Australia's National Science Agency

The State of Energy Transition Technologies

Australian research, development and demonstration (RD&D) opportunities

SYNTHESIS REPORT

December 2025

Citation and authorship

CSIRO (2025) The State of Energy Transition Technologies: Australian research, development and demonstration (RD&D) opportunities. CSIRO, Canberra.

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CSIRO and the authors are grateful to individuals or organisations that generously gave their time to provide input to this project through Steering Committee meetings, consultations, reviews and feedback as well as scientists and researchers from CSIRO. We would also like to thank the Australian Council of Learned Academies (ACOLA), including the Australian Energy Transition Research Plan Steering Committee for their input and support. This is a CSIRO report and should not be taken as representing the views or policies of individuals or organisations consulted.

We would like to thank the Steering Committee, Peter Mayfield, Dietmar Tourbier, Helen Brinkman, Stephen Craig, Stuart Whitten, James Deverell, Ben Creagh, Lukas Young and Sandra Oliver, and the Energy Economics team at CSIRO, Paul Graham, Jenny Hayward, Luke Reedman and James Foster, for their input. We would also like to specifically thank Dominic Banfield, Andrew Beath, Brian Clennell, Jason Czapla, Claudia Echeverria Encina, Sarb Giddey, Peter Grubnic, Adrien Guiraud, Chad Hargrave, Patrick Hartley, Andrew Higgins, Allison Hortle, Tara Hosseini, Nikolai Kinaev, Chris Knight, Daniel Lane, Jim Patel, Fiona Scholes, Vahid Shadravan and Max Temminghoff for their advice and feedback.

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Strategic investment to maximise the impact of research, development and demonstration (RD&D) will be essential for Australia's energy transition.

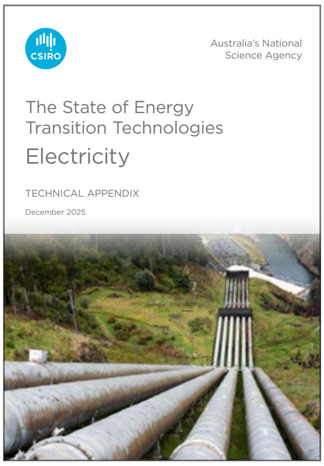
RD&D will be pivotal in informing and driving the change required to achieve the energy transition and Australia's net zero ambitions. It provides evidence and new knowledge to inform policy and industry decisions; it helps develop and demonstrate technologies to increase energy system security and resilience; it supports international collaboration to reduce duplication; and it creates new intellectual property that can position Australia to attract global investments in low emissions technologies and manufacturing. Effectively harnessed RD&D can enhance the feasibility, efficiency, and pace of Australia's energy transition.

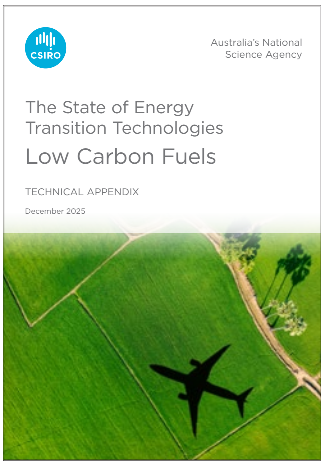
With limited RD&D resources and a broad array of emerging low emissions technologies, Australia faces the important task of strategically and collaboratively optimising its resources to maximise national benefit.

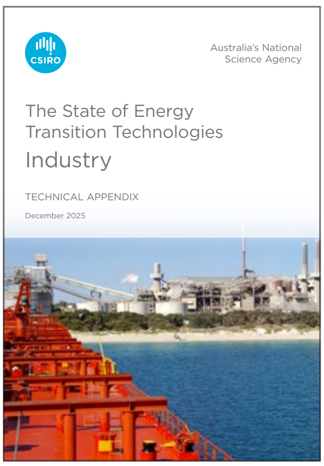
This study explores opportunities to accelerate the deployment of low emissions technologies and position Australia's research ecosystem at the forefront of sustainable innovation.

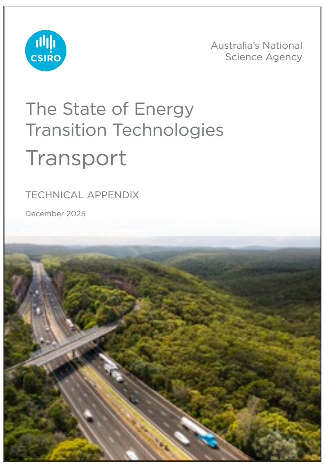
This study, *The State of Energy Transition Technologies*, identifies opportunities for RD&D to support the adoption of technologies that can accelerate cost-effective, low-risk, and integrated technology pathways required for Australia's energy transition. It is not intended to prescribe research strategies or technologies for Australia or any individual organisation or favour one technology over another. Rather, it serves as a resource to support constructive dialogue and help navigate the energy transition by capitalising on national RD&D strengths.

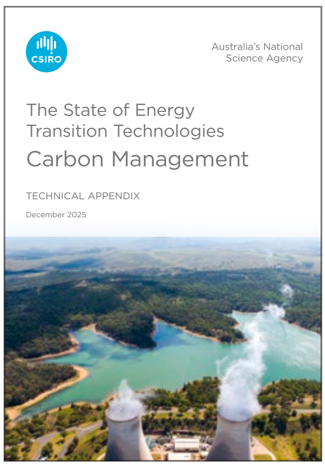
Given the breadth of Australia's energy transition, the study concentrates on technologies and RD&D opportunities across the electricity, low carbon fuels, industry, transport and carbon management sectors in Australia.









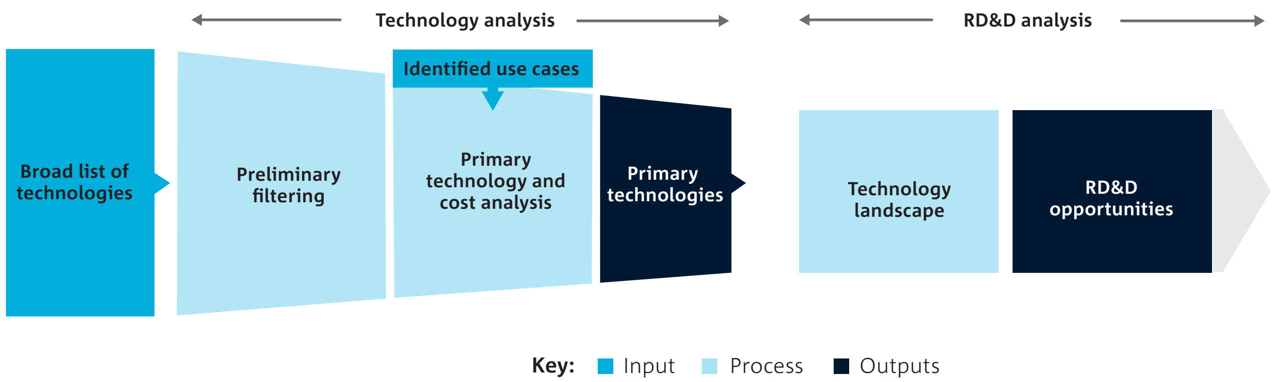


This study uses a framework to evaluate a diverse range of technologies to help explore opportunities for RD&D across the vast and rapidly growing low emissions technology landscape.

This study leverages global literature and CSIRO expertise, to design and apply a technology analysis framework that explore RD&D opportunities.

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 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.

To support technology and RD&D discourse and inform decision making, it is important that this analysis is not viewed as static. This study requires regular revision to ensure the technologies explored, and RD&D opportunities identified, evolve in line with science and technology advances, Australia's changing energy landscape, and the global transition. This requirement emphasises the importance of maintaining a flexible technology analysis framework, reviewing and expanding the Australian use cases, evaluating the filters used, and updating data as it becomes available.



Technology landscape

The technologies that are explored through this framework are described as primary technologies. These primary technologies were used to develop a technology landscape for each sub-sector, consisting of a set of primary technologies, and auxiliary technologies and energy efficiency solutions necessary for successful deployment.

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

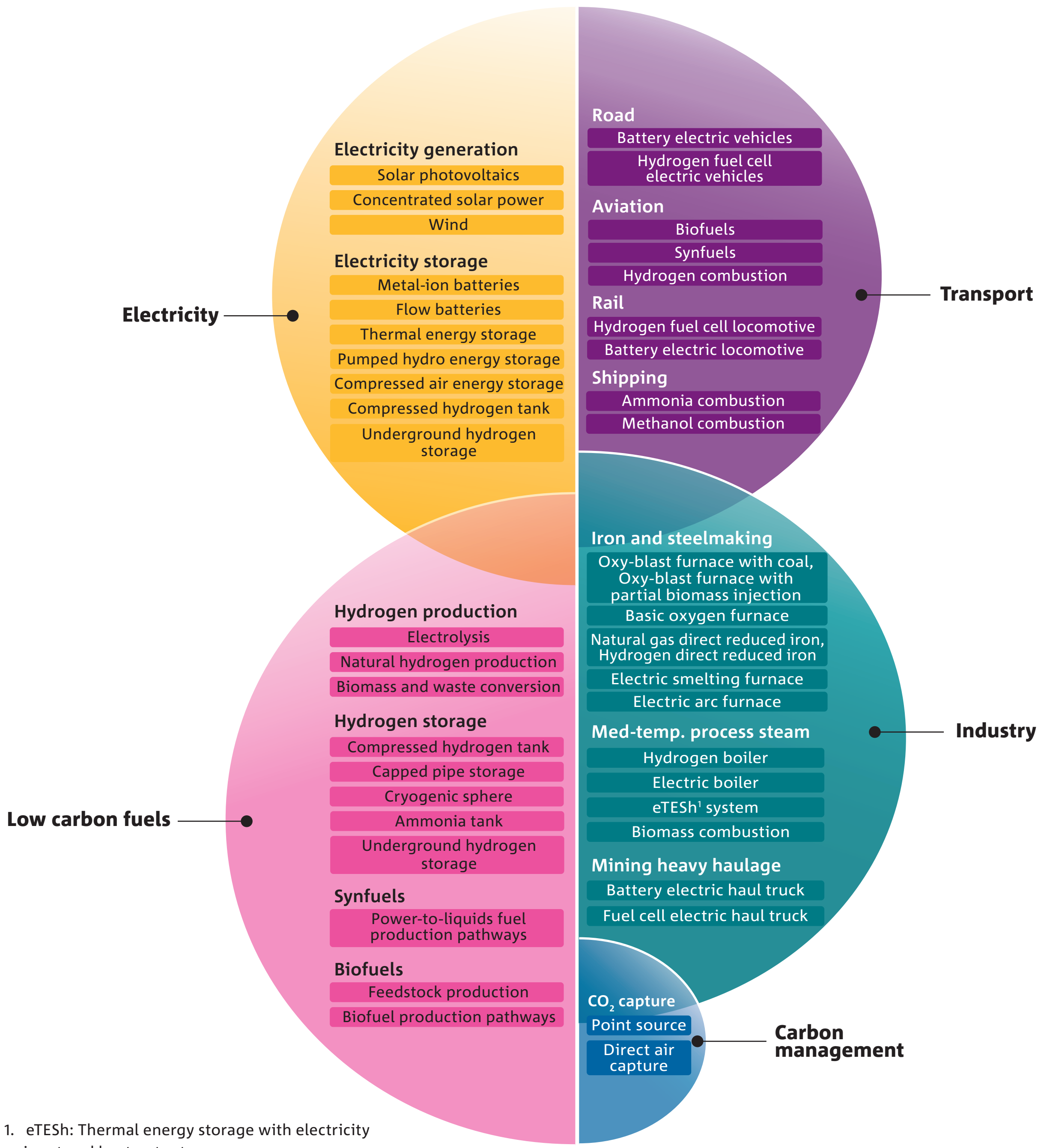
Auxiliary technologies, excluding energy efficiency solutions, are required for the deployment or enhanced performance of the primary technology, including but not limited to distribution and fuelling infrastructure, and tools to optimise operations.

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.

To support Australia's energy transition, this study identified 43 primary technologies to guide the exploration of RD&D opportunities that could drive impactful technological progress.

This study examined over 100 low emissions technologies relevant to the sub-sectors analysed, identifying 43 primary technologies that have the potential to be feasibly deployed in Australia and are suitable for specific use cases identified across each sub-sector.

Figure 1: Overview of the low emissions technologies analysed and their relevant sub-sectors



1. eTESh: Thermal energy storage with electricity input and heat output

Across these 43 technologies, five cross-cutting RD&D themes have emerged that could help optimise efforts and enhance the feasibility, efficiency, and pace of Australia's energy transition.

Australia's RD&D ecosystem is an invaluable asset with significant potential to enhance the country's energy transition if used effectively. This study presents opportunities for RD&D across electricity, low carbon fuels, transport, industry and carbon management sectors. This includes RD&D opportunities for the explored primary and auxiliary technologies, as well as for identified energy efficiency technologies.

Five cross-cutting themes emerged that could help guide Australia's approach to RD&D and ultimately help to optimise national RD&D investments alongside global partners. Targeted efforts across these themes can reduce costs, deliver breakthrough technologies with superior performance, and develop solutions and tools that ensure the safe and sustainable production, storage, transport and use of low emissions energy. Additionally, these efforts can improve community and environmental outcomes.

1. Developing solutions specific to Australia
2. Achieving and exceeding cost forecasts through RD&D
3. Supporting the demonstration and scale-up of technologies
4. Developing technology-agnostic energy efficiency solutions
5. Enabling adoption through interdisciplinary research

RD&D focus area 1: Developing solutions specific to Australia

Australia has the unique opportunity to develop low emissions technologies that will best serve its industrial mix, energy systems and transport networks, with consideration to the country's geography and geology.

Compared with other countries, Australia's vast geography, low population density, and sparse and distributed communities, industries, transport networks, and energy resources create a uniquely complex landscape for decarbonisation. These characteristics present specific challenges for low emissions technologies that may not be prioritised by international stakeholders but represent areas where Australia's RD&D ecosystem can lead and innovate.

Australia's decarbonisation strategy and technology development must be underpinned by region-specific and highly tailored RD&D efforts that maximise the potential of its diverse industry, transport and energy systems. Australia's diverse geography and geology are also an opportunity to develop world leading expertise in several geologically dependent technologies, such as underground hydrogen storage, compressed air energy storage, pumped hydro storage, carbon capture and storage (CCS) alongside exploring the potential of natural hydrogen production.

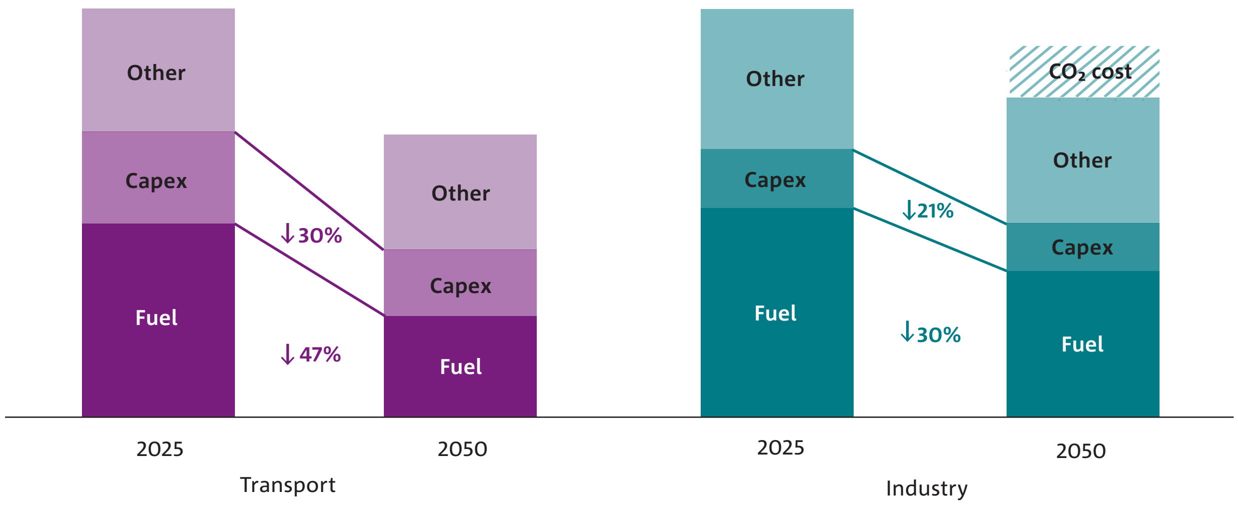
While many of the technologies explored are projected to become cost-competitive with their incumbents in the future, this outcome is not guaranteed.

RD&D focus area 2: Achieving and exceeding cost forecasts through RD&D

There is a need to not only maintain cost projections, but also exceed them, particularly in cases where a cost competitive low emissions technology is not available.

The successful deployment and emissions reduction potential of low emissions technologies are closely tied to their commercial viability, particularly when compared with incumbent technologies. The projected 2050 levelised cost improvements associated with transport and industry sector technologies are dominated by potential improvements to fuel costs (input electricity, low carbon fuel or biomass), highlighting the importance of RD&D in the electricity and low carbon fuels sectors to help create material changes for these technologies (Figure 2). Emerging technologies in industry and transport also have the potential to realise significant performance improvements. While not leading factors, RD&D to reduce capital costs and optimise operating costs can play a role in meeting and exceeding the 2050 levelised cost forecasts in this study.

Figure 2: Projected average percentage reductions between 2025 and 2050 levelised costs (normalised to 2025), by sector



CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050.

The successful deployment of low emissions technologies, and the realisation of their associated emission abatement, requires investment in their demonstration in an Australia context.

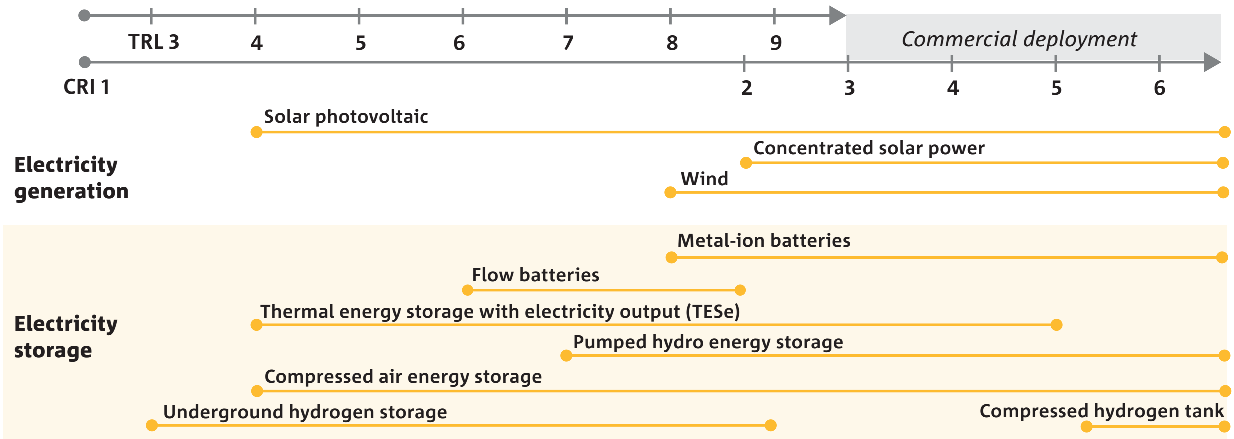
RD&D focus area 3: Supporting the demonstration and scale-up of technologies

Of the 43 explored primary technologies, only 14 are currently regarded as ready for commercial deployment, highlighting the need for RD&D investment to support both demonstration and scale-up of low emissions technologies, and to achieve the benefits of learning by doing.

Electricity

Although the current state of low emissions large-scale electricity generation technologies reflects the progress achieved by RD&D in this sector over the past several decades, there remain opportunities for RD&D to advance the next generation of technology development to achieve better cost outcomes. The range of requirements for electricity storage use cases requires a diverse mix of technologies, and investment is required to progress several of the technologies explored to be ready for commercial deployment.

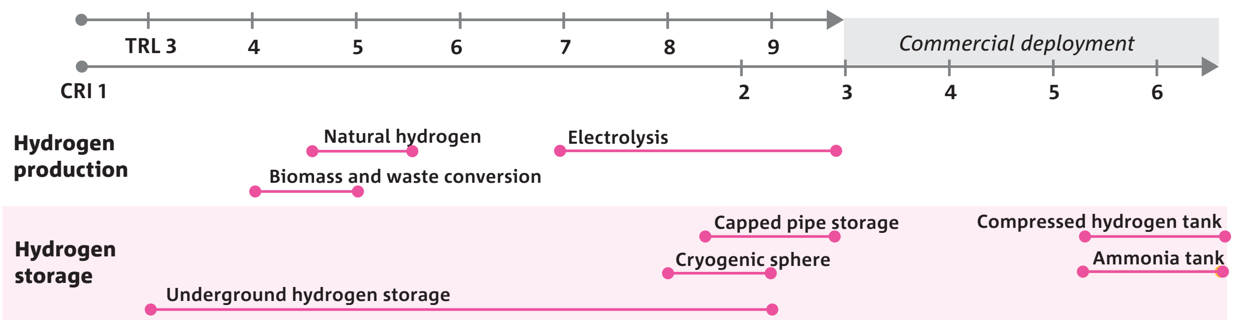
Figure 3: Summary of electricity sub-sector technological maturity



Low carbon fuels

Compressed hydrogen and ammonia tanks are commercially deployed, but no large-scale (>50 t/day) net-zero hydrogen production methods currently exist. Proton exchange membrane, alkaline and solid oxide electrolysis require RD&D to meet the required performance and cost targets when coupled with renewable electricity generation, while natural hydrogen production, although proven at small scales, requires RD&D to both identify deposits of natural hydrogen and establish large-scale hydrogen production facilities. Australia's geology offers an opportunity to progress and demonstrate underground hydrogen storage (UHS). Hard rock lined caverns, depleted hydrocarbon fields, and salt caverns require RD&D to ensure entrapment of the hydrogen, although the most technologically mature UHS systems are yet to be demonstrated at small scales.

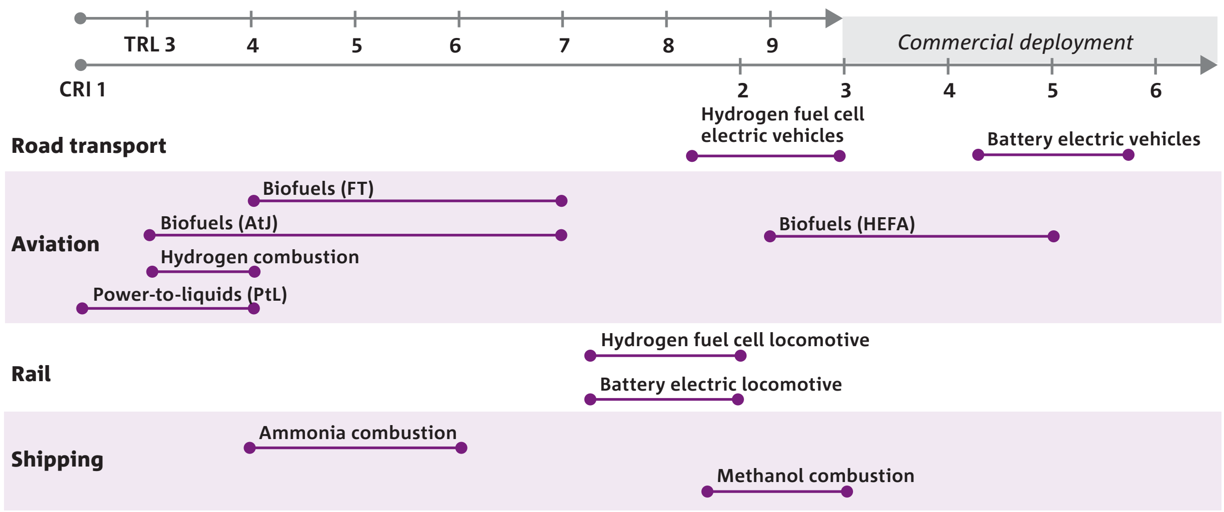
Figure 4: Summary of low carbon fuels sub-sector technological maturity



Transport

For transport, although consumer adoption of battery electric road vehicles is growing and demand for biofuels (sustainable aviation fuel) in the aviation industry is increasing, the use of low emissions technologies in other transport modes, such as rail and shipping, requires further RD&D to ensure they are both cost competitive and meet the demands of heavy haulage and the travel distances required.

Figure 5: Summary of transport sub-sector technological maturity

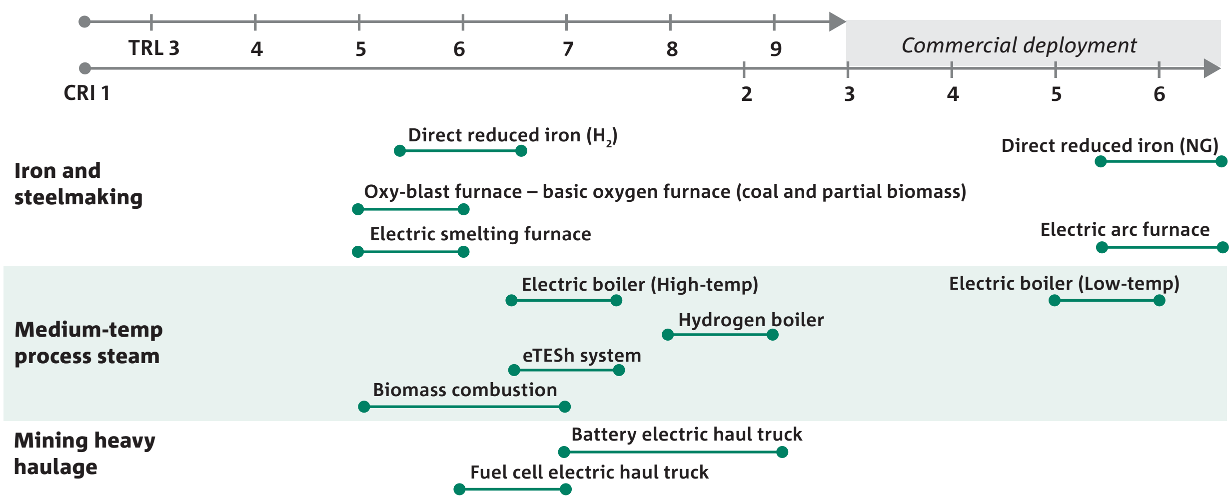


FT: Fischer-Tropsch AtJ: Alcohol-to-jet HEFA: Hydroprocessed esters and fatty acids

Industry

The need for investment in demonstration activities is apparent for industry, where only three of the explored technologies are commercially available today. There is a significant opportunity to demonstrate these technologies in the Australian context, particularly for iron and steelmaking where differences in iron ore content and mineralogy can alter the performance and efficiency of the steelmaking technology.

Figure 6: Summary of industry sub-sector technological maturity



NG: Natural gas

RD&D focus area 4: Developing technology-agnostic energy efficiency solutions

RD&D to enhance the energy and fuel efficiency of demand-side technologies can improve the costs and performance of both incumbent technologies and their low emissions alternatives, which will be important for reducing emissions in both the short and long term.

Improving the energy efficiency of industry and transport technologies is a critical strategy for decarbonisation, regardless of the use case or energy source used. High upfront costs, combined with the need for extensive supporting infrastructure, are major barriers to initial investment and widespread adoption of several low emissions technologies. Investment in energy efficiency solutions could support the industry and transport sectors as they transition by reducing the amount of energy required to deliver immediate and long-term emissions reductions while also lowering operational costs and improving system performance.

In transport, advances in lightweighting, aerodynamics, and drivetrain efficiency will make technologies across all transport modes more energy-efficient, independent of the fuel used. Operational improvements and energy management technologies further reduce energy use and enhance system efficiency. For industrial processes, optimising input material efficiencies will be critical to reducing emissions. Improvements in heat management, including reducing heat loss or improving waste heat recovery systems, are further opportunities to enhance process efficiency. These activities can be supported and enabled by digitalisation and the development of sensors that can inform and optimise operational strategies.

RD&D focus area 5: Enabling adoption through interdisciplinary research

Technical development is only one part of the puzzle and coordinated social, environmental, policy and regulation research actions will be important to address the drivers of and barriers to the uptake of these technologies.

Through the analysis of RD&D opportunities this report has also identified several opportunities for non-technical RD&D across several areas (Figure 7). These research areas focus on enabling the safe, effective, and socially accepted deployment of low emissions technologies. They span environmental impact analysis, policy and regulatory actions, community engagement, and modelling to guide strategic decision-making and technology optimisation.

Figure 7: Non-technical RD&D areas and examples of identified RD&D opportunities

Environmental

E.g. While biofuels have the potential to play a valuable role as a low carbon fuel, their broader adoption will depend on the accurate assessment and considered management of biomass resources to ensure sustainability of supply.

Policy, regulation and standards

E.g. Regulatory changes to enable natural hydrogen exploration, or the development of standards and procedures to ensure the safe storage and bunkering of ammonia or methanol fuels.

Community engagement and social licence

E.g. With diverse electricity generation and storage technologies available, engaged communities will be key to ensure deployment aligns with their priorities, concerns and delivers equitable outcomes.

Modelling

E.g. Techno-economic analysis will be essential to narrow technology selection for specific use cases, and to inform future *State of Energy Transition Technologies* cost analysis with real world data.

Electricity

RD&D that reduces the cost of electricity will underpin Australia's cross-sectoral decarbonisation objectives and have a significant impact on the financial viability of several abatement pathways.

Challenge

Electrification and the use of renewables underpin many of Australia's cross-sectoral decarbonisation strategies and will require the deployment and integration of technologies and infrastructure at an accelerated pace. However, Australia's electricity system is unique, spanning both interconnected and isolated grids, with relatively low density compared to international regions. The transition of Australia's electricity supply must be carefully planned to ensure it occurs seamlessly while continuing to provide reliable energy services to consumers and industry.

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 electricity generation in Australia, as well as energy storage solutions for short, medium and long duration grid scale demands:

- **Electricity generation** analyses electricity generation technologies that can be centralised and can produce electricity at grid-scale with the capacity to operate reliably. Identifying decarbonisation technologies in the context of this use case is considered essential for achieving net-zero targets by 2050. Three technologies were explored in more detail to identify RD&D opportunities.
- **Electricity storage** analyses storage technologies across three discharge durations: short, medium and long. These durations represent how long a storage technology can sustain its maximum discharge rate, which allows them to service different demand sectors and markets. Short duration storage can respond within hours, providing frequency regulation and peak shaving during high demand periods. Longer duration storage solutions offer a way to store energy during low demand times, and can provide a reliable energy supply for extended periods, such as during times of low energy generation. Seven technologies were explored in more detail to identify RD&D opportunities.

Electricity generation

RD&D can enhance the cost, efficiency, and performance of solar, wind, and concentrated solar power (CSP), and will be essential to developing the tools required to ensure grid stability and reliability in a high variable renewable energy (VRE) future.

Technology landscape: Large-scale electricity generation

Solar PV, wind, and CSP can provide scalable low emissions solutions for Australia's large-scale electricity generation needs, however, the increased penetration of VRE generation will require careful management to address challenges regarding power quality, grid stability, and reliability.

<table>
<tr><th>Solar photovoltaics (PV)</th><th>Wind</th><th>Concentrated solar power (CSP)</th></tr>
<tr><td colspan="2">• Grid-scale storage
• Transmission and distribution infrastructure</td><td>• Grid-scale storage
• Transmission and distribution infrastructure
• Thermal energy storage media</td></tr>
</table>

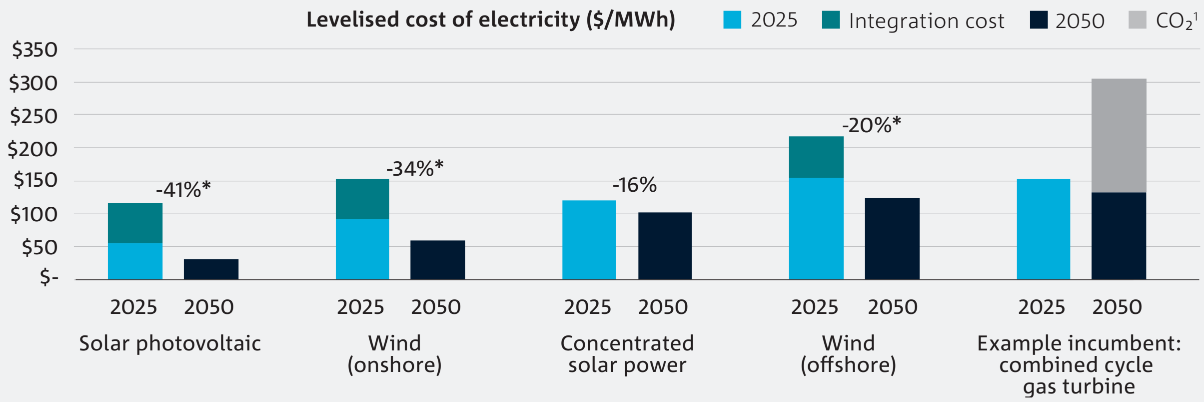
RD&D opportunities

<table>
<tr><th>Solar photovoltaics</th><td>• RD&D can lower solar costs through modular and automated deployment, cost-efficient materials like perovskites, and advanced cell architectures such as silicon-perovskite tandems that capture more of the solar spectrum.</td></tr>
<tr><th>Wind</th><td>• There are RD&D opportunities to reduce turbine costs and boost efficiency through new materials, and innovative design and approaches to manufacturing. These efforts can also help develop novel turbine designs suited to decentralised or urban settings.
• For offshore wind, RD&D can lower foundation costs and improve floating platform designs.</td></tr>
<tr><th>Concentrated solar power</th><td>• For CSP, RD&D can reduce costs, improve efficiency, and enhance combined generation and storage opportunities through advanced heat transfer fluids, and development of high-temperature, corrosion-resistant materials to enhance CSP system durability and longevity.</td></tr>
<tr><th colspan="2">Auxiliary</th></tr>
<tr><td colspan="2">• The increased penetration of VRE generation can lead to system-wide challenges regarding power quality, grid stability, and reliability, making RD&D on auxiliary technologies essential. RD&D opportunities span new inverter designs, tools and methods to support stability, planning, and restoration, technologies and business model innovations to optimise the use of distributed energy resources, and the development of new technologies for power system operator control rooms.
• See Electricity – Electricity storage for RD&D opportunities associated with thermal energy storage media.</td></tr>
</table>

Levelised cost analysis

Large-scale electricity generation

Solar and wind technologies are projected to have the lowest levelised costs of electricity in 2025 and 2050, even with the inclusion of integration costs associated with VRE technologies in 2025.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050.

* Differences between 2025 and 2050 levelised costs do not include the integration cost in 2025.

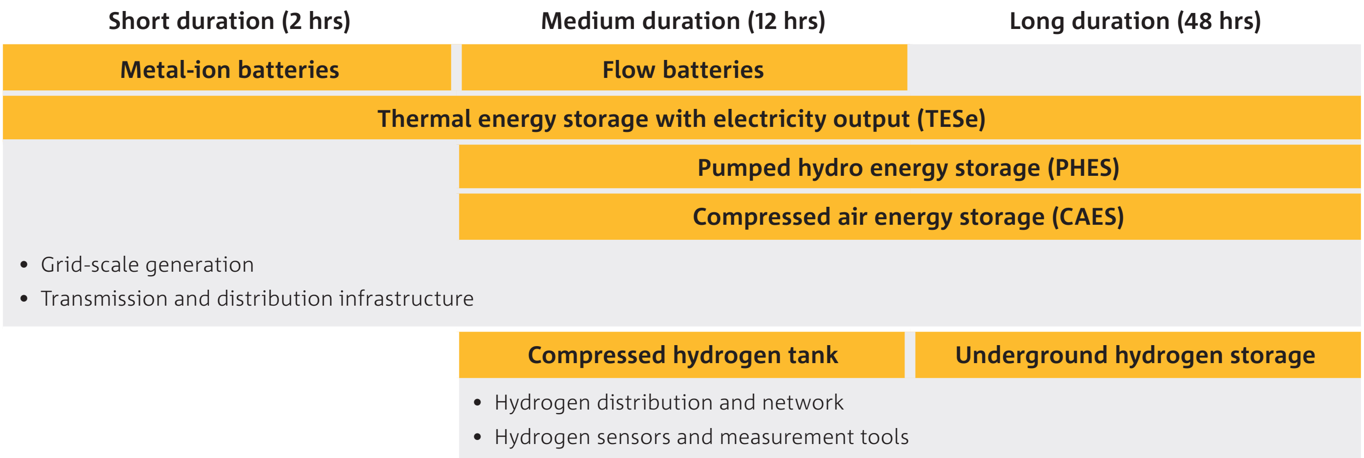
See technical appendices for assumptions.

Electricity storage

RD&D can address the key hurdles that must be resolved to enable the deployment of a diverse mix of electricity storage technologies in Australia.

Technology landscape: Short, medium and long duration storage

Australia requires a diversity of short, medium and long duration storage technologies to support the increased penetration of variable renewable energy generation.



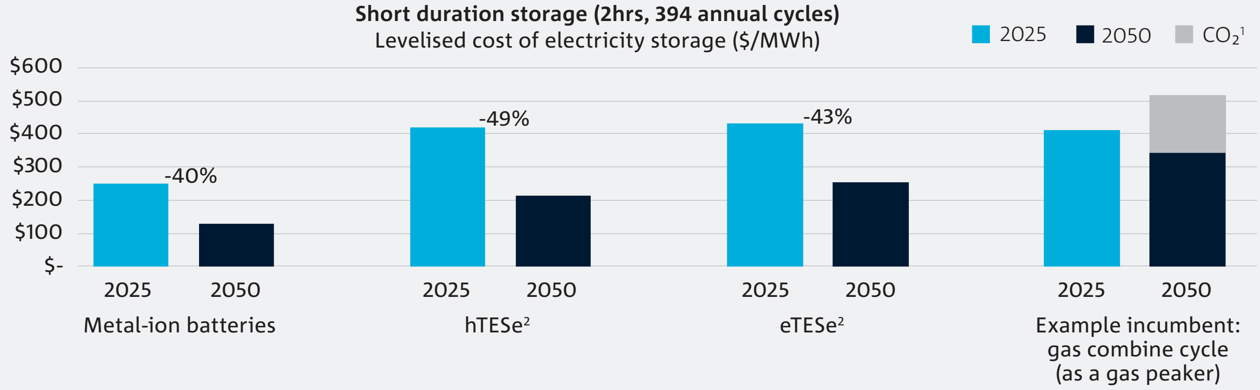
RD&D opportunities

Metal-ion batteries, Flow batteries	• There is an opportunity to both reduce costs and supply chain risk through RD&D into developing battery chemistries with more affordable and abundant materials. • Research to enhance battery lifespan will also be important for reducing the cost of ownership of battery storage systems.
Thermal energy storage with electricity output	• RD&D opportunities for thermal energy storage are oriented around improving operating costs and making the system better suited for the storage cycles required by the use case. • Research areas include efficiency improvement by addressing heat exchange inefficiencies, heat pump efficiency and overall round-trip efficiency to minimise energy losses, and increasing the durability and lifetime of systems through RD&D into materials to achieve better thermal cycle stability and durability.
Pumped hydro energy storage	• Although PHES is a mature technology that is commercial and used widely, further RD&D can lower project costs through modular or scalable designs, and optimising reservoir configurations that leverage the local environment. • RD&D of pumping units with variable speed capabilities will allow for more flexibility and integration with VRE generation technologies.
Compressed air energy storage	• To address the high costs associated with pressurising large volumes of air for CAES, RD&D is required to incorporate more advanced materials suited for the higher pressures associated with CAES to extend asset lifetimes, as well as efforts to achieve higher efficiency rates. • Further research is required to improve site selection and current understanding of the impacts of compressed air on natural reservoirs, as well as operational requirements.
Hydrogen technologies	See *Low Carbon Fuels – Hydrogen storage*
Auxiliary	
See *Electricity – Electricity generation* and *Low Carbon Fuels – Hydrogen storage*	

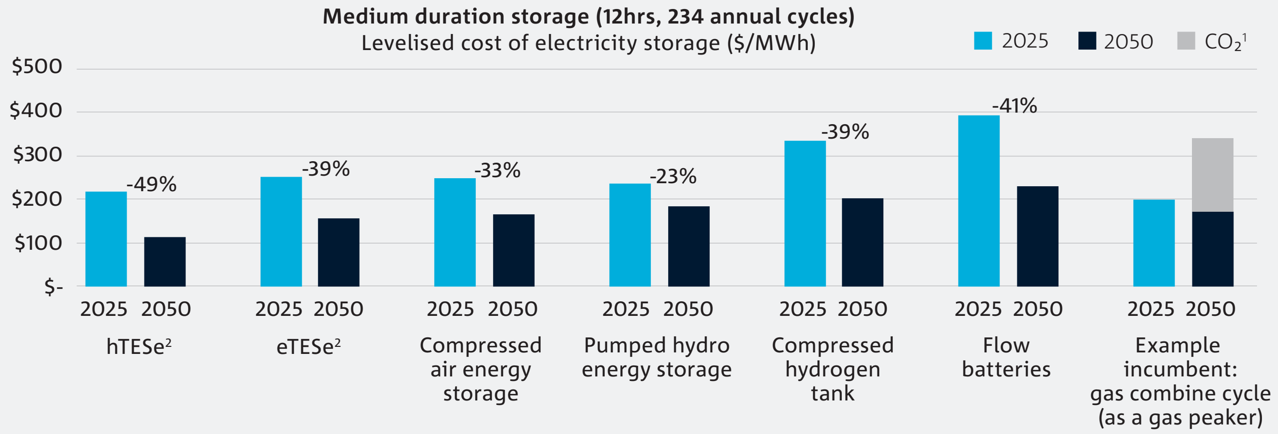
Levelised cost analysis

The competitiveness of the energy storage technologies explored varies by use case. Metal-ion batteries (for short duration) and TESe and PHES (for medium duration) are projected to be cost competitive with gas peaker plants in 2025. By 2050, all electricity storage technologies explored are projected to be competitive with gas peaker plants when accounting for a CO_2 emission cost.

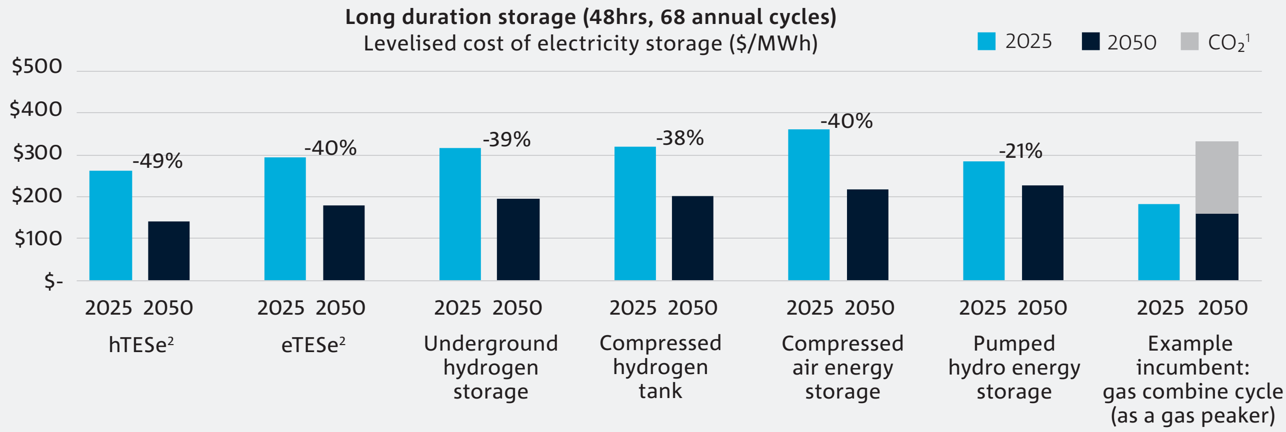
Short duration storage: 2hrs, 394 annual cycles



Medium duration storage: 12hrs, 234 annual cycles



Long duration storage: 48hrs, 68 annual cycles



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050.
2. hTESe: Thermal energy storage with heat input and electricity output; eTESe: Thermal energy storage with electricity input and electricity output.

See technical appendices for assumptions.

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 emissions 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.
- **Synthetic fuels** and **Biofuels** explores high-level RD&D opportunities across potential 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*).

Hydrogen production

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

Electrolysis, 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

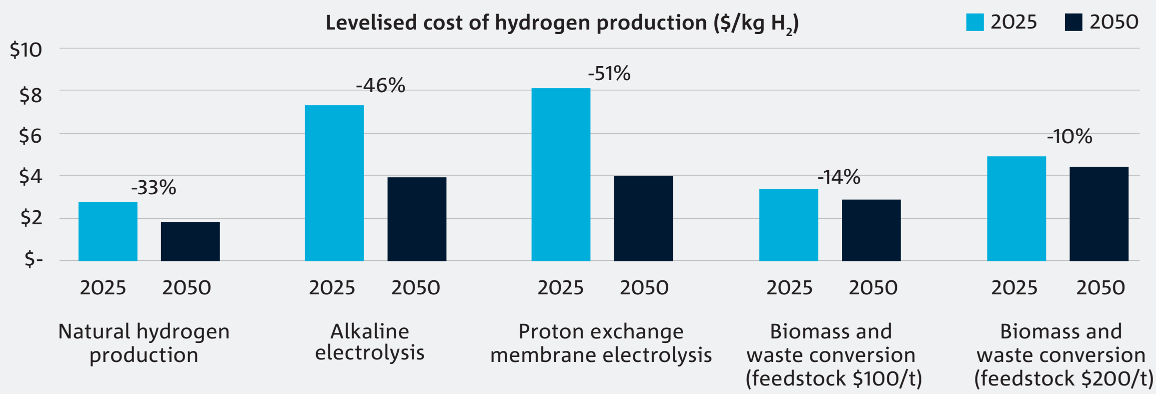
Electrolysis	• RD&D opportunities for electrolysis can support efforts to meet the required performance and cost targets set for commercially viable operations. Achieving these targets will be dependent on RD&D to reduce capital costs by minimising the costs of system-specific components, optimising 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 electrolysis 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 (>50 t/day)

Natural hydrogen is projected to be the lowest cost hydrogen production technology in 2050. Biomass and waste conversion, alkaline electrolysis (AE) and proton exchange membrane (PEM) electrolysis 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 technical appendices for assumptions.

Hydrogen storage

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 (and derivative) 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.

Short duration (12 hrs)	Medium duration (7 days)	Long duration (28 days)
Compressed hydrogen tank		
Capped pipe storage		
	Underground hydrogen storage (UHS)	
Cryogenic sphere		

- Hydrogen distribution technologies and networks
- Sensing and monitoring tools

Short duration (12 hrs)	Medium duration (7 days)	Long duration (28 days)
	Ammonia tank	

- Low emissions electricity generation
- Ammonia distribution

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

RD&D opportunities

Compressed hydrogen tank, Capped pipe storage	• 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.

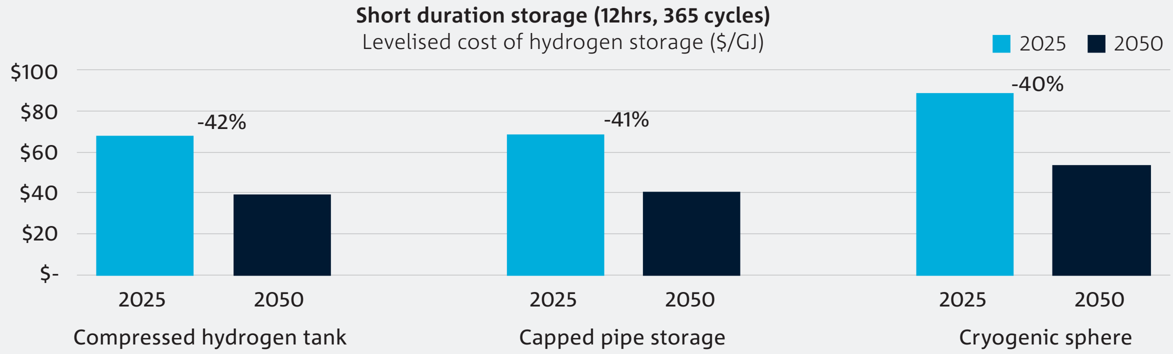
Auxiliary

- 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: 12hrs, 365 cycles

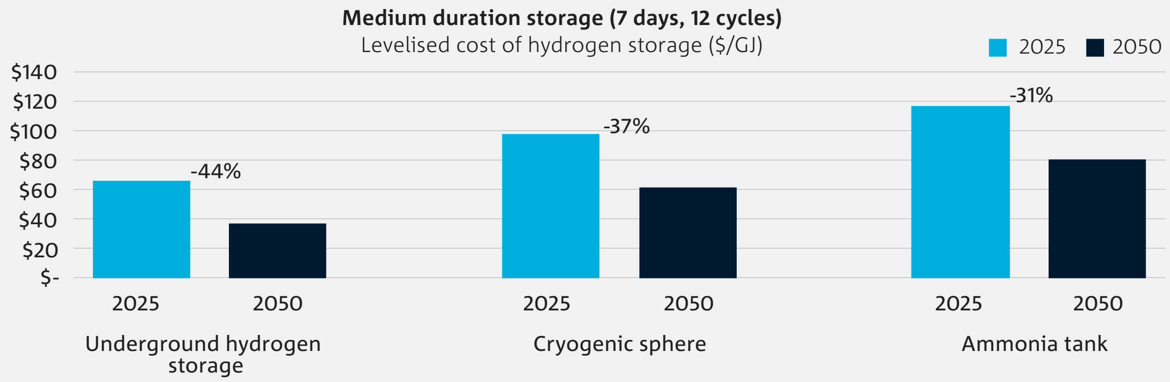
For the specific use case analysed, gaseous storage (compressed hydrogen tanks and capped pipe storage) were estimated to have a lower levelised cost of hydrogen storage when compared with cryogenic spheres, which are impacted by the additional cost of hydrogen liquefaction.



See technical appendices for assumptions.

Medium duration: 7 days, 12 cycles

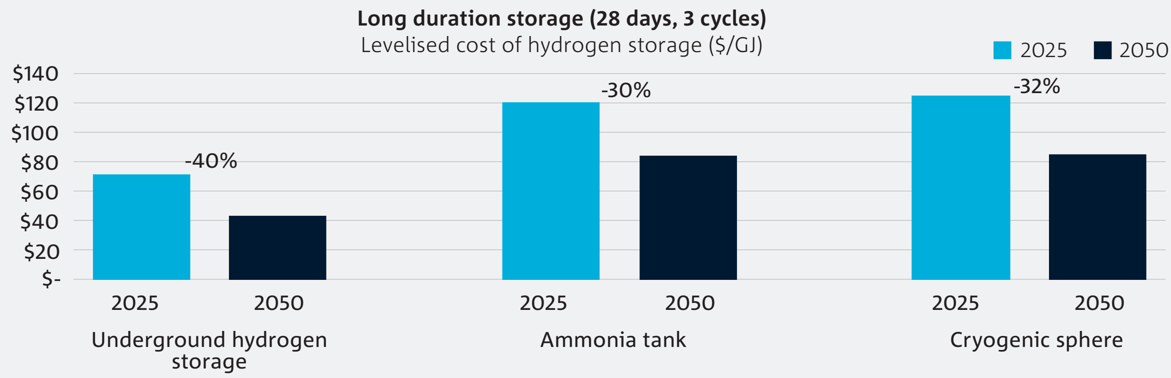
For the specific use case analysed, as a result of lower feedstock and componentry costs, UHS is projected to have the lowest cost of hydrogen storage, when compared with cryogenic spheres and ammonia tanks.



See technical appendices 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 technical appendices for assumptions.

Synfuels

There are multiple emerging pathways 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-liquid 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) 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

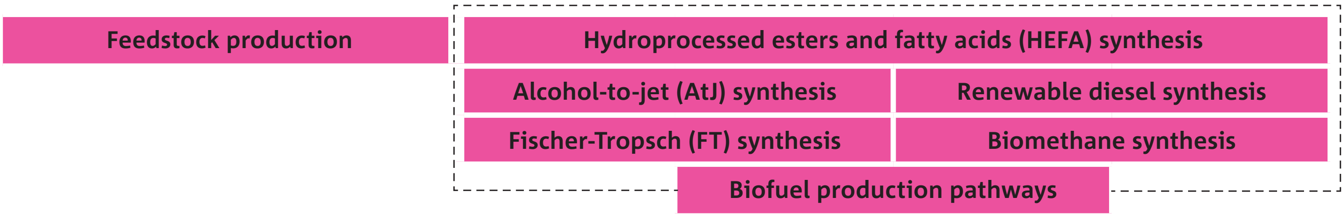
Note: Synthetic fuel technologies are explored in the *Transport* technical appendix for the shipping and aviation sub-sectors, with additional potential applications beyond the scope of this project. This sub-sector presents RD&D opportunities associated with synthetic fuel production, encompassing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

Biofuels

While biofuels have the potential to play a valuable role in Australia's low emissions energy mix, their adoption will require further RD&D 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.



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.
Biofuel 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* reports, with potential applications extending beyond the scope of this project. This sub-sector 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.

Transport

RD&D to support the development of low-cost low carbon fuels, and supporting recharging and refuelling infrastructure, will underpin the deployment of many low emissions technologies across transport sectors.

Challenge

The Australian transport sector – spanning road, aviation, rail and maritime transport – contributes to both the national and global economy and is a major source of the country's emissions and energy consumption. However, the sector is complex to decarbonise given the variation in energy demands, asset and infrastructure requirements, and routes, across different transport modes.

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 across road and non-road transportation sub-sectors:

- **Road transport** analyses low emissions technologies for passenger vehicles, rigid trucks and articulated trucks. In Australia, road transport operations are diverse, and these use cases are illustrative of the common needs of vehicles within the light-, medium- and heavy-duty vehicle sub-sectors, respectively. Two technologies were explored in more detail to identify RD&D opportunities.
- **Aviation** analyses emissions abatement technologies for a medium-range commercial plane (equivalent to an aircraft with 180-passenger capacity). Although aviation operations are diverse, this use case is a common example of Australia's aviation activities and serves numerous domestic routes. Three technologies were explored in more detail to identify RD&D opportunities.
- **Rail** analyses low emissions technologies for a short-range heavy haulage freight train on a route reflective of Pilbara iron ore mining activities. Australia's heavy haul operations are energy-intensive due to high-weight penalties. This use case distinguishes Australian rail transport from many global operations, in which decarbonisation trials for alternative low emissions technologies largely focus on passenger applications. Two technologies were explored in more detail to identify RD&D opportunities.
- **Shipping** analyses low emissions technologies for a deep-sea freight vessel (Panamax class). Australia's role in global trade is significant and contributes substantially to international trade emissions, and decarbonising deep-sea shipping remains particularly challenging due to the need for high energy density fuels that can sustain multi-week voyages without refuelling. Two technologies were explored in more detail to identify RD&D opportunities.

Road transport

Advancing battery and fuel cell technologies through RD&D, alongside robust charging and hydrogen infrastructure, is key to scaling battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (hydrogen FCEVs).

Technology landscape: Light, medium and heavy-duty road vehicles

BEVs and hydrogen FCEVs are projected to be the most cost-effective technologies for decarbonising road transport in Australia, with the suitability of each technology varying by the type of road vehicle, as well as the specific context in which it is used.

Light-duty vehicles (Passenger)	Medium-duty vehicles (Rigid trucks)	Heavy-duty vehicles (Articulated trucks)
Battery electric vehicles (all three vehicle types)		
• Charging infrastructure • Battery system integration		
	Hydrogen fuel cell electric vehicles (medium- and heavy-duty)	
	• Hydrogen refuelling, storage and distribution infrastructure	

RD&D opportunities

Battery electric vehicles	• Cost reductions will support greater BEV penetration in road transport. Improving the energy densities of lithium-ion batteries and exploring alternative chemistries could increase vehicle range and reduce the cost of the BEV system. • Research to reduce the thermal runaway susceptibility of batteries will be important for resolving associated safety concerns.
Hydrogen fuel cell electric vehicles	• Hydrogen FCEVs are a relatively less mature technology compared to BEVs, and RD&D to resolve durability challenges and support the scale-up and streamlining of hydrogen FCEV manufacturing will help progress this technology for deployment. • Novel hydrogen storage systems of increased capacity and reduced weight could also increase medium and heavy-duty hydrogen FCEV range. • Material and componentry innovations could increase hydrogen FCEV performance and efficiency targets, and serve to reduce costs.

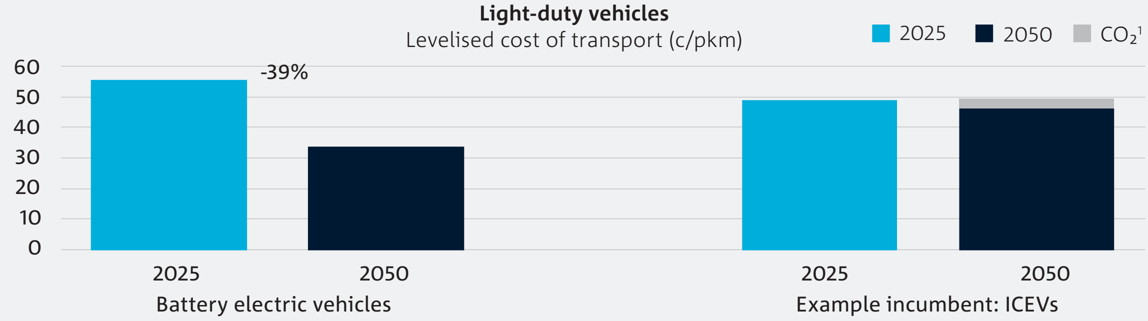
Auxiliary

- The effective deployment and widespread adoption of these technologies can only be achieved if supporting infrastructure is also developed. This includes a widespread network of charging systems and hydrogen refuelling stations, as well as the large-scale production, distribution and storage of hydrogen and renewable electricity.
- Faster fill rates will also be required to support heavy-duty vehicles with larger on-board energy capacities.

Levelised cost analysis

Light-duty vehicles (passenger)

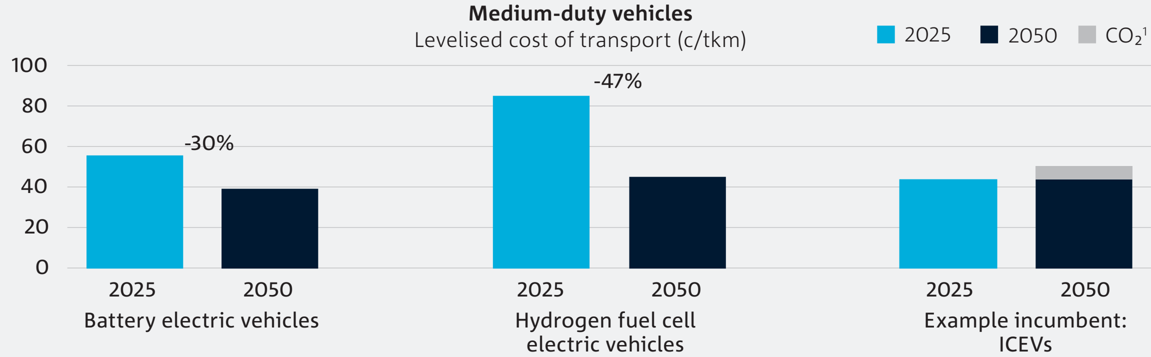
By 2050, BEVs are projected to be the most cost-effective option for light-duty vehicles due to lower fuel and capital costs than incumbent internal combustion engine vehicles (ICEVs).



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions. Note, c/pkm = cents/passenger – km.

Medium-duty vehicles (rigid trucks)

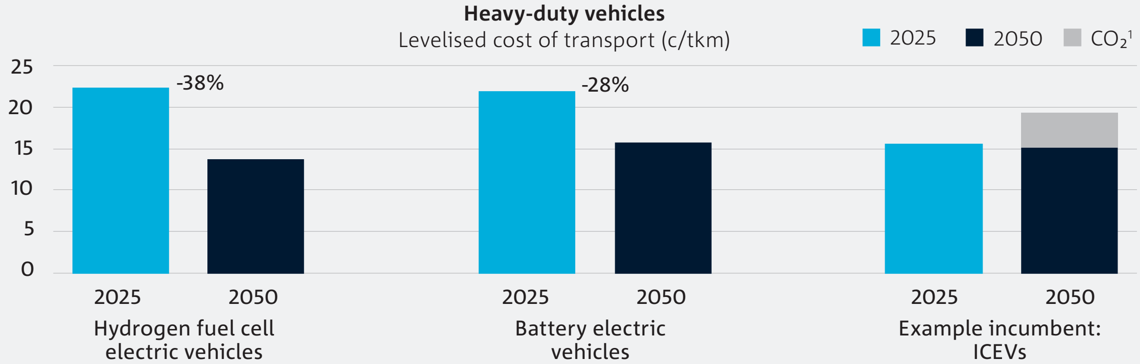
BEVs are also projected to be the most cost effective option for medium-duty vehicles in 2050. FCEVs, which are increasingly more competitive when vehicle utilisation increases, are expected to be similar to ICEVs.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions. Note, c/tkm = cents/tonne – km.

Heavy-duty vehicles (articulated trucks)

Despite relatively higher FCEV capital costs, FCEV vehicles remain the most cost-effective option for heavy-duty vehicles by 2050. BEV costs for heavy-duty vehicles could be reduced through the use of centralised infrastructure providing lower charging costs, and by taking advantage of idle periods.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions. Note, c/tkm = cents/tonne – km.

Aviation

Continued RD&D will improve the process efficiency required to produce drop-in biofuels and synfuel to reduce costs, alongside developing the novel plane architecture and infrastructure needed for hydrogen combustion propulsion.

Technology landscape: Medium-range commercial plane (180-passenger capacity)

Aircraft have long asset lives, often spanning several decades, making frequent replacement economically and practically challenging. Drop-in fuels like biofuels (HEFA, AtJ, FT pathways) and synfuels (power-to-liquid fuels) offer viable alternatives to reduce emissions. Novel technologies, such as hydrogen combustion, show promise but require complete redesigns of aircraft and airport infrastructure due to hydrogen's distinct chemical properties.

Biofuels	Synfuels
• Feedstock processing • Distribution and storage infrastructure	• Carbon capture and utilisation (CCU) • Low emissions electricity generation, distribution • Monitoring, reporting and verification (MRV)

Hydrogen combustion
• Hydrogen liquefaction technologies • Production, transportation, and storage infrastructure • Refuelling infrastructure

RD&D opportunities

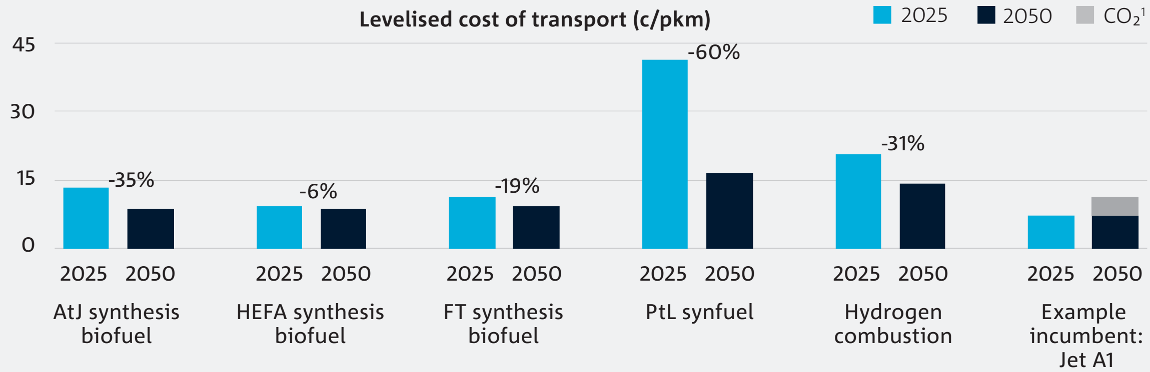
Biofuels	• Cost reductions will drive widespread adoption of biofuels. Advancing RD&D to refine process efficiencies and improve feedstock processing, fuel synthesis, and fuel upgrading techniques will support cost improvements. • Aligning biofuel composition with jet fuel standards at higher blends will enable drop-in use and can further improve industry abatement. • Developing sustainable and scalable feedstock supply chains is critical for aviation biofuel production.
Synfuels	• Research on synthetic fuel production mainly aims to reduce feedstock costs, particularly for renewable hydrogen and CO_2 feedstocks. • Innovations in process efficiency and reducing energy and material needs will likely continue to advance synthetic fuel development.
Hydrogen combustion	• Aircraft combustion systems need redesigning to run on hydrogen fuel, necessitating extensive development and validation to ensure they operate safely and efficiently. • Integrating cryogenic hydrogen storage into aircraft poses engineering and material challenges, requiring RD&D to create new plane architecture and airport infrastructure.

Auxiliary
• RD&D is required to improve process efficiencies across feedstock supply chains. This is aimed at ensuring cost-effective, reliable supplies of feedstock such as biomass for biofuels, renewable hydrogen for combustion, and renewable hydrogen and CO_2 for synfuels. • Tailored solutions are required to develop new, or adapt existing, fuel storage and distribution infrastructure across Australia's network of airports.

Levelised cost analysis

Medium-range commercial passenger plane (180 passengers)

By 2050, biofuels are projected to be the most cost-effective option for due to lower feedstocks costs. Synthetic fuels (PtL) may meet 'drop-in' requirements where biogenic fuels are unavailable. Additionally, hydrogen combustion can serve as a mid-range cost alternative to drop-in fuels.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050.

See technical appendices for assumptions. Note, c/pkm = cents/passenger – km.

Rail

Continued RD&D is required to improve battery electric and hydrogen-powered technology systems, alongside enhancing rail operations and reducing fuel costs.

Technology landscape: Short-range (700km return) heavy haulage freight train (2000m train length)

Battery electric and hydrogen locomotives offer strong emissions reduction potential. Adopting these technologies in Australia requires the development of fast charging or hydrogen infrastructure, with diesel-electric hybrids and renewable diesel expected to be solutions in the short-term.

Hydrogen fuel cell locomotive	Battery electric locomotive
• Hydrogen storage, distribution and refuelling infrastructure	• Energy storage and charging systems

RD&D opportunities

Hydrogen fuel cell locomotive	• RD&D can improve fuel cell efficiency and the durability of fuel cell membranes and catalysts. In particular, demonstrating systems under Australian heavy haulage conditions will be important in verifying their commercial prospects in real-life conditions. • For onboard liquid hydrogen storage systems, RD&D can be used to enhance operational safety, optimise storage designs, extend system lifespans (by improving durability of low-temperature materials) and minimise boil-off.
Battery electric locomotive	• Given the large size of battery systems required for heavy haul freight applications, significant improvements can be achieved through RD&D for battery energy densities and material combinations. These can apply to both hybrid and fully electric locomotives through developments in current and next-generation battery chemistries.

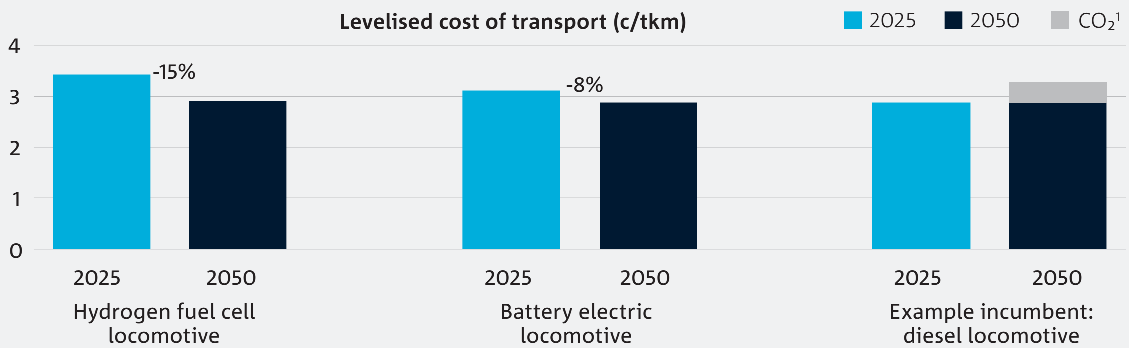
Auxiliary

- RD&D in auxiliary technologies can support the development of ultra-fast charging systems, develop tools to optimise rail operations, such as locomotive-tender configurations and rail-to-grid battery energy storage systems.
- For hydrogen-powered trains auxiliary technology RD&D includes the advancement in hydrogen refuelling and dispensing equipment, including on-site compression.
- Beyond continued RD&D that reduces fuel costs (particular for hydrogen), RD&D into flexible train configurations may also support hybridised trains, which can be optimised to meet specific route and application needs, combining the benefits of both battery electric and hydrogen-powered technology systems.

Levelised cost analysis

Short-range heavy haulage freight train (700km return journey, 2000m train length)

Battery electric and hydrogen fuel cell configurations are projected to be competitive with diesel in 2050 when accounting for a CO_2 emission cost.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions. Note, c/tkm = cents/tonne – km.

Shipping

RD&D is required to reduce the price premium and safety risks associated with synthetic and hydrogen-derived fuels compared to marine gas oil, by 2050.

Technology landscape: Deep-sea freight vessel (Panamax class) on a 12,100km journey

Methanol and ammonia combustion are alternative technology options to conventional marine gas oil (MGO) ships. Methanol internal combustion engine (ICE) vessels are commercially available (with dual-fuelled engines that operate on both methanol and conventional MGO being readily adopted). Ammonia combustion systems can be retrofitted into existing vessels and use conventional liquefied petroleum gas infrastructure. Shipping infrastructure compatibility and strict handling requirements will drive technology preference.

Ammonia combustion	Methanol combustion
• Ammonia storage and bunkering	• Methanol storage and bunkering

RD&D opportunities

RD&D that achieves cost reductions for fuel (hydrogen and CO_2) production is crucial for adopting alternative fuels in the shipping sub-sector. For both methanol and ammonia, RD&D into power systems and on-board fuel storage can help improve efficiency and enhance safety and environmental outcomes.

Ammonia combustion	• Compared to methanol, ammonia ICE vessels face more technical challenges with further RD&D required to advance engine development, overcome operating barriers such as low combustion reactivity and flame speed, and develop componentry to reduce N_2O emissions.
Methanol combustion	• Improving the efficiency and fuel economy of methanol ICE vessels can help reduce operating expenses associated with high methanol fuel costs. • RD&D into the efficiency of emerging methanol fuel cells may ease energy and storage demands, reducing their impact on payload.

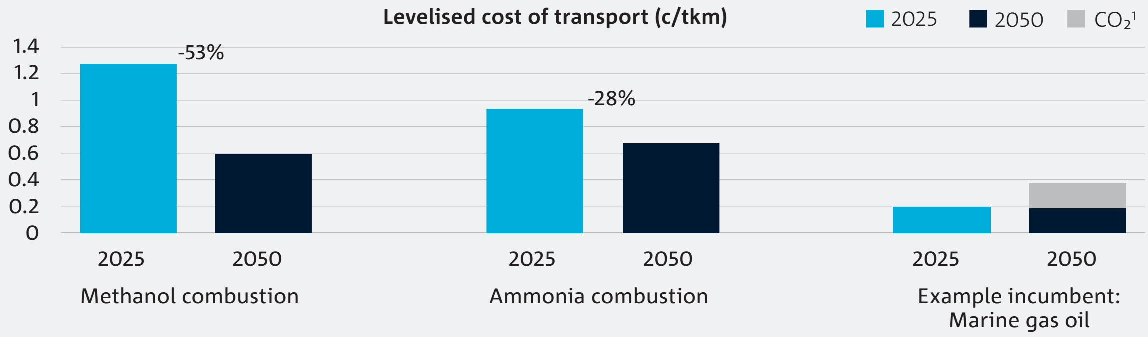
Auxiliary

- Deploying these technologies depends on the development of effective storage and bunkering systems that ensure safe handling, refuelling and integration with port infrastructure. Ammonia bunkering, unlike MGO, requires optimised flow rates and enhanced safety measures. Methanol bunkering is more similar to conventional fuels, though RD&D into corrosion-resistant materials may still be needed.
- While there are mature ammonia storage options, RD&D into ammonia and methanol storage systems can help reduce the space needed for fuel. In some cases, vessel redesign may be needed to store enough fuel to match the energy capacity to a conventional fuel.

Levelised cost analysis

Deep sea Panamax freight vessel (12,100km international shipping route)

Ammonia and methanol combustion technologies remain more expensive than the incumbent (MGO), even with a CO_2 emission cost, for the modelled cost profile.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions. Note, c/tkm = cents/tonne – km.

Transport energy efficiency solutions

Improving energy efficiency in transport is a critical strategy for decarbonisation, regardless of the mode of transport or the energy source used.

By reducing the amount of energy required to move people and goods, energy efficiency measures can deliver immediate and long-term emissions reductions while also lowering operational costs and improving system performance. Advances in lightweighting, aerodynamics, and drivetrain efficiency will make technologies across all modes – from cars to aircraft – more energy-efficient. Operational improvements like smart traffic systems, route optimisation, and energy management technologies further reduce energy use and enhance system efficiency. Together, these measures form a robust foundation for reducing emissions in transport, independent of the specific technologies or fuels in use.

ENERGY EFFICIENCY SOLUTIONS	ROAD	AVIATION	RAIL	SHIPPING
Drag reduction and design	Advanced aerodynamic design	Retrofitting existing planes to reduce drag, wake vortex (e.g., exterior paints that minimise surface roughness)	Advanced aerodynamic design and drag reduction devices (i.e., nose fairings)	Streamlined hulls and structural modifications that minimise friction and leverage hydrodynamic principles
Light weighting	Advanced composite and low weight materials	Advanced composite and low weight materials	Advanced composite and low weight materials	Advanced composite and low weight materials
Technology and componentry improvement	Advanced materials for enhanced powertrain efficiencies; common vehicle architecture	Incremental engine efficiencies (e.g., geared turbofans, open rotor)	Improved wheel/rail lubricants	Lighter, more durable engines with enhanced engine and thermal efficiencies; integration of waste heat recovery systems
Traffic and logistics management technologies	Software advancements and driver's aids for optimised driving patterns; algorithms for real-time traffic prediction	Incorporating performance-based navigation flight procedures	Software advancements and driver's aids (incl. artificial intelligence and machine learning) for speed management and inter-train communication	Automated vessel and digitalisation platforms to optimise vessel speed, routes, port scheduling, and delivery of port services
Energy management solutions	Energy recovery systems such as advanced regenerative braking	Electric / assisted taxiing	Smart pneumatic braking, efficient energy recovery and conversion systems, rail-to-grid battery storage integration	Optimisation of waste heat recovery energy systems

Industry

RD&D to lower the cost of electricity and low carbon fuels can help drive the economic viability of low emissions technologies for alumina digestion, iron and steelmaking, and mining heavy haulage operations.

Challenge

Australian industry is made up of a diverse range of sectors that play a crucial role in both domestic and international markets and contribute significantly to gross domestic product, exports and employment. However, it also remains one of the largest contributors to Australia's total emissions and energy consumption. The complexity of industry decarbonisation pathways, driven by differences in individual operation asset configurations, process requirements, asset lifetimes, site location and technology availability, requires investment across the distribution or co-location of low carbon fuel production and renewable energy generation infrastructure, and energy efficiency 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 across three industry sub-sectors:

- **Iron and steelmaking** analyses low emissions technologies that provide emissions abatement pathways for a blast furnace – basic oxygen furnace (BF-BOF) steel mills reaching its end of life. Conventional iron and steelmaking is an energy- and emissions-intensive high-temperature heat process. Five technologies were explored in more detail to identify RD&D opportunities.
- **Medium-temperature process steam** analyses technology options that can provide emissions abatement pathways, adopting the digestion phase of alumina refining as a use case. Alumina digestion is a process extracting alumina from bauxite ore and accounts for a significant amount of medium-temperature process steam emissions in Australia. Four technologies were explored in more detail to identify RD&D opportunities.
- **Mining heavy haulage** analyses low emissions technology options that can transport significant volumes of mined materials in open-pit operations. Due to their significant energy consumption, high emissions intensity, and demanding operational requirements, heavy-duty diesel trucks present a decarbonisation challenge for the mining industry. Two technologies were explored in more detail to identify RD&D opportunities.

Iron and steelmaking

Advancing Australia's low-emission iron and steelmaking will require targeted RD&D investment in technology demonstrations using Australian ores, complemented by tailored strategies to reduce energy demand across operations.

Iron and steelmaking glossary:

- oxyBF: oxygen blast furnace
- HBI: hot briquetted iron
- BOF: basic oxygen furnace
- NG-DRI: natural gas direct reduced iron
- H_2-DRI: hydrogen gas direct reduced iron
- ESF: electric smelting furnace
- EAF: electric arc furnace

Technology landscape: Brownfield and greenfield pathways for a 2Mtpa BF-BOF steel mill

Iron and steelmaking involve complex processes and long asset lifetimes, requiring both brownfield and greenfield decarbonisation pathways and investment in both mature and emerging technologies.

Brownfield pathway technologies	Greenfield pathway technologies
oxyBF with coal, oxyBF with partial biomass injection	**NG-DRI, H_2-DRI**
• Agglomeration • HBI/DRI handling and transport mechanisms • Biomass feedstock processing	• Renewable hydrogen production, storage and distribution infrastructure • HBI/DRI handling and transporting mechanisms • Component modelling • Agglomeration
BOF	**ESF, EAF**
• Control systems for slag optimisation	• Beneficiation • Renewable electricity generation, storage and transmission infrastructure • HBI/DRI handling and transporting mechanisms • Slag utilisation techniques

Carbon capture and storage (CCS) – see *Carbon Management*

Energy efficiency solutions

- Carbon capture and utilisation
- Slag and material utilisation
- Waste heat recovery
- Beneficiation
- Sensing and analytics
- Advanced digital modelling

RD&D opportunities

Brownfield pathway technologies

oxyBF	• As an established process, RD&D opportunities for blast furnace ironmaking centre on optimising input/output streams to improve energy and material efficiencies and reduce emissions, and enabling the use of lower energy- and emissions-intensive ores. • Partial biomass injection as a substitute for coal and coke requires further piloting and demonstration to investigate the impacts that biomass can have on operations and steelmaking recycling streams.
BOF	• Optimisation of low carbon alloying materials and inputs, such as direct reduced iron (DRI) and alloys, will enable greater portions of scrap to be used in basic oxygen furnaces.

Greenfield pathway technologies

DRI	• Although direct reduction processes have been demonstrated at pilot scales, there is a need to demonstrate Australian ores in direct reduction processes using natural gas or hydrogen. This includes demonstrating the beneficiation and agglomeration of Australia's magnetite and hematite-goethite ores for use in shaft and fluidised bed reactors, to determine their feasibility. • Full reactor designs require RD&D to optimise the process at commercial scales.
ESF	• Demonstrating DRI-based production routes with lower-grade Australian ores is essential to fully characterise technical and operational requirements to accurately inform costs and areas of cost improvement.
EAF	• RD&D opportunities to reduce the high energy demand of electric arc furnaces (EAFs) include process optimisation and novel instrumentation to enable data collection. • Substituting the chemical energy component of the process with electrical energy to electrify the entire process.

Auxiliary

- CCS RD&D across the various brownfield and greenfield production pathways is needed to improve its performance and economic as an auxiliary system.
- RD&D to improve beneficiation to address the increasing impurity content within Australia ores will support improvements in both the quality and efficiency of iron and steelmaking in Australia.
- Similarly, RD&D into agglomeration of Australian-based ores is required for shaft-based DRI routes.
- Exploring alternatives to coal for carbon supply can be employed in both electric melter types and reduce reliance on fossil fuels for carburising the metal during steelmaking.

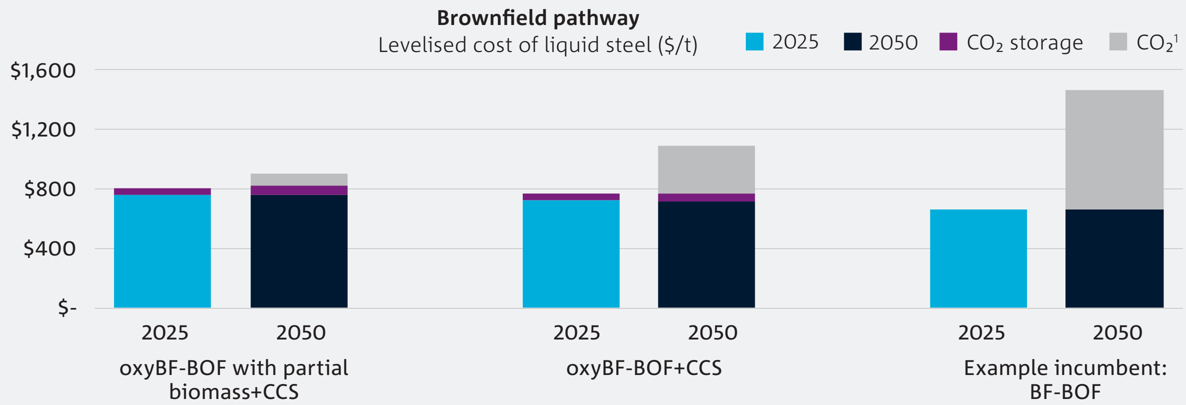
Energy efficiency solutions

- Given the inherent requirement of carbon in steelmaking processes, optimising materials efficiencies will be critical to reducing the carbon emissions and waste impacts that are attributed to steel products.
- Advanced waste heat recovery systems capable of operating under harsh operating conditions and recovering heat from high-temperature process by-products provide another opportunity to enhance process efficiency, supported by suitable energy storage systems.
- Digitalisation is expected to play a continued role in improving the energy efficiency of steelmaking operations and de-risking the scale-up of emerging systems, and sensors can inform operational strategies to effectively integrate variable renewable energy into increasingly electrified plants.

Levelised cost analysis

Brownfield pathway: Relining of a 2 Mt/year BF-BOF steel mill

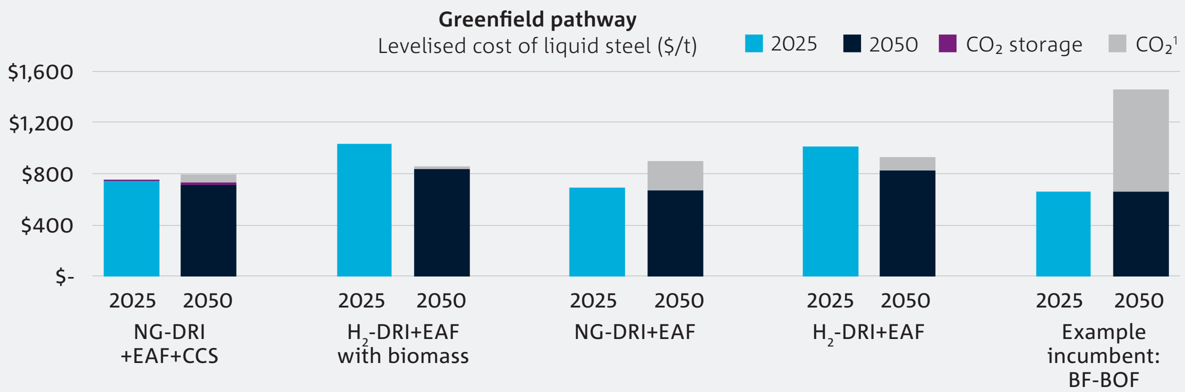
CCS with partial biomass is projected to be the lowest cost BF-BOF pathway in 2050 for brownfield sites, but is only competitive when a CO_2 emission cost is applied to the incumbent BF-BOF process.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions.

Greenfield pathway: Retirement of a 2 Mt/year brownfield BF-BOF steel mill

Emerging technologies, such as natural gas and hydrogen-based direct reduction routes are likely to offer greater long-term emissions reductions via greenfield asset end-of-life transitions and are projected to be significantly more cost competitive than incumbent BF-BOF pathways when accounting for a CO_2 emission cost.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions.

Medium-temperature process steam

As energy is typically the largest component of operating costs for alumina refineries, low emissions boilers, thermal energy storage with electricity input and heat output (eTESh) systems and biomass combustion will benefit from RD&D to improve process energy efficiency.

Technology landscape: Alumina digestion, 100 t/hr, using steam produced at 210°C (8 bar)

A variety of boiler technologies using low emissions fuels can play a role in supporting the transition.

Electric boiler	eTESh system
• Co-located generation infrastructure • Off-grid generation infrastructure • Integrated storage systems	
Hydrogen boiler	**Biomass combustion**
• Hydrogen production, storage and distribution systems • Co-located infrastructure	• Feedstock pre-treatments

Energy efficiency solutions

- Heat exchanges and flash vessels
- Tube digestion
- Double digestion
- Thermal energy solution
- Mechanical vapour recompression

RD&D opportunities

Electric boiler	• Trials and integration testing are needed to support the upper temperature range of medium-temperature (and pressure) electric boilers. • Auxiliary technologies such as integrated energy storage, and the co-location or off-grid support of electricity generation infrastructure may help to reduce electricity input costs, as a key driver for potential system cost reductions.
eTESh system	• Although TES systems have been deployed for other applications, applying TES systems for large-scale industrial steam requires further RD&D and commercial trials. • Improving thermal insulation and thermal management will lower the amount of heat lost, and therefore fuel used, by the process.
Hydrogen boiler	• Hydrogen flames have poor radiative properties, and to improve efficiency there are RD&D opportunities in exploring non-greenhouse gas additives to enhance flame glow.
Biomass combustion	• Minimising and managing the occurrence of fouling, ash and agglomeration will help to preserve reactor performance and efficiency. • RD&D efforts will advance resistive materials, preserving reactor integrity and extending their lifespan.

Auxiliary

See *Electricity – Electricity generation* and *Electricity storage* and
Low Carbon Fuels – Hydrogen production and *Hydrogen storage*

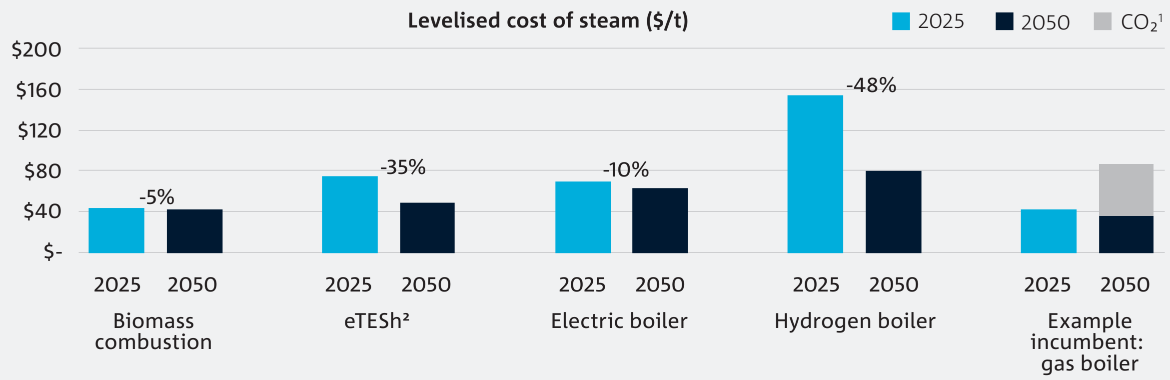
Energy efficiency solutions

- Demonstrations at scale to integrate solutions that minimise heat loss, such as thermal energy storage (TES) and tube digestion, can work to lower fuel consumption and decrease fuel costs per unit of alumina produced.
- The more efficient use of fuel can be encouraged through solutions such as digestion and mechanical vapour recompression (MVR), which require increased development and demonstration to be applied at scale for medium-temperature process steam applications.

Levelised cost analysis

Alumina digestion (100 tonnes per hour at 210°C and 8 bar)

Focus on improving the economic viability of auxiliary technologies will be crucial to the deployment of electric and hydrogen boilers, as fuel costs are the primary driver influencing the levelised cost of each technology.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050. See technical appendices for assumptions.

2. eTESh: thermal energy storage with electricity input and heat output.

Mining heavy haulage

To meet performance requirements, low emissions technologies for mining heavy haulage require RD&D to achieve the necessary energy density improvements for on-board hydrogen or batteries.

Technology landscape: Open-pit heavy haulage truck (299t carrying capacity)

Battery electric haul trucks (BEHTs) and fuel cell electric haul trucks (FCEHTs) are long-term decarbonisation options for Australia's mining sector, but the transition will also benefit from a focus on energy efficiency solutions.

Battery electric haul truck

- Charging infrastructure
- Off-grid production and storage infrastructure

Fuel cell electric haul truck

- Hydrogen refuelling infrastructure
- On-grid hydrogen storage and distribution networks
- Off-grid production and storage infrastructure

Energy efficiency solutions

- Trolley assist
- In-pit crushing conveying
- Autonomous trucks
- Electro-mechanical flywheels
- Regenerative braking
- Digital fleet management tools/software

RD&D opportunities

Battery electric haul truck	• As the battery pack is the primary cost driver and performance constraint for battery electric haul trucks (BEHTs), there are RD&D opportunities to help realise the energy dense, durable and cost-effective mobile battery systems needed for BEHTs to become widely adopted. • Improvements to the energy density of lithium-ion based batteries could support the cost-competitiveness of BEHTs by reducing the number of battery cells needed for a given capacity. • Exploring alternative battery chemistries that use earth abundant materials, or fewer critical minerals, could lower BEHT costs while maintaining their performance. • Optimising battery pack design and cell integration to maximise payload, alongside improvements to battery cycle life, could reduce total cost of ownership and improve BEHT utilisation. • Understanding how temperature, depth-of discharge and duty cycle characteristics such as haul road grade, length and terrain, impact batteries could extend their lifespan and lower replacement costs.
Fuel cell electric haul truck	• For fuel cells, the primary challenge for RD&D is to progress the technology and manufacturing economies of scale of proton exchange membrane (PEM) fuel cells to be cost-competitive with diesel haulage engines. • Research opportunities are focused on developing new catalyst materials or structures to improve fuel cell durability and minimise reliance on expensive materials, such as platinum. • For on-board hydrogen storage, improvements to the energy density of on-board hydrogen storage could improve the commercialisation and large-scale prospects of the technology. Current research directions include compression, cryo-compression and liquid storage prototypes, but RD&D is required to ensure safety due to the volatility of hydrogen gas at high pressures.

Auxiliary

- RD&D is required to develop the necessary supporting infrastructure for the on-site deployment of BEHTs and FCEHTs. Developing advanced charging systems, improving hydrogen refuelling networks and expanding on-site renewable power cost-effectively will enable these technologies to support the sub-sector's transition.
- The development of advanced compression systems with lower energy consumption and operational costs is also required to improve the economics of on-board hydrogen storage.

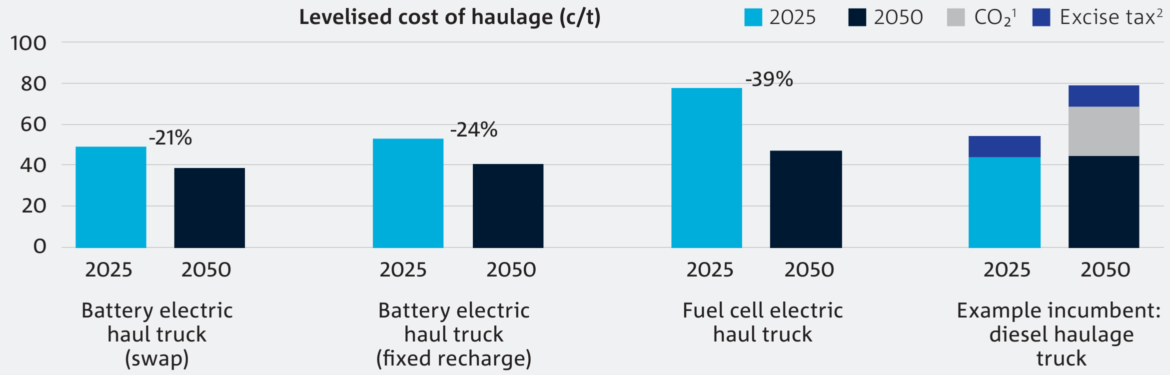
Energy efficiency solutions

- In the near term, the high upfront costs of these technologies, combined with the need for extensive supporting infrastructure, are major barriers to initial investment and widespread adoption. A mix of energy efficiency solutions could support the sub-sector as it transitions, offering near-term cost and emission reductions that are technology-agnostic.

Levelised cost analysis

Open-pit heavy haulage truck (299t carrying capacity)

For heavy-duty haulage trucks, which demand significant energy consumption and high utilisation rates, large-scale fleet electrification or the integration of hydrogen fuel cells provide the most cost-competitive options in 2050.



1. CO_2 cost: A CO_2 emission cost is applied to each tonne of emissions produced by a particular technology, consistent with the IEA NZE scenario in 2050.

2. Fuel excise is typically claimed back via a fuel tax credit for this use case. The perceived cost of diesel and renewable diesel haulage trucks would therefore not include this component, reducing their levelised cost.

See technical appendices for assumptions.

Carbon Management

Effective carbon management is needed to support the decarbonisation of hard-to-abate industries, reduce Australia's emissions and reach net-zero targets by 2050.

Challenge

Carbon management will play a critical role in sectors that are not straightforward to decarbonise with renewable energy technologies. These sectors are typically described as 'hard-to-abate' as they often rely on carbon from fossil fuels as building blocks for products (e.g., steel, chemicals, plastics), require high energy density fuels for long-distance transport (e.g., long-haul aviation), or produce emissions inherently in their processes (e.g., cement production).

Beyond this, carbon management will be needed to counterbalance residual emissions in the atmosphere and to achieve and sustain net negative emissions, which will be critical to stabilising the global climate. While achieving significant emissions reductions is first and foremost essential, durable carbon removals will be critical to meeting the goals of the Paris Agreement to limit warming to below 2°C.

Scope of analysis

This analysis highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of carbon management technologies:

- **CO_2 capture** explores high-level RD&D opportunities across point source capture and direct air capture (DAC) technologies.
- **CO_2 storage** and **CO_2 utilisation** summarises RD&D opportunities identified in *CSIRO's CO_2 Utilisation Roadmap (2021)* and *CSIRO's Australian Carbon Dioxide Removal Roadmap (2025)*.

CO_2 capture

While carbon management technologies will play a significant role in Australia's energy transition, adoption will require RD&D to significantly reduce their cost and energy demands.

Technology landscape

Several technologies explored as part of this analysis, particularly in the *Industry* sector, could leverage carbon management technologies (i.e., technologies that capture, store or use CO_2) as part of their transition strategy. Depending on how these technologies are deployed, they can be used to reduce hard-to-abate emissions, offset emissions from incumbent fossil fuel infrastructure or permanently remove atmospheric CO_2.

Point source	Direct air capture (DAC)

RD&D opportunities

CO_2 capture	
Point source	• Improving the design of point source reactors and their materials, as well as process optimisation, could lower system costs, improve capture efficiency and improve the feasibility of this technology for adoption.
Direct air capture	• Developing durable, efficient and low-cost capture materials could extend asset lifetimes and maximise CO_2 capture. • RD&D aimed at emerging low-TRL DAC technologies could help reduce their cost and energy demands. These reductions could be furthered through modular plant designs or by DAC systems that integrate waste heat or energy from other industrial processes.

Auxiliary

- Optimising retrofit strategies could expand the use of point source carbon capture in existing industrial facilities.
- Developing advanced measurement and verification systems could support the commercial viability of all carbon capture technologies.
- Effective deployment and widespread adoption of these technologies can only be achieved if supporting renewable energy production and storage infrastructure is developed.

Levelised cost analysis

- Note: CO_2 capture technologies are referred to in the *Electricity, Low Carbon Fuels, Industry*, and *Transport* technical appendices, with potential applications extending beyond the scope of this project. This sub-sector presents RD&D opportunities associated with point source and direct air capture, for information purposes only. As no use case was defined, no levelised cost analysis was performed.

CO_2 storage and CO_2 utilisation

RD&D opportunities

CO_2 storage

- CO_2 can be stored above ground, dispersed in open environments, in living organisms or deep underground in geological formations. RD&D to improve the reliability of CO_2 storage capacity estimates, as well as their effectiveness, could help justify significant upfront costs and resource requirements.

CO_2 utilisation

- CO_2 can be captured from emission sources or the atmosphere and converted into valuable low- or zero-emission products (e.g., fuels, chemicals, building materials). Opportunities exist to reduce costs and improve the efficiency of conversion technologies through novel catalysts, reactor designs or advanced bioengineering. Doing so could reduce industries' reliance on CO_2 derived from fossil resources and support a circular carbon economy.

Conclusion

With limited RD&D resources and many emerging low emissions technologies, Australia must strategically prioritise efforts through strong collaboration across research, government, and industry to maximise national benefit.

This study examined 43 primary technologies relevant to the electricity, low carbon fuels, transport and industry sectors, to identify RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. This assessment of RD&D opportunities requires regular revision such that it evolves in line with science and technology advances, Australia's changing energy landscape, and the global transition.

Achieving the cost forecasts identified by this study and creating opportunities to surpass them will be essential for technology uptake and in ultimately achieving the associated emissions abatement identified. The opportunities identified across these technologies and their sub-sectors highlighted five key themes for RD&D:

1. Australia has unique challenges for low emissions technologies associated with its geography, geology, industrial mix and energy systems that international stakeholders may not prioritise but are vital for Australia to solve.
2. RD&D has a key role to play in achieving and exceeding 2050 levelised cost forecasts across both energy supply and demand technologies, through its potential to reduce input costs for demand-side technologies and improve technology capital and operating costs.
3. Of the 43 explored primary technologies, only 14 are currently regarded as ready for commercial deployment, highlighting the need for RD&D investment to support both demonstration and scale-up of low emissions technologies, and to achieve the benefits of learning by doing.
4. RD&D to enhance energy and fuel efficiency can improve the cost and performance of both incumbent technologies and their low emissions alternatives, which will be important for reducing emissions in the short and long term.
5. Technical development is only one part of the puzzle, and addressing the drivers of and barriers to the uptake of these technologies requires coordinated and interdisciplinary research actions.

The RD&D opportunities highlighted by this study are intended to support constructive dialogue and help navigate the energy transition by capitalising on national RD&D strengths. The breadth of RD&D opportunities identified by this study cannot be addressed by one organisation or stakeholder, highlighting a need for collaboration to achieve the target outcomes. Domestic and international collaboration can support the delivery of these RD&D efforts and maximise Australia's economic benefits from its resources and investments.

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