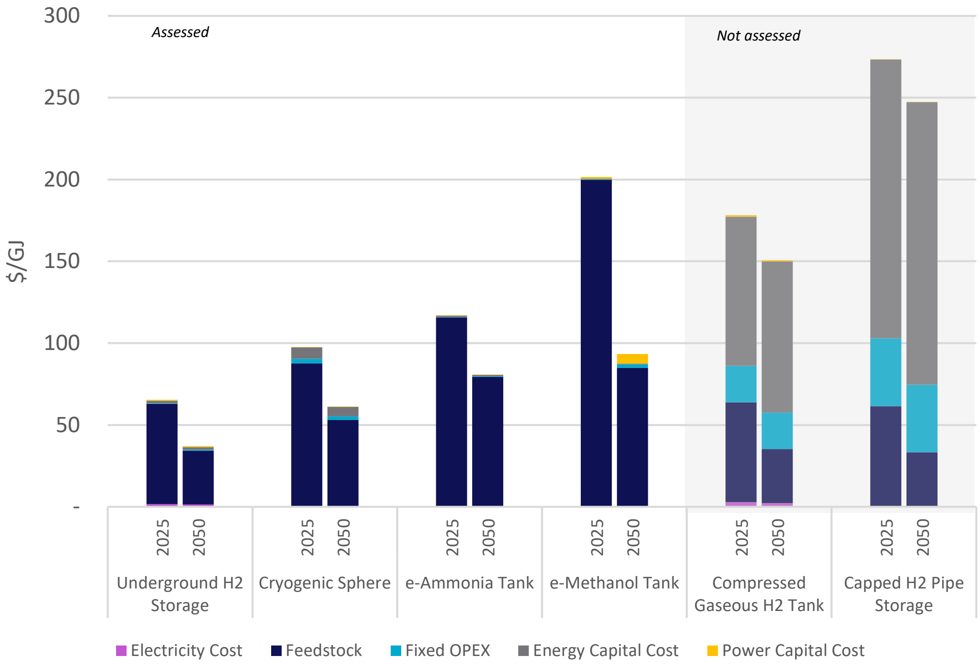
[113] Levelised costs of storage as e-ammonia and e-methanol include the conversion from hydrogen to a hydrogen carrier (either ammonia or methanol), storage as a hydrogen carrier and the conversion back to hydrogen.

tanks and capped pipe storage do not meet the storage capacity criteria for medium duration hydrogen storage, they are included for completeness.

Figure 12: Levelised cost of hydrogen storage – Medium duration[114]



Compressed hydrogen tanks and capped pipe storage do not meet the storage capacity criteria for medium duration storage. Their notably higher energy capital costs and proportional fixed operating costs reflect the challenge of scaling these options to meet the energy requirements imposed by the medium duration use case.

Underground hydrogen storage (UHS)

Owing to a need for larger storage capacity in the medium duration use case, UHS is projected to be the most cost competitive technology in 2025 and 2050. This is driven by its lower feedstock costs and minimal costs across other components.

Cryogenic spheres, ammonia and methanol tanks

Feedstock costs continue to dominate the overall levelised costs of each hydrogen storage option in the medium duration use case. As a result, cryogenic spheres, ammonia tanks (with e-ammonia) and methanol tanks (with e-methanol) have higher levelised costs than in the short-duration use case. Their relative rankings remain the same and is owing to the relative cost of producing the required hydrogen fuel carrier. Cryogenic sphere is estimated to be the lowest cost of these three options, followed by ammonia tank; both are deemed to meet the cost filter, noting that these solutions possess higher capital and operational costs than the hydrogen carrier tank options.

With a cost differential between methanol tanks (with e-methanol) and these lower cost technologies, methanol tanks do not meet the cost filter.

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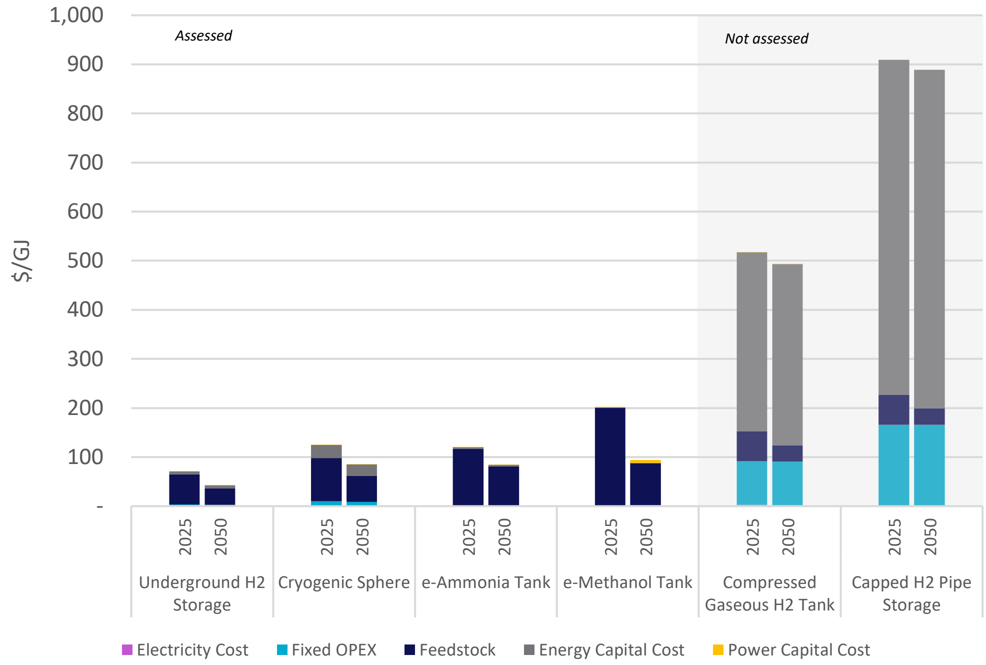
[114] Levelised costs of storage as e-ammonia and e-methanol include the conversion from hydrogen to a hydrogen carrier (either ammonia or methanol), storage as a hydrogen carrier and the conversion back to hydrogen.

Long duration hydrogen storage

The levelised cost of long duration hydrogen storage is modelled based on a 28-day storage duration and three charging cycles per year (Table 14). The levelised costs of technologies that are considered practical for the long duration use case are shown in Figure 13. While gaseous storage in compressed hydrogen tanks and capped pipe storage do not pass the preliminary filtering stage for long duration hydrogen storage, they are included for completeness.

Figure 13: Levelised cost of hydrogen storage – Long duration[115]



Compressed hydrogen tanks and capped pipe storage do not meet earlier filtering criteria. Regardless, the longer duration use case imposes greater energy requirements on each hydrogen storage option. As a result, the levelised costs of gaseous storage options via compressed hydrogen tanks or capped pipe storage are further inflated by higher capital and operating costs. Consequently, the gap between gaseous storage options and all other options is estimated to be even larger in the long duration case.

Underground hydrogen storage (UHS)

UHS is projected to be the most cost competitive hydrogen storage option in both 2025 and 2050 in the long duration end-use case relative to other assessed technologies. At longer durations, its cost competitiveness is driven by its low feedstock costs and its minimal costs across all other components.

Cryogenic spheres

The energy capital costs for cryogenic spheres increase with storage capacity. For the long duration use case, less energy is stored on an annual basis, and therefore each GJ of energy bares a greater portion of the fixed capital and operational costs; increasing the levelised cost of storage. This increase is particularly seen in costs attributed to the energy intensive liquefaction process.

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[115] Levelised costs of storage as e-ammonia and e-methanol include the conversion from hydrogen to a hydrogen carrier (either ammonia or methanol), storage as a hydrogen carrier and the conversion back to hydrogen.

This renders it less cost competitive than ammonia tanks storing e-ammonia, but more cost competitive than methanol tanks storing e-methanol.

Ammonia and methanol tanks

Feedstock costs continue to dominate the overall levelised costs of both hydrogen carriers in the long duration use case. However, the feedstock costs of methanol tanks continue to dominate its levelised cost and is relatively less cost competitive than ammonia tanks (and cryogenic spheres).

5.5 Technology landscape

Key information – Technology landscape

Based on the identified *Primary technologies*, a technology landscape was developed to guide the RD&D opportunity analysis and capture the complexity of the energy system networks and their interdependencies with other technological systems. This was informed by literature review and stakeholder input, and comprised of:

Use case

Primary technologies directly contribute to emissions reduction within a given sector.

Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

Energy efficiency solutions can reduce energy usage across primary and/or auxiliary technologies. These solutions are cross-cutting, technology agnostic and likely to be applicable across an identified use case.

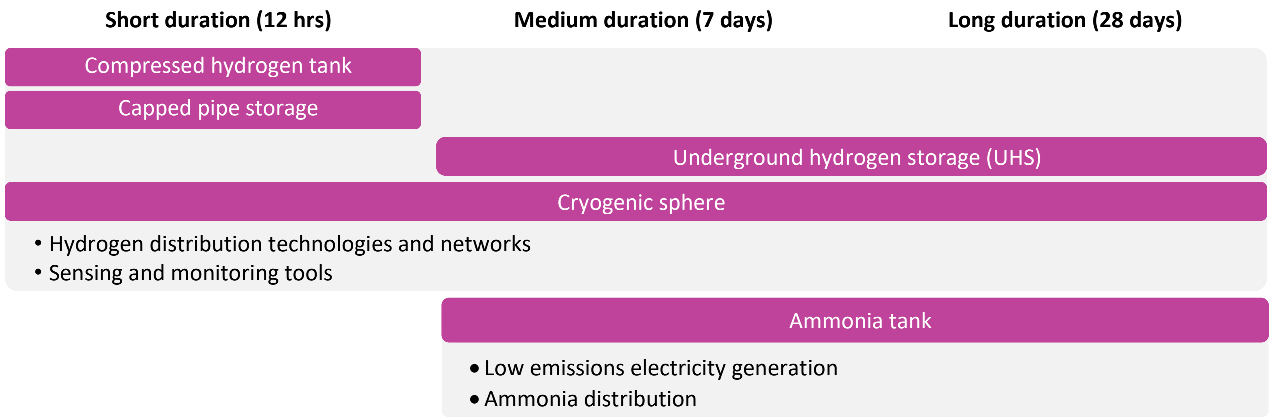
The technology analysis framework identified a number of hydrogen (and derivative) storage technologies as *Primary technologies* for short, medium and long-duration storage use cases. Gaseous storage can present a solution for smaller volumes with frequent discharge needs, while subsurface storage solutions (UHS) can accommodate increased storage capacities. Applications requiring long duration, high-capacity storage may also be serviced by storage solutions with increased volumetric energy density, like cryogenic spheres and ammonia tanks.

Although not explored further, the other low emissions technologies evaluated in this report (Table 13) could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the hydrogen storage subsector. Further RD&D could unlock breakthrough innovations in these technologies, highlighting the need for ongoing assessments to maintain Australia's understanding of the current state of low emissions technologies and future opportunities for RD&D.

The associated auxiliary technologies identified for analysis are outlined in Figure 14 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

For hydrogen (and derivative) storage, the primary technology element(s) refer to both sub-components within a primary technology system, and adjacent processes required for the operation of the primary technology. This typically involves the containment system required for storage and co-located processing equipment, such as compression and purification equipment.

Figure 14: Technology landscape identification – Hydrogen storage



The associated auxiliary technologies and energy efficiency solutions identified for analysis are outlined in Table 19 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Auxiliary technologies

These storage solutions cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 19. For distribution, there are several viable hydrogen distribution systems that enable transfer between production, storage and end-use facilities. While processing steps can allow for hydrogen (and derivatives) to be converted to various states for transportation, project specific technoeconomic modelling is required to determine optimal storage and distribution technology pairings. Here, the methods of distribution have been paired with storage systems of the same chemical state as on principal this serves to minimise conversion losses.

Table 19: Auxiliary technologies – Hydrogen production

Primary Technology	Auxiliary Technology	Description
Compressed hydrogen tank	**Distribution – gaseous pipeline**	Hydrogen gas is compressed and injected directly or blended into pipeline networks, facilitating both hydrogen storage and delivery.
	Distribution – gaseous tube trailer	Hydrogen gas is transported in steel high pressure tubes at 180-250 bar, and in lighter composite pressure vessels (Type II & III) at 350-500 bar.
	Sensing and monitoring tools	Systems required for the reliable, efficient and safe operation of gaseous hydrogen tank storage.
Capped pipe storage	**Distribution**	As for compressed hydrogen storage. Given the large volumes of hydrogen required for this storage solution, more volumetrically dense means of distribution may be adopted.
	Sensing and monitoring tools	Systems required for the reliable, efficient and safe operation of gaseous hydrogen pipe storage.
Underground hydrogen storage (UHS)	**Distribution**	As for compressed hydrogen storage. Given the large volumes of hydrogen required for this storage solution, more volumetrically dense means of distribution may be adopted.
	Sensing and monitoring tools	Systems required for the reliable, efficient and safe operation of UHS storage, including: • Prospecting technologies for geological exploration and site assessments. • Monitoring tools for safe and optimised operation.
	Modelling tools	Modelling tools and methodologies to assess subsurface conditions and optimise injections/withdrawal cycles.

Cryogenic sphere	**Distribution – Liquid hydrogen trailer (by road)**	Liquid hydrogen is transported in cryogenic vessel trailers at below -253°C.
	Distribution – Liquid hydrogen tanker (by sea)	Liquid hydrogen is transported by tanker ship, requiring specialised thermal insulation to minimise boil-off gas rates, compared to natural gas tankers. On loaded legs, tankers aim to use boil-off gas as fuel.
	Distribution – Liquid organic hydrogen tanker (by sea)	LOHC are pairs of hydrogen-lean and hydrogen-rich organic compounds that store hydrogen and can be transported at ambient temperature and pressure using existing chemical tankers. The hydrogen can be extracted via the application of heat or catalysis.
	Sensing and monitoring tools	Systems required for the reliable, efficient and safe operation of cryogenic sphere storage, including minimising boil-off.
Ammonia tank	**Distribution – Ammonia tanker (by sea)**	Ammonia is shipped in fully refrigerated, non-pressurised vessels, often designed to carry LPG.
	Renewable electricity generation (including CSP for high temperature ammonia synthesis)	The infrastructure and networks required to generation and distribute renewable electricity for end use or inputs into a range of processes.
	Electrolysis	A direct water splitting process whereby electricity is passed through an electrolyte solution to stimulate the splitting of water into its hydrogen and oxygen constituents (see *Section 4 Hydrogen production*).

Energy efficiency solutions

No explicit energy efficiency technologies were identified for hydrogen (and derivative) storage; rather, incremental energy efficiency improvements will be a core focus of RD&D efforts across primary and auxiliary technologies.

5.6 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the associated technology landscape, spanning primary and auxiliary technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include **non-technical RD&D opportunities.** Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

A summary of RD&D opportunities can be seen in Table 20. For some technologies, these opportunities are associated with specific technology subcomponents. Technologies typically consist of different system components, that are integrated or work in tandem, which may have specific RD&D needs or be at different stages of technology maturity. These maturity groupings informed the analysis of the type of research efforts required, such as targeted RD&D to overcome technical challenges (emerging, TRL 4-6) or the demonstration of full-scale, or near-full scale systems (mature, TRL 7-9).

Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

Table 20: Summary of RD&D opportunities – Hydrogen storage[116]

		Compressed hydrogen tank		Capped pipe storage		Underground hydrogen storage (UHS)		
		Containment vessel	Compression	Containment vessel	Compression	Storage reservoir	Compression	Purification
Primary technologies	**C**	Metal & metal-composite pressurised vessels	Positive displacement compressor	Steel pipelines (various grades)	Positive displacement compressor	Salt cavern	Positive displacement compressor	Cryogenic H_2 separation and purification
	M	-	Electrochemical compressors	Polymeric materials (i.e., HDPE)	-	-	-	-
	E	-	Metal hydride compressors	Fibre-reinforced polymers, Carbon-fibre composites	Turbo compressors	Fast cycling salt cavern, lined hard rock cavern, depleted gas field storage	Turbo compressors	Membrane and absorption H_2 separation & purification
Primary RD&D		• Reduce storage costs (see '*Levelised cost analysis')* through: - E.g. Developing affordable storage materials • Improve performance attributes such as safety, durability and storage capacity **(Target: 20 tonnes, cf. 1.1 tonnes)** through - E.g. Material innovations - E.g. Monitoring tools to detect material degradation and leakage		• Reduce storage costs (see '*Levelised cost analysis')* through: - E.g. Developing affordable storage materials • Improve performance attributes such as safety, durability and storage capacity through increased pressures **(Target: 120bar, cf. 90)**, - E.g. Material innovations - E.g. Monitoring tools to detect material degradation and leakage		• Further explore, identify and characterise geological formations to improve understanding of UHS potential through: - E.g. Mapping critical geo-structural subsurface characteristics like wall thickness, fault zones, porosity, permeability and fracture networks. • Assess and quantify geo-mechanical and geo-chemical risks to improve operational safety: - E.g. Investigating the effects of hydrogen (or other) subsurface interactions and cycle frequency across reservoir types. • Reduce cost of purification through: - E.g. Minimising platinum group metal (PGM) content - E.g. Reducing energy intensity **(Target: 2.5kWh/kg, cf. 3.5)** - E.g. Increasing system lifetimes **(Target: 20 years, cf. 5)**		
		• Reduce compressor costs by improving performance characteristics through: - E.g. Improving electrical efficiency **(Target: 30-200bar: 2kWh/kg cf. 3 |<900bar: 3kWh/kg cf. 6)**, - E.g. Increasing compressor reliability (**'Mean time between failure' target: 60,000hrs, cf. 25,000)** - E.g. Increasing asset lifetimes **(Target: 20 years, cf. 10)** • Develop high throughput compressor systems for large-volume storage (i.e., pipe storage and UHS) through: - E.g. Material advancements for centrifugal-type turbo compressors						
Auxiliary		• Progress the development of gaseous distribution by improving materials and system designs e.g. increasing storage densities and pressures of gaseous tube trailers; improving the structural integrity of existing and new pipeline infrastructure. • Ensure safe operation of hydrogen storage systems through highly sensitive hydrogen sensors to detect leakage (Target: ppb-level sensitivity) and measurement tools to monitor material degradation over time.						

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cf. – Compare

[116] TRL categories: Emerging (E) = TRL 4-6, Mature (M) = TRL 7-9, Commercial (C) = CRI 2-6; Please note, Levelised Cost forecasts refer to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering. All other targets are technical targets, pertaining to the operation of the technology or system itself.

		Cryogenic sphere	Ammonia tanks		
		Containment	**Containment**	**NH_3 production**	**H_2 regeneration**
Primary technologies	**C**	Double-wall vacuum insulated storage sphere	NH_3 tanks	-	High temp NH_3 cracking; Cryogenic H_2 separation and purification
	M	-	-	Electrolysis NH_3 production with VRE (HaberBosch)	-
	E	Next generation insultation and thermal management systems	-	Direct ammonia synthesis	Low temp NH_3 cracking; Membrane and absorption H_2 separation & purification
Primary RD&D		• Reduce storage costs (see '*Levelised cost analysis'*) through: - E.g. Improving storage efficiencies by optimising thermal management and cold energy recovery, and minimising boil-off **(Target: 0%)** - E.g. Material innovations and extending material lifespan under cryogenic conditions. • Improve safety performance through - E.g. Collecting leak frequency data and developing behaviour models to inform risk management and safety protocols - E.g. Monitoring tools to detect material degradation and leakage	• Reduce storage costs (see '*Levelised cost analysis')* by reducing the cost of ammonia synthesis and hydrogen regeneration, through: - E.g. Incremental process improvements and new pathway development - E.g. Optimised catalysts and reactors allowing for reactions under milder conditions and increased efficiencies or reduced requirements for expensive materials • Reduce cost of purification through: - E.g. Minimising platinum group metal (PGM) content - E.g. Reducing energy intensity **(Target: 2.5kWh/kg, cf. 3.5)** - E.g. Increasing system lifetimes **(Target: 20 years, cf. 5)** - E.g. Improving hydrogen recovery factor **(Target: 95%, cf. 80%)**		
Auxiliary RD&D		• Progress the development of cryogenic distribution by improving materials and system designs. - E.g. Minimising boiloff and extending material lifespans under low-temperature conditions for cryogenic sphere storage • Ensure safe operation of hydrogen storage systems through: - E.g. Developing highly sensitive hydrogen sensors to detect leakage **(Target: ppb-level sensitivity)** and measurement tools to monitor material degradation • Reduce costs of liquefaction **(LCOS Target: $2.36, cf. $3.11)** through: - E.g. Reducing energy intensity **(Target: 6-8kWh/kg, c.f., 10-12)** - E.g. Improving round-trip efficiency	• Improve transport efficiency, safety and dual use potential on carrier ships through: - E.g. Minimising and recapturing ammonia boil off.		

5.6.1 Compressed hydrogen tank

To overcome its low volumetric energy density under ambient conditions, hydrogen can be stored as a compressed gas in pressure vessels or other structures (see also *5.6.2 Capped pipe* storage and *5.6.3 Underground* hydrogen storage (UHS)). Compressed hydrogen tank is a commercially mature, well-established storage method that involves storing hydrogen gas at pressures typically between 350-750 bar (ranging from 100-825 bar) in specialised containment vessels.

Storage vessels must meet demanding mechanical requirements to ensure safety and performance at high pressures. This includes high tensile strength (resistance to deformation under pressure), adequate energy density (hydrogen storage per unit volume), and material compatibility (non-reactivity or diffusivity with hydrogen).[117] There are four classifications of storage vessels, which are defined by their composition:[118]

- Type I vessels are metal-only cylinders (e.g., carbon steel or low alloy steel),
- Type II vessels consist of a load-bearing metal-liner, wrapped with a fibre-resin composite,
- Type III vessels consist of a thin metal-liner, wrapped with a high-strength fibre-resin composite,
- Type IV vessels consist of a polymer liner, wrapped with a fibre-resin composite.

For stationary applications, the compressed gas is typically stored in high-pressure vessels comprised of steel or composite materials (Type I & II), which must balance structural integrity with material cost.[119] Composite materials are generally expensive and limit potential cost reductions for large-scale hydrogen storage.[120] Type III and IV tanks generally have higher material costs but can service different mobility needs where strength-to-weight ratios are of increased importance.

Primary technologies

The development of affordable stationary storage materials will underpin the deployment of large-scale, high-pressure hydrogen storage infrastructure.

Large-scale stationary hydrogen storage is constrained by the high cost of advanced composite materials required for high-pressure containment (please refer to *'Levelised cost analysis*' for cost forecasts across the defined profiles). Fibre-resin composites are used in type II, III and IV vessels to provide the tensile strength required for safe storage at elevated pressures. For stationary storage, these materials offer enhanced structural and durability, and contribute to increased hydrogen storage efficiencies and reduced vessel size. However, high costs remain a major barrier to deployment, particularly for large-scale applications where cost per kilogram of hydrogen storage must be minimised.[121] RD&D can assist in identifying and developing lower-cost composite alternatives to enable cost-effective long-term material performance of hydrogen storage infrastructure.

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[117] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080; Abdalla MM, Hossain S, Nisfindy OB, Azad AT, Dawood M, Azad AK (2018) Hydrogen production, storage, transportation, and key challenges with applications: A review. Energy Conversion and Management 165, 602-627. https://doi.org/10.1016/j.enconman.2018.03.088

[118] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080; Langmi H, Engelbrecht N, Modisha P, Bessarabov D (2022) Chapter 13 – Hydrogen Storage in Electrochemical Power Sources: Fundamentals, Systems and Applications. In Hydrogen Production by Water Electrolysis. (Eds. T Smolinka, J Garche), 455-486.

[119] CSIRO (2021) Hydrogen Technology Marketplace: Metal-composite pressurised vessels. <https://www.csiro.au/en/work-with-us/ip-commercialisation/hydrogen-technology-marketplace/metal-composite-pressurised-vessels> (accessed 13 January 2025).

[120] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

[121] International Energy Agency (IEA) (2019) The Future of Hydrogen: Seizing today's opportunities. IEA. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf (accessed 13 January 2025).

Material innovations could improve the capacity, durability and safety of stationary hydrogen storage, balancing performance alongside cost.

Mitigating hydrogen embrittlement to extend the lifetimes of high-pressure vessels and improve operational safety is a major challenge for metal-based components (e.g., metal cylinders and liners). This phenomenon occurs when hydrogen atoms diffuse into the metal lattice, leading to brittleness, cracking under stress, associated safety risks – such as explosions and the formation of hydroxyl radicals that break down methane or deplete the ozone.[122] The risk of hydrogen embrittlement increases with temperature and pressure fluctuations and can therefore be impacted by the frequency of filling and withdrawal cycles. Advancements in material science to identify more resilient alloys and coatings, and develop predictive models and monitoring tools to detect material degradation can minimise these risks and ensure safe operation.[123] These improvements could also enable the design of larger capacity aboveground tanks (target: 20 tonnes, c.f., 1.1 tonnes), supporting increased production and demand.

Storage costs can also be reduced by improving the performance characteristics conditioning processes; namely the efficiency, reliability and throughput of compressors.

Mechanical positive displacement compressors, such as reciprocating piston, diaphragm, and hydraulic types, are widely used within industry with mature designs and operational procedures. Benefiting from longstanding incremental improvements, no significant RD&D opportunities are identified. In these systems, hydrogen is drawn into a compression chamber which is reduced in size to achieve the desired pressure.

There are various opportunities, however, to support the development of emerging, high performance non-mechanical compressors that exploit electrochemical, adsorption or absorption principles. These systems offer potential advantages such as lower material wear and improved hydrogen purity due to the absence of lubricants and moving parts. RD&D focused on improving the electrical efficiency (target: 2kWh/kg c.f., 3kWh/kg for 30-200bar or 3kWh/kg c.f., 6kWh/kg for <900bar); reliability, through increased lifetimes (target: 20 years, c.f., 10 years) and reduced 'mean time between failure' (target: 60,000hrs, c.f., 25,000hrs); and throughput of these systems could improve cost effectiveness and minimise energy losses associated with storage.[124] This will involve addressing technical challenges associated with the various compressor types. For example:[125]

- Metal hydride systems suffer from slow hydrogen adsorption/desorption kinetics, are energy consumptive, and are weight constrained.[126]

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[122] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080; Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM (2021) Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems, and policy options. Energy Research & Social Science 80, 102208. https://doi.org/10.1016/j.erss.2021.102208

[123] Abdalla MM, Hossain S, Nisfindy OB, Azad AT, Dawood M, Azad AK (2018) Hydrogen production, storage, transportation, and key challenges with applications: A review. Energy Conversion and Management 165, 602-627. https://doi.org/10.1016/j.enconman.2018.03.088; Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM (2021) Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems, and policy options. Energy Research & Social Science 80, 102208. https://doi.org/10.1016/j.erss.2021.102208; Dwivedi SK, Vishwakarma M (2018) Hydrogen embrittlement in different materials: A review. International Journal of Hydrogen Energy 43(46), 21603-21616. https://doi.org/10.1016/j.ijhydene.2018.09.201

[124] European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 January 2025); Air A, Shamsuddoha M, Gangadhara Prusty B (2023) A review of Type V composite pressure vessels and automated fibre placement-based manufacturing. Composites Part B: Engineering 253. https://doi.org/10.1016/j.compositesb.2023.110573

[125] RECIP (2022) Hydrogen Compression White Paper. <https://www.recip.org/wp-content/uploads/2023/01/2022-EFRC-WhitePaper-Hydrogen-Compression.pdf> (accessed 13 January 2025).

[126] Metal hydride compressors with outlet pressures up to 200bar are commercially available, however, systems with higher pressure outputs are under development. Sdanghi, G. et al., 2019. Modelling of a hydrogen thermally driven compressor based on cyclic adsorption-desorption on activated carbon. International Journal Hydrogen Energy, 44(31), 16811–16823. https://doi.org/10.1016/j.ijhydene.2019.04.233

- Electrochemical systems face high efficiency losses at high pressure and challenging water management.
- Adsorption/desorption systems are at an earlier stage of development and currently face challenges related to chemical stability and ageing of the adsorbent.

Auxiliary technologies

Improving materials and system designs for compressed hydrogen distribution is a critical network enabler for the development of a reliable hydrogen industry.

Hydrogen distribution systems are a vital part of energy storage networks, enabling hydrogen to be stored, transported and delivered to end users. The choice of distribution pathway, and its viability, depends on a multitude of factors including volume, delivery distance and terrain, infrastructure availability and chemical preferences; all of which are interrelated. Where possible, maintaining hydrogen in its gaseous form can minimise conversion losses; however gaseous distribution introduces similar challenges to tank storage, requiring advancements to overcome hydrogen embrittlement and leakage. As discussed in Section 4.4.1, atmospheric chemical reactions involving leaked hydrogen can change the abundance of certain greenhouse gases, further underscoring the need for leakage abatement techniques.

For short distances, gaseous tube trailers offer flexibility with the ability to adapt routes and volumes in accordance with delivery needs. Unlike stationary storage vessels, these trailers are weight sensitive. Improving onboard storage densities (target: 1500kg of hydrogen per tube, c.f. 1000)[127] will require lower weight, higher-pressure vessels (target: 700bar, c.f., <500),[128] driving interest in advanced materials. For example, type V hydrogen cylinders linerless tanks made solely from composite materials like carbon fibre are under investigation to improve both weight and pressure performance.[129]

For longer distances, including where existing natural gas infrastructure can be repurposed, pipeline distribution could be leveraged. However, pipelines face similar material degradation risks of embrittlement and leakage, particularly those constructed from steel-based alloys as typically adopted in legacy natural gas infrastructure. RD&D could help to assess the compatibility of existing assets, and to develop cost effective solutions for existing and legacy infrastructure. For example, novel polymeric and composite materials are being developed for new pipelines, and could be adapted to pipeline retrofits (i.e., interior sleeving).

In blending application where hydrogen is injected into natural gas networks as a transitionary measure, ongoing research efforts should inform safe and blending limits (0-100%) and to develop low-cost separation technologies for downstream recovery.[130] Examples include adapting conventional pressure swing adsorption and temperature swing adsorption technologies for low hydrogen flux. In some cases, pipeline infrastructure may also support storage efforts via 'pipeline packing' (see *5.6.2 Capped pipe storage, Auxiliary technologies).*

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[127] European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 January 2025).

[128] European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 January 2025); Air A, Shamsuddoha M, Gangadhara Prusty B (2023) A review of Type V composite pressure vessels and automated fibre placement-based manufacturing. Composites Part B: Engineering 253. https://doi.org/10.1016/j.compositesb.2023.110573

[129] Air A, Shamsuddoha M, Gangadhara Prusty B (2023) A review of Type V composite pressure vessels and automated fibre placement based manufacturing. Composites Part B: Engineering 253. https://doi.org/10.1016/j.compositesb.2023.110573

[130] U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office (2024) Hydrogen Production Multi-Year Program Plan. U.S. Department of Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf> (accessed 13 January 2025).

For other hydrogen distribution pathways, refer to *5.6.4 Cryogenic sphere* (liquid transport) and *5.6.5 Ammonia (ammonia tanker & LOHC).*

Technologies that manage flammability and leakage concerns are essential for the safe operation of hydrogen storage systems (including compressed hydrogen tanks, capped pipe storage, UHS and cryogenic spheres).

RD&D can assist in enhancing safety and mitigate risks by advancing hydrogen-specific monitoring and control systems.[131] This may include development of real-time, highly sensitive hydrogen sensors capable of detecting hydrogen permeation and leakage (target: ppb-level sensitivity), as well as predictive maintenance tools that monitor material degradation over time. In addition, standardised testing and validation procedures for operation and maintenance equipment are essential to ensure safe, reliable system performance across diverse applications, with adequate ventilation design and evidence-informed response protocols also contributing to safe deployment at scale. [132]

5.6.2 Capped pipe storage

This storage technology involves the storage of hydrogen in pressurised pipes that are capped and filled with maximum storage pressure that generally does not exceed 100 bar.[133] The process of underground pipe storage has been used for natural gas since the 1980s, whereby a series of pipelines with diameters of ~1.4m and sealed ends are buried at shallow depth. The length of the pipelines varies depending on storage capacity requirements but may reach several kilometres.[134]

Primary technologies

Similar to compressed hydrogen tank storage, material innovations could improve the capacity, durability and safety of gaseous pipe storage, balancing performance alongside cost.

Reducing costs in line with cost forecasts (please refer to *'Levelised cost analysis*' for cost forecasts across the defined profiles) can be achieved through the development of affordable storage materials. Hydrogen pipeline construction is an established practice; however, hydrogen pipelines face additional technical changes compared to those purpose-built for natural gas.

Mitigating hydrogen embrittlement is a principal challenge, occurring as hydrogen atoms diffuse into the containment material, reducing strength and durability.[135] To mitigate this, RD&D can serve to develop new materials, like polymeric materials and reinforced composites, alongside simulation and monitoring tools to assess material degradation.[136] For example, tools to measure mechanical properties of vessel microstructures and mapping techniques to understand and mitigate hydrogen embrittlement mechanisms

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[131] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

[132] Andersson J, Grönkvist S (2019) Large-scale storage of hydrogen. International Journal of Hydrogen Energy 44(23), 11901-11919. https://doi.org/10.1016/j.ijhydene.2019.03.063; Panfilov M (2016) Underground and pipeline hydrogen storage. In: *Compendium of Hydrogen Energy*, Volume 2: Hydrogen Storage, Transportation and Infrastructure, Woodhead Publishing Series in Energy, 91-115. https://doi.org/10.1016/B978-1-78242-362-1.00004-3

[133] Andersson J, Grönkvist S (2019) Large-scale storage of hydrogen. International Journal of Hydrogen Energy 44(23), 11901-11919. https://doi.org/10.1016/j.ijhydene.2019.03.063

[134] Tietze V, Luhr S, Stolten D (2016) Bulk Storage Vessels for Compressed and Liquid Hydrogen. In: Stolten D, Emonts B (eds) *Hydrogen Science and Engineering: Materials, Processes, Systems and Technology*, Chapter 27. Wiley. https://doi.org/10.1002/9783527674268.ch27

[135] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

[136] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2024) Hydrogen Pipelines. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-pipelines> (accessed 13 January 2025).

across varying material composition. These innovations can also allow for higher storage pressures (target: 120bar, c.f., 90 bar), increasing volumetric capacity and address hydrogen-induced cracking to minimise leakage (target: 0% leakage).[137]

Storage costs can also be reduced by improving the performance characteristics conditioning processes; namely the efficiency, reliability and throughput of compressors.

For large-volume pipe storage solutions, RD&D that lowers cost and increases the durability of compression systems for large volumetric flows will be important. [138] For large volumes, mechanical compressors are required. Mechanical positive displacement compressors, such as reciprocating piston, diaphragm, and hydraulic types, are widely used within industry with mature designs and operational procedures. Benefiting from longstanding incremental improvements, no significant RD&D opportunities are identified.

Centrifugal-type turbo compressors, currently at TRL 6, offer advantages in their ability to operate more continuously and reduce vibrations when attached to pipe (or UHS) systems. However, to achieve higher pressure ratios required for low weight hydrogen, these systems must operate at significantly higher rotational speeds than for heavier gases like methane.[139] RD&D can assist in the development of hydrogen-compatible materials and impeller designs that can withstand high centrifugal forces while maintaining structural integrity and performance over time.[140]

Auxiliary technologies

Improving materials and system designs for compressed hydrogen distribution is a critical network enabler for the development of a reliable hydrogen industry.

Hydrogen distribution systems are a vital part of energy storage networks, enabling hydrogen to be stored, transported and delivered to end users. The choice of distribution pathway, and its viability, depends on a multitude of factors including volume, delivery distance and terrain, infrastructure availability and chemical preferences; all of which are interrelated. Gaseous tube trailers and pipeline distribution are discussed at *5.6.1 Compressed hydrogen tank*.

Pipeline networks can also assist in storage, a process known as "line packing," in which surplus hydrogen is compressed into pipelines to temporarily store gas. Pipeline packing is distinct from traditional underground or tank storage, providing flexibility and can be particularly useful in integrated hydrogen systems when combined with other storage types like UHS. However, ongoing research can serve to optimise pipeline materials and ensure safe, long-term operation under pressurised hydrogen storage conditions.

For other hydrogen distribution pathways, refer to *5.6.4 Cryogenic sphere* (liquid transport) and *5.6.5 Ammonia* (ammonia tanker & LOHC).

Technologies that manage flammability and leakage concerns are essential for the safe operation of hydrogen storage systems (including compressed hydrogen tanks, capped pipe storage, UHS and cryogenic spheres).

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[137] Fekete JR, Sowards JW, Amaro RL (2015) Economic impact of applying high strength steels in hydrogen gas pipelines. International Journal of Hydrogen Energy 40(33), 10547–10558. https://doi.org/10.1016/j.ijhydene.2015.06.090

[138] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024); U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (2024) Hydrogen Pipelines. U.S. Department of Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-pipelines> (accessed 13 January 2025).

[139] Compared to higher molecular weight gases (i.e., methane), H2 requires higher impeller speeds (~3x) to realise similar pressure ratios. RECP (2023) Hydrogen Compression: Boosting the Hydrogen Economy. Renewable Energy Compression Forum. <https://www.recip.org/wp-content/uploads/2023/01/2022-EFRC-WhitePaper-Hydrogen-Compression.pdf> (accessed 13 January 2025); Tahan M-R (2022) Recent advances in hydrogen compressors for use in large-scale renewable energy integration. International Journal of Hydrogen Energy 47(83), 35275–35292. https://doi.org/10.1016/j.ijhydene.2022.08.128

[140] RECP (2023) Hydrogen Compression: Boosting the Hydrogen Economy. Renewable Energy Compression Forum. <https://www.recip.org/wp-content/uploads/2023/01/2022-EFRC-WhitePaper-Hydrogen-Compression.pdf> (accessed 13 January 2025).

Refer to section *5.6.1 Compressed hydrogen tank*.

5.6.3 Underground hydrogen storage (UHS)

Underground hydrogen storage (UHS) is a method for storing large quantities of hydrogen via its compression and injection through wells into subsurface formations. There are four main geological types of UHS, which include salt caverns, hard rock caverns, depleted oil and gas reservoirs and aquifers.[141] Aquifers are not discussed here, due to their lower technological maturity (TRL 3).

Primary technologies

Further exploration and characterisation of geological formations is critical to understanding the potential for UHS in Australia, including the suitability and capacity of prospective sites.

Continued exploration and characterisation of geological formations can help to form the evidence base through which Australia's potential for UHS can be understood. Suitable sites must demonstrate specific structural characteristics and geomechanical conditions for safe storage.[142] This includes mapping critical features such as halite thickness (salt caverns), fault zones, porosity, permeability and fracture networks.[143] A detailed understanding of these subsurface characteristics could help to optimise performance, mitigate risks, and inform site selection and infrastructure planning.

RD&D can support the quantification of geo-mechanical and geo-chemical risks associated with UHS operations to guide sustainable and safe storage design.

Cyclical injection and withdrawal of hydrogen in underground storage formations creates pressure and temperature fluctuations, induces stress changes, and can create chemical interactions between hydrogen and subsurface materials. These effects can compromise the structural integrity of wellbores, caprocks and reservoirs. For instance, salt caverns may experience accelerated salt creep, while depleted hydrocarbon reservoirs may face fault reactivation or caprock failure under frequent cycling.[144] Meanwhile, geochemical reactions between hydrogen and reservoir minerals, such as the dissolution or precipitation of minerals, can degrade rock stability and elevate the risk of hydrogen migration. There are RD&D opportunities to investigate and quantify the effects of hydrogen interactions and cycle frequency in UHS systems, as well as develop sustainable and safe cavern designs with improved discharge rates and pressure ranges.[145]

Hydrogen's small molecular size and high diffusivity pose significant challenges for long-term containment. Permeation through rock matrices or along faults may lead to gradual hydrogen loss or migration. Understanding the permeability characteristics of various rock types and developing effective containment strategies are valuable fields for further research. This may include field tests under operational conditions and the development of advanced simulation tools to predict migration pathways and inform efficient storage design.

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[141] Lord A, Kobos P, Borns D (2014) Geologic storage of hydrogen: Scaling up to meet city transportation demands. International Journal of Hydrogen Energy 39, 15570–15582. https://doi.org/10.1016/j.ijhydene.2014.07.121

[142] Ennis-King J, Michael K, Strand J, Sander R, Gree C (2021) Underground storage of hydrogen: Mapping out the options for Australia. Future Fuels CRC, Deliverable 5: Final Summary Report. <https://www.futurefuelscrc.com/wp-content/uploads/FutureFuelsCRC_UndergroundHydrogenStorage2021.pdf> (accessed 13 January 2025).

[143] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: a review. Geological Society, London, Special Publications 528, 73–86. https://doi.org/10.1144/SP528-2022-8.

[144] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: a review. Geological Society, London, Special Publications 528, 73–86. https://doi.org/10.1144/SP528-2022-8.

[145] Tarkowski R, Uliasz-Misiak B (2022) Towards underground hydrogen storage: A review of barriers. Renewable and Sustainable Energy Reviews 162, 112451. https://doi.org/10.1016/j.rser.2022.112451

Different geological formations (salt caverns, hard rock caverns, and oil and gas reservoirs) present unique challenges for hydrogen storage; each requiring targeted research to ensure containment, capacity, and improve cost outcomes.

There is opportunity for RD&D to assist in assessing, predicting and minimising 'salt creep' in salt caverns to minimise storage capacity reductions and associated costs. Salt (halite) caverns are the most mature UHS system, offering high gas deliverability (i.e. good injection/withdrawal characteristics compared to porous rocks,[146] low cushion gas requirements, and high sealing capacity.[147] However, long-term stability is limited by salt evolution (or 'salt creep'), the deformation of salt under mechanical stress, leading to a reduction in cavern volume. At depths greater than 2000m, salt creep can exceed 20% per year, undermining economic viability due to the need for repeated remining which can add significant operational delays and costs.[148]

Hard rock caverns and repurposed mining infrastructure offer potential in regions where other subsurface structures are unavailable. Legacy mine shafts, however, often require significant adaptation to address rock disturbances from past use and eliminate potential leakage pathways, such as old drill holes.[149] Engineering and materials advancements could enhance lining strategies to maximise hydrogen entrapment, while the construction of new hard rock cavern infrastructure could benefit from further investigation of economically viable approaches to excavation that preserve stability.[150]

Depleted oil and gas reservoirs are relatively abundant in Australia compared to other UHS structures, with an estimated total storage capacity across onshore and offshore fields of ~70,500PJ of hydrogen (~570MtH_2, excluding cushion gas requirements).[151] However, challenges include residual hydrocarbons that may interact with injected hydrogen, potentially affecting purity and long-term reservoir stability. These porous formations also introduce complex stress-strain and sorption behaviours due to hydrogen's unique fluid properties.[152] There are opportunities to develop robust, cheaper purification solutions, and improve containment strategies through, for example, laboratory and in-situ simulation and validation of subsurface dynamics.[153]

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[146] I.e., depleted oil/gas reservoirs.

[147] Amirthan T, Perera MSA (2023) Underground hydrogen storage in Australia: A review on the feasibility of geological sites. International Journal of Hydrogen Energy 48(11), 4300-4328. https://doi.org/10.1016/j.ijhydene.2022.10.218; Bradshaw M, Rees S, Wang L, Szczepaniak M, Cook W, Voegeli S, Boreham C, Wainman C, Wong S, Southby C, Feitz A (2022) Australian salt basins – options for underground hydrogen storage. Australian Journal of Earth Sciences. https://doi.org/10.1071/AJ22153

[148] Bradshaw M, Rees S, Wang L, Szczepaniak M, Cook W, Voegeli S, Boreham C, Wainman C, Wong S, Southby C, Feitz A (2022) Australian salt basins – options for underground hydrogen storage. Australian Journal of Earth Sciences. https://doi.org/10.1071/AJ22153; Ramesh Kumar K, Makhmutov A, Spiers CJ, Hajibeygi H (2021) Geomechanical simulation of energy storage in salt formations. Scientific Reports 11, 19640. https://doi.org/10.1038/s41598-021-99161-8

[149] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: a review. Geological Society, London, Special Publications 528, 73–86. https://doi.org/10.1144/SP528-2022-8

[150] Ennis-King J, Michael K, Strand J, Sander R, Gree C (2021) Underground storage of hydrogen: Mapping out the options for Australia. Future Fuels CRC, Deliverable 5: Final Summary Report. <https://www.futurefuelscrc.com/wp-content/uploads/FutureFuelsCRC_UndergroundHydrogenStorage2021.pdf> (accessed 13 January 2025); Amirthan T, Perera MSA (2023) Underground hydrogen storage in Australia: A review on the feasibility of geological sites. International Journal of Hydrogen Energy 48(11), 4300-4328. https://doi.org/10.1016/j.ijhydene.2022.10.218

[151] Includes accumulative production, remaining gas reserves and contingent resources based on data as of end 2019. Amirthan T, Perera MSA (2023) Underground hydrogen storage in Australia: A review on the feasibility of geological sites. International Journal of Hydrogen Energy 48(11), 4300-4328. https://doi.org/10.1016/j.ijhydene.2022.10.218; Muhammed NS, Haq B, Al Shehri D, Al-Ahmed A, Rahman MM, Zaman E (2022) A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. Energy Reports 8, 461-499. https://doi.org/10.1016/j.egyr.2021.12.002

[152] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J (2023) Underground hydrogen storage: a review. Geological Society, London, Special Publications 528, 73–86. https://doi.org/10.1144/SP528-2022-8; Heinemann, N., Alcalde, J. et al. 2021a. Enabling large-scale hydrogen storage in porous media – the scientific challenges. Energy & Environmental Science 14, 853–864. https://doi.org/10.1039/D0EE03536J

[153] Muhammed NS, Haq B, Al Shehri D, Al-Ahmed A, Rahman MM, Zaman E (2022) A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. Energy Reports 8, 461-499. https://doi.org/10.1016/j.egyr.2021.12.002 ; Ennis-King J, Michael K, Strand J, Sander R, Gree C (2021) Underground storage of hydrogen: Mapping out the options for Australia. Future Fuels CRC, Deliverable 5: Final Summary Report. <https://www.futurefuelscrc.com/wp-content/uploads/FutureFuelsCRC_UndergroundHydrogenStorage2021.pdf> (accessed 13 January 2025).

Improving the performance and cost-efficiency of compression and purification steps can support the viability of UHS.

Large-scale UHS requires efficient conditioning to manage injection and withdrawal processes. Prior to injection, dynamic high-throughput compressor systems are needed to pressurise large volumes of hydrogen. RD&D can serve to improve the efficiency, durability and cost-effectiveness of centrifugal type compressors to reduce operational energy demand (*5.6.2 Capped pipe storage*). Turbo compressors are also under investigation.

Purification processes are important for managing contamination of by co-stored gases or reaction by-products. Research can support cost reductions through efforts to reduce electrical energy efficiencies (target: 2.5kWh/kg, c.f., 3.5), extending system lifetimes (target: 20 years, c.f., 5), and minimising platinum group metal (PGM) in catalytic purification processes

Auxiliary technologies

Proving materials and system designs for compressed hydrogen distribution is a critical network enabler for the development reliable hydrogen industry.

Hydrogen distribution systems are a vital part of energy storage networks, enabling hydrogen to be stored, transported and delivered to end users. The choice of distribution pathway, and its viability, depends on a multitude of factors including volume, delivery distance and terrain, infrastructure availability and chemical preferences; all of which are interrelated. Where possible, maintaining hydrogen in its gaseous form can minimise conversion losses; however, given the large volumes of hydrogen required to sufficiently charge a UHS system, where pipelines are unavailable, denser forms of hydrogen distribution (i.e., cryogenic or via carriers) may be considered.

Gaseous tube trailers and pipeline distribution are discussed at *5.6.1 Compressed hydrogen* tank. For other hydrogen distribution pathways, refer to *5.6.4 Cryogenic sphere* (liquid transport) and *5.6.5 Ammonia* (ammonia tanker & LOHC).

Technologies that manage flammability and leakage concerns are essential for the safe operation of hydrogen storage systems (including compressed hydrogen tanks, capped pipe storage, UHS and cryogenic sphere).

Monitoring technologies and modelling tools are of particular importance to assess subsurface conditions and optimise injections/withdrawal cycles.

As for other gaseous storage systems, RD&D can assist in enhancing safety and mitigate risks by advancing hydrogen-specific monitoring and control systems.[154] This may include development of real-time, highly sensitive hydrogen sensors capable of detecting hydrogen permeation and leakage (target: ppb-level sensitivity), as well as predictive maintenance tools that monitor material degradation over time.

5.6.4 Cryogenic sphere

The volumetric density of hydrogen can be increased via its liquefaction to 70.85kg/m^3 at atmospheric pressure, requiring temperatures below -252.87°C.[155] This occurs through a multi-stage process of compression and cooling, where catalysts are used to accelerate to a molecular transition from a hydrogen's

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[154] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M (2021) Large-scale compressed hydrogen storage as part of renewable electricity storage systems. International Journal of Hydrogen Energy 46(29), 15671-15690. https://doi.org/10.1016/j.ijhydene.2021.02.080

[155] U.S. Department of Energy (n.d.) Hydrogen Storage. Office of Energy Efficiency & Renewable Energy. <https://www.energy.gov/eere/fuelcells/hydrogen-storage> (accessed 13 January 2025).

high-energy ‘ortho’ state (where both H_2 nuclei spin in the same direction) to it’s low-energy ‘para’ state (where the H_2 nuclei spin in opposite directions). While liquefied hydrogen is denser than in compressed gaseous form, the process of liquefaction is energy intensive, requiring up to 40% of the energy content of hydrogen for liquefaction and regasification processes.[156]

For large volumes, a spherical shape is typically adopted due to its lower surface-to-volume ratio which serves to reduce daily boil-off (the evaporation of liquid hydrogen). For smaller volumes of storage, cylindrical vessels with thicker walls may be adopted.[157] To further minimise boil-off spheres often feature a double-shell vacuum insulation which minimises heat transfer and additional insulation materials employed in the space between tank walls.[158]

Stainless steels are widely employed, with different alloy compositions of varying grades depending on application. While lightweight materials are a primary consideration for mobility applications, such as in marine, aviation, and space industries, for stationary purposes, weight is not a primary consideration.

Primary technologies

A cryogenic sphere storage system has two main components depending on end-use: a liquid hydrogen storage tank and in some cases, a regasification unit to convert the liquid hydrogen back into gaseous form.[159] Liquefaction generally occurs off site at a designated facility and is therefore considered an auxiliary technology in this context.

Cost reductions could be achieved by improving storage efficiencies through the mitigation of hydrogen losses.

Liquid hydrogen storage can suffer from high boil-off losses which reduce storage and therefore cost inefficiencies. Losses can occur at a rate as high as 5% per day, although typically <1% for large-scale systems. RD&D therefore presents opportunities to mitigate boil-off losses (target: 0% boil-off) and improve cost outcomes (please refer to *‘Levelised cost analysis*’ for cost forecasts across the defined profiles).[160]

A key contributor to boil-off is ‘ortho-para conversion’, an exothermic process in which hydrogen molecules transition from the 'ortho' spin state to the 'para' spin state at cryogenic temperatures, releasing heat and leading to unwanted evaporation.[161] Continuing research to develop of low-cost catalysts to accelerate this conversion during liquefaction and reduce heat generation in storage, as well as sensors to monitor ortho-para ratios in real time, could reduce conversion-related boil-off.[162]

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[156] Dagdougui, H, Sacile, R, Bersani, C, Ouammi, A (2018). Chapter 4 - Hydrogen Storage and Distribution: Implementation Scenarios. In Dagdougui, H, Sacile, R, Bersani, C, Ouammi, A (Eds.), Hydrogen Infrastructure for Energy Applications (pp. 37-52): Academic Press; Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y (2023) Hydrogen liquefaction and storage: Recent progress and perspectives. Renewable and Sustainable Energy Reviews 176, 113204. https://doi.org/10.1016/j.rser.2023.113204

[157] Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y (2023) Hydrogen liquefaction and storage: Recent progress and perspectives. Renewable and Sustainable Energy Reviews 176, 113204. https://doi.org/10.1016/j.rser.2023.113204

[158] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[159] Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y (2023) Hydrogen liquefaction and storage: Recent progress and perspectives. Renewable and Sustainable Energy Reviews 176, 113204. https://doi.org/10.1016/j.rser.2023.113204

[160] Zhang T, Uratani J, Huang Y, et al. (2023) Hydrogen liquefaction and storage: Recent progress and perspectives. Renewable and Sustainable Energy Reviews 176, 113204. https://doi.org/10.1016/j.rser.2023.113204

[161] CSIRO (2023) Ortho-para hydrogen conversion applied to hydrogen liquefaction. <https://research.csiro.au/hyresearch/ortho-para-hydrogen-conversion-applied-to-hydrogen-liquefaction/> (accessed 13 January 2025); Zhang TT, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y (2023) Hydrogen liquefaction and storage: Recent progress and perspectives. Renew Sustain Energy Reviews. 176, 113204. https://doi.org/10.1016/j.rser.2023.113204

[162] CSIRO (2024) Ortho- para hydrogen conversion. <https://research.csiro.au/hydrogenfsp/ortho-para-hydrogen-conversion/> (accessed 13 January 2025).

Thermal management also plays a central role, and improved thermal management materials and tank designs could limit external heat ingress. RD&D can assist the optimisation of insulation technologies (active and passive), heat exchangers and coolants, supported by thermodynamic modelling to evaluate system performance under operational conditions.

Larger storage tanks offer advantage due to low surface-to-volume ratios, reducing evaporation losses. However, they must be engineered to withstand large temperature gradients from cryogenic to room temperature. Advancing tank materials that balance thermal robustness (incl. fire and heat resistance), hydrogen embrittlement resistance, and mechanical strength, while remaining cost effective is an important RD&D challenge.[163]

RD&D can improve cryogenic hydrogen regasification by enabling the recovery of high-grade cold energy at scale.

The foremost challenge for liquid hydrogen regasification is the recovery of high-grade cold energy that is released during liquid evaporation at scale, however limited research and application has occurred to date. There is opportunity to leverage lessons from cold recovery of LNG regasification processes; however, even here, most high-grade applications have not been applied on a large scale.

Technologies that manage flammability and leakage concerns are essential for the safe operation of hydrogen storage systems (including compressed hydrogen tanks, capped pipe storage, UHS and cryogenic spheres).

These are discussed broadly under *5.6.1 Compressed hydrogen* tank*.*

In addition, the development of leak frequency data and models for the behaviour of liquid hydrogen could inform risk management and safety activities of large-scale storage.

Auxiliary technologies

Improving materials and system designs for cryogenic hydrogen distribution is a critical network enabler for the development of a reliable hydrogen industry, domestically and through international trade.

Hydrogen distribution systems are a vital part of energy storage networks, enabling hydrogen to be stored, transported and delivered to end users. The choice of distribution pathway, and its viability, depends on a multitude of factors including volume, delivery distance and terrain, infrastructure availability and chemical preferences; all of which are interrelated. Where possible, maintaining hydrogen in its cryogenic form can minimise conversion losses; however liquid distribution systems suffer many similar challenges to tank storage requiring material advancements to improve longevity at cryogenic temperature and maximise storage and distribution efficiencies.

Boil-off is a challenge for liquid hydrogen trailers, exacerbated by movement which may occur via transportation. To reiterate the target established above, the US DOE and Clean Hydrogen Joint Undertaking (EU) have communicated a goal to eliminate boil-off in all liquid hydrogen systems, largely via improvements in insultation technologies or integration of absorbent materials that allows for boil-off recapture.[164] Enhancing the durability of trailers and tanks is also essential. Materials must maintain structural integrity and insultation performance at temperatures approaching -250°C. Material assessments and durability

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[163] International Energy Agency (IEA) (2023) Clean Technology Guide. <https://www.iea.org/topics/clean-energy-technology> (accessed 10 December 2024).

[164] U.S. Department of Energy (2024) Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf> (accessed 13 January 2025); European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 January 2025).

testing at cryogenic conditions can support the development of strategies for extending material lifespan (Target: >30years, cf. 30 years).[165]

For international distribution, liquid tanks are a preferred for transport. These adapted LNG tankers require specialised thermal insultation to minimise boil-off gas rates during transit. Further innovations could enable insultation and thermal management systems that accommodated larger tanks (target: up to 30,000m^3, c.f., 4,700m^3).[166] On loaded trips, tankers aim to use boil-off gas as fuel, reducing fuel costs and emissions; RD&D is ongoing to develop more efficient recovery systems.

Pertaining to ecological risk mitigation, RD&D could support the development of oxygen displacement and enrichment (or other techniques) to reduce hazards associated with large liquid hydrogen spills.[167]

For other hydrogen distribution pathways, refer to *5.6.1 Compressed hydrogen tank* (gaseous distribution) and *5.6.5 Ammonia* (ammonia tanker & LOHC).

Storage costs can also be reduced by improving the performance characteristics conditioning processes; namely the efficiency of liquefaction equipment.

Liquefaction involves compressing and cooling hydrogen gas below its boiling point. The process requires at least 12 MJ/kg, which is about 64% more energy than converting hydrogen into a high-pressure gas.[168] When accounting for real world inefficiencies, current processes demand about 43 to 54MJ/kg. Given the energy intensive nature of this process, reducing the energy intensity of hydrogen liquefaction is central to improving round-trip efficiency and lowering storage costs in line with LCOS forecasts ($2.42/kg, cf. $3.19/kg). Central to reaching these targets are efforts to reduce energy consumption to 6-8kWh/kg$_{LH2}$ (c.f., 10-12kWh/kg$_{LH2}$).[169]

Efficiency gains may be delivered through the adoption of high-performance components, including compressors, expanders, heat exchangers, and insultation materials. [170] As well as system-level integration of high-grade cold energy recovery. This includes harnessing waste cold from co-located industrial processes or recovered boil-off, and may involve RD&D into novel mixed refrigerants and cold storage material. Development and demonstrations at scale will be required to verify the operability, cost effectiveness, and technical readiness of these higher efficiency liquefaction systems.

5.6.5 Ammonia

Ammonia is an inorganic chemical compound of nitrogen and hydrogen (NH_3), that can serve as a chemical hydrogen storage medium. Ammonia can be stored as liquid under close to ambient conditions in tanks, for

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[165] U.S. Department of Energy (2023) DOE Technical Targets for Hydrogen Delivery. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. <https://www.energy.gov/eere/fuelcells/doe-technical-targets-hydrogen-delivery> (accessed 13 January 2025).

[166] Kytömaa H, Wechsung A, Dimitrakopoulos G, Cook N, Jaimes D, Hur IY, Faraji S (2024) Industry R&D needs in hydrogen safety. Applications in Energy and Combustion *Science* 18, 100271. https://doi.org/10.1016/j.jaecs.2024.100271

[167] Kytömaa H, Wechsung A, Dimitrakopoulos G, Cook N, Jaimes D, Hur IY, Faraji S (2024) Industry R&D needs in hydrogen safety. Applications in Energy and Combustion *Science* 18, 100271. https://doi.org/10.1016/j.jaecs.2024.100271

[168] Banijamali SM, Ilinca A, Afrouzi AA, Rousse DR (2025) Optimizing Hydrogen Liquefaction Efficiency Through Waste Heat Recovery: A Comparative Study of Three Process Configurations. Processes 13(5):1349. https://doi.org/10.3390/pr13051349

[169] This also approximately aligns with identified DOE target of reducing energy consumption by 50% compared to current consumption levels (based on an 300 tonnes per day liquefaction plant). European Clean Hydrogen Alliance (2023) Clean Hydrogen JU SRIA Key Performance Indicators (KPIs). European Clean Hydrogen Alliance. <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> (accessed 13 January 2025); U.S. Department of Energy (2024) Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf>

[170] Al Ghafri SZ, Munro S, Cardella U, et al. (2022) Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Energy & Environmental Science 15, 2690-2731. https://doi.org/10.1039/D2EE00099G

example, -33°C at atmospheric pressure or ~10 bar pressure at atmospheric temperature.[171] It offers deployment advantages as a chemical with pre-existing industrial use cases, handling, storage and distribution infrastructure, and well-established regulation and safety procedures. Ammonia is less flammable than hydrogen and leakages are easier to detect. However, its toxicity poses risks to both personnel and environments, necessitating new risk assessments and tailored safety protocols where new industries are considering its adoption. It also has a higher energy density (12.7 MJ/L), even compared to liquid hydrogen (8.5 MJ/L), which can simplify storage requirements.

Primary technologies

Ammonia tanks are commercial and well established. However, there are RD&D opportunities to lower the cost of ammonia production through incremental process improvements and new pathway development.

Conventional ammonia synthesis involves hydrogen production via SMR which is combined with atmospheric nitrogen, separated from air by a cryogenic process, to form $NH_{3.}$ The reaction between nitrogen and hydrogen is termed the Haber-Bosch (HB) process and requires high temperatures (>400°C) and pressures (>200 bar), making it capital- and energy-intensive.[172] Renewable ammonia production can utilise existing HB infrastructure, instead coupled with electrolytic hydrogen production rather than fossil-fuel sourced hydrogen. This enables retrofitting of existing ammonia plants without major disruption.[173] Several MW-scale demonstrators have been announced, with some operational.[174]

To meet cost forecasts ($1.34/kg in 2050, c.f., $1.94/kg), there are opportunities to improve process efficiencies of production inputs. Electrolytic hydrogen production is costly in comparison to conventional feedstock, driving up feedstock and overall production costs (See 'Levelised cost'). RD&D efforts to reduce electrolyser and electricity costs and improve process efficiency will therefore improve the economics of downstream ammonia synthesis (See the *Hydrogen supply* section). Notably, solid oxide electrolysis systems that can utilise waste heat from the HB plant, may be particularly amenable by allowing for higher system efficiencies compared to low-temperature electrolysis systems.

To reduce system costs and better align with renewable energy supply, there opportunities to optimise HB routes for new system dynamics and develop new synthesis pathways. The partial inflexibility of the HB process, which typically operates at a continuous rate, is unable to readily adjust production in response to VRE availability.[175] RD&D can support improved integration by enhanced dynamic response an distributed energy supply. There are also a range of emerging modular synthesis routes for currently under development, such as electrochemical routes (TRL 1-2), chemical looping (TRL 1-4) and biological nitrogen fixation (TRL 1), which seek to bypass the need for dedicated hydrogen feedstock altogether.[176] While these

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[171] International PtX Hub (2024) Ammonia transport and storage. <https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-transport-and-storage.pdf> (accessed 14 January 2025).

[172] MacFarlane DR, Cherepanov PV, Choi J, Suryanto BHR, Hodgetts RY, Bakker J, Ferrero Vallana FM, Simonov AN (2021) A roadmap to the ammonia economy. ARC Centre of Excellence for Electromaterials Science, School of Chemistry, Monash University, Clayton, Victoria, Australia. <https://researchmgt.monash.edu/ws/portalfiles/portal/310071142/310069820_oa.pdf> (accessed 14 January 2025).

[173] MacFarlane DR, Cherepanov PV, Choi J, Suryanto BHR, Hodgetts RY, Bakker J, Ferrero Vallana FM, Simonov AN (2021) A roadmap to the ammonia economy. ARC Centre of Excellence for Electromaterials Science, School of Chemistry, Monash University, Clayton, Victoria, Australia. <https://researchmgt.monash.edu/ws/portalfiles/portal/310071142/310069820_oa.pdf> (accessed 14 January 2025).

[174] Ammonia Energy (2023) Technology status: Ammonia production from electrolysis-based hydrogen. <https://ammoniaenergy.org/articles/technology-status-ammonia-production-from-electrolysis-based-hydrogen/> (accessed 13 January 2025).

[175] Salmon N, Bañares-Alcántara R (2023) Impact of process flexibility and imperfect forecasting on the operation and design of Haber–Bosch green ammonia. RSC Sustainability 2023(4) 923-937. https://doi.org/10.1039/D3SU00067B

[176] Royal Society (2020) Green ammonia: Policy briefing. The Royal Society, London. <https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf> (accessed 14 January 2025).

alternatives remain at low TRL, they offer long-term potential for lower energy use, improved operational flexibility, and reduce chemical conversion related costs.[177]

Hydrogen retrieval and purification processes can be energy-intensive, presenting opportunities to lower costs through further RD&D.

To regenerate hydrogen gas after storage, NH_3 must be cracked (or catalytically decomposed) into hydrogen and nitrogen at high temperature (700°C). This can be achieved with inexpensive materials like iron, but to reduce energy requirements and operational costs, low temperature cracking methods under investigation. These often rely on the use of expensive rare-metal catalysts (like ruthenium), and RD&D could improve catalyst performance and durability and reduce reliance on expensive raw materials.[178]

Hydrogen required from cracking may also require purification, depending on end-use specification. Conventional separation approaches, such as cryogenic condensation of ammonia, are energy-intensive and face efficiency trade-offs if not efficiently heat integrated.[179] Alternative methods, such as membrane- and absorption-based separation, would benefit from further RD&D to improve selectivity, regeneration efficiency and long-term durability.[180]

Auxiliary technologies

Ammonia offers a technically mature and energy-dense option for international hydrogen distribution, although targeted RD&D is needed to improve transport efficiency, safety and its dual use potential.

Ammonia is already transported globally at-scale using refrigerated, non-pressurised vessels, often designed to carry liquefied petroleum gas (LPG), making it a preferred hydrogen carrier for long-distance shipping. Although ammonia storage facilities are expensive, ammonia is easier than molecular hydrogen to transport. When considering storage and transport together, ammonia-based hydrogen transport could be more cost-effective than moving molecular hydrogen directly, especially given the technological challenges of hydrogen transport.

Ongoing RD&D efforts aim to enhance system efficiencies, reduce losses by minimising and recapturing ammonia boil off; and design dual-purpose storage tanks and combustion systems to allow for ammonia-fuelled propulsion on carrier ships. Advancements in safety protocols and environmental controls will be critical to support large-scale adoption of ammonia-based hydrogen transport.

For other hydrogen distribution pathways, refer to *5.6.1 Compressed hydrogen tank* (gaseous distribution) and *5.6.4 Cryogenic sphere* (liquid transport).

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[177] Soloveichik G (2022) CSP for ammonia production. US Department of Energy, Hydrogen and Fuel Cell Technologies Office and ARPA-E. <https://www.energy.gov/sites/default/files/2022-02/Soloveichik%20-%20HFTO%2BARPAE%20-%20CSP%20for%20Ammonia%20Production.pdf> (accessed 14 January 2025).

[178] Royal Society (2020) Green ammonia: Policy briefing. The Royal Society, London. <https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf> (accessed 14 January 2025).

[179] Chen J, Li D, Klemeš JJ, Qian Y, Yang S (2021) A sustainable syngas cryogenic separation process combined with ammonia absorption refrigeration pre-cooling cycle. Journal of Cleaner Production 313, 127612. https://doi.org/10.1016/j.jclepro.2021.127612; Appl M (2011) Ammonia, 2. Production Processes. Ullmann's Encyclopedia of Industrial Chemistry. https://doi.org/10.1002/14356007.o02_o11

[180] Lamb KE, Dolan MD, Kennedy DF (2019) Ammonia for hydrogen storage: A review of catalytic ammonia decomposition and hydrogen separation and purification. International Journal of Hydrogen Energy 44(7), 3580–3593. https://doi.org/10.1016/j.ijhydene.2018.12.024; International PtX Hub (2024) Ammonia nitrogen and green hydrogen: Production and purification. International PtX Hub, Berlin. https://ptx-hub.org/wp-content/uploads/2024/01/International-PtX-Hub_202401_Ammonia-nitrogen-and-green-hydrogen-production-and-purification.pdf (accessed 14 January 2025).

6 Synthetic fuels (synfuels)

Executive summary

There are multiple pathways emerging to produce synthetic alternatives to replace fossil-derived fuels, and RD&D is needed to demonstrate these technologies are commercially viable.

Technology Landscape

Synthetic fuels (synfuels) are liquid or gaseous hydrocarbons synthesised from renewable energy and non-fossil feedstocks, and they offer scalable pathways to decarbonisation. Synfuels are closely related to e-fuels, a broader category encompassing all fuels produced from renewable electricity. Methanol can serve as both an energy carrier and a chemical feedstock, while power-to-liquids fuels, including renewable diesel and gasoline, can be refined to meet existing fuel specifications.

Power-to-liquids fuel production pathways

RD&D Opportunities

Power-to-liquids fuel production pathways

- Although Fischer-Tropsch (FT) synthesis is the most mature pathway at demonstration phase, with FT fuels approved for commercial use in aviation, RD&D efforts to scale critical inputs and reduce costs are required to grow the scale of this technology. Similar to methanol synthesis, this involves reducing the cost of acquiring hydrogen and CO_2. Efforts to improve reaction efficiencies can also help to make more economical use of these inputs.
- Other potential production pathways (methanol-to-jet and methanol-to-gasoline) that require RD&D to improve the associated chemical reaction and demonstrate the pathway with direct air capture.
- e-Methanol is currently challenged by its production costs, which are linked to the cost of hydrogen and CO_2. RD&D to improve electrolyser utilisation, efficiency and durability will have positive impacts on the cost of hydrogen production and upstream methanol synthesis. Similarly, acquiring cost effective CO_2 at scale will have similar impacts, whether from direct air capture, bioenergy with carbon, capture and storage (BECCS) or point-source industrial processes.
- Other pathways, include indirect CO hydrogenation and direct CO_2 hydrogenation, require RD&D to optimise reaction conditions and methanol conversion rates.

Levelised cost analysis

Note: Synthetic fuel technologies are explored in the *Transport* technical appendix for the shipping and aviation subsectors, with additional potential applications beyond the scope of this project. This subsector presents RD&D opportunities associated with synthetic fuel production, encompassing both fuel synthesis and the generation of inputs, for information purposes only. As no use case was defined, no levelised cost analysis was performed.

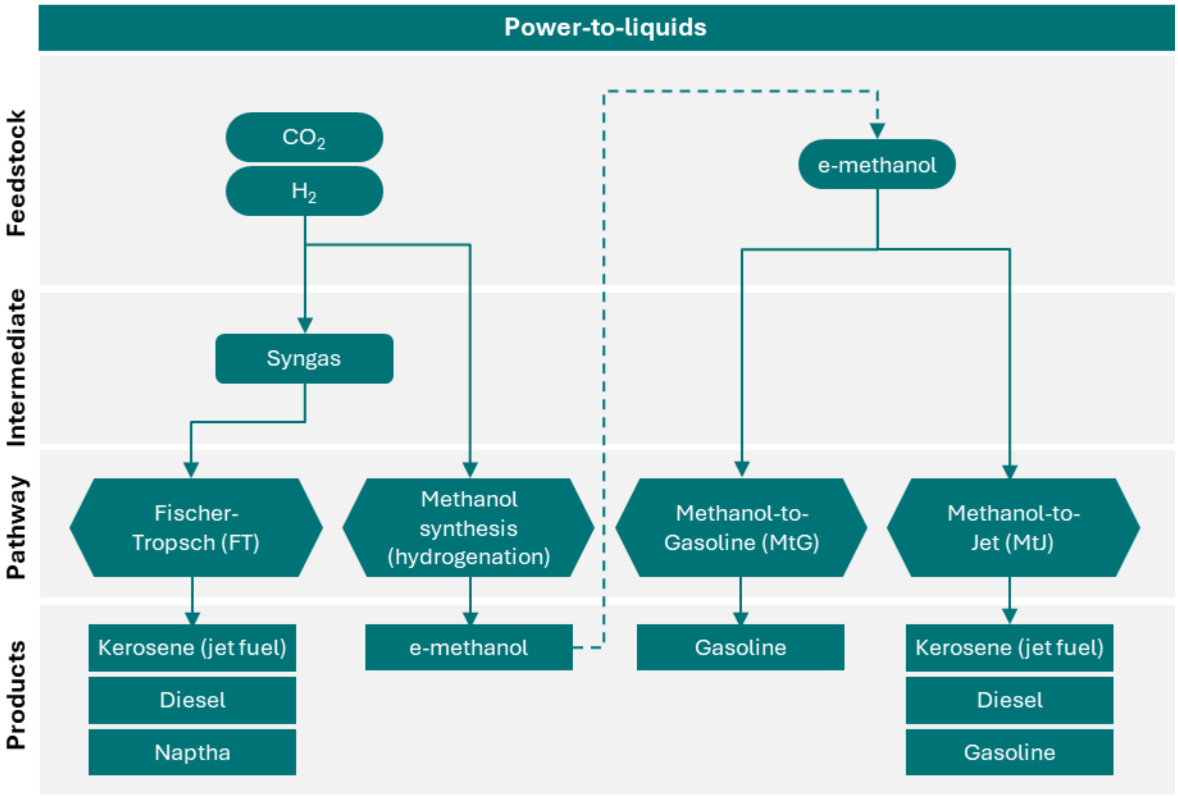
Overview

Synthetic fuels (synfuels) are liquid or gaseous hydrocarbons synthesised from renewable energy and non-fossil feedstocks, offering scalable pathways to decarbonisation. Hydrogen-based e-fuels produced from renewable electricity, such as ammonia, are addressed in the Hydrogen section of this report (see *Section 5 Hydrogen storage*). This section focuses on liquid synthetic fuels identified for the use cases in the aviation and shipping subsectors of the *Transport* technical appendix, which included power-to-liquids (PtL) and methanol, produced through the combination of electrolytic hydrogen and captured CO_2.

Synfuel production typically involves the generation of a syngas intermediate, a gas comprised of hydrogen and carbon monoxide, as depicted in Figure 15. For renewable synfuel pathways, hydrogen is produced via water electrolysis and CO_2 sourced from the atmosphere, biogenic resources or industrial point sources. These are discussed in the *Hydrogen production* section and *Carbon Management* technical appendix, respectively. This syngas serves as a feedstock for Fischer-Tropsch (FT) synthesis, methanol synthesis (hydrogenation), or other catalytic pathways, yielding hydrocarbon fuels with tailored properties.

These pathways enable the conversion of renewable energy into high-density hydrocarbons that can be stored, transported and used to replace fossil-derived fuels. Methanol can serve as both an energy carrier and a chemical feedstock, while other PtL fuels, including renewable diesel, gasoline, and aviation biofuels, can be refined to meet existing fuel specifications.

Figure 15: Simplified synthetic power-to-liquids fuel pathways explored across the *State of Energy Transition Technologies*[181]



The large-scale production of synthetic fuels could be constrained by the availability of captured CO_2. While point source capture could meet a portion of production demand, scaled manufacture will need emerging

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[181] Adapted from CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; IRENA and Methanol Institute (2021) Innovation Outlook: Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.<https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf>

carbon capture technologies that are currently cost prohibitive. Synfuel production is also heavily tied to renewable energy generation and electrolyser capacity, creating further dependencies.

6.1 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the associated technology landscape, spanning primary and auxiliary technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include **non-technical RD&D opportunities.** Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

Synthetic fuel technologies, specifically power-to-liquids fuels and methanol as a fuel, are explored in the *Transport* technical appendix for the shipping and aviation subsectors, with additional potential applications beyond the scope of this project. This section presents RD&D opportunities associated with the production pathways of these fuels, encompassing both fuel synthesis and the generation of inputs, for information purposes only.

6.1.1 Power-to-liquids (PtL) fuel production pathways

Power-to-liquids (PtL) is an umbrella term for processes that involves the production of fuels using non-biogenic feedstocks, such as hydrogen and CO_2, along with renewable energy sources.

Electrolytic hydrogen is then combined with CO_2 from carbon capture technologies to synthesise hydrocarbons. These hydrocarbons are transformed into synthetic fuels through a range of production processes, including Fischer-Tropsch (FT) and methanol synthesis (hydrogenation), which extends into other downstream pathways, including methanol-to-jet (MtJ) and methanol-to-gasoline (MtG).[182] Over 50 power-to-X (PtX) pilot projects have begun worldwide, indicating increased interest in synthetic fuels.[183]

Conventional methanol synthesis is emissions intensive. Methanol is generally produced via a process of natural gas steam methane reforming (SMR) and, to a lesser extent, coal gasification. In SMR-based production, natural gas is converted into a synthesis gas (syngas), a mixture of H_2, CO, and CO_2, which is subsequently processed into methanol through a synthesis loop.[184] Low-emissions methanol can be produced via two primary pathways. Biomethanol is derived from biomass feedstocks, through thermochemical or biochemical conversion processes. E-methanol is synthesised from electrolytic hydrogen

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[182] Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T (2018) Power-to-Liquids as Renewable Fuel Option for Aviation: A Review. Chem Ing Tech 90, 127. doi:10.1002/cite.201700129; Van Dyk S, Saddler J (2021) Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, potential and challenges; Detsios N, Theodoraki S, Maragoudaki L, Atsonios K, Grammelis P, Orfanoudakis NG (2023) Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review. Energies (Basel) 16,. doi:10.3390/en16041904; Ansell PJ (2023) Review of sustainable energy carriers for aviation: Benefits, challenges, and future viability. Progress in Aerospace Sciences 141,. doi:10.1016/j.paerosci.2023.100919

[183] Ansell PJ (2023) Review of sustainable energy carriers for aviation: Benefits, challenges, and future viability. Progress in Aerospace Sciences 141,. doi:10.1016/j.paerosci.2023.100919; Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T (2018) Power-to-Liquids as Renewable Fuel Option for Aviation: A Review. Chem Ing Tech 90, 127. doi:10.1002/cite.201700129; Detsios N, Theodoraki S, Maragoudaki L, Atsonios K, Grammelis P, Orfanoudakis NG (2023) Recent Advances on Alternative Aviation Fuels/Pathways: A Critical Review. Energies (Basel) 16,. doi:10.3390/en16041904

[184] Dalena F, Senatore A, Marino A, Gordano A, Basile M, Basile A (2018) Chapter a – Methanol Production and Applications: An Overview. https://doi.org/10.1016/B978-0-444-63903-5.00001-7.

and captured CO_2. This section primarily focused on RD&D opportunities associated with the production of e-methanol as a synthetic fuel.

Primary technologies

Varying production pathways are in development with ongoing RD&D required to address technical challenges, including process efficiency, catalyst development and scale-up.

Multiple power-to-liquid pathways are under active development, with varying levels of technical maturity and scale-up potential. FT synthesis is currently the most advanced, approved for aviation use by the International Civil Aviation Organisation. In contrast, MtJ and methanol-to-gasoline (MtG) remain at earlier stages of development.[185]

To date, RD&D has largely focused on process design and catalyst optimisation to improve conversions efficiencies and identify technology pathways with industrial prospects.[186] Continued research centred on the scale up of critical inputs, improving syngas conversion efficiencies and reducing the energy penalty of the reverse water gas shift reaction step can further development.

Beyond FT-fuels, alternative PtL routes aim to produce a range of hydrocarbons. MtG pathways, which convert methanol to gasoline-range hydrocarbons (C5-10), are commercially proven using fossil-based methanol[187] but is yet to be demonstrated with e- or bio-derived substitutes. MtJ pathways convert methanol to light olefins (C4-C8), which are oligomerised into hydrocarbons for jet fuel (C8-C15). These processes face technical hurdles including catalyst stability and selectivity.[188]

As a platform chemical, RD&D to improve methanol conversion pathways can enhance product yields, energy efficiency and hydrogen recovery to unlock broader value across chemicals, fuels and hydrogen supply chains.

Methanol is often utilised in subsequent reaction pathways to derive various chemicals, plastics, materials, and fuels. For example, methanol-to-olefins (MtO) processes account for 25% of global methanol consumption,[189] meanwhile methanol-to-gasoline (MtG) processes play an important role in deriving products suited for use as combustion fuels. Other methanol-to-X processes are product specific. Improving the energy efficiencies and scalability of derivative pathways can allow enhanced production of various products. Methanol can also act a hydrogen carrier, and the development of efficient dehydrogenation technologies to generate hydrogen could assist in shoring up hydrogen supply chains, but this is challenged by the energy inefficiency of the process and the importance of utilising the carbon resources used to produce the methanol.

Upstream reductions of feedstock and electricity costs could significantly lower the cost of PtL and methanol production.

To meet cost forecasts ($1.94/L in 2050, c.f., $5.01/L), there are opportunities to improve process efficiencies of production inputs (hydrogen and CO_2). Electrolytic hydrogen production is costly in comparison to conventional feedstock, driving up feedstock and overall production costs (See 'Levelised cost'). RD&D efforts

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[185] Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T (2018) Power-to-Liquids as Renewable Fuel Option for Aviation: A Review. Chem Ing Tech 90, 127. doi:10.1002/cite.201700129

[186] Zhao J, Yu Y, Ren H, Makowski M, Granat J, Nahorski Z, Ma T (2022) How the power-to-liquid technology can contribute to reaching carbon neutrality of the China's transportation sector? https://doi.org/10.1016/j.energy.2022.125058

[187] Exxon Mobil (2021) Fluidized bed methanol to gasoline (MTG): A reliable and cost-effective solution for production of renewable gasoline. <https://www.exxonmobilchemical.com/en/resources/library/library-detail/90446/fluidized_bed_methanol_to_gasoline_mtg_v6>

[188] Eyberg V, Dietrich V, Bastek S, Dossow M, Spliethoff H, Fendt S (2024) Techno-economic assessment and comparison of Fischer–Tropsch and Methanol-to-Jet processes to produce sustainable aviation fuel via Power-to-Liquid. https://doi.org/10.1016/j.enconman.2024.118728

[189] IRENA and Methanol Institute (2021) Innovation outlook: renewable methanol. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

to reduce electrolyser and electricity costs and improve process efficiency will therefore improve the economics of downstream methanol synthesis (See the *Hydrogen supply* section).[190] CO_2 cost is highly dependent on how it is sourced and can be acquired from biogenic sources, the atmosphere, as well as captured from the by-product streams of other industrial processes. This is covered in more detail in the *Carbon Management* technical appendix.

Incremental methanol synthesis process improvements and new pathway development could lead to further cost reductions.

Indirect CO hydrogenation mirrors conventional methanol synthesis routes, involving a two-step process involving a reverse water gas shift reaction followed by conventional syngas-to-methanol conversions. Though benefitting from similar catalyst and reactor designs to conventional processes, opportunities remain to enhance system efficiency through improved thermal integration to increase system efficiency and improved syngas composition control to increase methanol conversion rates.[191]

Direct CO_2 hydrogenation (also referred to as power-to-methanol or catalytic hydrogenation), is a more novel route under development. This single-step reaction between CO_2 and H_2 at moderate temperature (200-300°C) and pressure (30-80 bar) offers the potential for simplified reactor designs and scaling capacity and high responsiveness to fluctuating energy inputs.[192] Continuing RD&D to intensify production processes can support the development of this pathway, including by optimising reaction conditions and developing reactors that remove methanol as it is produced to shift the equilibrium forward. [193]

Both pathways would benefit from cross cutting efforts in catalyst development. The development of more active, stable and selective catalysts, particularly those that operate in milder temperature conditions, can reduce energy demands, enhance kinetics and prevent degradation under long-term operation.[194]

Though not discussed or modelled in this report, bio-methanol could present a more cost competitive solution compared to e-methanol production depending on the source of CO_2.[195]

If sustainable feedstock supply could be established, opportunities to simplify the feedstock logistics and the co-production of heat, electricity or other chemicals could improve overall plant economics (see *Section 7 Biofuels* for general discussion of bio-based fuel RD&D opportunities).[196]

Auxiliary technologies

The feasibility and viability of PtL and methanol production depends on the reliability of supporting networks, including low-cost renewable hydrogen, electricity, carbon capture, and logistics.

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[190] IRENA and Methanol Institute (2021) Innovation Outlook: Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.<https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf>

[191] Wolday A, Gujarathi A (2023) Multi-objective optimization of methanol production for energy efficiency and environmental sustainability. https://doi.org/10.1016/j.compchemeng.2023.108426; Scomazzon M, Barbera E, Bezzo F (2024) Alternative sustainable routes to methanol production: Techno-economic and environmental assessment. https://doi.org/10.1016/j.jece.2024.112674; Wolday A, Gujarathi A (2023) Multi-objective optimization of methanol production for energy efficiency and environmental sustainability. https://doi.org/10.1016/j.compchemeng.2023.108426; Scomazzon M, Barbera E, Bezzo F (2024) Alternative sustainable routes to methanol production: Techno-economic and environmental assessment. https://doi.org/10.1016/j.jece.2024.112674

[192] Borisut P and Nuchitprasittichai A (2019) Methanol production via CO_2 hydrogenation: sensitivity analysis and simulation-based optimization. Frontiers in Energy Research 7(81). < https://doi.org/10.3389/fenrg.2019.00081>

[193] Sollai S, Porchu A, Tola V, Ferrara F, Pettinau A (2023) Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment. https://doi.org/10.1016/j.jcou.2022.102345

[194] Alamia A, Partoon B, Rattigan E, Andresen G (2024) Optimizing hydrogen and e-methanol production through Power-to-X integration in biogas plants. https://doi.org/10.1016/j.enconman.2024.119175; Sollai S, Porchu A, Tola V, Ferrara F, Pettinau A (2023) Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment. https://doi.org/10.1016/j.jcou.2022.102345

[195] IRENA and Methanol Institute (2021) Innovation outlook: renewable methanol. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

[196] IRENA and Methanol Institute (2021) Innovation outlook: renewable methanol. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf

With greater reliance and ties to renewable energy patterns, the development of methanol plants that are able to accommodate dynamic fluctuations in electricity power generation and hydrogen and CO_2 feedstocks would be advantageous. However, there are numerous opportunities to for upstream developments.

For hydrogen production, storage and distribution, refer to the *Hydrogen production* and *Hydrogen (and derivatives) storage* sections.

For electricity generation and storage, refer to the *Electricity* technical appendix.

For carbon capture, refer to the *Carbon Management* technical appendix.

7 Biofuels

Executive summary

While biofuels have the potential to play a valuable role in Australia's low-emission energy mix, their adoption will require further RD&D needed to ensure sustainability of supply.

Technology Landscape

Several technologies explored as part of this analysis, particularly in the transport sector, could leverage biofuels – renewable fuels produced from biogenic feedstocks – as an energy source. The 'drop-in' nature of some biofuels can overcome challenges associated with long asset lifetimes and limited alternative infrastructure options. However, the use of biogenic feedstocks has land use trade-offs that require consideration and ensuring sustainability of supply will ultimately shape the scale and role that biofuels can play.

Feedstock production

Hydroprocessed esters and fatty acids (HEFA) synthesis
Alcohol-to-jet (AtJ) synthesis
Renewable diesel synthesis
Fischer-Tropsch (FT) synthesis
Biomethane synthesis
Production pathways

RD&D Opportunities

Feedstock production	• RD&D, particularly demonstration and testing, can improve feedstock production through the exploration of alternative feedstocks, such as those cultivated on marginal lands or in aquatic environments and those with higher growth rates. • Improvements in future farming systems, alternative approaches to cropping and advances in genetic engineering and synthetic biology can also contribute to increased biomass yields.
Production pathways	
HEFA synthesis	• RD&D to improve the reaction rates and yields of HEFA production pathways will be critical for improving the resource efficiency of limited feedstocks. • Exploring opportunities to valorise and convert captured hydrocarbons into other value-added products could improve the economics of HEFA synthesis.
FT synthesis	• There are opportunities to reduce the sensitivity of the process to the consistency of the feedstock through RD&D on pretreatment and sorting technologies, as well as post-processing methods that can further remove impurities and balance gas composition. • High capital costs associated with FT synthesis could be reduced through RD&D by targeting advancements in catalysts and reactor designs.
AtJ synthesis	• By advancing resilient catalytic materials and expanding the range of viable alcohol feedstocks, RD&D can unlock greater process efficiency, operational longevity, and feedstock flexibility.
Biomethane synthesis	• RD&D opportunities in biomethane production focus on boosting system efficiency and reliability through innovations in microbial management, reactor and pre-treatment technologies, and advanced gas upgrading methods.
Renewable diesel synthesis	• Renewable diesel can be produced through several pathways, including HEFA, FT and AtJ synthesis. Across these pathways, RD&D into catalysts and process conditions can be used to improve selectivity towards diesel-range compounds.

Levelised cost analysis

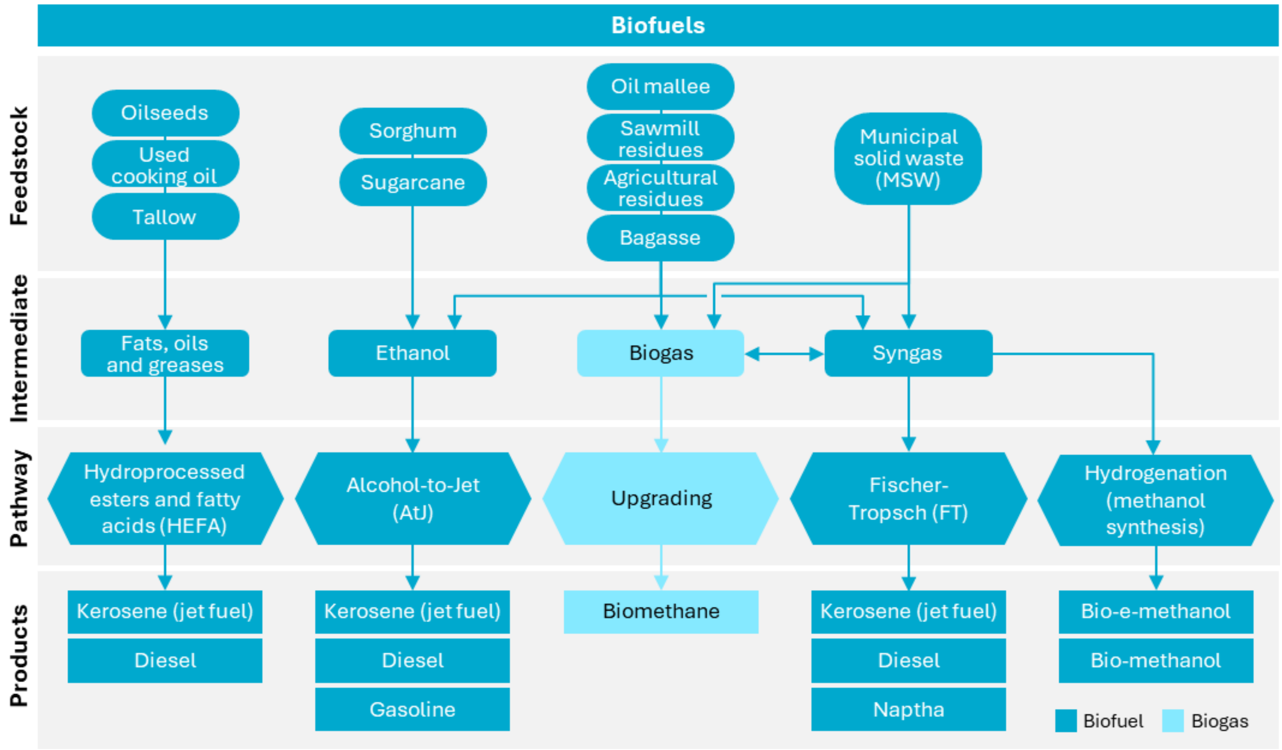
Note: Biofuel technologies are explored in the *Electricity* and *Transport* technical appendices, with potential applications extending beyond the scope of this project. This subsector presents RD&D opportunities associated with biofuel production, encompassing both fuel synthesis and the generation of inputs, for information purposes only. As no use case was defined, no levelised cost analysis was performed.

Overview

Biofuels are renewable liquid fuels produced from biogenic feedstocks. This section explores RD&D opportunities associated with the production of biofuel feedstock, three key liquid biofuel pathways: hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (AtJ), and Fischer-Tropsch (FT) synthesis, and biomethane production, as a renewable gas product. These technologies convert various biomass materials, such as oils, residues and waste materials, into drop-in replacements for conventional fossil fuels.

As displayed in Figure 16, these biofuel and biogas pathways offer the opportunity to co-produce hydrocarbon products. Processes are optimised to achieve product distributions based on refining conditions and market demands.

Figure 16: Simplified biofuel pathways explored across the *State of Energy Transition Technologies*[197]



Biofuels present opportunities for decarbonisation in sectors that require high-energy density fuels, and where their 'drop in' nature can overcome challenges associated with long asset lifetimes and infrastructure compatibility. In the aviation subsector, however, biofuels are certified for use as a drop-in blend with conventional jet fuel, typically up to 50% v/v, though ongoing research aims to enable higher blend rates and eventual 100% certification (see *Transport - Aviation* technical appendix). Biofuels could replace fossil-derived fuels in aviation, heavy transport, and industrial applications, while also serving as chemical feedstocks. Importantly, achieving market ready biofuels across various feedstocks and production pathways is a more impactful factor in achieving economy-wide emissions reduction goals, than targeting particular applications.[198]

While biofuels have the potential to play a valuable role in Australia's low emissions energy mix, their broader adoption will depend on the accurate assessment and considered management of biomass resources. Crop-based biofuels can compete with agriculture for land, water and other resources, while waste-feedstocks are

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[197] Adapted from CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; IRENA and Methanol Institute (2021) Innovation Outlook: Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.<https://www.methanol.org/wp-content/uploads/2020/04/IRENA_Innovation_Renewable_Methanol_2021.pdf>

[198] CSIRO (2025) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia. CSIRO, Canberra.

constrained by complex collection logistics and variability in quality. To maximise abatement potential through the establishment of a biofuels industry, a full range of feedstocks and commercial pathways are required, that can service end uses beyond a few select applications. Even with RD&D advancements to improve feedstock yields and conversion rates, the sustainable supply of biomass will ultimately shape the scale and role that biofuels will play in a future energy mix. For offtakers, adoption will be tied to the cost, availability and access of sustainable biomass. Beyond RD&D, coordinated infrastructure and supply chain planning, sustainability verification and policies will be required to ensure biofuels are deployed strategically and sustainably.

7.1 RD&D opportunity analysis

Key information – RD&D opportunity analysis

Continued RD&D will play a key role in maintaining current technology trajectories and can be used to create impactful improvements in technological outcomes related to cost and performance.

To support government and industry decision makers, this analysis identifies RD&D opportunities for the associated technology landscape, spanning primary and auxiliary technologies.

They have been developed based on a literature review and stakeholder input. Where possible, the analysis identifies cost projections or quantitative targets for technology development. These have been informed by model cost projections, literature, and the input of subject matter experts.

The analysis does not include **non-technical RD&D opportunities.** Although out of scope, research related to policy and regulation, social licence and participation, communication and engagement and governance are important drivers for the progression and adoption of low emission technologies.

Biofuel technologies are explored in the *Electricity* and *Transport* technical appendices. Biofuels present a transitionary solution, given their high energy density and ‘drop in’ nature which allows for the continued use of assets and infrastructure as new systems are developed. Notably, renewable diesel offers a direct replacement for conventional diesel, while biomethane is a direct replacement for natural gas. Uses are varied, with potential applications extending beyond the scope of this project.

This subsector presents RD&D opportunities associated with fuel and feedstock production, encompassing both fuel synthesis and the generation of inputs, for information purposes only.

7.1.1 Feedstock production

Primary technologies

Biofuel costs are closely tied to feedstock prices. RD&D that improves yields and processing efficiency can help shield against high production costs while easing land pressures by making better use of available resources.

Biogenic feedstocks are less energy dense than fossil sources, requiring greater feedstock input to produce the equivalent fuel yields.[199] These inefficiencies and high input costs make feedstock a dominant cost driver in biofuel pathways. The levelised cost analysis (see *Transport – Aviation* technical appendix), suggests that reductions in the cost of feedstock processing could reduce the production cost of aviation biofuels (B100) from $2.20-2.83/L today to $1.36-1.52/L by 2050. RD&D that improves feedstock conversion rates and resource efficiency can therefore play a critical role in achieving these cost forecasts.

Advances in genetic engineering and synthetic biology can be applied to both crops and microorganisms to increase yields, improve tolerance to environmental stressors, and optimise fuel conversion processes. For

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[199] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra.

instance, higher-fibre sugarcane varieties can enhance feedstock availability for biofuel conversion, while engineered oil crops can be modified to enhance oil content and the carbon length of oil chains.[200] Genetic engineering may also improve biomass resilience to environmental stressors. This is also applicable for fuel production from residual feedstocks, in which microorganisms can be engineered to optimise yields and reduce CO_2 emissions during fuel synthesis.[201]

Exploring alternative, underutilised or unused feedstocks and farming models can expand biofuel supply while delivering environmental co-benefits.

Biomass yields, per acre, can be increased by exploring alternative, underutilised or unused feedstocks, such as those cultivated on marginal lands or in aquatic environments (i.e., avoiding competition food crops, land and freshwater resources), those with higher growth rates and unused residues and waste.[202] Alternatives, such as algae, energy grasses and bio-wastes, may also offer environmental co-benefits such as enhanced CO_2 sequestration during cultivation. [203] Future farming systems and alternative approaches to cropping, for example dual purpose or integrated cropping, can also deliver co-benefits to Australian farms while improving feedstock production. As an example, short rotation trees can provide windbreaks, animal shelter, native habitat, erosion protection, among other advantages, with the leaves and branches harvested every 3-10 years.[204]

Demonstration facilities are critical for scaling new feedstock-to-fuel value chains.

Demonstration and testing facilities will be a crucial element of establishing high-potential feedstock-technology combinations, particularly for second-generation lignocellulosic feedstocks and third-generation novel feedstocks.[205] Investment in research and demonstration can help to de-risk these technologies and progress to investment and accreditation stages.

Auxiliary technologies

Data-driven tools and methodologies can optimise bioresource management and guide investment in higher-performing systems.

A suit of analytical tools, including techno-economic assessment, life cycle analysis, and spatial mapping, can support the optimisation of feedstock systems by evaluating performance, emissions impacts, and cost trade-offs. These methods are key to identifying the most promising feedstock and processing combinations and informing long-term investment decisions.[206]

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[200] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; Matsuoka et al (2014) Energy Cane: Its Concept, Development, Characteristics, and Prospects. Advances in Botany.

[201] Godar A, Kamoku C, Nielsen D, Wang X (2021) Synthetic biology strategies to address waste CO2 loss during biofuel production. https://doi.org/10.1016/j.coesh.2021.100305

[202] See, for example, Ng KS, Farooq D, Yang A (2021) Global biorenewable development strategies for sustainable aviation fuel production. Renewable and Sustainable Energy Reviews 150,. doi:10.1016/j.rser.2021.111502.

[203] Elkelawy M, Bastawissi HAE, Radwan AM, Ismail MT, El-Sheekh M (2021) Biojet fuels production from algae: conversion technologies, characteristics, performance, and process simulation. In Handbook of Algal Biofuels: Aspects of Cultivation, Conversion, and Biorefinery. 331–361. Elsevier doi:10.1016/B978-0-12-823764-9.00003-0; Martinez-Villarreal S, Breitenstein A, Nimmegeers P, Perez Saura P, Hai B, Asomaning J, Eslami AA, Billen P, Van Passel S, Bressler DC, Debecker DP, Remacle C, Richel A (2022) Drop-in biofuels production from microalgae to hydrocarbons: Microalgal cultivation and harvesting, conversion pathways, economics and prospects for aviation. Biomass and Bioenergy 165,. doi:10.1016/j.biombioe.2022.106555. CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra.

[204] McGrath, J., K. Goss, M. Brown, J. Bartle and A. Abadi (2017). "Aviation biofuel from integrated woody biomass in southern Australia." WILEY INTERDISCIPLINARY REVIEWS-ENERGY AND ENVIRONMENT 6(2): e221.

[205] CSIRO (2025) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia. CSIRO, Canberra.

[206] CSIRO (2025) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia. CSIRO, Canberra.

Integrated spatial analysis and dynamic data platforms can further enhance visibility into crop and residue availability, field production, land use, and regional co-benefits, supporting the optimal siting of biofuel facilities and sustainable resource management over time.[207]

Improving feedstock logistics can support biofuel supply chains.

Biofuel production can benefit from improved integration processes and supply chain logistics across collection and harvesting systems, including transportation, storage, and pre-processing.[208] This could involve the transition from a conventional logistics system in which biomass is moved over short distances for short-term storage, to advanced logistics systems which deliver infrastructure-compatible feedstocks with specified physical and chemical characteristics, longer-term stability, and bulk-material characteristics that facilitate transport over longer distances.[209]

Pre-treatment innovations and smart sorting technologies can enhance feedstock quality and process reliability.

Large-scale supply chain restructures could benefit from the implementation of feedstock pretreatment and preprocessing to limit and control the variability in biomass quality and to avoid process complications such as catalyst poisoning. This could be supported by the integration of artificial intelligence and machine learning systems, for example, employing Smart waste sorting using advanced imaging.[210]

7.1.2 HEFA pathway

The HEFA pathway involves hydrogenation and isomerisation of lipids (i.e., fats, oils and greases) into long-chain hydrocarbons, followed by hydroprocessing to produce fuel products. As a mature, commercialised process, incremental improvements, rather than significant innovations, are the focus for cost and efficiency gains.[211]

In Australia, feedstocks are limited and highly sought after, making research areas for feedstock preparation of high importance.[212]

Primary technologies

Improving HEFA reaction efficiency can serve to maximise yields from constrained feedstock supply.

Enhancing reaction rates and yields are key research areas for improving resource efficiency of limited feedstocks. This could be achieved via intensification techniques,[213] or by managing lower molecular weight hydrocarbon byproducts which adversely affect process efficiency and product yields.[214] These

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[207] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; CSIRO (2025) Opportunities and Priorities for a Low Carbon Liquid Fuel Industry in Australia. CSIRO, Canberra.

[208] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; US DOE, US DOT, USDA, US EPA (2022) SAF Grand Challenge Roadmap Flight Plan for Sustainable Aviation Fuel.

[209] DOE (2015) Quadrennial Technology Review 2015: Biomass Feedstocks and Logistics. Chapter 7: Technology Assessments. <https://www.energy.gov/sites/prod/files/2016/01/f28/QTR2015-7B-Biomass-Feedstocks-and-Logistics.pdf>

[210] NREL (2021) With NREL's feedstock research, algae and garbage could be ingredients for zero emissions fuels of the future. <https://www.nrel.gov/news/program/2021/with-nrels-feedstock-research-algae-and-garbage-could-be-ingredients-for-zero-emissions-fuels-of-the-future.html> (accessed June 2024).

[211] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra

[212] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra

[213] García-Hernández A, Segovia-Hernández J, Sánchez-Ramírez E, Zarazúa G, Araujo I, Quiroz-Ramírez J (2024) Sustainable aviation fuel from Butanol: A Study in optimizing Economic and Environmental impact through process intensification. https://doi.org/10.1016/j.cep.2024.109769

[214] Główka M, Wójcik J, Boberski P, Białecki T, Gawron B, Skolniak M, Suchocki T (2024) Sustainable aviation fuel – Comprehensive study on highly selective isomerization route towards HEFA based bioadditives. https://doi.org/10.1016/j.renene.2023.119696; Tao L, Milbrandt A, Zhang Y, Wang C (2017) Techno-economic and resource analysis of hydroprocessed renewable jet fuel. *Biotechnol Biofuels*. https://doi.org/10.1186/s13068-017-0945-3

hydrocarbons, including C1-C4 hydrocarbons such as propane, are produced during hydroprocessing. Further RD&D that investigates opportunities to valorise and convert captured hydrocarbons into syngas or other value-added products can improve economic propositions.[215]

Catalyst advancements can enhance product selectivity and improve system flexibility.

Developing more resilient catalysts with higher selectivity can optimise kerosene and diesel yields while minimising the formation of hydrocarbons.[216] More resilient catalysts can limit fouling and degradation caused by impurities, reducing downtime and extending operational lifetimes.[217] Advancements in high-pressure hydrotreaters and hydrocrackers can also enhance process flexibility to accommodate more variable feedstock qualities.

Auxiliary technologies

Integrated process control systems can enable optimisation across variable feedstock and product requirements.

Developing integrated process monitoring and control systems can assist in optimising process and managing feedstock variability and select for desired products.[218]

Input availability and management is central to HEFA performance.

In the HEFA process, hydrogen is employed in the hydroprocessing stage, where lipids are hydrogenated and isomerised into long-chain hydrocarbons. For research opportunities related to hydrogen production, storage and distribution, refer to the *Hydrogen production* and *Hydrogen storage* sections.

7.1.3 FT pathway

The FT pathway converts syngas from biomass gasification into liquid hydrocarbons via catalytic synthesis. For FT synthesis, RD&D can be leveraged optimise both the production of the syngas intermediate and the FT fuel production process.

Primary technologies

Syngas production

Consistent, high-quality syngas underpins FT fuel production, and RD&D can enhance its yield, purity, and process integration.

Syngas can be produced via the gasification of biomass or municipal solid wastes via thermochemical processing, however the process is highly sensitive to the consistency of feedstock. New pretreatment and sorting technologies, along with alternative approaches to gasification (including oxygen-blown and plasma

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[215] Van Dyke S, Saddler J (2021) Progress in Commercialization of Biojet /Sustainable Aviation Fuels (SAF): Technologies, potential and challenges. <https://www.ieabioenergy.com/wp-content/uploads/2021/06/IEA-Bioenergy-Task-39-Progress-in-the-commercialisation-of-biojet-fuels-May-2021-1.pdf>

[216] Monteiro R, dos Santos I, Arcanjo M, Cavalcante C, de Luna F, Fernandez-Lafuente R, Vieira R (2022) Production of Jet Biofuels by Catalytic Hydroprocessing of Esters and Fatty Acids: A Review. *Catalysts*. https://doi.org/10.3390/catal12020237;

[217] Główka M, Wójcik J, Boberski P, Białecki T, Gawron B, Skolniak M, Suchocki T (2024) Sustainable aviation fuel – Comprehensive study on highly selective isomerization route towards HEFA based bioadditives. https://doi.org/10.1016/j.renene.2023.119696; Tao L, Milbrandt A, Zhang Y, Wang C (2017) Techno-economic and resource analysis of hydroprocessed renewable jet fuel. *Biotechnol Biofuels*. https://doi.org/10.1186/s13068-017-0945-3

[218] Główka M, Wójcik J, Boberski P, Białecki T, Gawron B, Skolniak M, Suchocki T (2024) Sustainable aviation fuel – Comprehensive study on highly selective isomerization route towards HEFA based bioadditives. https://doi.org/10.1016/j.renene.2023.119696;

gasification) can improve syngas quality. Similarly, optimising post-gasification clean-up processes can further remove impurities and balance gas compositions to be suitable for FT synthesis.[219]

Though at lower TRL, syngas can also be produced via the reverse water gas shift (RWGS) reaction, which converts CO_2 and H_2 into CO. The CO is combined with additional hydrogen to produce a syngas ratio with the required composition. Enhancing thermal integration and heat recovery in this process can improve system efficiency.[220] Further RD&D into precise syngas composition control can improve fuel conversion rates and overall process yields.[221]

FT synthesis

Advancing catalyst and reactor design can unlock performance improvements and reduce capital costs.

FT synthesis involves feeding syngas into an FT reactor to produce longer-chain hydrocarbons. High capex costs could be reduced with further RD&D, including by targeting advancements in catalysts and reactor designs.[222] FT catalysts, typically cobalt- or iron-based, suffer from sintering and carbon deposition, which could be addressed through further research into catalyst formulations and regeneration techniques.

Auxiliary technologies

Integrated process control systems can enable optimisation across variable feedstock and product requirements.

Developing integrated process monitoring and control systems can assist in optimising process and managing feedstock variability and select for desired products.[223]

Input availability and management is central to FT performance.

For hydrogen production, storage and distribution, refer to the *Hydrogen production* and *Hydrogen storage* sections.

For electricity generation and storage, refer to the *Electricity* technical appendix.

For carbon capture, refer to the *Carbon Management* technical appendix.

7.1.4 AtJ pathway

In this pathway, alcohols such as ethanol and butanol are converted into fuels through dehydration, oligomerisation, and hydroprocessing steps. Ethanol-to-jet pathways are the most developed, with ethanol typically produced via the fermentation of simple sugars, or through the pretreatment and fermentation of lignocellulosic material. Methanol-to-jet pathways are also under development and could advantages if renewable methanol production (from green CO_2 and H_2) were to expand. Alternative intermediate

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[219] Mondal P, Dang G, Garg M (2011) Syngas production through gasification and cleanup for downstream applications — Recent developments. https://doi.org/10.1016/j.fuproc.2011.03.021.

[220] Wolday A, Gujarathi A, Ramteke M (2023) Multi-objective optimization of methanol production for energy efficiency and environmental sustainability. https://doi.org/10.1016/j.compchemeng.2023.108426; Scomazzon M, Barbera E, Bezzo F (2024) Alternative sustainable routes to methanol production: Techno-economic and environmental assessment. https://doi.org/10.1016/j.jece.2024.112674; Ljungstedt H, Pettersson K, Harvey S (2013) Opportunities for Heat Integration of Biomass-based Fischer-Tropsch Crude Production at Scandinavian Kraftliner Mill Sites. http://dx.doi.org/10.1016/j.energy.2013.09.048.

[221] Lu Y, Lee T (2007) Influence of the Feed Gas Composition on the Fischer-Tropsch Synthesis in Commercial Operations. http://dx.doi.org/10.1016/S1003-9953(08)60001-8

[222] Keunecke A, Dossow M, Dieterich V, Spliethoff H, Fendt S (2024) Insights into Fischer–Tropsch catalysis: current perspectives, mechanisms, and emerging trends in energy research. https://doi.org/10.3389/fenrg.2024.1344179

[223] Wentrup J, Pesch G, Thoming J (2022) Dynamic operation of Fischer-Tropsch reactors for power-to-liquid concepts: A review. https://doi.org/10.1016/j.rser.2022.112454.

pathways, including butanol, are also being investigated for their ability to produce fuels with greater feedstock flexibility and improved properties.[224]

Primary technologies

Improving process efficiency and feedstock flexibility can reduce the overall cost of fuel production, aided by research to enhance catalyst stability and diversify alcohol intermediates.

Oligomerisation catalysts currently used for alcohol upgrading suffer from coke formation, which reduces operational lifespan. RD&D into new materials with higher resistance to deactivation can enhance process efficiency and reliability.[225]

Ethanol is the dominant alcohol feedstock. Efficient processing of lignocellulosic biomass can improve ethanol availability without competing with food production. RD&D into integrated pretreatment and fermentation technologies, including microbial engineering and enzymatic hydrolysis, can lower processing costs and enable more scalable, sustainable ethanol production pathways.[226]

Though ethanol is the dominant alcohol feedstock, exploring alternative alcohol intermediates could further improve performance and broaden feedstock flexibility.[227]

Auxiliary technologies

Integrated process control systems can enable optimisation across variable feedstock and product requirements.

Developing integrated process monitoring and control systems can assist in optimising process and managing feedstock variability and select for desired products.[228]

Input availability and management is central to AtJ performance.

For hydrogen production, storage and distribution (for hydrogenation steps), refer to the *Hydrogen production and Hydrogen storage* sections.

For electricity use (for pretreatment, fermentation and control systems), refer to the *Electricity* technical appendix.

7.1.5 Biomethane pathway

Though not explored in use-case assessments, biomethane can act as a direct replacement for any application that operates on natural gas.

Biogas is produced through anaerobic digestion of organic feedstocks such as agricultural residues, animal manure, and municipal solid waste, which is upgraded to biomethane by removing impurities such as CO_2, H_2S, and moisture.

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[224] García-Hernández A, Segovia-Hernández J, Sánchez-Ramírez E, Zarazúa G, Araujo I, Quiroz-Ramírez J (2024) Sustainable aviation fuel from Butanol: A Study in optimizing Economic and Environmental impact through process intensification. https://doi.org/10.1016/j.cep.2024.109769

[225] Misra P, Alvarez-Majmutov A, Chen J (2023) Isomerization catalysts and technologies for biorefining: Opportunities for producing sustainable aviation fuels. https://doi.org/10.1016/j.fuel.2023.128994

[226] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra

[227] García-Hernández A, Segovia-Hernández J, Sánchez-Ramírez E, Zarazúa G, Araujo I, Quiroz-Ramírez J (2024) Sustainable aviation fuel from Butanol: A Study in optimizing Economic and Environmental impact through process intensification. https://doi.org/10.1016/j.cep.2024.109769

[228] Luo Y, He Y, Zhang R, Lou D, Zhu R, Zhu C, Li Q (2023) A novel integrated process for selective preparation of jet-range fuels from low carbon alcohols and ABE. https://doi.org/10.1016/j.fuproc.2022.107603.

Primary technologies

Enhancing microbial performance and reactor design can improve biogas yields and unlock greater feedstock efficiency.

Strategies and RD&D opportunities for biomethane production include enhancing anaerobic digestion efficiency through microbial management techniques (i.e., bioaugmentation, microbial enrichment etc.), improved reactor designs, and optimised feedstock pre-treatment.[229]

Improving gas upgrading efficiency can reduce costs and increase the purity and recovery of biomethane.

Advanced biogas upgrading technologies can improve the economics and scalability of biomethane systems. This can be enabled through RD&D, including advancements in membrane separation can enhance selectivity and durability while reducing energy consumption during CO_2 and H_2S removal.[230] Innovations in pressure swing adsorption, such as multi-bed systems with optimised cycle times and advanced adsorbent materials, can further improve gas purity, recovery rates, and operational efficiency.[231]

Auxiliary technologies

Integrated supply chains could strengthen environmental and economic outcomes.

Efficient feedstock logistics, including collection, transportation, and storage, are critical for scalable biomethane production. Further advancements in carbon capture technologies can also enhance environmental outcomes by capturing CO_2 from the upgrading process for utilisation or storage. For carbon capture, refer to the *Carbon Management* technical appendix.

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[229] Obileke K, Makaka G, Tangwe S, Mukumba P (2024) Improvement of biogas yields in an anaerobic digestion process via optimization technique. *Environ Dev Sustain*. https://doi.org/10.1007/s10668-024-04540-6; Harirchi, S., Wainaina, S., Sar, T., Nojoumi, S. A., Parchami, M., Parchami, M., Varjani, S., Khanal, S. K., Wong, J., Awasthi, M. K., & Taherzadeh, M. J. (2022). Microbiological insights into anaerobic digestion for biogas, hydrogen or volatile fatty acids (VFAs): a review. https://doi.org/10.1080/21655979.2022.2035986; Elsayed A, Kakar F, Abdelrahaman A, Ahmed N, AlSayed A, Zagloul M, Muller C, Bell K, Santoro D, Norton J, Marcus A, Elbeshbishy E (2024) Enhancing anaerobic digestion Efficiency: A comprehensive review on innovative intensification technologies. https://doi.org/10.1016/j.enconman.2024.118979.

[230] Ardolino F, Cardamone G, Parrillo F, Arena U (2020) Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective. https://doi.org/10.1016/j.rser.2020.110588.

[231] O'Connell A, Konti A, Padella M, Prussi M, Lonza L (2019) Advanced Alternative Fuels Technology Market Report 2018. European Commission, Luxembourg.

8 Appendix

A.1 Glossary

TERM	DEFINITION
Abiogenic	Abiogenic refers to substances, materials, or processes that are not derived from living organisms. It describes things originating from non-biological sources. In fuel and energy contexts, abiogenic carbon sources include fossil fuels and synthetic fuels produced through non-biological pathways. Potential feedstocks include biomass used for starch and sugar production, and cellulosic biomass for isobutanol production.
Alkaline electrolysis (AE)	Commonly referred to by its acronym AE, alkaline electrolysis is a method used to produce hydrogen by splitting water into hydrogen and oxygen using electricity. This process uses a liquid alkaline solution.
Anion exchange membrane (AEM)	Commonly referred to by its acronym AEM, an anion exchange membrane is a type of semipermeable membrane designed to conduct anions (negatively charged ions) while blocking gases like oxygen and hydrogen.
Annual cycles	The amount of time an energy storage system can discharge its stored energy at its rated power capacity before depleting its energy reserves.
Biological hydrogen production	Biological hydrogen production refers to the generation of hydrogen gas (H_2) through biological processes involving microorganisms.
Biomass	Biomass refers to organic material that comes from plants and animals, and it is a renewable source of energy. Biomass can be used directly for heating or power generation, or it can be converted into biofuels.
Biomass waste gasification	Biomass waste gasification is a process that converts organic waste materials, such as agricultural residues, forest residues, and municipal solid waste, into a mixture of gases known as syngas (synthesis gas).
Biomass waste pyrolysis	Biomass waste pyrolysis is a process that thermally decomposes organic waste materials, such as agricultural residues, forest residues, and municipal solid waste, in the absence of oxygen.
Biophotolysis (direct and indirect)	The process by which light energy is used to split water molecules into hydrogen and oxygen. Direct biophotolysis is where light energy directly splits water molecules into hydrogen and oxygen using the photosynthetic machinery of the organism. Indirect involves a two-step process where light energy first drives the production of organic compounds, which are then used to produce hydrogen.
Boil-off	Boil off refers to the process where a liquid, typically a cryogenic liquid like liquefied natural gas (LNG) or liquid hydrogen, evaporates due to heat absorption from its surroundings.
Capped pipe storage	Pipelines with sealed ends are laid underground and then filled with compressed hydrogen (up to 100 bar).
Carbon capture, utilisation and storage (CCUS)	Commonly referred to by its acronym CCUS, carbon capture utilisation and storage is where high-concentration CO_2 is captured from various sources (point source emissions, the atmosphere or biological sources), and permanently stored in deep geological formations and/or converted into valuable lower or zero emissions products.
Carbon cycle	The carbon cycle is the natural process through which carbon atoms are exchanged among the Earth's atmosphere, oceans, soil, and living organisms.
Claude cycle	A process used for the liquefaction of gases, particularly air. It involves a combination of isentropic (adiabatic) expansion and Joule-Thomson (JT) expansion to achieve the cooling necessary for gas liquefaction.
Compressors - Centrifugal type	A type of dynamic turbomachinery that increases the pressure of a gas by converting kinetic energy into potential energy.
Compressors - Non-mechanical	Non-mechanical compressors are devices that compress gases without using moving mechanical parts like pistons or rotors. Instead, they rely on alternative methods such as electrochemical reactions or adsorption-desorption processes.

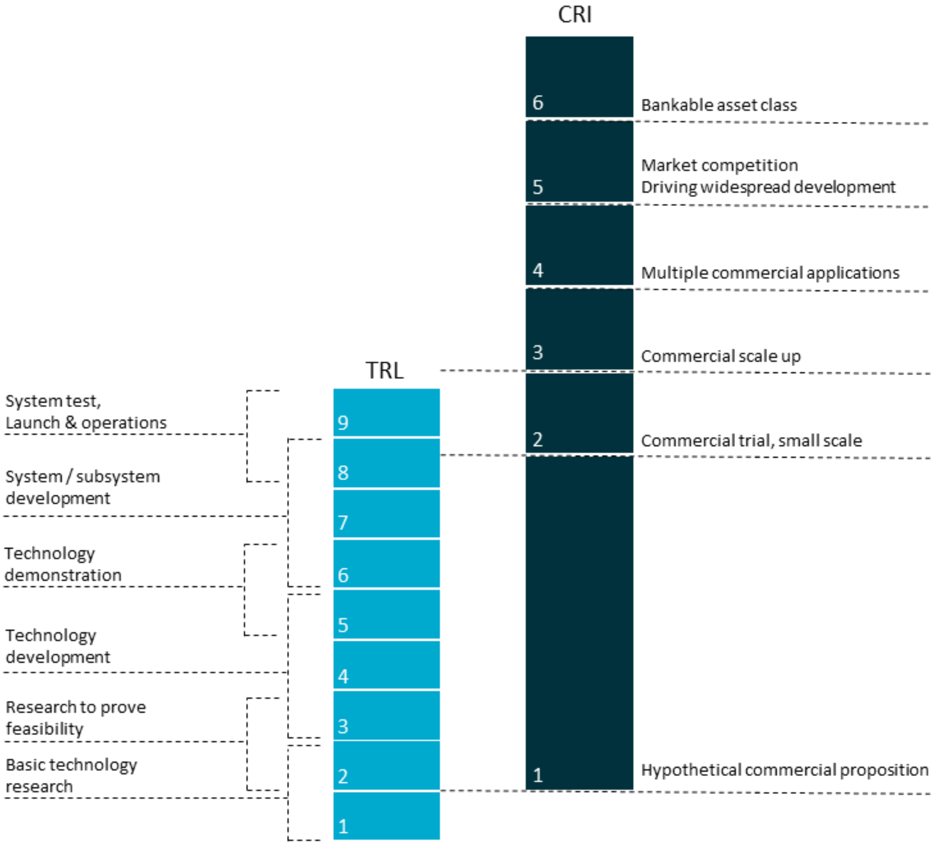
Compressors - Positive displacement	A type of compressor that works by trapping a fixed volume of gas and then mechanically reducing its volume to increase its pressure.
Compressors - Turbo	A type of dynamic compressor that uses a rotating impeller (or turbo wheel) to increase the velocity of air or gas, which is then converted into pressure as the air slows down in a diffuser.
Compressed hydrogen tank	Hydrogen is compressed at high pressure (up to 800 bar) in steel or carbon fibre tanks.
Concentrated solar thermal (CST)	Commonly referred to by its acronym CST, concentrated solar thermal specifically refers to the initial generation and storage of thermal energy in concentrated solar power technology.
Cycling frequency	The rate at which hydrogen is absorbed and desorbed in storage systems.
Dark fermentation	A biological process used to produce hydrogen gas from organic substrates without the presence of light.
Direct normal irradiation (DNI)	Commonly referred to by its acronym DNI, direct normal irradiation is the measure of the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the sun's rays.
Discharge frequency	The rate at which hydrogen is released or utilised in various applications, such as hydrogen fuel cells or storage systems.
Distributed energy resources (DER)	Commonly referred to by its acronym DER, distributed energy resources are small scale units of local energy generation connected to the grid at the distribution level. These resources can include solar panels, wind turbines, energy storage systems etc.
Electrochemical compressor	A device that compresses hydrogen gas using electrochemical reactions, rather than mechanical means.
Electrolysis	A direct water splitting process where electricity is passed through an electrolyte solution to stimulate the splitting of water into its hydrogen and oxygen constituents.
First generation feedstock	First-generation feedstocks are types of biomasses that are often used for food, such as corn, soy, and sugarcane. Biofuels are made through fermentation or chemical processes that convert the oils, sugars, and starches in the biomass into liquid fuels.
Fischer-Tropsch (FT) process	A series of chemical reactions that convert a mixture of carbon monoxide (CO) and hydrogen (H_2), known as syngas, into liquid hydrocarbons.
Gasification	A process that converts carbonaceous materials, such as biomass or fossil fuels, into a mixture of gases, including hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2).
Gasification Fischer-Tropsch (G-FT)	Commonly referred to by its acronym G-FT, gasification Fischer-Tropsch refers to a process in which solid biomass undergoes gasification at elevated temperatures to obtain a mixture of gases ("synthesis gas" or "syngas") comprised of carbon monoxide (CO) and hydrogen. After purification, the syngas is synthesized into a mixture of liquids and gases containing hydrocarbon chains with different sizes, in a catalytic reaction (termed the Fischer-Tropsch process (FT)).
Geogenic	Processes, materials, or phenomena that originate from geological activities or the Earth's natural processes e.g., naturally occurring hydrogen.
Haber-Bosch process	An industrial method for synthesizing ammonia (NH_3) from nitrogen (N_2) and hydrogen (H_2).
Higher heating value (HHV)	In the context of electrolysers, measures the total energy released during hydrogen combustion, accounting for the condensation of water vapor.
Hybrid light and dark fermentation	A process that combines both light-dependent (photofermentation) and light-independent (dark fermentation) methods to produce biohydrogen.
Hydrogen embrittlement	A phenomenon where metals become brittle and prone to cracking due to the absorption and diffusion of hydrogen atoms into the material. Particularly relevant to hydrogen storage systems.
Hydrogen purification	The process of removing impurities and contaminants from hydrogen gas.
Hydrogen separation	The process of isolating hydrogen gas from a mixture of gases.

Hydrogen storage	Energy is stored by producing hydrogen, that can then be stored in different forms and later converted back into electricity using fuel cells or steam turbines. Hydrogen can be stored using a variety of mechanisms, including tanks and underground storage.
Indirect land use change (ILUC)	Commonly referred to by its acronym ILUC, indirect land-use change refers to land use change outside the area of focus. It occurs as a consequence of change in use or management of land within the area of focus, such as through market or policy drivers. For example, if agricultural land is diverted to biofuel production, forest clearance may occur elsewhere to replace the former agricultural production.
Isentropic expansion	A thermodynamic process in which a gas or fluid expands without any heat exchange with its surroundings, meaning the process is both adiabatic (no heat transfer) and reversible.
Liquefaction	The process of turning a solid or a gas into liquid.
Liquefied petroleum gas (LPG)	Commonly referred to by its acronym LPG, liquefied petroleum gas is a flammable hydrocarbon gas that is liquefied through pressurization. It is primarily composed of propane (C_3H_8) and butane (C_4H_{10}), and is commonly used as a fuel for heating, cooking, and automotive applications.
Liquid organic hydrogen carriers (LOHC)	Commonly referred to by its acronym LOHC, liquid organic hydrogen carriers are organic materials that can be reversibly converted between hydrogenated (hydrogen-rich) and dehydrogenated (hydrogen-lean) forms to store and release hydrogen; and are characterised by their liquid state in both forms.
Lithium ion batteries (Li-ion)	Commonly referred to by its acronym Li-ion, lithium ion batteries are a type of rechargeable battery that relies on lithium ions moving between the anode and cathode to store and release energy.
Lower heating value (LHV)	In the context of electrolysers, measures the energy released during hydrogen combustion, excluding the energy from condensing water vapor.
Metal hydride compressor	A type of hydrogen compressor that utilizes metal hydrides to absorb and desorb hydrogen gas.
Microbial electrolysis	A process that uses microorganisms to produce hydrogen gas or other valuable compounds through electrolysis.
Municipal solid waste (MSW)	Commonly referred to by its acronym MSW, municipal solid waste includes a wide range of materials such as product packaging, food scraps, yard waste, furniture, clothing, bottles, and appliances.
Oxidation	A chemical reaction in which a substance loses electrons, often involving the addition of oxygen or the removal of hydrogen.
Photofermentation	A biological process where photosynthetic bacteria convert organic substrates into biohydrogen using light energy.
Photovoltaics (PV)	Commonly referred to by its acronym PV, photovoltaics refers to technologies that convert sunlight directly into electricity using semiconductor materials.
Platinum group metals (PGMs)	Commonly referred to by its acronym PGMs, platinum group metals are a group of six metallic elements that have similar physical and chemical properties.
Proton exchange membrane (PEM) electrolysis	Commonly referred to by its acronym PEM, proton exchange membrane electrolysis is a form of electrolysis that utilizes an acidic solid polymer electrolyte membrane.
Seawater electrolysis	A process that uses electricity to split seawater into hydrogen and oxygen gases.
Second generation feedstock	Second-generation feedstocks are produced from non-food biomass, such as perennial grass and fast-growing trees. The processes to make biofuels are more complex and less developed than for first-generation feedstocks, often involve converting fibrous non-edible material (cellulose) into fuel.
Sodium ion batteries (Na-ion)	Commonly referred to by its acronym Na-ion, sodium ion is a positively charged ion formed when a sodium atom loses one electron.
Solid oxide electrolysis (SOE)	Commonly referred to by its acronym SOE, solid oxide electrolysis is a form of electrolysis that utilises a solid oxide (or ceramic) electrolyte. It operates at high temperatures which can be obtained via integration with industrial processes, consequently increasing energy efficiencies
Steam methane reforming (SMR)	Commonly referred to by its acronym SMR, steam methane reforming is an industrial process for producing hydrogen from methane, which is the primary component of natural gas.

Tank-to-wheel (TtW)	Commonly referred to by its acronym TtW, tank-to-wheel refers to the analysis of emissions and energy consumption that occur during the operation of a vehicle, from the point when fuel is added to the tank until it is used to power the vehicle.
Thermal integration	A process that involves optimizing the use of thermal energy within a system to reduce energy consumption and costs while enhancing efficiency. This is achieved by systematically analysing and rearranging the flow of heat in processes to maximize the recovery of waste heat and minimize energy losses.
Thermal load cycling	The process of repeatedly subjecting a material or system to varying temperatures, typically alternating between high and low extremes. This process is used to test the durability and performance of materials and components under conditions that simulate real-world thermal stresses.
Turbo compressor	A type of dynamic compressor that uses a rotating impeller to add energy to a gas, increasing its pressure and velocity.
Underground hydrogen storage (UHS)	Commonly referred to by its acronym UHS, underground hydrogen storage is when hydrogen is compressed and injected into geological or engineered subsurface structures including salt caverns, depleted gas fields, aquifers or excavated caverns.
Variable renewable energy (VRE)	Commonly referred to by its acronym VRE, variable renewable energy refers to renewable energy sources that produce electricity intermittently, depending on environmental conditions. This includes sources like wind power and solar power, which are not continuously available due to their dependence on weather and time of day.
Volumetric energy density	A measure of the amount of energy stored in a given volume of a substance or system.
Wastewater electrolysis	An advanced water treatment method that uses electrochemical processes to remove contaminants from wastewater.
Well-to-tank (WtT)	Commonly referred to by its acronym WtT, well-to-tank refers to the lifecycle emissions and energy consumption associated with the production, processing, and transportation of fuels before they are used in vehicles or other applications.

A.2 Technology maturity rating index

Figure 17: Technology Readiness Levels and Commercial Readiness Index[232]



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[232] Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf> (accessed 6 January 2025).

A.3 Technology analysis framework supplementary information

A.3.1 Broad list of technologies

Over 500 technologies were identified from most recent literature and existing global databases, such as the IEA Clean Energy Technology Guide,[233] publications from domestic[234] and international[235] government bodies, and prominent literature from Australian research centres (e.g., ClimateWorks Australia,[236] Net Zero Australia,[237] and the CSIRO[238]).

These technologies were assigned to key (sub)sectors. As the level of detail varied across sources only technologies that directly contribute to emissions reduction efforts were considered as inputs to the prioritisation framework. This ensured a structured and objective filtering process to prioritise technologies.

A.3.2 Primary technology analysis criteria, by subsector

To technically evaluate technologies, criteria were identified for each (sub)sector to assess each technology's ability to meet the functional requirements of its use case. For example, for Transport, use cases require a minimum travel distance between refuelling/recharging, therefore a 'range' performance parameter was included. For energy applications in which a scale of production or storage is required by the use case, a performance parameter that assessed the capacity of a technology was used.

The threshold for each criterion was established based on the performance of conventional technologies used for the same application, using values sourced from literature.

Table 21: Technology analysis framework criteria used, by (sub)sector

		Subsector	Criteria
Energy supply	**Electricity**	Electricity generation	Levelised cost
		Electricity storage	Discharge duration Levelised cost
	L	Hydrogen production	Scalability

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[233] IEA (2023) ETP Clean Energy Technology Guide, <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide>

[234] Australian Government (2021) Low Emissions Technology Statement 2021. Department of Industry, Science, Energy and Resources. <dcceew.gov.au/sites/default/files/documents/low-emissions-technology-statement-2021.pdf; Australian Government (2020) Technology Investment Roadmap. Department of Industry, Science, Energy and Resources. <Technology Investment Roadmap Discussion Paper (storage.googleapis.com)>

[235] U.S. Department of Energy (2022) ARPA-E Strategic Vision Roadmap, August 2022. Report to Congress. <arpa-e.energy.gov/sites/default/files/2022 ARPA-E Strategic Vision Roadmap.pdf> (accessed 15 November 2023).

[236] Climateworks (2020), Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia <https://www.climateworkscentre.org/wp-content/uploads/2020/04/Decarbonisation-Futures-March-2020-full-report-.pdf> (accessed 6 September 2023); Jointly with Climate-KIC Australia, Australian Industry Energy Transition Initiative (2023) Pathways to industrial decarbonisation. <https://energytransitionsinitiative.org/wp-content/uploads/2023/08/Pathways-to-Industrial-Decarbonisation-report-Updated-August-2023-Australian-Industry-ETI.pdf> (accessed 14 July 2023).

[237] Net Zero Australia (2023) Modelling Summary Report. <https://www.netzeroaustralia.net.au/wp-content/uploads/2023/04/Net-Zero-Australia-Modelling-Summary-Report.pdf> (accessed 14 July 2023); Net Zero Australia (2023) Downscaling reports (series). <https://www.netzeroaustralia.net.au/final-modelling-results/> (accessed 19 February 2024).

[238] CSIRO (2023) Renewable energy storage roadmap. <https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Energy-and-Resources/Renewable-Energy-Storage-Roadmap>; CSIRO (2021) CO2 Utilisation Roadmap - CSIRO. <https://www.csiro.au/-/media/Services/Futures/21-00285_SER-FUT_REPORT_CO2UtilisationRoadmap_WEB_210810.pdf>; CSIRO (2023) Sustainable Aviation Roadmap <https://www.csiro.au/en/research/technology-space/energy/sustainable-aviation-fuel>; CSIRO (2023) Hydrogen vehicle refuelling infrastructure <https://www.csiro.au/en/about/challenges-missions/hydrogen/hydrogen-vehicle-refuelling-infrastructure>; CSIRO (2023) Pathways to Net Zero Emissions – An Australian Perspective on Rapid Decarbonisation. <https://www.csiro.au/en/research/environmental-impacts/decarbonisation/pathways-for-australia-report>

			Levelised cost
		Hydrogen storage	Storage capacity Discharge frequency Levelised cost
Energy demand	Transport	Road Aviation Rail	Refuelling duration Minimum range requirement Levelised cost
		Shipping	Safety Minimum range requirement Levelised cost
	Industry	Iron and steelmaking	Plant capacity Levelised cost
		Medium temperature steam	Resource scalability Levelised cost
		Mining heavy haulage	Truck utilisation Levelised cost

A.4 Abatement potential data repository

Table 22: Abatement potential sources and assumptions – Low carbon fuels

Subsector	Abatement threshold		Emissions data		Source
	Threshold	**Explanation**	**Direct emissions**	**Indirect emissions**	
Hydrogen production	100%	Technology options were compared against a *'zero-emissions' benchmark*, based on the availability of technology solutions with significant abatement potential by 2050 and the impact that non-zero emissions energy supply sources can have on the overall life cycle emissions of an energy sector seeking to achieve their individual emissions targets.	Full fuel cycle	No	IEA (2021)[239]
Hydrogen storage	*Not applicable*				

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[239] IEA (2021) Comparison of the emissions intensity of different hydrogen production routes. International Energy Agency. https://www.iea.org/data-and-statistics/charts/comparison-of-the-emissions-intensity-of-different-hydrogen-production-routes-2021 (accessed 11 December 2024).

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