Australia's National
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The State of Energy Transition Technologies

Transport

TECHNICAL APPENDIX

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Citation and authorship

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Acknowledgement

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Contents

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

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 emission 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 subsectors, 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 global 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. Three technologies were explored in more detail to identify RD&D opportunities.

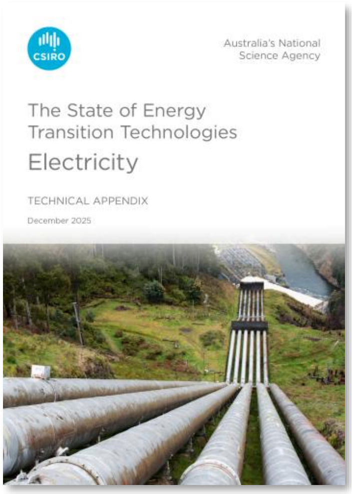
2 Transport overview

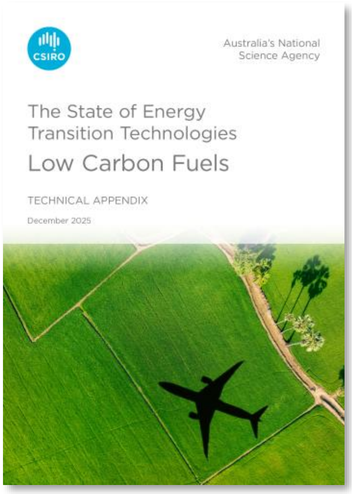
Research, development and demonstration (RD&D) will be pivotal in informing and driving the change required to achieve the energy transition and Australia's net zero ambitions. However, with limited resources and a broad array of emerging low emissions technologies, Australia faces the important task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

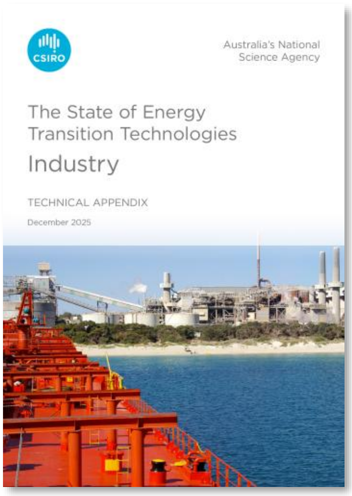
This study, *The State of the Energy Transition technologies,* highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. It is not intended to prescribe research strategies for Australia or any 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.

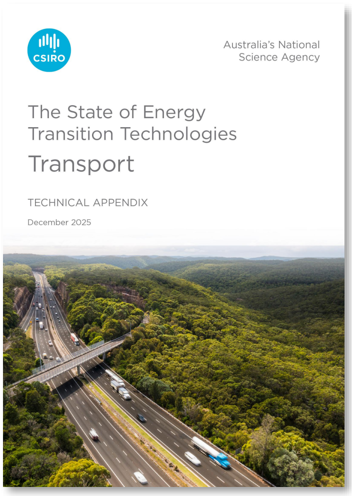
2.1 This report

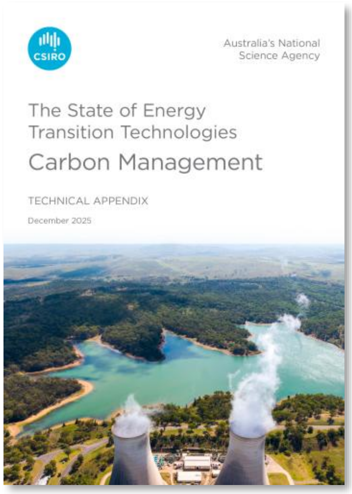
The State of the Energy Transition Technologies consists of a Synthesis report and five technical appendices spanning a range of Australian energy supply and demand related sectors. This report, focused on transport, is to be considered alongside the other reports, and aims to evaluate a diverse range 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.











2.2 Australia’s transport energy needs

The Australian transport sector encompasses a wide range of activities that are crucial to domestic and international connectivity, significantly contributing to GDP and employment. This sector includes road, aviation, rail and maritime transport, as well as related services and infrastructure. Key supply chains within the transport sector include vehicle manufacturing, fuel production, and logistical support services, which generate substantial revenue. For example, according to the Bureau of Infrastructure and Transport Research Economics’ 2024 Yearbook, the transport sector contributes 4.6% of Australia’s GDP and generates $113.1 billion in annual revenue.[1]

Transport significantly contributes to both the national and global economy, while being a major source of the country's emissions and energy consumption. In 2022, Australian domestic transport sector was responsible for emitting over 120 $MtCO_2e$, which accounted for 28% of the country's total domestic emissions.[2] These numbers represent full fuel cycle emissions, and include Scope 1, 2 and 3 emissions that arise from vehicles, aircraft, locomotives and ships.

Decarbonising transport is complex and the variation in energy demands across different transport modes significantly influences emissions reduction strategies. Non-road sectors, including aviation and shipping, are characterised by particularly high energy requirements and extended asset lifetimes, which present unique challenges for emissions abatement. Fuel costs constitute a dominant expense across all transport modes, making the reduction of fuel consumption without compromising efficiency crucial. While shifting transport demand from more energy-intensive to less energy-intensive modes is difficult due to established infrastructure and consumer habits, changes in the relative importance of transport subsectors with more cost-effective low emissions technologies could accelerate decarbonisation.

Regional diversity adds another layer of complexity, necessitating tailored solutions to address specific challenges like travel distances, road conditions, and shipping routes. The successful transition to a sustainable and competitive transport sector will necessitate substantial investment in supporting infrastructure. Urban environments, ports, terminals, and airports must adapt to accommodate this transition. The development of such infrastructure is essential and must progress concurrently with technology deployment across all transport sectors.

Balancing economic growth with net-zero targets will require Australia to make considered investment decisions that are aligned with the transformative changes expected in Australia’s energy system. Accelerating low emissions and cost-effective technologies will be essential for positioning Australia’s transport sector to remain globally competitive in a decarbonised future.

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[1] Inclusive of Australia’s transport, postal and warehousing industries in 2023-24. See Table 1.1a, Bureau of Infrastructure and Transport Research Economics (BITRE) (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[2] See, e.g., 28% in 2022. Australian Government (2024) National Greenhouse Accounts. Department of Climate Change, Energy, the Environment and Water. <https://www.greenhouseaccounts.climatechange.gov.au/> (accessed 28 March 2025); Table 11.6, Bureau of Infrastructure and Transport Research Economics (BITRE) (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

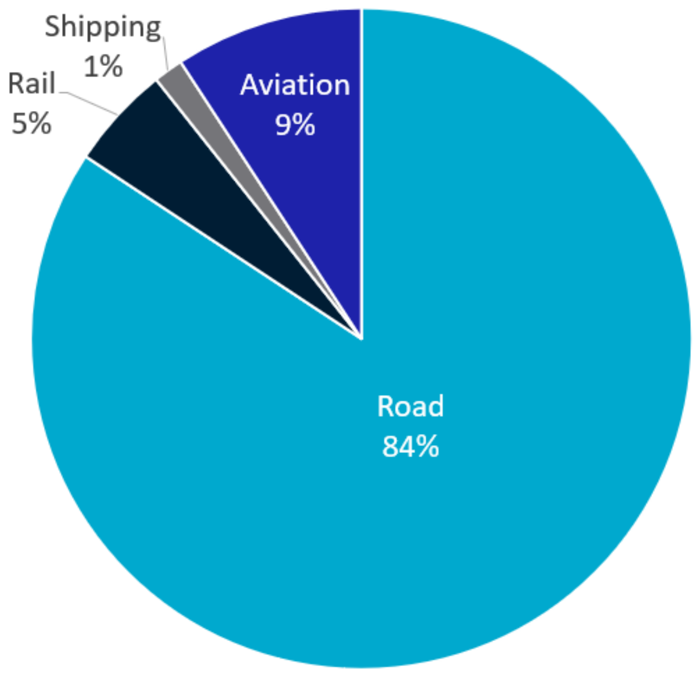
2.3 Scope of this report

This report highlights RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts across essential transportation modes.

In 2023-24, domestic transport in Australia produced 128.5 $MtCO_2e$, covering the four key modes: road, aviation, rail, and domestic maritime transport. Road transport was the largest contributor, accounting for 84% of the emissions, followed by aviation at 9%, rail at 5%, and domestic maritime transport at 1%.[3] These modes are all integral to the nation's economy and will continue to play a vital role in the future. However, each mode presents unique challenges in terms of emissions reduction and the transition to lower-carbon alternatives.

Given the decarbonisation of these transport modes will be a key step forward for Australia's energy transition, this analysis focuses on exploring low emissions technologies and RD&D opportunities within road, aviation, rail and maritime transport (see Figure 1).

Figure 1: Percentage share of transport emissions by transport mode, 2023-24[4]



[3] Bureau of Infrastructure and Transport Research Economics (BITRE) (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[4] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

Overview of subsectors analysed within the report

Road

Australia's road transport system is extensive, supporting the movement of people and goods across vast distances.

Road vehicles contributed approximately 108 $MtCO_2e$ to the nation's total emissions in 2023-24,[5] with the road fuel mix dominated by fossil fuels.[6] This subsector covers the wide range of road-going vehicles, ranging from personal passenger cars to multi-trailer freight trucks (commonly referred to as 'road trains').

The role road transport plays in society and industry, particularly in a geographically dispersed country like Australia, presents logistical challenges for low emissions technologies. The diversity of vehicle types, each with different requirements for distance, frequency of use, passenger carrying capacity or payload, and refuelling infrastructure adds to the complexity. The shift from traditional fossil fuels to low emissions alternatives will necessitate significant investment in new infrastructure and technologies across a large and varied network to meet sectoral demand.

Aviation

The aviation industry is a critical component of Australia's transport network, connecting the country and facilitating domestic travel.

In 2023-24, aviation was responsible for approximately 12 $MtCO_2e$ of emissions, representing 9% of Australia's total transport emissions.[7] The subsector encompasses domestic passenger and freight flights, with passenger flights accounting for most operations.[8] The high energy density required for flight is a significant challenge to decarbonisation, and long-asset lifetimes have focused technology development on both solutions that leverage existing engines and platforms in addition to RD&D on entirely new low emissions aircraft designs.

Supporting infrastructure is required to develop in tandem with new aviation technologies, suggesting significant investment. The subsector's economic and operational viability will require supportive policies and advancements in fuel and infrastructure technology to ensure safety and efficiency. The global nature of aviation necessitates international cooperation and standardisation.

Rail

Rail transport in Australia encompasses both passenger and freight services, offering an efficient and often more sustainable alternative to road transport.[9]

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[5] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[6] Federal Chamber of Automotive Industries (2024) VFACTs Vehicle Sales Data. (accessed 28 March 2025).

[7] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[8] Bureau of Infrastructure and Transport Research Economics (BITRE) (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[9] Australasian Railway Association (2020) Value of Rail 2020. <https://ara.net.au/wp-content/uploads/REPORT-ValueofRail2020-1.pdf> (accessed 21 February 2025).

Rail transport emitted 6.5 $MtCO_2e$ in 2023-24, primarily due to the use of diesel locomotives.[10] The subsector's diverse operational needs, considering varying distance, terrain, energy use, frequency, capacity, and passenger capacity or freight loads, along with the need for specialised refuelling infrastructure, suggest that multiple technologies and strategies will be needed to decarbonise rail.

Transitioning to low emissions technologies is crucial for reduce rail emissions. Investment in RD&D is necessary to advance new technologies that are efficient and commercially viable. While these novel solutions may require substantial investment in new infrastructure and rolling stock, adopting energy efficiency solutions in existing diesel-powered trains can provide immediate environmental impact.

Shipping

Australia's shipping sector is essential for international trade and the movement of goods along the nation's extensive coastline. Additionally, it plays a significant role in national defence, tourism, and transportation services, including ferry operations.

In 2023-24, maritime transport emitted 2 $MtCO_2e$, or 1% of Australia's total transport emissions.[11] The sector faces unique challenges in decarbonising due to the long distances (often exceeding 10,000 km) and high energy requirements of shipping.

While low emissions fuels that can be retrofitted into existing vessels are expected to be of interest to industry stakeholders in the near term, the ideal low emissions technologies for shipping will need to consider the asset lifetimes of existing ships and their ability to shift significant cargo. Port and terminal infrastructure will need to change in line with the adoption of new energy systems for shipping. In the meantime, emissions reductions could be achieved through improving the fuel efficiency of the existing diesel ship.

[10] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024.
<https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[11] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024.
<https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

3 General methodology

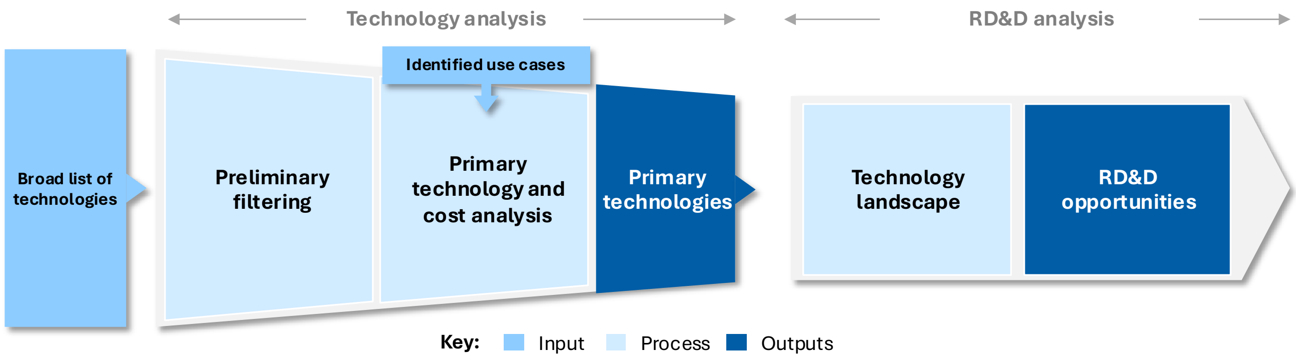
The State of Energy Transition Technologies report methodology was designed to highlight RD&D opportunities that could support the scale-up, de-risking, and deployment of low emissions technologies, advancing Australia's decarbonisation efforts. The methodology adopts a multi-stage approach (see Figure 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.[12]
- **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 the *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).

[12] 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.

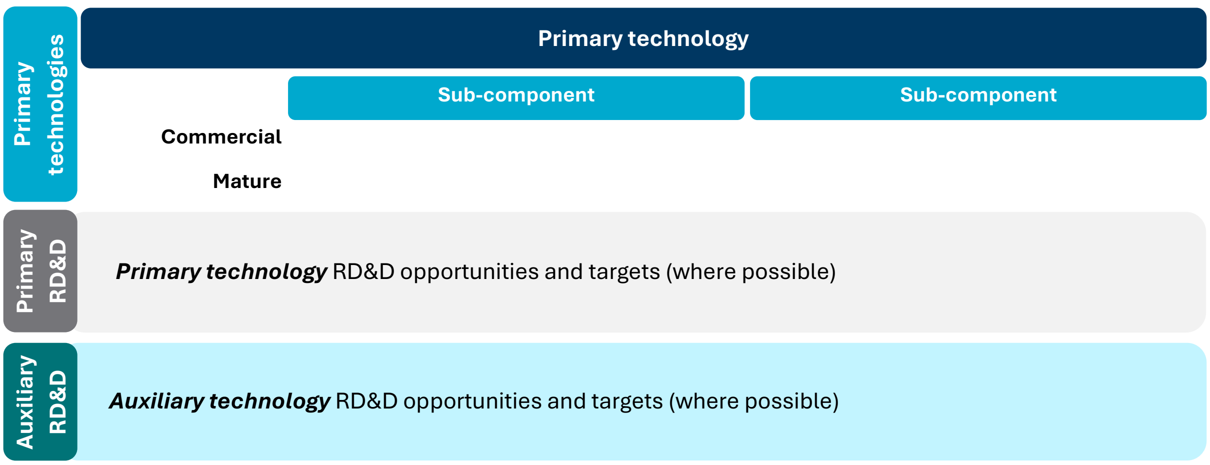
RD&D opportunity analysis

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 Road transport

4.1 Executive summary

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 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	Battery electric vehicles	Battery electric vehicles
• Charging infrastructure • Battery system integration		
	Hydrogen fuel cell electric vehicles	Hydrogen fuel cell electric vehicles
	• Hydrogen refuelling, storage and distribution infrastructure	

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

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 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 FCEV range. • Material and componentry innovations could increase FCEV performance and efficiency targets, and serve to reduce costs.

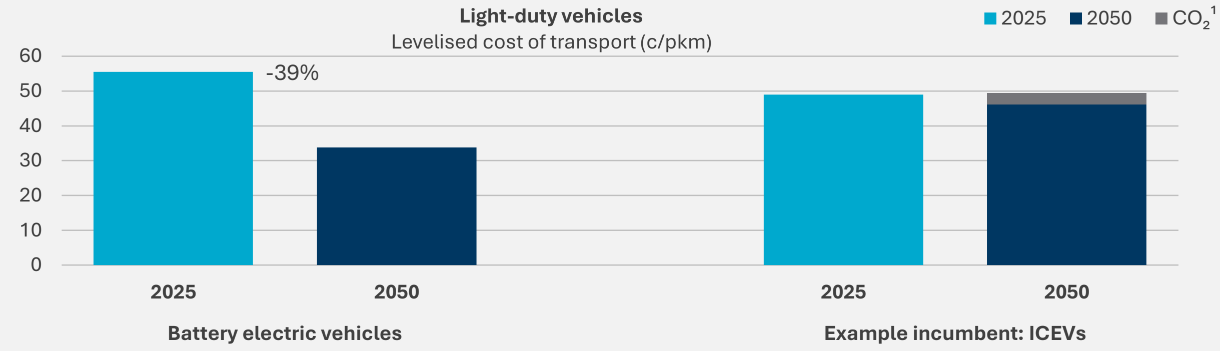
Auxiliary

- 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)

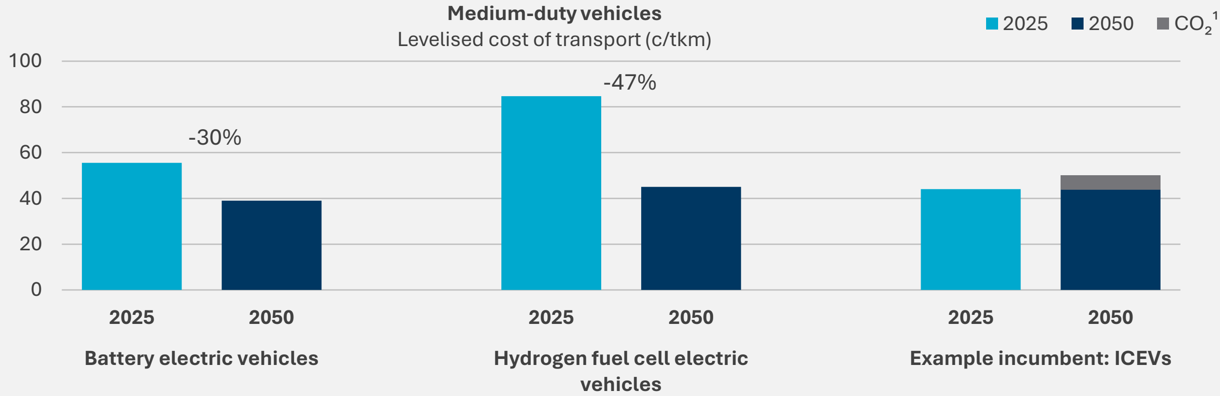
By 2050, BEVs are projected to be the most cost-effective option for light-duty vehicles due to lower fuel and capital costs than incumbent internal combustion engine vehicles (ICEVs).



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 *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions. Note, c/pkm = cents/passenger – km.

Medium-duty vehicles (rigid trucks)

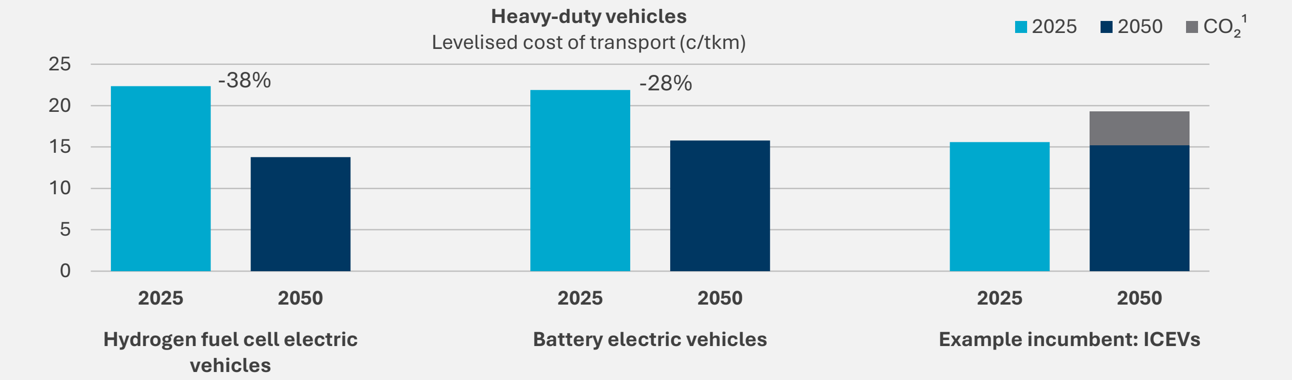
BEVs are also projected to be the most cost effective option for medium-duty vehicles in 2050. FCEVs, which are increasingly more competitive when vehicle utilisation increases, are expected to be similar to ICEVs.



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 *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* 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.



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4.2 Introduction

Road transport is the largest source of emissions in Australia's transport sector. On road vehicles, including passenger vehicles, light commercial vehicles, heavy-duty trucks, buses and motorcycles contributed approximately 108 $MtCO_2e$ to the nation's total emissions in 2023-24. This accounts for 84% of Australia's total transport emissions.[13] Despite an increase in the uptake of low emissions technologies, direct CO_2 emissions from fossil fuel combustion in the road sector has risen by 200 Mt since 2015.[14]

The road transport sector supports Australia's economy by enabling passenger travel, freight movement, public transit, and commercial services. For example, in 2022-2023 road transport contributed to approximately 31% of domestic freight and employed 297,000 Australians.[15] Given its economic importance and emissions impact, identifying the effective decarbonisation technologies for different vehicle types is considered essential for achieving Australia's net-zero targets by 2050.

Passenger and light commercial vehicles account for 71% of Australia's road transport emissions, with medium to heavy-duty trucks and buses contributing the remaining 29%.[16] Globally, the IEA anticipates that electrification and biofuels will support the decarbonisation of road transport to 2030, with electricity representing three-quarters of energy consumption by 2050.[17] While emissions reductions opportunities exist, each transport mode requires supporting refuelling or recharging infrastructure networks and has distinct requirements that will shape the type of technology deployed. RD&D – across vehicle technologies, their networks, and cross cutting fields to support broader energy efficiency gains, will play an instrumental role in de-risking low emissions technologies, accelerating their performance, and enabling their deployment.

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[13] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[14] International Energy Agency (2023) The Breakthrough Agenda Report: accelerating sector transitions through stronger international collaboration. < https://iea.blob.core.windows.net/assets/d7e6b848-6e96-4c27-846e-07bd3aef5654/THEBREAKTHROUGHAGENDAREPORT2023.pdf>

[15] Bureau of Infrastructure and Transport Research Economics (2024) Australian infrastructure and Transport statistics – Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf>

[16] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[17] International Energy Agency (2023) Net Zero Roadmap: A Global Pathway to Keep the 1.5°C degree Goal in Reach. <https://iea.blob.core.windows.net/assets/8ad619b9-17aa-473d-8a2f-4b90846f5c19/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf>; IEA (2023) Road transport: Net Zero Emissions Guide. <https://www.iea.org/reports/road-transport> (accessed March 2025).

The substantial energy use, high emissions intensity, and varied operational demands of on-road vehicles present a significant decarbonisation challenge. This chapter presents an analysis of low emissions technologies for road transport to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support the scale-up, de-risking, and deployment of these technologies.

4.2.1 Road transport use case(s)

To explore low emissions technologies in the road transport subsector, three use cases have been defined to reflect the common needs of vehicles within the light-, medium- and heavy-duty vehicle segments, respectively (see Table 1). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with these use cases.

Each use case is defined by a single vehicle type, representing the vehicle class with the highest emissions within the segment; an annual range, representing the annual kilometres travelled by the vehicle type;[18] and the effective capacity of the vehicle. The maximum vehicle capacity is adjusted to an effective capacity to account for real world factors typical for each end use. In the light-duty end use this adjustment accounts for vehicle occupancy. In the medium-duty and heavy-duty end uses it accounts for the assumed proportion of backhauling and the reduced maximum payload capacity of battery electric vehicles due to battery weight.

These use cases are illustrative and present requirements that technologies must be able to meet in order to service Australia's domestic road transport subsector. In reality, road transport operations are diverse with significant variability across vehicle class, payloads and distances, particularly for heavier duty vehicles.

Table 1: Use case(s) – Road transport

Use case(s)	Light-duty vehicle (LDV)	Medium-duty vehicle (MDV)	Heavy-duty vehicle
Description:	**A passenger car travelling 11,120km per year, carrying an average 1.7 passengers.[19]** Passenger vehicles are responsible for 49% of total road emissions and 64% of total motorised passenger travel in Australia.[20]	**A rigid truck travelling 39,200km per year with an effective capacity of 4.7t, when accounting for backhauling.[21]** Rigid trucks are responsible for 11% of total road emissions and for moving 18% tkm of road freight transport in Australia.[22]	**An articulated truck travelling 148,800km per year and an effective capacity of 12t, when accounting for backhauling.[23]** Articulated trucks are responsible for 16% of total road emissions and 79% tkm of road freight transport in Australia.

[18] The annual kilometres travelled assumption for a rigid / articulated truck is calculated as the average annual kilometres travelled over the asset life of a new rigid / articulated truck, respectively, and accounts for the typical variation in annual kilometres travelled over this asset life. These figures have been derived from Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia (2020); Bureau of Infrastructure and Transport Research Economics, Australian Infrastructure and Transport Statistics Yearbook 2023, Road Statistics, <https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023> (accessed 04 March 2024).

[19] The annual kilometres travelled assumption is the national average distance travelled by a light-duty vehicle sourced from the Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia (2020).

[20] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[21] Effective capacity reduces to 4.1 tonnes for BEVs. This accounts for the assumed proportion of backhauling and the reduced maximum payload capacity of BEV vehicles due to battery weight.

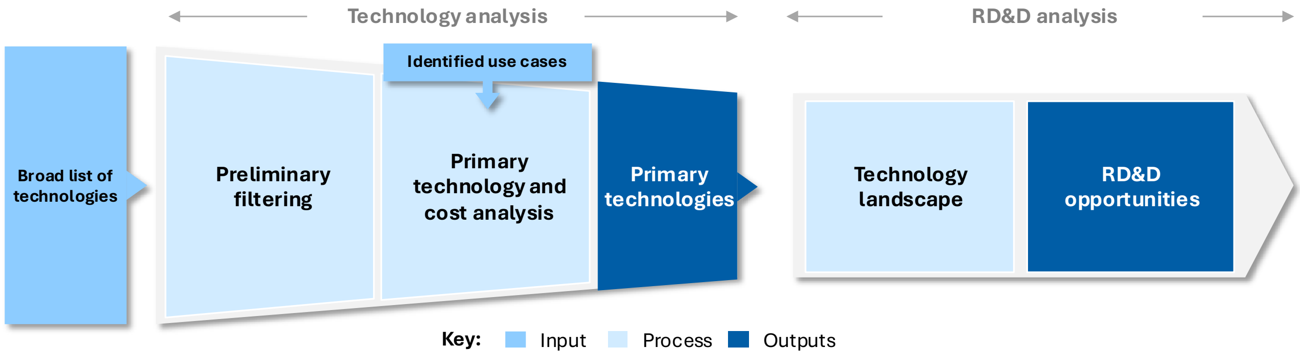
[22] BITRE (2023) Australian Infrastructure and Transport Statistics – Yearbook 2023, Transport Energy and Environment, https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023/transport-energy-environment; BITRE (2023) Australian Infrastructure and Transport Statistics – Yearbook 2023, Road, https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023/road

[23] Effective capacity reduces to 10 tonnes for BEVs. This accounts for the assumed proportion of backhauling and the reduced maximum payload capacity of BEV vehicles due to battery weight.

4.3 Methodology: Road transport 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 decarbonisation across various vehicle types. 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 road transport



4.3.1 Broad technology list

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

Table 2: Technology category definitions – Road transport

Technology category	Definition
Battery electric vehicles (BEVs)	Vehicles that employ batteries arranged in a battery pack and combined with inverters and electric motor to convert electrical energy into mechanical energy.
Biomethane	Vehicles that employ an internal combustion engine fuelled by compressed biomethane.
Hybrids	Vehicles with a battery system and combustion engine, where the vehicle runs on electric power at slow speeds and is refuelled using petrol/diesel.
Plug-in hybrids	Vehicles with a battery system and combustion engine, where a larger battery allows for extended range compared to a hybrid vehicle. They can be recharged via a power outlet.
Hydrogen combustion	Vehicles that employ an internal combustion engine fuelled by e-hydrogen.
Hydrogen fuel cell electric vehicles (Hydrogen FCEVs)	Vehicles which employ a hydrogen fuel cell system that generates electric power from e-hydrogen, driving an electric traction system.
Renewable diesel	Vehicles where renewable diesel, or HVO (hydrotreated vegetable oil), is used as a 'drop-in' hydrocarbon fuel equivalent to conventional diesel.
e-methanol	Vehicles that employ an internal combustion engine fuelled by e-methanol.
Liquefied natural gas (LNG)	Vehicles that employ an internal combustion engine fuelled by LNG.

4.3.2 Additional preliminary filtering criteria

An additional preliminary filter has been adopted for road transport: *Resource scalability*. This filter was incorporated in recognition of the high energy demands for the subsector and the need for a small set of common refuelling/recharging solutions to ensure network interoperability. Securing long-term energy supply that can meet sector-wide needs will also be important for reducing resource bottlenecks.

The resource scalability filter evaluates whether the energy supply of a given technology is achievable at the scale needed for road transport, when considering feedstock resource constraints and renewable energy generation potential. It assesses estimates of resource inputs and determines whether there are resource constraints that may inhibit the ability of energy supply to meet sectoral energy demand.

Please note, it does not consider the capital and operating costs of energy recovery, supply chain implementation, or market factors related to the adoption of a given technology. This filter is designed to assess technologies suitable for a broad sectoral transition; other solutions may be adopted in the near-term or in niche cases where transitioning to more involved technology systems is limited.

4.3.3 Primary technology filters

The performance requirements and characteristics of road vehicles is highly variable and dependant on their utility, with many vehicles sharing common weight, refuelling and range characteristics. Technology assessment involved evaluating the technologies identified through preliminary filtering against three performance filters for each use case (Table 3). These performance filters were deemed to be core operational requirements that will enable or limit technology uptake, particularly in applications that require high utilisation rates.

The thresholds for 'refuelling/recharging duration' were ascertained based on the characteristics of a conventional petrol or diesel vehicle of the given vehicle class and were sourced from literature.

The 'minimum range requirement' represents the threshold range a vehicle must achieve on a single refuel or recharge to meet typical daily operational needs of its vehicle class without significant disruption to existing logistics patterns. For articulated trucks, the 475km threshold reflects the maximum distance a solo driver can reasonable travel (at an average pace of 90km/hr) before requiring a rest break under standard work and rest requirements. It is acknowledged that many rest stops currently lack recharging and refuelling facilities, with new infrastructure developments required regardless of the technologies adopted. As such, the threshold is intended as a benchmark for single-driver travel segments and does not reflect the requirements for uninterrupted long-haul operations.

The lowest cost mitigation technologies able to meet the designated refuelling duration and minimum range requirement for a single trip, were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 4.4.2 Primary technology analysis.*

Table 3: Technology filtering criteria, by use case – Road transport

Subsector	Road transport		
Use case(s)	**Light-duty vehicle (LDV)**	**Medium-duty vehicle (MDV)**	**Heavy-duty vehicle**
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 meets or exceeds an abatement threshold of 90%, relative to a conventional incumbent technology.		
	Resource scalability The energy supply of a given technology can meet the demands of the road transport sector, when considering feedstock resource constraints.		
Primary technology filters	**Refuelling/recharging duration**[24] Technology can meet an acceptable threshold refuelling duration, based on the time taken to refuel a conventional internal combustion engine (ICE) technology.		
	6-12 hours (overnight)	< 15minutes (generally 7-10 minutes)	< 30minutes (generally 10-20 minutes)
	Minimum range requirement (single trip) Technology can meet an acceptable distance threshold in a single trip.		
	38 km per day (daily average)[25]	450 km[26]	475 km[27]
	Levelised Cost of Transport (LCOT) in 2050 Technologies projected to be cost competitive by 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.		

4.4 Technology analysis

This chapter outlines the process of identifying primary technologies for domestic road transport. Following the technology analysis framework process, **battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) emerged as primary technologies for further RD&D exploration.** 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 road transport decarbonisation, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. Further work is required to account for barriers to scalability (for example, the competition for biomass feedstock from other sectors has not been considered here). The results of the technology analysis for the road subsector are provided in Table 4.

[24] Requirements for refuelling duration and minimum range were selected based on characteristics of current technologies and/or expected use patterns (i.e., overnight charging for privately owned LDVs)

[25] ABS (2020) Survey of Motor Vehicle Use, Australia, https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

[26] Based on the operation of an inner-city 2-door bus, with rigid trucks assumed to follow similar logistics patterns. TfNSW (n.d.) TfNSW Bus Procurement Panel, Two Door City Bus (A) Specification. https://www.transport.nsw.gov.au/operations/buses-and-coaches/tfnsw-bus-procurement-panel

[27] Distance travelled at 90km/hr before a single driver requires a rest break under standard work and rest requirements. For reference, solo truck drivers must not work for more than: i) 5 ¼ hours (in a 5 ½-hour period) without a 15minute rest break; ii) 7 ½ hours (in an 8-hour period) without 30 minutes rest (in 15-minutes blocks); and iii) 10 hours (in an 11-hour period) without 60minutes rest (in 15-minutes blocks). <https://www.nhvr.gov.au/safety-accreditation-compliance/fatigue-management/work-and-rest-requirements>. Assuming an average speed of 90km/hour, a driver may reasonably travel ~475km in 5.25hours before requiring a break during which refuelling could occur. Please note, this assumption is subject to vary based on real-world factors such as load size, traffic congestion and speed limits, and weather conditions.

Table 4: Technology analysis results – Road transport[28]

Meets criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering | 2. Primary technology analysis

Technologies	Maturity	Abatement potential[29]	Resource scalability	Light-duty vehicles: Passenger vehicle – Refuelling duration	Minimum range req	LCOT (2050)		Medium-duty vehicles: Rigid truck – Refuelling duration	Minimum range req	LCOT (2050)		Heavy-duty vehicles: Articulated truck – Refuelling duration	Minimum range req	LCOT (2050)	
Threshold	*TRL >3*	*90% decrease in emissions*	*Surmountable energy supply limitations*	*6-12 hours*	*≥38km*	*c/p-km*		*<15min*	*≥450km*	*c/t-km*		*<30min*	*≥475km*	*c/t-km*	
Battery electric vehicles (BEVs)	CRI 5	98%		15 minutes – 12 hours	≤450km	34	★	15 minutes – 12 hours	600km; payload reductions possible	39	★	30 minutes – 7 hours	750km; payload reductions likely	16	★
Biomethane	TRL 9	20-100% or net negative													
Hybrid electric vehicles (HEVs)	CRI 6	29%													
Plug-in hybrid electric vehicles (PHEVs)	CRI 5	69%													
Hydrogen combustion	TRL 6	100%	Potential input supply limitations	3-5min	200-300km	63		<15min	156km			<20mins	433km		
Hydrogen fuel cell electric vehicle (Hydrogen FCEV)	TRL 9	100%	Potential input supply limitations	3-5min	650-750km	57		<15min	350-450km	45	★	<20mins	1000-1640km	14	★
Renewable diesel	CRI 5	40-75%													
e-methanol	TRL 8-9	100%	Potential input supply limitations	3-5min	620km	47		<15min	460km	48		<20mins	1280km	18	
Liquefied natural gas (LNG)	CRI 4	17%													

[28] Details for these figures, including sources and assumptions, are found in Table 6 (abatement potentials); Table 7 (Resource scalability); Table 8 (Refuelling/recharging duration requirement); Table 9 (Range); and under 'Levelised cost analysis' and *Technical Appendix: Levelised cost analysis* (LCOT).

[29] Emissions estimates encompass the full fuel cycle, where abatement potential is compared against a conventional ICE passenger vehicle with an emissions estimate of 237gCO_2/km. A 90% abatement potential threshold was set for road transport to reflect the availability of cost competitive low emissions technology solutions by 2050. This threshold was based on the expected availability of technologies which produce no direct emissions, but where indirect emissions reflective of the electricity grid mix may still be present. See 'Abatement potential' for further detail.

4.4.1 Preliminary filtering

Key information – Preliminary filtering

Four 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.
- **Resource scalability:** The energy supply of a given technology can meet the demands of the road transport sector.

Relevance to Australia

All technologies were found to meet this criterion across the designated use cases, as they can be reasonably deployed in the Australian context.

Technological maturity

All technologies were found to meet this criterion, possessing a TRL greater than 3 (Table 5). Maturity ratings are informed by desktop research, drawing on the IEA Clean Energy Technology Guide.[30]

Table 5: Technology maturities – Road transport

Technology category	TRL
Battery electric vehicles (BEVs)	• CRI 5 (Li-ion)
Biomethane	• TRL 9
Hybrid electric vehicles (HEVs)	• CRI 6
Plug-in hybrid electric vehicles (PHEVs)	• CRI 5
Hydrogen combustion	• TRL 6
Hydrogen fuel cell electric vehicle (Hydrogen FCEV)	• TRL 9
Renewable diesel	• CRI 5
e-methanol	• TRL 8-9
Liquefied natural gas (LNG)	• CRI 4

Abatement potential

Key information – Abatement potential

The abatement potential criterion identifies technologies that 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.

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

- 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 *Appendix **A.4**.*

The abatement potential was assessed against a conventional petrol internal combustion engine (ICE) vehicle train, with an emissions intensity of 236.7gCO_2e/km. This was representative of a conventional ICE passenger vehicle with a fuel mix comprising of 90% gasoline and 10% E10 (Californian petrol mix).[31] A 90% abatement potential threshold was set for road transport to reflect the availability of cost competitive low emissions technology solutions by 2050. This threshold also accounts for residual emissions in the grid, recognising that some fossil fuel capacity will likely remain in the long term.

The emissions estimates (in CO_2 equivalents) were largely extracted from the US Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, and are reported in Table 6. Greenhouse gas emissions considered, include methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2). Figures reflect full fuel-cycle emissions, encompassing well-to-pump emissions (including indirect land use change (ILUC), biogenic sequestration, and fuel production), and tailpipe emissions from fuel combustion (CH_4, N_2O, and CO_2). Together, these constitute 'well-to-wheel' emissions. Emissions borne from the manufacturing and construction of vehicles, storage and energy generation equipment were not captured.

While this source allows for estimation of abatement potentials across an extensive range of fuel sources, the GREET model has been developed in reference to the US (and/or Californian) energy system and will therefore not directly reflect exact emissions reductions in the Australian setting. For technologies that rely on electricity or electricity-derived fuels (i.e., hydrogen or synthetic fuels), efforts were made to adjust grid-supplied electricity emissions to reflect a prospective 2050 grid intensity in which 5% of current electricity generation occurs from peaking gas and the remainder generated from renewable resources.

Hydrogen electrolysis facilities are assumed to operate with a 60% utilisation factor in 2050: aligning with electricity generation from variable renewable energy (VRE). Only operating electrolysers when renewable generation assets are online can enable zero emissions hydrogen production and allow for cost savings compared to higher utilisation rates (see *Low Carbon Fuels* technical appendix).

Biofuel estimates were unable to be obtained in the road transport model and therefore were taken from alternative sources.

[31] Argonne National Laboratory (2019) R&D GREET Fuel-Cycle Model.

Table 6: Abatement potentials – Road

	Well-to-pump			*Pump-to-wheel*	TOTAL		
Technology	**Land-use change** *gCO_2e/km*	**Biogenic CO_2** *gCO_2e/km*	**Fuel production** *gCO_2e/km*	**Tailpipe** *gCO_2e/km*	**Well-to-wheel** *gCO_2e/km*	**Abatement potential** *Pass: 90%*	**Source/assumptions**
Petrol (90% gasoline, 10% E10)	***1.62***	***-13.36***	***46.85***	***201.61***	**236.73**		Argonne National Laboratory (2019)
BEVs	-	-	*5.64*[32]	-	*5.64*	98%	Assumes low emissions electricity inputs.
Biomethane	*Breakdown unavailable through GREET*					20-100% or net negative	Zhou et al. (2021)[33] Avoided emissions from landfill/other disposal, can allow for negative emissions.
Hybrids	*1.16*	*-9.58*	*33.61*	*143.87*	*169.06*	29%[34]	Argonne National Laboratory (2019); California petrol mix.
PHEVs	*0.5*	*-4.11*	*15.35*	*61.74*	*73.47*	69%[35]	Argonne National Laboratory (2019); Low emissions electricity inputs.
Hydrogen combustion	-	-	-	-	-	100%	Hydrogen production facility is assumed to operate at 60% utilisation, aligning with 100% VRE generation.
Hydrogen FCEVs	-	-	-	-	-	100%	
Renewable diesel	*Breakdown unavailable through GREET*					40-75%[36]	Xu et al. (2022); Cai et al. (2022)
e-methanol	*Assumed to be 100% if produced from renewable electricity and CO_2 from DAC*					100%	No source.
LNG	-	-	*33.16*	*164.31*	197.47	17%[37]	Argonne National Laboratory (2019); Feedstock assumed to be North American natural gas

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[32] Fuel economies were adopted from GREET (5.45km/kWh) and emissions calculated based on a grid intensity of 0.0307kgCO_2-e per kWh. This is based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions.

[33] Zhou Y, Swidler D, Searle S, Baldino C (2021) LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF BIOMETHANE AND HYDROGEN PATHWAYS IN THE EUROPEAN UNION. <https://theicct.org/sites/default/files/publications/lca-biomethane-hydrogen-eu-oct21.pdf>

[34] Literature supports a range of 30-40%. See, for example, Andersson Ö, Börjesson P (2021) The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications. Applied Energy 289,. doi:10.1016/j.apenergy.2021.116621; National Transport Commission (2022) Carbon Dioxide Emissions Intensity for New Australian Light Vehicles 2021.; Orecchini F, Santiangeli A, Zuccari F (2015) Biomethane use for automobiles towards a CO 2-neutral energy system Graphic abstract. Energy Procedia 81, 124. doi:10.1016/j

[35] Literature supports a range of 70-80%. See for example: Andersson Ö, Börjesson P (2021) The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications. Applied Energy 289,. doi:10.1016/j.apenergy.2021.116621; National Transport Commission (2022) Carbon Dioxide Emissions Intensity for New Australian Light Vehicles 2021

[36] For biofuels, when accounting for ILUC, 100% abatement is unlikely to be achieved. Emissions estimates for renewable diesel are highly variable, depending on feedstock, pathway and methodology. Range reflects widely cited estimates from literature: Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. doi:10.1039/d2se00411a; Jeswani HK, Chilvers A, Azapagic A (2020) Environmental sustainability of biofuels: A review: Environmental sustainability of biofuels. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 476,. doi:10.1098/rspa.2020.0351; Xu H, Ou L, Li Y, Hawkins TR, Wang M (2022) Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environmental Science and Technology 56, 7512. doi:10.1021/acs.est.2c00289

[37] Literature supports a range of 15-25%, see, for example, IRENA (2018) Biogas for road vehicles: technology brief. International Renewable Energy Agency; Orecchini F, Santiangeli A, Zuccari F (2015) Biomethane use for automobiles towards a CO 2-neutral energy system Graphic abstract. Energy Procedia 81, 124. doi:10.1016/j

Biomethane and renewable diesel

Biomethane can meet the criteria when some waste residues (second generation feedstocks) are employed for production. For renewable diesel, neither first- nor second-generation feedstocks were deemed not to meet this filtering criterion when assessing technologies suitable for a broad sectoral transition; other solutions may be adopted in the near-term or in niche cases where transitioning to more involved technology systems is limited (see Box 1).

For large-scale biomethane and renewable diesel adoption, production will likely rely on a mix of first- and second-generation feedstocks, including waste residues.

For renewable diesel production, first- or second-generation feedstocks are unlikely to achieve 90% abatement when considering both direct and indirect emissions, failing to meet the abatement criteria. Estimates sourced from Xu et al. (2022)[38] and Cai et al. (2022)[39] suggest renewable diesel synthesis from first-generation crops (canola, soybean) and second-generation sources (used cooking oil) can abate 40-55% and up to 75% of emissions respectively. In these analyses, tailpipe emissions are assumed to be zero, where the CO_2 emissions from combusting renewable diesel is offset by the CO_2 absorbed during plant growth.

For biomethane, analysis of production in the EU using maize (first-generation crop), similarly found significant emissions arising from maize cultivation and land-use change with reductions only 30%.[40]

However, employing waste residues for biomethane production can result in net neutral or net negative emissions when accounting methods consider avoided emissions from landfill or conventional waste treatment pathways.[41] Organic wastes, such as food wastes and municipal solid waste residues, are suitable for biomethane production due to the typical high moisture and carbohydrate content which are amenable to anaerobic digestion.[42] This process captures and utilises methane that would have otherwise been produced during decay in landfills.

Biomethane results were obtained from Zhou et al. (2021)[43] and serve to highlight the uncertainties and sensitive nature of emissions intensities. Reduction potential across waste residues ranged between 20 to over 100%, therefore meeting the criteria where these waste residues are employed and where operational factors, such as methane leakage, are managed. This variability was mainly due to upstream methane leakage, material displacements from the usage of waste products (i.e., fertiliser adoption due to lack of manure availability), and varying rates of methane flaring to reduce CO_2 emissions in conventional waste management pathways.

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[38] Xu H, Ou L, Li Y, Hawkins TR, Wang M (2022) Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environmental Science and Technology 56, 7512. doi:10.1021/acs.est.2c00289

[39] Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. doi:10.1039/d2se00411a

[40] Obtained via secondary analysis on GREET outputs. Parameters were aligned to reflect EU environment. For further details, see Zhou Y, Swidler D, Searle S, Baldino C (2021) LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF BIOMETHANE AND HYDROGEN PATHWAYS IN THE EUROPEAN UNION. <https://theicct.org/sites/default/files/publications/lca-biomethane-hydrogen-eu-oct21.pdf>

[41] O'malley J, Searle S, Pavlenko N (2021) INDIRECT EMISSIONS FROM WASTE AND RESIDUE FEEDSTOCKS: 10 CASE STUDIES FROM THE UNITED STATES. <https://theicct.org/wp-content/uploads/2021/12/indirect-emissions-waste-feedstocks-US-white-paper-v4.pdf>

[42] O'malley J, Searle S, Pavlenko N (2021) INDIRECT EMISSIONS FROM WASTE AND RESIDUE FEEDSTOCKS: 10 CASE STUDIES FROM THE UNITED STATES. <https://theicct.org/wp-content/uploads/2021/12/indirect-emissions-waste-feedstocks-US-white-paper-v4.pdf>

[43] Zhou Y, Swidler D, Searle S, Baldino C (2021) LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF BIOMETHANE AND HYDROGEN PATHWAYS IN THE EUROPEAN UNION. <https://theicct.org/sites/default/files/publications/lca-biomethane-hydrogen-eu-oct21.pdf>

Hybrids and plug-in hybrid electric vehicles

Hybrid and plug-in hybrid electric vehicles do not meet the abatement criteria, due to the emissions associated with fossil fuel combustion. Land-use and biogenic sequestration figures reflect the Californian petrol mix.

Hybrid vehicles are often discussed as a transitionary technology solution that has led to further advancements in BEVs. In the long-term, hybrid vehicles are expected to be replaced by fully electrified vehicles to entirely decarbonise the sector.

LNG

The use of LNG results in a 17% decrease in full fuel cycle emissions compared to conventional petroleum-based fuels, failing to meet the criteria.

Box 1: The impact of renewable diesel on heavy-duty road transport

Renewable diesel could significantly aid in the decarbonisation of existing road transport fleets in the near-term as well as for infrequent, long distance freight routes that lack sufficient charging/refuelling infrastructure.

Although electric and hydrogen-powered vehicles can offer higher levels of abatement, their commercial viability in the heavy-duty segment remains limited, where higher density fuels are required and where supporting infrastructure may be insufficient.

While hydrogen and electric-based options emerge as desirable low emissions alternatives from an abatement perspective, infrastructure barriers and technical hurdles are limiting to nearer term adoption. Renewable diesel could function as a practical 'drop in' option to service existing haulage fleets until retirement, where replacing these vehicles before their end of life is not economically viable.

Resource scalability

The resource scalability criterion identifies where the energy supply of a given technology can meet the demands of the road transport sector, when considering feedstock resource constraints and renewable energy generation potential.

It assesses estimates of resource inputs and determines whether there are resource constraints that may inhibit the ability of energy supply to meet sectoral energy demand. Technologies are determined to meet the criterion where energy supplies could reasonably meet the energy demand of the road transport sector. Technologies do not meet the criterion where the road transport energy demands cannot be met by energy supply. Please note, it does not consider the capital and operating costs of energy recovery, supply chain implementation, or market factors related to the adoption of a given technology.

BEVs

Battery electric vehicles meet the scalability filter, with constraints on electricity supply expected to be minimal.

Hydrogen-fuelled (combustion, fuel cells)

Hydrogen-fuelled vehicles meet the scalability filter with caveats, due to potential input limitations for large-scale electrolytic hydrogen production. Electrolysis pathways (see the *Low Carbon Fuels* technical appendix) require large amounts of electricity to operate, necessitating grid network upgrades and scaled renewable generation capacity to meet hydrogen production demands. 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.

e-methanol vehicles

e-methanol vehicles meet the scalability filter with caveats, due to potential input limitations.

Synthetic fuels, such as e-methanol, could be constrained by the supply of CO_2 in the long term. While point source capture could meet a portion of production demand, large-scale deployment will require additional sources of CO_2 from alternative capture technologies such as DAC. However, these alternatives are currently limited by high costs, energy demands and low technological maturity.

Biomethane vehicles

Biomethane vehicles do not meet the scalability filter, due to potential limitations in the supply of suitable residual feedstocks.

In order to be considered net negative or carbon neutral, biomethane production relies on the availability of waste residues such as municipal solid waste (MSW), agricultural and sawmill residues, and sugarcane bagasse. Analysis was conducted (Table 7), to estimate the total energy available from biomethane produced from domestic waste residues and to assess whether this supply could meet Australia's 2022 road energy demand. Feedstock data was sourced from national databases, with the theoretical useable portion of energy determined for each feedstock type. To calculate volumetric fuel potential, the useable energy was multiplied by production yield and subsequently converted to energy units based on the energy density of biomethane.

Please note, this analysis presents a liberal approach to estimating the energy available for Australia's road transport subsector. The approach does not account for feedstock competition from other uses (e.g., food, recycling, animal feed, export) or alternative bioenergy pathways, whereby feedstocks to produce biofuels for aviation and hard to abate sectors will likely constrain large-scale biomethane production and adoption. It also does not consider that some existing supply chains already operate with high efficiencies and minimal waste; for example, sawmill residues and wood chips are commonly valorised into secondary products, such as MDF boards and pellets. This analysis also excludes market factors and incentives that could influence the diversion of feedstocks across competing applications.

This analysis indicates that biomethane production from domestic residual feedstocks cannot meet the total energy demand of Australia's road transport subsector. These feedstocks were determined to satisfy between 61-64% (682-712PJ) of 2022 demand, which totalled 1115PJ.

Table 7: Biomethane resource scalability potential – Road

Feedstock			Fuel production		Energy conversion	
Feedstock	Feedstock availability, 2022 (kt)[44]	Useable energy from feedstock	Pathway	Yield (m^3/ton feedstock)[45]	Energy density conversion factor (MJ/m^3)	Final energy (PJ)

[44] ABARES (2023a) Australian crop report: March 2023, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities; ABARES (2023b), Agricultural commodities: March quarter 2023, Outlook tables - data tables, Sugar, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data; DCCEEW (2022) National Waste Database

[45] **MSW, Agricultural residues and sawmill residues:** Alberici S, Grimme W, Troop G (2022) Biomethane production potentials in the EU: Feasibility of REPowerEU 2030 targets, production potentials in the Member States and outlook to 2050. A Gas for Climate report. https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_national-biomethane-potentials_070722.pdf; **Sugar:** Fang C, Boe K, Angelidaki I (2011) Anaerobic co-digestion of by-products from sugar production with cow manure. Water Research, 45,11. 10.1016/j.watres.2011.04.008. **Sugarcane bagasse:** Agarwal N, Kumar M, Ghosh P, Kumar S, Singh L, Vijay V, Kumar V (2022) Anaerobic digestion of sugarcane bagasse for biogas production and digestate valorization. Chemosphere, 295. 10.1016/j.chemosphere.2022.133893. **Sorghum:** Mathias DJ, Edwiges T, Ketsub N, Singh R, Kaparaju P (2023) Sweet Sorghum as a Potential Fallow Crop in Sugarcane Farming for Biomethane Production in Queensland, Australia. Energies, 16, 18. 10.3390/en16186497

Municipal solid waste (MSW)*	13,307	100%	Gasification or Anaerobic digestion	324	36.65	158
Agricultural residues*	44,144	100%	Anaerobic digestion	250		404
Sawmill residues*	5,759	100%	Gasification or Anaerobic digestion	423		89
Sugar	4,123	100%	Anaerobic digestion	170-280		26 -42
Sugarcane bagasse*	9,027	76%	Anaerobic digestion	120-240		30-60
Sorghum	2,648	100%	Anaerobic digestion	175-230		17-22

** Indicates waste feedstocks*

4.4.2 Primary technology analysis

Key information – Primary technology analysis

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

- **Refuelling/recharging duration:** Technologies that meet an acceptable replenishing duration, based on the time taken refuel a conventional internal combustion engine (ICE) engine.
- **Minimum range requirement (single trip):** Technologies that meet an acceptable distance threshold in a single trip, based on usage patterns.
- **Levelised cost of transport:** 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.

Refuelling/recharging duration

This filter defines an acceptable refuelling/recharging time for technologies applied to a given use case, compared against conventional ICE technology. Thresholds were ascertained based on the characteristics of a conventional petrol or diesel vehicle of the given vehicle class, and were sourced from literature. Results are provided in Table 8.

The refuelling duration of any given vehicle will be dictated by the flow rate of a particular pump (liquid/gaseous fuels) or charging rate (electricity). Engine retrofit technologies that are based on ICE or fuel cell drivetrains can enable alternative vehicles to have refuelling durations not dissimilar to incumbent petrol or diesel vehicles, meeting the criteria threshold. Marginally higher refuel times may be attributed to fuels that require additional processing steps like compression and temperature regulation, for example, hydrogen. However, these technologies can still achieve competitive refuelling times that position them well to fulfill end-uses that require shorter refuelling times, compared to vehicles with longer replenishing times (such as BEVs). This is important in high utilisation applications.

Table 8: Refuelling/recharging durations – Road

Technologies *Threshold*	**Passenger vehicle** *6-12 hours*	**Rigid truck** *<15 mins (generally 7-10 mins)*	**Articulated truck** *<30 mins (generally 10-20 mins)*
BEVs	**Level 1 (1.4-3.7kW):** Full charge ~12 hours (10-20km/hr) **Level 2 (7-22kW):** Full charge 6-12 hours (40-100km/hr) **Level 3 (25-350kW):** Full charge 15-45 minutes (>150km/hr)[46]	Similar to LDVs[47]	**Level 3 (250-350kW):** Full charge 5-7 hours **Level 3 (600kW):** Full charge in 2 hours (400km/hr) **Level 4 (~1MW):** Full charge in 30 minutes to 1 hour (800-1200km/hr)[48]
Hydrogen combustion	3-5 minutes[49]	7-15 minutes[50]	15-20 minutes[51]
Hydrogen FCEVs	3-5 minutes[52]	7-15 minutes	15-20 minutes[53]
e-methanol	3-5 minutes	7-15 minutes	15-20 minutes

While BEV charging times are substantially higher than refuelling times in most cases, rapidly expanding charging infrastructure, higher charging capacities, and advancements in battery technologies are addressing this shortfall. Behavioural and usage patterns, such as overnight dwell periods, can allow for charging without inconvenience; however, high utilisation operations will experience more disruption and may require designated fast charging infrastructure/smart charging solutions to minimise reliance on public infrastructure.

Minimum range requirement (single trip)

The minimum range requirement defines a distance (in km) that must be able to be achieved in a single trip, for a given technology and use case. This was identified as a core operating requirement that will enable or limit technology uptake, particularly in applications requiring high utilisation rates or long trip durations.

The distance thresholds for each use case reflect the minimum range a vehicle must be able to travel to minimise disruption to existing logistics patterns. For passenger vehicles, this is taken as the Australian daily average for the vehicle class.[54] For rigid trucks, a daily distance was determined based on the operations of a

[46] Electric Vehicle Council A-Z of EV Charging | Australian EV Charger Map. <https://electricvehiclecouncil.com.au/a-z-charging/> (accessed 29 October 2024); Transport for NSW Charging an electric vehicle. <https://www.transport.nsw.gov.au/projects/electric-vehicles/charging-an-electric-vehicle> (accessed 29 October 2024)

[47] Given the range requirements for MDVs and LDVs are similar and charging speeds are constant, full charge durations will not vary significantly.

[48] Transport and Environment (2020) Comparison of hydrogen and battery electric trucks: Methodology and underlying assumptions; International Energy Agency (2019) Global EV Outlook. <https://iea.blob.core.windows.net/assets/7d7e049e-ce64-4c3f-8f23-6e2f529f31a8/Global_EV_Outlook_2019.pdf>

[49] Hydrogen and Fuel Cell Technologies Office DOE (n.d.) Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles. https://www.energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles (accessed 29 October 2024)

[50] Hyfindr (2023) Hydrogen Refueling. <https://hyfindr.com/en/hydrogen-knowledge/hydrogen-refueling> (accessed 24 October 2024)

[51] Wolfe S et al. (2023) Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia. CSIRO and GHD Advisory; Walker III TK (2023) Zero Emission Long-Haul Heavy-Duty Trucking. <https://cdn.catf.us/wp-content/uploads/2023/03/13145547/zero-emission-long-haul-heavy-duty-trucking-report.pdf>

[52] Hydrogen and Fuel Cell Technologies Office DOE (n.d.) Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles. https://www.energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles (accessed 29 October 2024)

[53] Wolfe S et al. (2023) Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia. CSIRO and GHD Advisory; Walker III TK (2023) Zero Emission Long-Haul Heavy-Duty Trucking. <https://cdn.catf.us/wp-content/uploads/2023/03/13145547/zero-emission-long-haul-heavy-duty-trucking-report.pdf>

[54] DCCEEW (2023) The National Electric Vehicle Strategy, Department of Climate Change, Energy, the Environment and Water, Canberra.

metro passenger bus, assuming it is proximal to high utilisation rigid truck usage.[55] For articulated trucks, the 475km threshold reflects the maximum distance a solo driver can reasonably travel (at an average pace of 90km/hr) before requiring a rest break under standard work and rest requirements. It is acknowledged that many rest stops currently lack recharging and refuelling facilities, with new infrastructure developments required regardless of the technologies adopted. As such, the threshold is intended as a benchmark for single-driver travel segments and does not reflect the requirements for uninterrupted long-haul operations.[56]

For infrequent, long distance freight routes that lack alternative refuelling infrastructure, renewable diesel will likely be an intermediary solution supported by its 'drop-in' nature; particularly for rigid and articulated trucks.

The on-board energy storage capacity, which will influence vehicle range, is dependent on the volumetric and gravimetric energy density of a given fuel type. Energy systems with lower densities may be constrained by on-board capacity limits and must be balanced with trade-offs for vehicle weight and fuel efficiency. Another factor is drivetrain efficiency, with more efficient energy conversions also improving range and cost performance. This is why hydrogen FCEVs (higher efficiency) will outperform their hydrogen combustion counterpart (lower efficiency) when comparing energy storage capacity to vehicle range.

Thresholds for range were selected based on usage patterns of conventional ICE technologies for each use case, sourced via desktop research. Results are provided in Table 9.

Table 9: Minimum range requirement, single trip – Road

Technologies *Threshold*	**Passenger vehicle** *38km, (Australian daily avg)*	**Rigid truck** *450km*	**Articulated truck** *475km*
BEVs	≤450km[57]	600km,[58] Using the case study in the cost assessment (below), marginal payload reductions of <1% were observed (2022)[59]	756km.[60] Using the case study in the cost assessment (below), payload reductions of 14% were observed (2022)[61]

[55] Transport for NSW (n.d.) BUS PANEL SPECIFICATION NO 3 <https://www.transport.nsw.gov.au/operations/buses-and-coaches/tfnsw-bus-procurement-panel> (accessed 24 October 2024).

[56] Please note, that this assumption is subject to vary based on real-world factors such as load size, traffic congestion and speed limits, and weather conditions. Under standard work and rest requirements, solo truck drivers must not work for more than: i) 5 ¼ hours (in a 5 ½-hour period) without a 15minute continuous rest break; ii) 7 ½ hours (in an 8-hour period) without 30 minutes rest (in 15-minutes blocks); and iii) 10 hours (in an 11-hour period) without 60minutes rest (in 15-minutes blocks). <https://www.nhvr.gov.au/safety-accreditation-compliance/fatigue-management/work-and-rest-requirements>

[57] DCCEEW (2023) The National Electric Vehicle Strategy, Department of Climate Change, Energy, the Environment and Water, Canberra.

[58] For example, MAN Global (n.d.) The New MAN eTGS: The eTruck for Heavy-duty Distribution Transport. <https://www.man.eu/global/en/truck/all-models/the-man-tgs/the-man-etgs/overview.html> (accessed 31 October 2024).

[59] Assumes a battery power density of 200Wh/kg. Increased payload capacity (+5%) observed in 2040, with battery power density assumed to grow to 400Wh/kg.

[60] Despite reaching the minimum range based on rest limitations, drivetrain range is substantially shorter than ICE and other alternative drivetrain option, resulting in longer rest stops due to increased charging times. Walker III TK (2023) Zero Emission Long-Haul Heavy-Duty Trucking. <https://cdn.catf.us/wp-content/uploads/2023/03/13145547/zero-emission-long-haul-heavy-duty-trucking-report.pdf>; Tesla's 37 tonne semi model has an officially stated range of 800km. TESLA (n.d.) Semi: The Future of Trucking is Electric. <https://www.tesla.com/semi> (accessed 31 October 2024).

[61] Assumes a battery power density of 200Wh/kg. Payload reductions could fall to 1% in 2040, with battery power density assumed to grow to 400Wh/kg.

Hydrogen combustion	200-300km[62]		156km[63]		433km[64]	
Hydrogen FCEVs	650-756km[65]		350-450km		1000-1640km[66]	
e-methanol	671km[67]		461km[68]		1,277km[69]	

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Transport (LCOT) was estimated to determine the viability of each technology considered. LCOT is defined as the average net present cost per unit of output (in c/passenger-km or c/tonne-km), over a vehicle's lifetime.

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 of new deployments 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 (Passenger vehicles), Figure 8 (Rigid trucks) and Figure 9 (Articulated trucks). The following technologies were projected to be cost competitive, distinguished by a cost differential in LCOT relative to other assessed technologies; suggesting areas of promise for further RD&D activity.

- **Passenger vehicle:** BEVs;

[62] Candelaresi D, Valente A, Iribarren D, Dufour J, Spazzafumo G (2021) Comparative life cycle assessment of hydrogen-fuelled passenger cars. International Journal of Hydrogen Energy 46, 35961. doi:10.1016/j.ijhydene.2021.01.034

[63] Limited data available. For a rigid truck with a 250L (65 gallon) fuel storage capacity, a diesel combustion engine with a fuel efficiency of 9MJ/km could travel 985km per tank. If fuel storage capacity remained the same but was replaced with gaseous hydrogen storage @ 700bar and a hydrogen combustion engine with a fuel efficiency of 7.5MJ/km, the tank range would fall 85% to just 156km.

[64] Limited data available. For a Class 8 long haul truck with a 1135L (300 gallon) fuel storage capacity, a diesel combustion engine with a fuel efficiency of 15MJ/km could travel 2730km per tank. If fuel storage capacity remained the same but was replaced with gaseous hydrogen storage @ 700bar and a hydrogen combustion engine with a fuel efficiency of 12.5MJ/km, the tank range would fall 85% to 433km.

[65] HFCEV Vehicle specification table: https://data.aaa.asn.au/ev-index/

[66] Lower bound is based on the range of a liquid hydrogen 40t fuel cell truck demonstrated under real life traffic conditions, see https://www.daimlertruck.com/en/newsroom/pressrelease/development-milestone-daimler-truck-tests-fuel-cell-truck-with-liquid-hydrogen-51975637; Upper bound sourced from literature, Walker III TK (2023) Zero Emission Long-Haul Heavy-Duty Trucking. <https://cdn.catf.us/wp-content/uploads/2023/03/13145547/zero-emission-long-haul-heavy-duty-trucking-report.pdf>

[67] Limited data available. For a passenger vehicle with a 65L fuel storage capacity, a petrol combustion engine with a fuel efficiency of 1.75MJ/km could travel 1336km per tank. If fuel storage capacity remained the same but was replaced with methanol and a hydrogen combustion engine with a fuel efficiency of 1.52MJ/km, the tank range would fall 50% to 671km.

[68] Limited data available. For a rigid truck with a 250L (65 gallon) fuel storage capacity, a diesel combustion engine with a fuel efficiency of 9MJ/km could travel 985km per tank. If fuel storage capacity remained the same but was replaced with methanol and a methanol combustion engine with a fuel efficiency of 8.4MJ/km, the tank range would fall 53% to 461km.

[69] Limited data available. For a Class 8 long haul truck with a 1135L (300 gallon) fuel storage capacity, a diesel combustion engine with a fuel efficiency of 15MJ/km could travel 2730km per tank. If fuel storage capacity remained the same but was replaced with methanol storage and a methanol combustion engine with a fuel efficiency of 14MJ/km, the tank range would fall 53% to 1277km.

- **Rigid trucks:** BEVs and hydrogen FCEVs. Hydrogen FCEVs will likely be preferred where longer ranges and faster refuelling times are required, allowing for greater operational flexibility;
- **Articulated trucks:** BEVs and hydrogen FCEVs. A range of zero emission technologies are likely to be required across whole articulated truck fleets, and the choice of technology will depend on specific applications. As an example, BEVs may be the preferred solution for shorter routes with sufficient charging stations, but hydrogen FCEVs preferred in applications with higher carrying capacities.

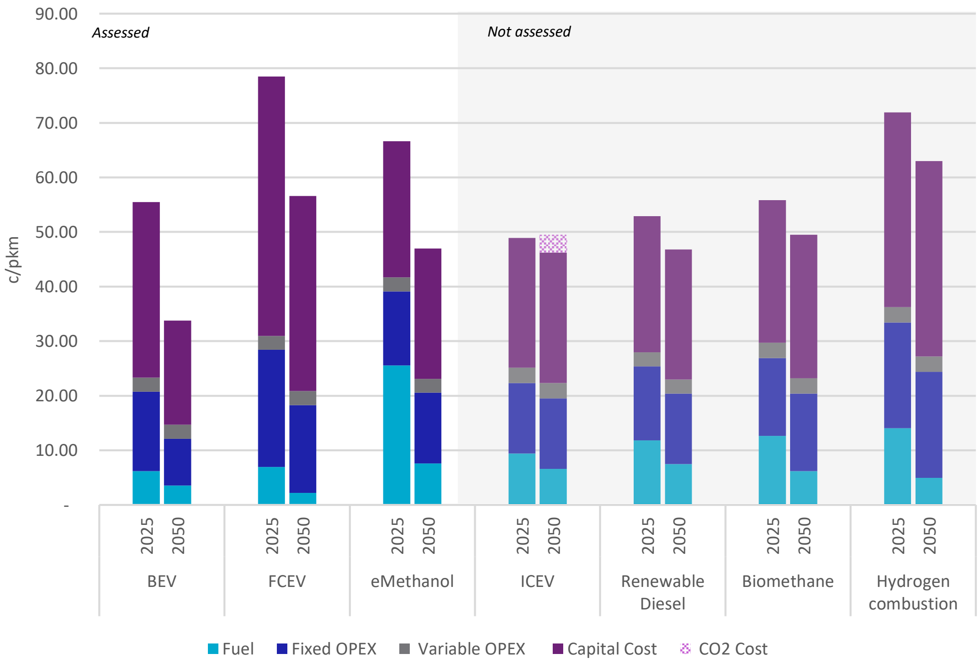
This economic assessment is based on the use case characteristics established in *Technical Appendix: Levelised cost analysis* and Table 3. This assessment does not capture the cost of deploying sufficient refuelling infrastructure, and instead considers the cost of vehicle ownership and operation.

Additional technologies included for each use case include renewable diesel, biomethane and hydrogen combustion vehicles. These technologies did not meet the earlier filtering criteria with cost analysis conducted for reference only. In particular, renewable diesel may be an intermediary solution in the near-term as well as for infrequent, long distance freight routes that lack sufficient charging/refuelling infrastructure, supported by its 'drop-in' nature. This is particularly for heavy-duty trucking applications (i.e., articulated trucks) in which higher density fuels are required and where infrastructure is limited.

Light-duty vehicle use case

The LCOT for the light-duty vehicle segment is measured on a per passenger-km basis (c/pkm). The economic assessment calculates the total cost of transport of a light-duty a passenger car that travels 11,120km per year and carries an average of 1.7 passengers.[70,71] Results are presented in Figure 7.

Figure 7: Levelised cost of transport (c/pkm) – Light-duty vehicles



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[70] The annual kilometres travelled assumption is the national average distance travelled by a light-duty vehicle sourced from the Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia (2020).

[71] The passenger vehicle occupancy assumption is derived from Bureau of Infrastructure and Transport Research Economics, Australian Infrastructure and Transport Statistics Yearbook 2023, Road Statistics and Passenger Statistics, <https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023> (accessed 04 March 2024).

An ICE vehicle is included as a technology benchmark, though it is not assessed. Fuel costs for diesel and petrol are assumed consistent. ICE vehicles are estimated to remain the lowest cost technology in 2025, noting that no CO_2 emission cost is applied in the near term. In 2050, other mitigation technologies present a more competitive value proposition.

Renewable diesel and biomethane are modelled to have similar capital and operating costs to ICE vehicles, with overall cost competitiveness of the three options dictated by fuel price. Of these, renewable diesel is estimated to be less expensive compared to ICE vehicles in the long-term once a CO_2 emission cost is applied. Though it does not meet the earlier emissions abatement criteria, it could provide a drop-in solution where other technologies are not feasible or where greater operational flexibility is required.

BEVs

BEVs are projected to be the lowest cost option in 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.

This is driven by lower fuel and capital cost projections in the long-term. This analysis uses an electricity price aligned to public fast-charging infrastructure, taken as $0.58/kWh in 2025 and falling to $0.44/kWh in 2050. BEV operating costs could be further reduced if they are combined with home charging and distributed energy resources. Capital costs are assumed to fall to $35,600 from $60,300 once adjusting for inflation.

Hydrogen FCEVs

Hydrogen FCEVs are projected to have relatively higher levelised costs for the light-duty segment use case in 2050, of the technologies assessed. Here, the cost of refuelling with gaseous hydrogen is assumed to fall from $13.73/kg to $6.96/kg. Adjusting annual kilometres does not have a material impact on the relative cost competitiveness of hydrogen FCEVs over BEVs, with annual km exceeding 700,000km before hydrogen FCEVs reach parity with their fully electric counterpart.

Compared to hydrogen FCEVs, a combination of higher capital costs and poorer round-trip efficiency renders hydrogen combustion to be the most expensive mitigation solution in 2050. This solution was not formally assessed.

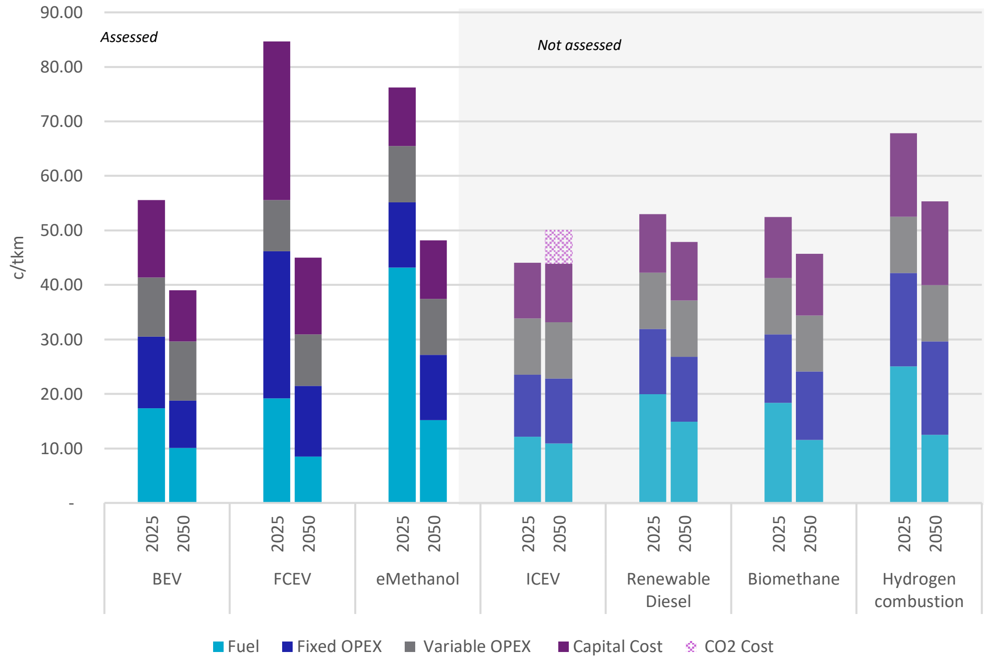
E-methanol

This assessment assumes the adoption of e-methanol as the fuel and an ICE drivetrain. E-methanol was determined to be marginally less costly than the ICE vehicle modelled in 2050. This technology option is modelled to have similar operating and capital costs to ICE vehicles, with overall cost competitiveness largely dictated by the price of fuel and, therefore, CO_2 and hydrogen fuel inputs. E-methanol prices were assumed to fall from $3.07/L (2025) to $1.30/L (2050) owing to cost reductions in CO_2 from direct air capture (DAC) and electrolytic hydrogen.

Medium-duty vehicle use case

The LCOT for the medium-duty vehicle segment is measured on a per tonne-km basis (c/tkm).[72] The economic assessment calculates the total cost of transport of a rigid truck that travels 39,200km per year (107km/day) and carries 10 tonnes.[73] Results are presented in Figure 8.

Figure 8: Levelised cost of transport (c/tkm) – Medium-duty vehicles



An ICE vehicle operating on diesel fuel is included as a technology benchmark, though it is not assessed. ICE vehicles are estimated to remain the lowest cost technology in 2025, noting that no CO_2 emission cost is applied in the near term. In 2050, other mitigation technologies present a more competitive value proposition.

Renewable diesel is estimated to be less expensive compared to ICE vehicles in the long-term once a CO_2 emission cost is applied. Though it does not meet the earlier emissions abatement criteria, it could provide a drop-in solution where other technologies are not feasible or where greater operational flexibility is required.

Some cost components (such as logistics costs) are not currently included as they are common across all technologies and do not affect the relative costs of each technology option.

BEVs

In 2050, BEVs are projected to be the lowest cost option, distinguished by a cost differential in LCOT relative to other assessed technologies. This is driven by the technologies lower projected costs across all cost categories, and when accounting for a CO_2 emission cost. This analysis uses an electricity price aligned to public fast-charging infrastructure, taken as $0.58/kWh in 2025 and falling to $0.44/kWh in 2050. BEV operating costs

[72] Our levelised cost analysis of medium-duty vehicles does not consider other vehicles within the segment, such as buses.

[73] The annual kilometres travelled assumption is calculated as the average annual kilometres travelled over the asset life of a new rigid truck, and accounts for the typical variation in annual kilometres travelled over this asset life. These figures have been derived from Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia (2020); Bureau of Infrastructure and Transport Research Economics, Australian Infrastructure and Transport Statistics Yearbook 2023, Road Statistics, <https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023> (accessed 04 March 2024).

could be further reduced if they are combined with cheaper charging through centralised infrastructure and by taking advantage of idle periods.

Hydrogen FCEVs

In the short-term, hydrogen FCEVs are estimated to have higher levelised costs relative to other technology options. However, they are projected to become more cost competitive over the longer-term due to projected reductions in hydrogen fuel costs and the incorporation of a CO_2 emission cost for ICE vehicles.

Hydrogen FCEVs also become increasingly more competitive when vehicle utilisation increases; making this solution more economically viable in applications with higher annual kilometres travelled. Hydrogen FCEVs also offer operational benefits and may be more viable compared to BEVs in certain applications, such as those requiring very heavy loads or in back-to-base applications with short turnaround times.

E-methanol

This assessment assumes the adoption of e-methanol as the fuel and an ICE drivetrain. This technology option is modelled to have similar operating and capital costs to ICE vehicles, with overall cost competitiveness largely dictated by the price of fuel and, therefore, CO_2 and hydrogen fuel inputs. e-methanol prices were assumed to fall from $3.07/L (2025) to $1.30/L (2050) owing to cost reductions in CO_2 from direct air capture (DAC) and electrolytic hydrogen.

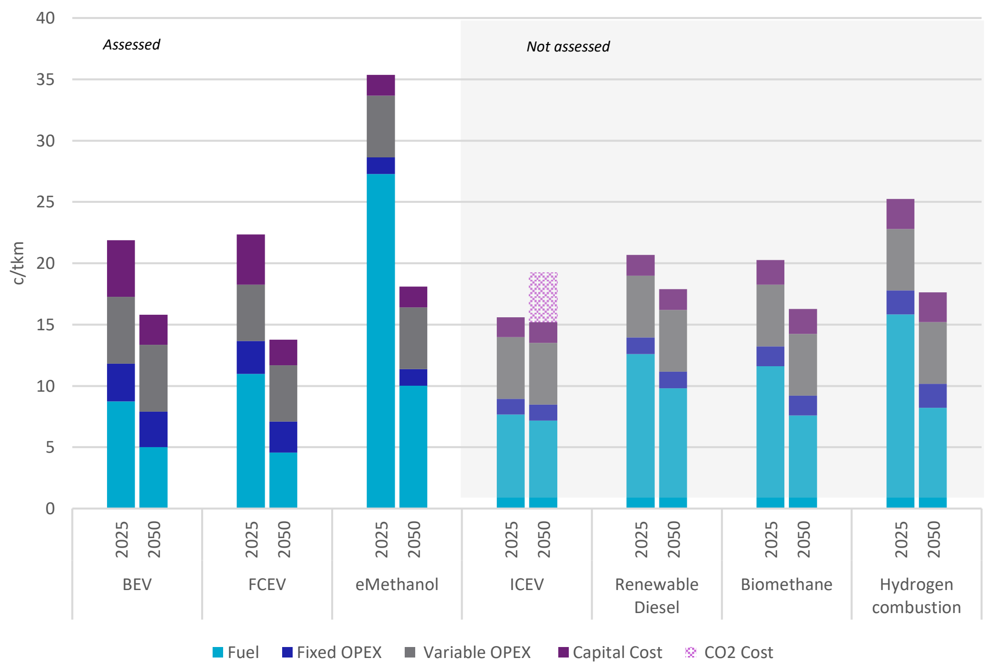
Heavy-duty freight use case

The LCOT for the heavy-duty vehicle segment is measured on a per tonne-km basis (c/tkm). The economic assessment calculates the total cost of transport of an articulated truck that travels 148,800km per year and carries 27 tonnes (22 tonnes for BEVs).[74] Results are presented in Figure 9.

This analysis is a simplification of the wide range of real-world use cases that articulated trucks serve in Australia, and the unique range, payload, route and refuelling infrastructure of a given use case will influence the viability of each technology. Understanding how different low or zero emission heavy vehicle technologies can play a role across Australia's diverse heavy freight task is an important area for future research. This research should also consider the interaction between the vehicle and transport infrastructure (e.g. road design, bridge and culvert mass limits), and the interaction with energy infrastructure and potential co-benefits that this infrastructure could deliver.

[74] The annual kilometres travelled assumption is calculated as the average annual kilometres travelled over the asset life of a new articulated truck, and accounts for the typical variation in annual kilometres travelled over this asset life. These figures have been derived from the Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia (2020); Bureau of Infrastructure and Transport Research Economics, Australian Infrastructure and Transport Statistics Yearbook 2023, Road Statistics, <https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023> (accessed 04 March 2024).

Figure 9: Levelised cost of transport (c/tkm) – Heavy-duty vehicles



An ICE vehicle operating on diesel fuel is included as a technology benchmark, though it is not assessed. ICE vehicles are estimated to remain the lowest cost technology in 2025, noting that no CO_2 emission cost is applied in the near term.

Renewable diesel is estimated to be less expensive compared to ICE vehicles in the long-term once a CO_2 emission cost is applied. Though it does not meet the earlier emissions abatement criteria, it could provide a drop-in solution where other technologies are not feasible or where greater operational flexibility is required.

Please note that some cost components (such as logistics costs) are not included in the analysis as they are common across all technologies and do not affect the relative costs of each technology option.

Hydrogen FCEVs

Hydrogen FCEVs are projected to have the lowest unit cost in 2050, based on assumed reductions in the cost of hydrogen fuel and improvements in energy efficiency, as well as the incorporation of a CO_2 emission cost. This technology assumes liquid hydrogen refuelling, with a cost of $16.92/$9.37 (2025/2050) attributed to the fuel, including production, liquefaction and distribution.

BEVs

BEVs present as the next lowest cost grouping in 2050. They are projected to have lower costs than ICE vehicles in 2050 when accounting for a CO_2 emission cost, based on assumed improvements in battery technology and efficiency. This analysis uses an electricity price aligned to public fast-charging infrastructure, taken as $0.58/kWh in 2025 and falling to $0.44/kWh in 2050. BEV operating costs could be further reduced if they are combined with cheaper charging through centralised infrastructure and by taking advantage of idle periods. The range and refuelling duration of BEVs will be key determinants of their viability for Australia's heavy freight task.

E-methanol

This assessment assumes the adoption of e-methanol as the fuel and an ICE drivetrain. E-methanol vehicles possess similar capital and operating costs as ICE vehicles, and as such, their higher levelised cost is primarily driven by fuel prices. The fuel price of e-methanol is largely dictated by the cost of its fuel inputs, including direct air capture CO_2 and green hydrogen, rendering it the highest mitigation technology both in the short and long-term.

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

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 BEVs and hydrogen FCEVs as *Primary technologies* for light-duty, medium-duty and heavy-duty vehicle use cases.

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the road transport 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 and energy efficiency solutions identified for analysis are outlined in Figure 10 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Figure 10: Technology landscape identification – Road transport

Light-duty vehicles | **Medium-duty vehicles** | **Heavy-duty vehicles**

Battery electric vehicles

- Charging infrastructure
- Battery system integration

Hydrogen fuel cell electric vehicles

- Hydrogen refuelling, storage and distribution infrastructure

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

Auxiliary technologies

BEVs and hydrogen FCEVs cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 10.

Table 10: Auxiliary technologies – Road transport

Primary technology	Auxiliary technology	Description
BEVs	**Conductive battery charging infrastructure**	Charging systems that transfer electricity via physical connection, capable of providing charging power outputs across various levels, including: • Level 3, fast-charging: 250-350kW • Level 3, fast-charging: 350kW-1MW • Level 4 ultra-fast charging: >1MW
	Inductive wireless charging systems	Charging systems that use electromagnetic fields for wireless power transfer.
	Charging management systems	Charging systems that optimise the charging process by dynamically adjusting power outputs based in grid-conditions, electricity prices, and user preferences.
	Battery swapping (alt. to charging)	Exchange of depleted batteries for fully charged ones at dedicated stations.
	Battery integration	The integration of individual battery cells into the vehicle, including: Cell-to-pack technology, where cells are integrated into the battery pack, eliminating the module step and reducing weight and complexity and improving energy density. Cell-to-chassis (CTC) technology, where cells are integrated directly into the vehicle's chassis, maximising space utilisation, reducing weight, and improving energy density
	Low emissions electricity generation and distribution	Infrastructure required to produce and transport low emissions electricity to end-users. Refer to the *Electricity* technical appendix for further detail.
Hydrogen FCEVs	**Mechanical on-site compression**	Conventional on-site compression that leverages mechanical-based methods to compress hydrogen gas.
	Non-mechanical on-site compression	Non-mechanical on-site compression that leverages chemical or adsorption-based methods to compress hydrogen gas.
	Hydrogen dispensing	Dispenser nozzle that safely transfers compressed hydrogen from storage tanks to the vehicle's onboard storage with appropriate pressure control and temperature management.
	Hydrogen storage and distribution	The infrastructure and technologies required to store compressed or liquefied hydrogen and distribute it to refuelling stations.

Energy efficiency solutions

For road transport, there are a range of energy efficiency solutions that will also support emissions mitigation efforts. The solutions outlined in Table 11.

Table 11: Energy efficiency solutions – Road transport

Energy efficiency solution	Description
Lightweighting and design	Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter and more aerodynamic vehicles
Technology and componentry improvement	Improves energy efficiency by improving drivetrain/transmission efficiencies

Traffic and logistics management technologies	Improves energy efficiency by optimising driving patterns and operation. This can also allow for reduced road congestion and allow for vehicles to travel more compactly at consistent speeds (platooning)
Energy management solutions	Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, enhancing battery life

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 associated 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 technology RD&D opportunities can be seen in Table 12. 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: all cost-related targets have been obtained from literature and reflect aspirational costs required to make a technology cost competitive, agnostic of country-specific RD&D. While converted into Australian currency, these figures assume large impacts from economies of scale which may not represent Australia's capacity for manufacturing. Elsewhere, Levelised Cost forecasts have been determined, referring to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology analysis.

Table 12: Summary of RD&D opportunities – Road transport[75]

	Battery electric vehicle				Hydrogen FCEV	
	Battery chemistries					
		Metal-ion	Metal-S	Redox flow	Fuel cell	On-board storage
Primary technologies	**Commercial**	Li-ion	-	-	-	-
	Mature	Na-ion	-	-	PEM fuel cell and componentry	H_2 tanks
	Emerging	Li solid state, Zn-Mn oxide	Li-S	V-RFB	-	-
Primary RD&D	• Reduce battery cell costs **(Target, cell-level: $75-150/kWh, cf. $150-290)** through: - E.g. Improving energy densities **(Target: Li-ion, 320-360Wh/kg, cf. 200-300Wh/kg)** - E.g. Adopting more affordable material compositions. • Increase vehicle ranges **(Target: 800-1000km)** • Improve thermal stability of batteries				• Reduce fuel cell costs **(Targets: LDVs $45/kW, cf. $80; HDVs $90/kW, cf. $250)** through: - E.g. Streamlining manufacturing processes - E.g. Improving fuel cell efficiency **(Targets: LDVs 70%, cf. 65%; HDVs 72%, cf. 64%)** - E.g. Improving fuel cell durability **(Target: LDVs 8,000hrs; HDVs 30,000hrs, cf. >10,000hrs)**	• Cost reductions • Increased storage capacity • Safety, durability improvements • Weight reduction
Auxiliary RD&D	• Support adoption through the development of electric vehicle supply equipment: - E.g. Fast and ultra-fast charging systems **(Targets: 350kW-1MW LDVs; >1MW MDV/HDVs)**, smart charging solutions • Reduce weight and complexity of battery integration into the vehicle				• Support adoption through the development of hydrogen refuelling infrastructure: - E.g. Faster fill rates for vehicles with high energy requirements **(Target: 10 kg/min avg over the duration of the fill, cf. ~2kg/min)** • For Hydrogen distribution and storage RD&D opportunities, see *Low Carbon Fuels* report	

cf. – Compare.

[75] TRL categories: emerging = TRL 4-6, mature = TRL 7-9, commercial = CRI 2-6; Please note, here, all cost-related targets are obtained literature, reflecting aspirational costs required to make a technology cost competitive, agnostic of country-specific RD&D. While converted into Australian currency, these figures assume large impacts from economies of scale which may not represent Australia's capacity for manufacturing. Elsewhere, Levelised Cost forecasts have been determined, referring to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology filtering.

4.6.1 Battery electric vehicles (BEVs)

Battery electric vehicles (BEVs) are propelled by an electric motor, rather than an ICE. Electricity is stored in a large traction battery pack to power the electric motor during discharge, while charging occurs via dedicated electric vehicle supply equipment (EVSE).[76] The battery component of the BEV system is the main cost driver and technical limiter to the performance and adoption of electric vehicles today. As such, this is the primary focus for ongoing RD&D, supported by charging system and thermal management developments. The remaining components are considered mature and are largely well-understood.

Lithium-ion (Li-ion) batteries are the current standard for BEVs, owing to their maturity, relatively high round trip efficiency (about 85%)[77] and high energy density (above 300Wh/kg).[78]

Primary technologies

RD&D that centres on reducing battery cell costs ($/kWh) will continue to be a linchpin in achieving greater BEV adoption.

Across chemistries, achieving higher energy densities, adopting more affordable material compositions, and leveraging manufacturing efficiencies could each allow for improved cost efficiencies.[79] The majority of the cost of a battery system is driven by the battery cell, which typically makes up 70-80% of battery pack costs, and 25-30% of total BEV manufacturing costs.[80] Some estimates from literature suggest that battery cell costs for Li-ion systems could fall to $75-150/kWh by 2035 (c.f., $150-290).[81]

Attaining greater energy densities than current 'best available' battery systems (i.e., 200-300Wh/kg for Li-ion),[82] is one strategy for reducing battery cell costs. By lowering the material mass of the cell per unit of

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[76] Alternative Fuels Data Center (n.d.) How Do All-Electric Cars Work? U.S. Department of Energy. <https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work> (accessed 24 October 2024)

[77] Cole W, Frazier A (2020) Cost Projections for Utility-Scale Battery Storage: 2020 Update. National Renewable Energy Laboratory (NREL). <https://www.nrel.gov/docs/fy20osti/75385.pdf>

[78] IRENA (2019) Utility-scale batteries: Innovation landscape brief. International Renewable Energy Agency, Abu Dhabi; Zubi G, Dufo-López R, Carvalho M, Pasaoglu G (2018) The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 89, 292. doi:10.1016/j.rser.2018.03.002; Annegret Stephan, Tim Hettesheimer, Christoph Neef, Thomas Schmaltz, Steffen Link, Maximilian Stephan, Jan Luca Heizmann, Axel Thielmann (2023) Alternative Battery Technologies Roadmap 2030+. doi:10.24406/publica-1342.

[79] Roy H, Roy BN, Hasanuzzaman M, Islam MS, Abdel-Khalik AS, Hamad MS, Ahmed S (2022) Global Advancements and Current Challenges of Electric Vehicle Batteries and Their Prospects: A Comprehensive Review. Sustainability (Switzerland) 14. doi:10.3390/su142416684

[80] Slowik P, Isenstadt A, Pierce L, Searle S (2022) Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022–2035 timeframe, the International Council on Clean Transport.

[81] Annegret Stephan, Tim Hettesheimer, Christoph Neef, Thomas Schmaltz, Steffen Link, Maximilian Stephan, Jan Luca Heizmann, Axel Thielmann (2023) Alternative Battery Technologies Roadmap 2030+. doi:10.24406/publica-1342.; Slowik P, Isenstadt A, Pierce L, Searle S (2022) Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022–2035 time frame, the International Council on Clean Transport. Where required, cost targets are converted from EUR to AUD by applying a conversion rate of 1AUD=0.61EUR and USD to AUD by applying a conversion rate of 1AUD=0.66USD, representing annual average exchange rates from Feb 2023 – Feb 2024.

[82] Li J, Du Z, Ruther RE, An SJ, David LA, Hays K, Wood M, Phillip ND, Sheng Y, Mao C, Kalnaus S, Daniel C, Wood DL (2017) Toward Low-Cost, High-Energy Density, and High-Power Density Lithium-Ion Batteries. JOM 69, 1484. doi:10.1007/s11837-017-2404-9

energy, the size and weight of the battery pack is minimised, effectively reducing pack costs.[83] To achieve this, researchers are considering the use of high-energy materials for battery electrode development.[84]

The material composition of Li-ion batteries, while stable and high-performing, creates high material overheads and is one driver for the development of alternative battery technologies as another strategy for reducing costs.[85] Exploring alternative battery chemistries could also reduce a BEVs reliance on costly critical minerals. Chemistries being investigated include alternative metal-ion derivatives (i.e., Na-ion, Zn-Mn oxide), metal-sulphur (i.e., Li-S), redox-flow (i.e., V-RFB), and emerging solid state battery systems (i.e., Li SSB).

Automation of stack production and realising economies of scale can also serve to reduce manufacturing costs of battery systems, regardless of chemistry.[86]

Improving vehicle range and battery thermal stability, alongside cost reductions, are key performance metrics that could also increase BEV adoption.

Energy density and efficiency improvements can also serve to increase vehicle ranges and therefore address range anxiety. Some estimates suggest that BEVs with ranges of 800-1000km could be realised with next-generation battery technologies.[87]

Increasing interest in alternative battery chemistries is also driven by opportunities to improve upon safety concerns such as susceptibility to thermal runaway.[88] Battery systems that can employ non-flammable or low-risk materials (such as aqueous electrolytes or electrodes with low reactivity) or that offer desirable operating conditions (such as 0V discharge), can minimise the likelihood of combustion. For reactive materials, such in the case of Li-ion batteries, the flammability or reactivity of the materials must be countered by efforts at the pack level, such as employing thermal insulation, wrapping the battery in inert gases, or optimising battery designs for safety.[89]

Auxiliary technologies

There are several auxiliary systems and networks required to enable successful electrification and BEV uptake. In the context of BEVs, auxiliary technologies refer to electric vehicle supply equipment (EVSE) and battery-vehicle integration, as a means to enhance the performance of battery systems.

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[83] Slowik P, Isenstadt A, Pierce L, Searle S (2022) Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022–2035 time frame, the International Council on Clean Transport.

[84] Gutsch M, Leker J (2024) Costs, carbon footprint, and environmental impacts of lithium-ion batteries – From cathode active material synthesis to cell manufacturing and recycling. Applied Energy 353. doi:10.1016/j.apenergy.2023.122132https://www.sciencedirect.com/science/article/pii/S0306261923014964; Annegret Stephan, Tim Hettesheimer, Christoph Neef, Thomas Schmaltz, Steffen Link, Maximilian Stephan, Jan Luca Heizmann, Axel Thielmann (2023) Alternative Battery Technologies Roadmap 2030+. doi:10.24406/publica-1342.

[85] Annegret Stephan, Tim Hettesheimer, Christoph Neef, Thomas Schmaltz, Steffen Link, Maximilian Stephan, Jan Luca Heizmann, Axel Thielmann (2023) Alternative Battery Technologies Roadmap 2030+. doi:10.24406/publica-1342.

[86]Roy H, Roy BN, Hasanuzzaman M, Islam MS, Abdel-Khalik AS, Hamad MS, Ahmed S (2022) Global Advancements and Current Challenges of Electric Vehicle Batteries and Their Prospects: A Comprehensive Review. Sustainability (Switzerland) 14. doi:10.3390/su142416684; Slowik P, Isenstadt A, Pierce L, Searle S (2022) Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022–2035 time frame, the International Council on Clean Transport.

[87] Fichtner M (2022) Recent Research and Progress in Batteries for Electric Vehicles. Batteries and Supercaps 5,. doi:10.1002/batt.202100224; Toyota (2023) Media release: Toyota sets out advanced battery technology roadmap. <https://media.toyota.co.uk/toyota-sets-out-advanced-battery-technology-roadmap/> (accessed 24 October 2024).

[88] Best AS, Cavanagh K, Preston C, Webb A, Howell S (2023) Lithium-ion battery safety: A report for the Australian Competition and Consumer Commission (ACCC).

[89] Feng X, Ren D, He X, Ouyang M (2020) Mitigating Thermal Runaway of Lithium-Ion Batteries. Joule 4, 743. doi:10.1016/j.joule.2020.02.010

RD&D to advance electric vehicle supply equipment is expected to play a significant role in supporting the adoption of BEVs.

For charging systems, achieving fast and ultra-fast speeds of 350kW-1MW for light-duty vehicles, and >1MW for medium and heavy-duty vehicles[90] could prove to be a major lynch point for driving adoption. Developing charging systems up to 1MW (TRL 8) and greater than 1MW (TRL 6-7) will be particularly important for applications with high utilisation rates or fast turnaround times, or where there are high energy demands (i.e., heavy duty freight or mine haulage trucks, see the *Industry* technical appendix for further detail).[91] Achieving higher power outputs could be achieved by developing advanced materials with enhanced thermal and electrical properties to reduce and manage thermal loads in the charging unit and cables, and by optimising vehicle battery and ultracapacitor combinations for rapid charging.[92]

Battery swapping as an alternative to changing could be considered (TRL 7-8),[93] but requires further technoeconomic assessment of future battery systems and location analysis to determine their viability.[94]

Improving smart charging solutions, that can dynamically adjust power outputs based in grid-conditions, electricity prices, and user preferences and maintain battery health, could assist in managing electricity demands. This may be realised through the integration of Information Technologies (IT) and Operational Technologies (OT), including remote sensing and big data analytical tools.

Continued efforts to streamline battery integration into the vehicle and address end-of-life challenges, could allow for manufacturing and performance benefits.

Battery vehicle integration (i.e., cell-to-pack or cell-to-chassis technology)[95] is an ongoing research area by leading BEV manufacturers, enabling further cost reductions and performance benefits. By reducing intermediary integration steps during manufacturing, the weight and complexity of the vehicle can be minimised and energy density increased. Continuing to advance joint development of chassis and battery systems that manage electrochemical stability and safety concerns are cornerstone research points enabling further battery vehicle integration.[96]

Battery integration, however, can further complicate end-of-life management processes, necessitating that the reparability, dismantlability and recyclability of integrated systems also be considered in tandem.

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[90] For passenger vehicles. IEA (2024) ETP Clean Energy Technology Guide. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed 24 October 2024).

[91] Fast-charging systems with power outputs of 250-250kW are mature (CRI 6). IEA (2024) ETP Clean Energy Technology Guide. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed 24 October 2024).

[92] Burnham A, Dufek EJ, Stephens T, Francfort J, Michelbacher C, Carlson RB, Zhang J, Vijayagopal R, Dias F, Mohanpurkar M, Scoffield D, Hardy K, Shirk M, Hovsapian R, Ahmed S, Bloom I, Jansen AN, Keyser M, Kreuzer C, Markel A, Meintz A, Pesaran A, Tanim TR (2017) Enabling fast charging – Infrastructure and economic considerations. Journal of Power Sources 367, 237. doi:10.1016/j.jpowsour.2017.06.079

[93] Note: TRL is higher (CRI 2-5) for two- to three-wheelers. IEA (2024) ETP Clean Energy Technology Guide. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed 24 October 2024).

[94] Wu Y, Zhuge S, Han G, Xie W (2022) Economics of Battery Swapping for Electric Vehicles—Simulation-Based Analysis. Energies 15,. doi:10.3390/en15051714

[95] Cell-to-pack is at CRI3-6 and is being investigated by industry proponents, i.e., CATL (n.d.) R&D: Innovative Technology. <https://www.catl.com/en/research/technology/>; Cell-to-chassis integration is at TRL 7

[96] Kampker A, Heimes HH, Offermanns C, Vienenkötter J, Robben T (2023) Framework and Classification of Battery System Architectures. World Electric Vehicle Journal 14,. doi:10.3390/wevj14040088

4.6.2 Hydrogen fuel cell electric vehicles (Hydrogen FCEVs)

Like other electric vehicles, hydrogen FCEVs are propelled by an electric motor rather than an internal combustion engine. Electricity is produced using a fuel cell, in which pressurised hydrogen and air is passed through a fuel cell creating a flow of electrons, powering the motor. The power of the vehicle is largely governed by the size of the electric motor(s) and supported by an appropriately sized fuel cell and battery combination. Compared to a BEV, the battery system in a hydrogen FCEV is smaller in size and primarily used for recapturing braking energy, providing additional power during short acceleration events and to smooth out the power delivered from the fuel cell.[97]

With competitive energy densities and efficiencies to internal combustion engines, hydrogen FCEVs are well suited to the transport sector, particularly extended-range applications.[98]

Given the maturity of the electrical components of a hydrogen FCEV, the primary technology RD&D opportunities discussed below centre on the fuel cell stack and hydrogen storage tank. Commentary regarding battery chemistries can be found in the section above.

Primary technologies

Hydrogen FCEVs are challenged by the high costs of the fuel cell stack, with RD&D presenting opportunities to overcome high production costs during manufacturing.

Box 2: Fuel cell variants

Of the various fuel cell variants, proton exchange membrane fuel cell (PEMFC) systems are the most mature (TRL 9) with notable advantages such as high-power density and dynamic characteristics.[99] These cells are characterised by their use of a thin polymeric membrane as a solid electrolyte and lightweight platinum materials on either side of the permeable membrane.[100] Other fuel cell types are considered for non-road applications (See *6 Rail*).

The US Department of Energy (DOE) is targeting a best-case long-term cost of $45/kW for LDV hydrogen fuel cells (cf. $80/kW).[101] This should be viewed as an aspirational target 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.

[97] US DOE (n.d.) How do electric vehicles work using hydrogen? <https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work> (accessed November 2024).

[98] Vengatesan S, Jayakumar A, Sadasivuni KK (2024) FCEV vs. BEV — A short overview on identifying the key contributors to affordable & clean energy (SDG-7). Energy Strategy Reviews 53,. doi:10.1016/j.esr.2024.101380

[99] Madheswaran DK, Thangamuthu M, Gnanasekaran S, Gopi S, Ayyasamy T, Pardeshi SS (2023) Powering the Future: Progress and Hurdles in Developing Proton Exchange Membrane Fuel Cell Components to Achieve Department of Energy Goals—A Systematic Review. Sustainability (Switzerland) 15,. doi:10.3390/su152215923

[100] Pollet BG, Kocha SS, Staffell I (2019) Current status of automotive fuel cells for sustainable transport. Curr Opin Electrochem 16, 90. doi:10.1016/j.coelec.2019.04.021

[101] A proposed target of $90/kW has been developed for HDVs (cf. $250), based on a manufacturing capacity of 500k systems/year. While converted into Australian currency, these figures assume large impacts from economies of scale which may not represent Australia's capacity for manufacturing. US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf

Addressing high costs of manufacture could be realised through material innovations and streamlined manufacturing, supported by economies of scale. These efforts will serve to counter the high material costs stemming from high platinum loadings, membranes, and bipolar plates.[102]

Fuel cell cost forecasts could also be achieved by improving technical performance characteristics; namely, fuel cell efficiency and durability.

Best case efficiency targets have been set by the US DOE Hydrogen and Fuel Cell Technologies Office, pursuing 70% for light-duty vehicles (cf. 65%) and 72% for heavy-duty (cf. 64%).[103] Meeting these efficiency targets without compromising cost competitiveness will largely depend on componentry improvements, with RD&D advancements in catalysts, ion-conducting membranes, system engineering, and water and thermal management likely instrumental in improving fuel cell attributes.[104] The DOE has also established targets for key componentry, including electrocatalysts, membrane electrolytes, and bipolar plates.[105]

Improving durability (target: 8,000hrs for light-duty, 30,000hrs for heavy-duty, cf. >10,000hrs)[106] will similarly require innovations in catalyst and membrane compositions, verified by stringent testing protocols.[107]

Developing low cost, light weight and durable on-board hydrogen storage systems is a complex RD&D challenge, that if overcome could encourage hydrogen FCEV adoption.

Mobility applications rely on high-pressure hydrogen storage tanks (TRL 8-9), capable of storing gaseous hydrogen at high pressures up to 700bar. While technically mature, RD&D is a fundamental lever to reduce costs without compromising strength, durability or safety. Type III[108] and IV[109] tanks are generally preferred for transport applications due to their favourable strength-to-weight ratios, but remain expensive due to their material composition. Opportunities exist to lower costs through the identification and development of lower cost composite materials, design optimisation and scalable manufacturing processes.

Type V liner-less composite tanks, currently in earlier stages of development, offer additional weight reductions and potential for higher-pressure storage, but face higher costs and are not yet commercialised.[110]

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[102] Whiston MM, Azevedo IL, Litster S, Whitefoot KS, Samaras C, Whitacre JF (2019) Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles. Proceedings of the National Academy of Sciences of the United States of America 116, 4899. doi:10.1073/pnas.1804221116; Cost estimate converted from USD, https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-fuel-cell-technologies.pdf.

[u] DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

[104] Madheswaran DK, Thangamuthu M, Gnanasekaran S, Gopi S, Ayyasamy T, Pardeshi SS (2023) Powering the Future: Progress and Hurdles in Developing Proton Exchange Membrane Fuel Cell Components to Achieve Department of Energy Goals—A Systematic Review. Sustainability (Switzerland) 15,. doi:10.3390/su152215923.

[105] US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdfhttps://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf; https://www.energy.gov/eere/fuelcells/doe-technical-targets-polymer-electrolyte-membrane-fuel-cell-components

[106] US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf; https://www.energy.gov/eere/fuelcells/doe-technical-targets-fuel-cell-systems-and-stacks-transportation-applications

[107] Madheswaran DK, Thangamuthu M, Gnanasekaran S, Gopi S, Ayyasamy T, Pardeshi SS (2023) Powering the Future: Progress and Hurdles in Developing Proton Exchange Membrane Fuel Cell Components to Achieve Department of Energy Goals—A Systematic Review. Sustainability (Switzerland) 15,. doi:10.3390/su152215923.

[108] Type III vessels consist of a thin metal-liner, wrapped with a high-strength fibre-resin composite

[109] Type IV vessels consist of a polymer liner, wrapped with a fibre-resin composite.

[110] 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>

Auxiliary technologies

Developing advanced hydrogen refuelling infrastructure, could help facilitate the successful deployment of hydrogen FCEVs, especially for high-energy, low downtime vehicles and applications.

Hydrogen dispensing involves the transfer of compressed hydrogen from storage tanks to a vehicular onboard storage vessel with appropriate pressure control and temperature management.[111] To cater to vehicles with high energy requirements, achieving faster fill rates (target: 10 kg/min average over the duration of the fill, cf. ~2kg/min)[112] will be an important adoption factor. Where demands are large and hydrogen is stored in liquid form, developing high-throughput, low-boil-off cryopumps that vaporise and pressurise liquid hydrogen may also be necessary.

There are also opportunities to improve nozzle attachment/detachment mechanisms to overcome technical limitations, such as the nozzle 'freezing' in place from ice accumulation.

The feasibility of hydrogen FCEVs will be influenced by the production, storage and distribution of hydrogen for operational use.

For details on hydrogen network RD&D opportunities Refer to the *Low Carbon Fuels* technical appendix.

4.6.3 Energy efficiency solutions

Further RD&D in solutions that reduce energy use in road transport will also support emissions mitigation efforts. The solutions outlined in Table 13 are technology-agnostic with the ability to improve energy efficiencies across a range of technology types and systems.

Central to these efforts will be an ongoing commitment to advanced materials research. Beyond battery and fuel cell systems, as discussed above, advanced materials can also be applied to: (1) vehicle structures to reduce weight, such as vehicle chassis and body panels;[113] (2) electronics to improve power train efficiencies, such as super/semi-conductors and advanced magnetic materials;[114] and (3) thermal management systems to improve thermal efficiencies, such as heat exchangers for battery cooling and insulation materials.[115]

Table 13: Energy efficiency RD&D opportunities – Road transport

Theme	RD&D opportunities
Drag reduction and design *Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles.*	• Design vehicles with improved aerodynamics to enhance energy efficiency and reduce air resistance
Lightweighting *Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.*	• Develop advanced composite materials and alloys with high strength and low weight

[111] Wolfe S et al. (2023) Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia. CSIRO and GHD Advisory; US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

[112] US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office. https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf.

[113] Zhang W, Xu J (2022) Advanced lightweight materials for Automobiles: A review. Mater Des 221,. doi:10.1016/j.matdes.2022.110994

[114] Lipman T, Maier P (2021) Advanced materials supply considerations for electric vehicle applications. MRS Bull 46, 1164. doi:10.1557/s43577-022-00263-z

[115] Dan D, Zhao Y, Wei M, Wang X (2023) Review of Thermal Management Technology for Electric Vehicles. Energies (Basel) 16,. doi:10.3390/en16124693

Technology and componentry improvement *Improves energy efficiency by improving drivetrain/transmission efficiencies*	• Advanced materials, such as electronics and advanced magnetic materials, to improve powertrain and thermal efficiencies[116] • Electric drivetrain components (motors, power electronics) that optimise energy conversion and reduce losses • Common architectures to enhance operability[117]
Traffic and logistics management technologies *Improves energy efficiency by optimising driving patterns and operation. This can also allow for reduced road congestion and allow for vehicles to travel more compactly at consistent speeds (platooning)*	• Develop driver aids and automation technologies to improve energy efficiency through optimised driving patterns. This requires: o Software advancement (AI and ML) for vehicle-to-vehicle and vehicle-to-infrastructure communication technologies; o Hardware advances (sensors, communications and computing); and o Cybersecurity measures for in-vehicle communication systems to address privacy and safety concerns • Develop algorithms for real-time traffic prediction and optimisation
Energy management solutions *Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, enhancing battery life*	• Improve efficiency of energy recovery systems such as advanced regenerative braking technologies

[116] Zhang W, Xu J (2022) Advanced lightweight materials for Automobiles: A review. Materials and design, 221. https://doi.org/10.1016/j.matdes.2022.110994; Lipman T, Maier P (2021) Advanced materials supply considerations for electric vehicle applications. MRS bulletin, 46. https://doi.org/10.1557/s43577-022-00263-z; Dan D, Zhao Y, Wei M, Wang X (2023) Review of Thermal Management Technology for Electric Vehicles. Energies (Basel) 16,. doi:10.3390/en16124693

[117] Unlike conventional ICE vehicles that have benefitted from years of integration with well-understood vehicle architecture, FCEVs are at an earlier stage of development with newer models incorporating updates from new technology developments and user experiences. Common architectures could enable fleet operators, maintenance workers, and manufacturers to foster a more cohesive and inter-operable transport system. Wolfe S et al. (2023) Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia. CSIRO and GHD Advisory.

5 Aviation

5.1 Executive summary

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	• CO_2 capture and utilisation (CCU) • Low emissions electricity generation and distribution • Monitoring, reporting and verification (MRV)

Hydrogen combustion

- Hydrogen liquefaction technologies
- Production, transportation, and storage infrastructure
- Refuelling infrastructure

Energy efficiency solutions

- Technology and componentry improvement
- Drag reduction and design
- Energy management solutions
- Lightweighting
- Traffic and logistics management technologies

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.

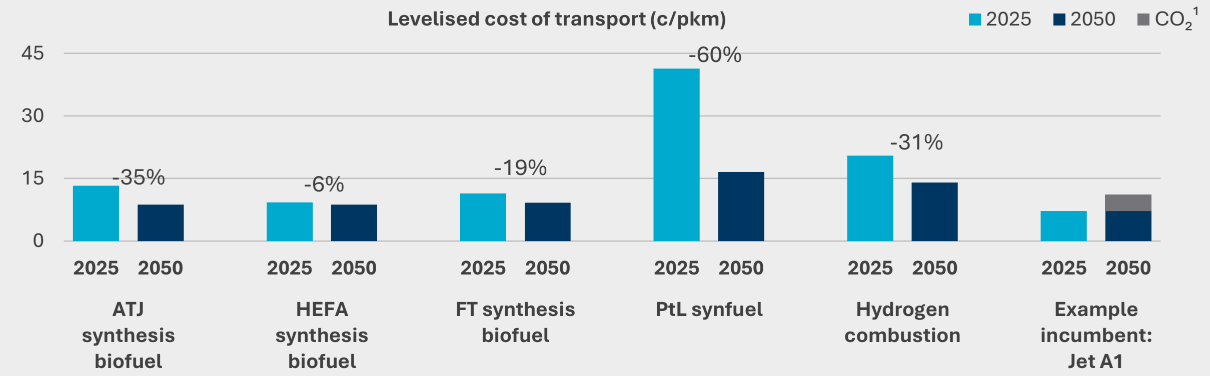
Auxiliary

- 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 *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions. Note, c/pkm = cents/passenger – km.

5.2 Introduction

The aviation subsector faces significant challenges in reducing emissions while maintaining operational efficiency and economic viability. The aviation subsector emitted 12 $MtCO_2e$ in 2023-24, accounting for 9% of Australia's total transport emissions.[118] A typical 90-minute, medium-range commercial passenger flight is the most common type of domestic flight in Australia.[119] These flights serve numerous domestic routes and are therefore a crucial segment for decarbonisation efforts.

Aircraft have long asset lives, often spanning several decades, making frequent replacement economically and practically challenging. As such, there is a desire to find low emissions solutions that can integrate seamlessly with the current systems, allowing for the preservation of existing aircraft and airport infrastructure to maximise the return on investment and maintain operational efficiency.

There is also interest in shifting to novel fuels and technologies with increased emissions abatement potential. Each novel technology presents opportunities and challenges that require focused RD&D efforts. These emerging technologies require careful consideration in terms of scalability, cost, and infrastructure integration. For example, an aircraft operating on novel fuels may require entirely new storage, distribution, and refuelling infrastructure, which presents substantial initial costs and logistical challenges. The development of supporting systems, such as efficient fuel distribution networks, is vital for the successful implementation of these decarbonisation solutions. Despite these hurdles, the potential for significant emissions reductions and long-term sustainability creates clear opportunity for RD&D to support the transition towards these innovative fuel solutions.

Balancing the preservation of existing assets with the development of new technologies and infrastructure is crucial for the aviation subsector's successful transition to low emissions technologies over the near- and long term. This balance will require substantial investment, technological advancements, and supportive regulatory frameworks to address both the economic viability and environmental impact of the shift. These factors must be managed to achieve significant emissions reductions and ensure the long-term sustainability and competitiveness of the aviation industry.

This chapter presents an assessment of low emissions technologies for the aviation subsector to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support, and possibly accelerate, the deployment of these technologies.

5.2.1 Aviation use case(s)

To explore low emissions technologies in the aviation subsector, a single use case has been defined to reflect a medium-range commercial plane carrying 180 passengers on a 2-hour flight (see Table 14). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

This use case is representative of a flight profile based on the median domestic flight duration (weighted by pkm),[120] and was based on a Boeing 737-800 aircraft with a 180-passenger capacity. A supplementary case

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[118] Climate Change Authority (2024) Sector Pathways Review: Transport. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReviewTransport.pdf> (accessed 21 March 2025).

[119] Defined by passenger levels, as at December 2024. BITRE (2024) Domestic Airlines Data – December 2024. <https://www.bitre.gov.au/sites/default/files/documents/domestic-airlines-dec-2024.xlsx> (accessed 28 March 2025); Qantas (2025) Flight Deals – Melbourne to Sydney. <https://www.qantas.com/au/en/flight-deals/flights-from-melbourne-to-sydney.html/mel/syd/economy> (accessed 28 March 2025); Qantas (2025) Flight Deals – Brisbane to Sydney. <https://www.qantas.com/au/en/flight-deals/flights-from-brisbane-to-sydney.html/bne/syd/economy> (accessed 28 March 2025).

[120] BITRE (2024) Domestic aviation activity, Statistical Report, BITRE, Canberra ACT

study was also conducted (see Box 4), to assess the feasibility of technology options for a less energy intensive application. This case study reflects a short-range 60-minute flight, with an 18 passenger capacity.

These use cases are illustrative and present requirements that technologies must be able to meet in order to service Australia's domestic aviation industry. In reality, operations in Australia are diverse and require aircraft of varying size and carrying capacity, over variable distances.

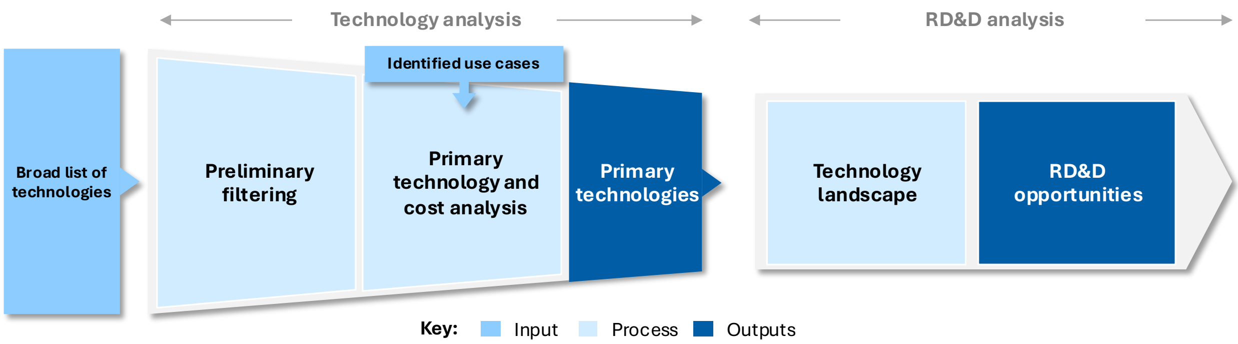
Table 14: Use case(s) – Aviation

Use case(s)	Medium-range passenger flight
Description:	**A medium-range commercial plane carrying 180 passengers on a 2-hour flight.** The vast majority of aviation services in Australia are passenger flights,[121] with the most common flight time being about 90 minutes. As a subsector, domestic aviation is responsible for 12 $MtCO_2e$, which equates to 59% of domestic non-road emissions.[122]

5.3 Methodology: Aviation inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies used helps explore RD&D opportunities with the potential to support and accelerate the advancement of low emissions technologies for the aviation subsector. It focuses on identifying technologies with the potential to contribute to decarbonisation efforts for medium-range commercial flights. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress. could drive impactful progress (Figure 11).

Figure 11: Technology and RD&D analysis framework for aviation



5.3.1 Broad technology list

A broad technology list comprised of seven technologies was developed (Table 15). These technologies were then passed through four preliminary filters: relevance to Australia, technological maturity, abatement potential and resource scalability. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case(s).

[121] Based on unpublished BITRE statistics supplied to CSIRO.

[122] BITRE (2023)) (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

Table 15: Technology category – Aviation

Technology category	Definition
Battery electric	Aircraft using batteries as primary power source.
Hydrogen combustion	Aircraft engine combusts hydrogen as primary fuel source.
Hydrogen fuel cells	Aircraft using hydrogen fuelled fuel cells to power the engine.
Synthetic fuels	Aviation fuels created using renewable hydrogen and electricity, that are used to drive the engine. CO_2 sources for PtL can be obtained from carbon capture (i.e., Direct Air Capture or point source) or from biogenic sources.
Biofuels (HEFA)	Biofuels typically produced using waste fats and oils, which are hydrotreated.
Biofuels (FT)	Biofuels typically produced using carbohydrate, waste and residue feedstocks. These are gasified into syngas and then catalytically converted into fuel.
Biofuels (AtJ)	Biofuels typically produced using carbohydrate, waste and residue feedstocks. These are converted into alcohols (e.g. ethanol) and subsequently put through chemical processes such as dehydration, oligomerisation and hydrogeneration to create jet fuel.

5.3.2 Additional preliminary filtering criteria

An additional preliminary filter has been adopted for aviation: *Resource scalability* (Table 16). This filter was incorporated in recognition of the high energy demands for the subsector, where higher energy density fuels and fuel standardisation is crucial. Unlike road transport, aviation faces weight and volumetric constraints which limits the number of solutions available for the sector, making fuel scalability a key determinant of deployment feasibility.

The resource scalability criterion evaluates whether the energy supply of a given technology is achievable at the scale needed for aviation, when considering feedstock resource constraints and renewable energy generation potential. It assesses estimates of resource inputs and determines whether there are resource constraints that may inhibit the ability of energy supply to meet sectoral energy demand.

Please note, it does not consider the capital and operating costs of energy recovery, supply chain implementation, or market factors related to the adoption of a given technology.

5.3.3 Primary technology filters

Applications in non-road transportation are commonly grouped together due to their extreme performance requirements and high energy demands that are not typically faced by road transport vehicles. To assess potential mitigation technologies, relative to an aircraft operating on conventional jet fuel (CJF), three performance parameters were adopted: **range, refuelling duration and cost** (Table 16)**.** These performance parameters, were deemed to be core operational requirements that will enable or limit technology uptake, particularly given the energy and cost intensive nature of the subsector.

The thresholds for range and refuelling duration were ascertained based on the characteristics of an aircraft of the same class with CJF. The range reflects the distance of a 2-hour flight approximately 1,300km, accounting for a 15% fuel reserve requirement.[123] The refuelling duration reflects the time required for a

[123] BITRE (2024) Domestic aviation activity, Statistical Report, BITRE, Canberra ACT.

complete tank fill, assuming a single nozzle point.[124] This considers a standard refill time with a buffer period to account for logistical factors.

The lowest cost mitigation technologies able to meet these thresholds were prioritised. Further details on the selected parameters are provided in Section *5.4.2 Primary technology analysis.*

Table 16: Technology filtering criteria – Aviation

Subsector	Aviation
Use case(s)	**Medium-range passenger flight**
Preliminary filtering criteria	**Relevance to Australia** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions. For further detail, please see *Appendix A.3*.
	Technology maturity Technology has a TRL greater than 3. The TRL index can be found in A.2.
	Abatement potential Technology meets or exceeds an abatement threshold of 60%, relative to an aircraft of the same class operating on conventional jet fuel (CJF).
	Resource scalability The energy supply of a given technology can meet the demands of the aviation transport sector, when considering feedstock resource constraints.
Primary technology parameters	**Minimum range requirement** Technology can meet an acceptable distance threshold in a single trip.
	Refuelling duration Technology can meet an acceptable threshold refuelling duration, compared to the time taken to refuel the aircraft with conventional jet fuel.
	Levelised Cost of Transport (LCOT) in 2050 Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.

[124] James R (2021) How long to refuel an airplane? – 15 most common planes. PilotTeacher. <https://pilotteacher.com/how-long-to-refuel-an-airplane-15-most-common-planes/> (accessed 3 July 2024). Used as an example plane, an Airbus A320 is expected to take 24 minutes to refuel a tank from 0% to 100% (i.e. with no reserve fuel in tank), assuming a single nozzle point is being used. This has been rounded to 30 minutes to account for a range of factors, including fuel load and availability of fuelling infrastructure.

5.4 Technology analysis

Box 3: Aviation fuel terminology

The term biofuels, as used in this chapter, refers to liquid aviation fuels derived from biogenic sources. These are commonly referred to as biogenic low carbon liquid fuels (LCLFs) or sustainable aviation fuels (SAFs).[1] Common feedstocks include carbohydrates (e.g. bagasse, sorghum), wastes (e.g. tallow, used cooking oil), residues (e.g. agricultural, sawmill) and oilseeds (e.g. canola, cottonseed).[1] Common production pathways including using hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch synthesis (FT), and alcohol-to-jet conversion (AtJ).[1]

The term synthetic fuels, as referred to in this chapter, refers to liquid fuels generated from renewable electricity by synthesising electrolytic hydrogen that is then reacted with captured or recycled carbon dioxide.[1] The resultant hydrocarbons are then further processed (e.g. through FT or AtJ processes) to produce liquid synthetic fuels such as e-methanol, di-methyl ether (DME) and drop-in synthetic diesel, petrol and jet fuels.[1] In the aviation industry, these fuels may also be referred to as abiogenic LCLFs, e-fuels or 'power-to-liquids'.

This chapter outlines the process of identifying primary low emissions technologies that can best service Australia's aviation subsector. Following the technology analysis framework process, **biofuels (HEFA, FT and AtJ) and synthetic fuels (or power-to-liquid, PtL) emerged as primary technologies for further RD&D exploration.** These technologies were able to service the designated use case and satisfy all criteria.

The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in aviation decarbonisation, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. Although biofuels are projected to be lower cost than hydrogen-based solutions, given limits on scalability, the latter is likely to be required in the longer term. While the biofuel parameters reflect B100 applications,[125] given the maximum blending rate currently allowable is 50%, the use of blends will be needed to support decarbonisation in the near term.

The results of the technology analysis for aviation are provided in Table 17.

[125] B100 refers to pure, or neat, biofuel in an unblended form.

Table 17: Technology analysis results – Aviation[126]

Meets filter criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering

2. Primary technology analysis

Technologies	Maturity	Abatement potential[127]	Resource scalability	Refuelling	Range	LCOT (2050)	
				Medium range: 2-hour flight with 180 passengers			
Threshold	*TRL>3*	*≥60% decrease in emissions*	*Surmountable energy supply limitations*	*≤37.5 minutes*	*>1,500km*	*c/p-km*	
Battery electric	TRL 4-6	91%		~3 – 22 hours			
Hydrogen combustion	TRL 3-4	100%		4-14 minutes	Reduced payloads	14	★
Hydrogen fuel cells	TRL 4-6	100%		3-11 minutes	Reduced payloads	Inconclusive	
Synthetic fuels: Power-to-liquid (PtL) fuels	TRL 2-4	91%	Potential input supply limitations	9-25 minutes	>1500km	17	★
Biofuels: Hydroprocessed esters and fatty acids (HEFA)	TRL 9 – CRI 5	16-90%	Potential input supply limitations	9-25 minutes	>1500km	9	★
Biofuels: Fischer-Tropsch (FT)	TRL 4-7	60-95%	Potential input supply limitations	9-25 minutes	>1500km	9	★
Biofuels: Alcohol-to-jet (AtJ)	TRL 3-7	70-90%	Potential input supply limitations	9-25 minutes	>1500km	9	★

[126] Details for these figures, including sources and assumptions, are found in Table 19 (abatement potentials); Table 20 (scalability potential); Table 21 (Refuelling/recharging duration requirement); Table 22 (Range); and under 'Levelised cost analysis' and *Technical Appendix: Levelised cost analysis* (LCOT).

[127] Aviation is often classified as a hard-to-abate sector due to its reliance on highly energy-dense fuels and the immaturity of abatement options. As a result, a 60% abatement threshold was set, relative to the aircraft operating on conventional jet fuel (CJF), to reflect the most cost-competitive solutions by 2050 (i.e. biofuels) that are able to draw on feedstocks that do not compete with food.

5.4.1 Preliminary filtering

Key information – Preliminary filtering

Four 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.
- **Resource scalability:** The energy supply of a given technology can meet the demands of the aviation transport sector.

Relevance to Australia

All technologies were found to meet this criterion as they can be reasonably deployed in the Australian context.

Technological maturity

All technologies were found to meet this criterion, possessing a TRL greater than 3. Some AtJ production pathways were not considered, due to lower maturity ratings (Table 18).

Maturity ratings are informed by desktop research, drawing on the IEA Clean Energy Technology Guide,[128] CSIRO's Sustainable Aviation Fuel Roadmap,[129] and the US Department of Energy's Pathways to Commercial Liftoff Report for Sustainable Aviation Fuel.[130]

Table 18: Technology maturities – Aviation

Technology	TRL
Battery electric	• TRL 4-6
Hydrogen combustion	• TRL 3-4
Hydrogen fuel cells	• TRL 4-6
Synthetic fuels (Power-to-liquids)	• TRL 2-4
Biofuels (HEFA)	• TRL 9 – CRI 5 ○ HEFA - used cooking oil: CRI 2-5 ○ HEFA - oilseeds (soy): TRL 8-CRI 2
Biofuels (FT)	• TRL 4-7
Biofuels (AtJ)	• TRL 3-7 ○ Ethanol-to-jet (EtJ): TRL 3-7 ○ Methanol-to-jet (MtJ): TRL 3-7

Abatement potential

Key information – Abatement potential

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

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

[130] U.S. Department of Energy (2025) Liftoff: Sustainable Aviation Fuel – Updated 2.6.25. <https://liftoff.energy.gov/wp-content/uploads/2024/12/LIFTOFF_-Sustainable-Aviation-Fuel_Updated-2.6.25.pdf> (accessed 17 February 2025).

The abatement potential criterion identifies technologies that 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***.

The abatement potential was assessed against a single aisle passenger aircraft operating on conventional jet fuel (CJF), with an emissions intensity of 85.1gCO_2 e/MJ. Aviation is often classified as a hard-to-abate sector due to its reliance on highly energy-dense fuels and the immaturity of abatement options.[131] As a result, a 60% abatement threshold was set. This threshold reflects the most cost-competitive solutions by 2050 (i.e. biofuels) that can draw on feedstocks that do not compete with food. While there is likely to be further improvement in zero-emissions technologies (e.g. hydrogen aircraft), these are not projected to be as competitive in 2050.

Aviation has specific, internationally recognised conventions around carbon abatement and emissions estimations which are reflected throughout the following analysis. In particular, biogenic biofuels must meet sustainability criteria, including a fuel lifecycle emissions baseline under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA); a methodology defined by the International Civil Aviation Organisation (ICAO).[132]

The emissions estimates (in CO_2 equivalents), as outlined in Table 19, draw upon the US Argonne National Laboratory's GREET model which assesses lifecycle emissions and environmental impact of given fuel and technology options. Specifically, the ICAO-GREET model was employed: a version developed to estimate and verify the default core life cycle analysis of the CORSIA-approved Sustainable Aviation Fuel (SAF) pathways. Greenhouse gas emissions considered include methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2). Other pollutants are, such as ozone and contrails, are not included.

For technologies reliant on electricity, grid-born electricity emissions were adjusted to reflect a prospective 2050 grid intensity in which 5% of current electricity generation occurs from peaking gas and the remainder is generated from renewable resources.[133] For hydrogen-fuelled aircraft, hydrogen electrolysis facilities are assumed to operate with a 60% utilisation factor in 2050, aligning with electricity generation from variable renewable energy (VRE). Tailoring electrolyser operation to periods of renewable generation can enable zero emissions hydrogen production and allow for cost savings compared to higher utilisation rates (see the *Electricity* and *Low Carbon Fuels* technical appendices).

These principles similarly apply to synthetic fuels. The CO_2 component is assumed to be sourced from direct air capture (DAC), ensuring that combustion emissions are offset by prior capture. Hydrogen is produced via the process above during periods of surplus renewable generation.

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[131] IRENA (2024) Decarbonising hard-to-abate sectors with renewables: Perspectives for the G7. International Renewable Energy Agency.

[132] ICAO (2024) ICAO Default Life Cycle Emissions Values for CORSIA Eligible Fuels. March 2024. <https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20March%202024.pdf>

[133] The emissions intensity (0.0307kgCO_2-e per kWh or 8.54gCO_2-e per MJ) is based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions.

Table 19: Abatement potentials – Aviation

Technology	ILUC gCO_2e/MJ	Biogenic CO_2 gCO_2e/MJ	Well-to-pump gCO_2e/MJ	Pump-to-wake gCO_2e/MJ	Well-to-wake gCO_2e/MJ	Abatement *Threshold: 60%*	Source/assumptions
Conventional jet fuel	**-**	**-**	**11.9**	**73.2**	**85.1**		**Argonne National Laboratory (2019)**
Battery electric	-	-	7.4	-	7.4	91%	Assumes low emissions electricity inputs.
Hydrogen combustion	-	-	-	-	-	100%	Hydrogen production facility is assumed to operate at 60% utilisation, aligning with 100% VRE generation
Hydrogen fuel cells	-	-	-	-	-	100%	
Synthetic fuels (Power-to-liquids)	-	-	-	-	-	100%	Low emissions hydrogen production and CO_2 from DAC (required for large scale production, see 'Resource scalability').
Biofuels *(theoretical abatement potential based on 100% biofuel drop-in)*							
HEFA 1. Soybean 2. Canola 3. *Camelina** 4. *Tallow** 5. *UCO**	1. 25.8 2. 26.0 3. -13.4 4. 0.0 5. 0.0	1. -70.2 2. -70.2 3. -70.2 4. -70.2 5. -70.2	1. 38.5 2. 45.6 3. 38.9 4. 18.9 5. 9.0	1. 70.5 2. 70.5 3. 70.5 4. 70.5 5. 70.5	1. 64.6 2. 71.9 3. 25.8 4. 19.1 5. 9.2	1. 24% 2. 16% 3. 70% 4. 78% 5. 89%	Argonne National Laboratory (2019)
FT 1. *Forest residue** 2. *MSW**	1. - 2. -	1. -70.2 2. -70.2	1. 3.9 2. 19.9	1. 70.5 2. 84.6	1. 4.2 2. 34.2	1. 95% 2. 60%	Argonne National Laboratory (2019)
AtJ (ethanol) 1. *Forest residue** 2. *Agricultural residues** 3. *Solid waste**	1. - 2. - 3. -	1. -70.2 2. -70.2 3. -70.2	1. 24.9 2. 24.6 3. 9.7	1. 70.5 2. 70.5 3. 70.5	1. 25.2 2. 24.9 3. 10.0	1. 70% 2. 71% 3. 88%	Argonne National Laboratory (2019)

**Feedstocks that do not compete with food*

For biofuels, Indirect land use and change (ILUC) emissions have been incorporated into extracted results, drawing upon the ICAO-CORSIA methodology.[134] The reported well-to-wake figures represent a theoretical abatement potential based on a 100% biofuel drop-in replacement for CJF. However, their current usage is constrained to blends with conventional jet fuel up to 50% by volume.

Electricity-based fuels

The main emissions contributor for the full fuel cycle impact is the source of electricity or fuel inputs. For technologies that rely on electricity or electricity-derived fuels (i.e., hydrogen or synthetic fuels), it is assumed that they are generated from low emissions sources, allowing these technologies to meet the criteria.

Biofuels

HEFA fuel pathways that rely on first generation crops (i.e., soybean, canola) do not meet this criterion, largely driven by the impacts of ILUC. However, the threshold can be met when second generation sources are adopted (i.e., residual feedstocks and non-edible crops).

First-generation crops are those that are edible crops that are grown on cultivable land. While they can result in emissions reductions compared to CJF, their abatement potential is less substantial compared to second- and third-generation feedstocks. These crops can have significant environmental impacts due to potential land use changes, deforestation and competition with food production for land and water resources. More recent studies have suggested that ILUC impacts may be overstated and that it could be possible to produce first-generation feedstocks that do not seriously impact on food security or land use.[135] However, importantly, in the Australian context, second to fourth generation feedstocks are likely to present a competitive advantage with the ability to deliver much greater volumes of feedstock,[136] while not imposing ILUC impacts.

Access to sufficient and sustainable feedstock supply will be a significant constraining factor to the practical abatement levels achieved by this solution (See *5.6.1 Biofuels* and the *Low Carbon Fuels* technical appendix).

Resource scalability

The resource scalability criterion identifies where the energy supply of a given technology can meet the demands of the aviation transport sector, when considering feedstock resource constraints and renewable energy generation.

It assesses estimates of resource inputs and determines whether there are resource constraints that may inhibit the ability of energy supply to meet sectoral energy demand. Technologies are deemed to meet the criterion where energy supplies could reasonably meet the demands of domestic and international aviation services operating in Australia. Technologies do not meet the criterion where the total sector energy demands cannot be met by energy supply.

It does not consider the capital and operating costs of energy recovery, supply chain implementation, or market factors related to the adoption of a given technology.

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[134] ICAO (2024) ICAO Default Life Cycle Emissions Values for CORSIA Eligible Fuels. March 2024.

[135] Rosillo-Calle, F. (2016). "A review of biomass energy-shortcomings and concerns." JOURNAL OF CHEMICAL TECHNOLOGY AND BIOTECHNOLOGY 91: 1933-1945.

[136] Farine, D. R., D. A. O'Connell, R. J. Raison, B. M. May, M. H. O'Connor, D. F. Crawford, A. Herr, J. A. Taylor, T. Jovanovic, P. K. Campbell, M. I. A. Dunlop, L. C. Rodriguez, M. L. Poole, A. L. Braid and D. Kriticos (2012). "An assessment of biomass for bioelectricity and biofuel, and for greenhouse gas emission reduction in Australia." Global Change Biology Bioenergy 4(2): 148-175; CSIRO (2023). Sustainable aviation fuel roadmap. Canberra, Australia

Battery electric

Electrified aircraft meet the scalability filter, with constraints on electricity supply expected to be minimal.

Hydrogen-fuelled (combustion, fuel cells)

Hydrogen-based solutions meet the scalability filter with caveats, due to potential input limitations for large-scale electrolytic hydrogen production. Electrolysis pathways (see the *Low Carbon Fuels* technical appendix) require large amounts of electricity to operate, necessitating grid network upgrades and scaled renewable generation capacity to meet hydrogen production demands. Meanwhile water availability could pose a challenge in arid and water-constrained regions of Australia, whereby regional-specific studies are required to determine the feasibility of electrolysis developments.

Synthetic fuels

Synthetic fuels meet the scalability criteria with caveats, due to potential input limitations. Synthetic fuels could be constrained by the supply of CO_2 in the long term. While point source capture could meet a portion of production demand, large-scale deployment will require additional sources of CO_2 from alternative capture technologies such as DAC. However, these alternatives are currently limited by high costs, energy demands and low technological maturity. Synfuel production is also heavily tied to renewable energy generation and electrolyser capacity, both of which create infrastructure dependencies in order to scale production capacity.

Biofuels (HEFA, AtJ, FT)

Biofuels meet the scalability criteria with caveats. Though aviation energy demands could theoretically be met by domestic residual feedstocks, the scale of production and strategic adoption of biofuels will be dependent on resource management decisions and constrained by competing demands and market conditions.

Analysis was conducted (Table 20), to estimate the total energy available from biofuels produced from domestic residual feedstocks, and to assess whether this supply could theoretically meet the demands of domestic and international aviation services operating in Australia. While food crops can be used for fuel production, this analysis considers waste residues only, for their greater abatement potential and to avoid competing interests with Australia's food production and export markets.

Feedstock data was sourced from national databases, with the theoretical useable portion of energy determined for each feedstock type drawing on literature. To calculate volumetric fuel potential, the useable energy was multiplied by production yield and subsequently converted to energy units based on the energy density of the derived jet fuel.

The results of this analysis suggest that residual feedstocks are able to satisfy 3 to 5 times (280-457PJ) 2022 domestic aviation energy demand (91PJ), and 1.5 to nearly 3 times the energy required to satisfy 2022 domestic and international aviation demand (168PJ).

However, in reality, other factors including feedstock competition for other uses, supply chain establishment, economic proposition and market factors will each impact the capacity for aviation biofuel production. Please note, this analysis presents a liberal approach to estimating the energy available for the aviation subsector. The approach does not account for feedstock competition from other uses (e.g., food, recycling, animal feed, export) or alternative bioenergy pathways, and excludes market factors and incentives that could influence the diversion of feedstocks across competing applications.

Table 20: Biofuel resource scalability potential – Aviation

Feedstock			Fuel production		Energy conversion	
Feedstock	Feedstock availability, 2022 (kt)[137]	Useable energy from feedstock	Pathway	Process efficiency [138]	Energy density conversion (MJ/L)	Final energy (PJ)
Canola	6,820	40%	HEFA	49-85%	34.5	59-101
Cottonseed	1,536	15%	HEFA	60%		6
Tallow*	434	100%	HEFA	60-72%		11-14
Municipal solid waste (MSW)*	13,307	100%	Gasification + FT	4-10%		23-58
Agricultural residues*	44,144	100%	Gasification + FT	10-15%		196-288
Sawmill residues*	5,759	100%	Gasification + FT	10-15%		26-38
Sugar	4,123	1t feedstock = 513L ethanol	AtJ	50-60%		36-44
Sugarcane bagasse*	9,027	100%	Gasification + FT	6-15%		24-59
Sorghum	2,648	1t feedstock = 420L ethanol	AtJ	50-60%		19-23

** Indicates waste feedstocks*

5.4.2 Primary technology analysis

Key information – Primary technology analysis

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

- **Refuelling/recharging duration:** Technologies that meet an acceptable replenishing duration, based on the time taken refuel a conventional internal combustion engine (ICE) engine.

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[137] ABARES (2023a) Australian crop report: March 2023, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities; ABARES (2023b), Agricultural commodities: March quarter 2023, Outlook tables - data tables, Sugar, Australian Bureau of Agricultural and Resource Economics and Sciences. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data; DCCEEW (2022) National Waste Database

[138] **Canola:** Pereira L, Maclean H, Saville B (2017) Financial analyses of potential biojet fuel production technologies. Biofuel, Biproducts & Biorefining, 44, 4. DOI: 10.1002/bbb.1775l; Han J, Elgowainy A, Cai H, Wang M (2013) Life-cycle analysis of bio-based aviation fuels. Bioresource technology, 150. DOI: 10.1016/j.biortech.2013.07.153; **Cottonseed:** CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; **Tallow:** Tao L, Milbrant A, Zhang Y, Wang Wei-Cheng (2017) Techno-economic and resource analysis of hydroprocessed renewable jet fuel. Biotechnology for Biofuels and Biproducts. **MSW:** CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; And derivation from Niziolek A, Onel O, Floudas C (2017) Municipal solid waste to liquid transportation fuels, olefins, and aromatics: Process synthesis and deterministic global optimization. Computers & Chemical Engineering, 102; Luz F, Rocha M, Lora E, Venturini O, Andrade R, Leme M, Almazán del Olmo O (2015) Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. Energy Conversion and Management, 103; Jones S, Zhu Y, Valkenburg C (2009) Municipal Solid Waste (MSW) to Liquid Fuels Synthesis, Volume 2: A Techno-economic Evaluation of the Production of Mixed Alcohols. Prepared for the US Department of Energy by Pacific Northwest National Laboratory. **Remaining feedstocks:** Diederichs G (2015) Techno-Economic Assessment of Processes that Produce Jet Fuel from Plant-Derived Sources; Pereira L, Maclean H, Saville B (2017) Financial analyses of potential biojet fuel production technologies. Biofuel, Biproducts & Biorefining, 44, 4; Bressanin JM, Klein BC, Chagas MF, Watanabe MDB, Sampaio ILdM, Bonomi A, Morais ERd, Cavalett O (2020) Techno-Economic and Environmental Assessment of Biomass Gasification and Fischer–Tropsch Synthesis Integrated to Sugarcane Biorefineries. Energies, 13, 17.

- **Minimum range requirement (single trip):** Technologies that meet an acceptable distance threshold in a single trip.
- **Levelised cost of transport:** 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.

Refuelling/recharging duration

This filter defines an acceptable refuelling/recharging time for technologies applied to the use case. This was identified as a core operating requirement of aircraft that will enable or limit low emission technology uptake, particularly in applications with high utilisation rates. In the aviation industry, this time is often paired with additional tasks (e.g., boarding), and referred to as 'turnaround time'. The requirements for refuelling /recharging time were selected based on characteristics of CJF technology, as sourced from literature. Results are provided in Table 21 (rounded to the nearest minute), with additional detail on methodology and the assumptions found in *Appendix A.3.3.*

Refuelling duration for an aircraft technology is limited by the efficiency of a specific airport's auxiliary technologies, including the flow rate of a particular nozzle (liquid/gaseous fuels) or charging rate (electricity). It is important to note that the average refuelling / recharging duration during day-to-day operation may be lower, since the aircraft does not always fly the maximum range mission.[139] The threshold is based on the 37.5-minute turnaround time currently allocated for a Boeing 737-800,[140] assuming this is the maximum time available for refuelling. Refuelling usually takes part of this time (~16.2 minutes), however it is feasible to conduct a range of these activities simultaneously.

It is assumed that all technologies are refuelling or recharging from 15% to 100% of the available tank or battery, acting as representative for the reserve requirements mandated for commercial planes.[141] Battery swapping has not been considered in this analysis, as the gravimetric density required to have a battery feasible of being swapped during the regular 'turnaround time' of a Boeing 737-800 was considered unrealistic.[142]

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[139] de Vries R, Wolleswinkel RE, Jacobson DR, Bonnema M, Thiede S (2024) Battery Performance Metrics for Large Electric Passenger Aircraft. *34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*. <https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0636_paper.pdf> (accessed 23 June 2025).

[140] Boeing (2023) 737-800BCF Converted Freighter. <https://www.boeing.com/content/dam/boeing/boeingdotcom/commercial/services/assets/brochure/737_800BCF.pdf> (accessed 23 June 2025).

[141] See, e.g., ICAO (2022) Annex 6, Part I — International Commercial Air Transport — Aeroplanes (Twelfth Edition). <https://www.icao.int/safety/CAPSCA/PublishingImages/Pages/ICAO-SARPs-(Annexes-and-PANS)/Annex%206.pdf> (accessed 23 June 2025). This approach is consistent with other papers; see, e.g., de Vries R et al. (2024) Battery Performance Metrics for Large Electric Passenger Aircraft. *34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*. <https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0636_paper.pdf> (accessed 23 June 2025).

[142] This rationale does not consider complete re-designs of plane structures, where it might make battery swapping more feasible. Similarly, battery swapping becomes more feasible for very small commuter craft such as eVTOLs.

Table 21: Refuelling/recharging durations – Aviation, medium-range flight

Technologies	Re-fuelling/recharging duration (to nearest minute)		
	Upper bound	Lower bound	Meets criteria?
Boeing 737-800 (conventional)	25	9	
Threshold			37.5 minutes
Battery electric	1,316 (~22 hours)	170 (~3 hours)	
Hydrogen combustion	14	4	
Hydrogen fuel cells	11	3	
Synthetic fuels	25	9	
Biofuels (HEFA)	25	9	
Biofuels (FT)	25	9	
Biofuels (AtJ)	25	9	

Synfuels / Biofuels

Synfuels and biofuels are designed to be 'dropped in' to a conventional aircraft with minimal to no modifications. They have chemical and physical properties (including density, viscosity, energy content) that are identical to or within the certified specification range of conventional Jet A1. This allows them to achieve similar refuelling durations to CJF and makes them compatible with existing refuelling infrastructure, like distribution pipelines.

Hydrogen aviation

Hydrogen aviation meets the criteria. Both hydrogen combustion and hydrogen fuel cell variations have lower bound refuelling times that meet the threshold, and upper bounds that do not.

Fuel cell engines are expected to be more energy efficient (70%)[143] than combustion engines (45%)[144] and are required to reach the lower heating value of hydrogen (saving about 18% in kWh per kg of hydrogen used compared to hydrogen combustion, which requires a higher heating value). Fill rates across both technologies are expected to be consistent, with the upper bound assuming a single nozzle point in use, assuming a LH_2 mass flow rate of approximately 5 kg/s.[145] The lower bound refuelling time suggests a 20kg/s flow rate, an indicated scenario from literature, given proper precautions and technological advancements. [146]

[143] Assumes use of a reversible fuel cell: U.S. Department of Energy (2024) Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan 2024. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf> (accessed 23 June 2025).

[144] Adler EJ, Martins JRRA (2023) Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. Progress in Aerospace Sciences 141:100922. https://doi.org/10.1016/j.paerosci.2023.100922; Campe R (2019) Hydrogen co-combustion in ICE. *ICCT ZEV Workshop*, San Francisco, July 2019. <https://theicct.org/sites/default/files/2_Campe_H2_combustion_ICE_PUBLIC.pdf> (accessed 23 June 2025); Stępień Z (2021) A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges. Energies 14(20):6504. https://doi.org/10.3390/en14206504

[145] With a 6-inch inner diameter, similar to current airport refuelling infrastructure. Postma-Kurlanc A, Leadbetter H, Pickard C (2022) Hydrogen infrastructure and operations. *Airports, Airlines and Airspace, FlyZero, Aerospace Technology Institute*. https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf (accessed 23 June 2025); Babuder D, Lapko Y, Hoelzen J, Zingg D (2025) Operational performance in sustainable aviation: an in-depth analysis of turnaround times of future commercial narrowbody liquid hydrogen aircraft. International Journal of Sustainable Aviation 11(1):1-38. https://doi.org/10.1504/IJSA.2025.145735

[146] Mangold J, Silberhorn D, Moebs N, Dzikus N, Hoelzen J, Zill T, Strohmayer A (2022) Refuelling of LH2 aircraft – assessment of turnaround procedures and aircraft design implications. Energies 15(7):2475. https://doi.org/10.3390/en15072475; Babuder D et al. (2025) Operational performance in sustainable aviation: an in-depth analysis of turnaround times of future commercial narrowbody liquid hydrogen aircraft. International Journal of Sustainable Aviation 11(1):1-38. https://doi.org/10.1504/IJSA.2025.145735

This analysis does not consider the weight of the plane being flown and assumes a consistent total usable energy requirement equivalent to that of a conventional Boeing 737-800. Hydrogen aviation will necessitate a complete aircraft redesign and may involve additional weight and drag due to the storage and cooling equipment needed onboard. Studies so far have not determined whether the net effect of higher energy per unit mass and storage penalties will result in an increase or decrease in the energy used for any given flight. [147]

Additional processing, such as the temperature regulation required for cryogenic hydrogen, has not been considered in this analysis and may cause longer refuel times.

Battery electric

Battery electric aviation does not meet the criteria for recharging. Evidence available for battery electric aviation is uncertain and circumstantial, and battery swapping has not been considered for this analysis. The upper bound charge assumptions used are based off current state-of-the-art charging output available to heavy duty vehicles of 3.75 MW, and lower bound assumptions are derived from a future plane with a 15.4 MW battery that is assumed to have a 'C rate' of 1.7.[148] A 15.4 MW battery is smaller than required for this use case, given an equivalent to the conventional energy capacity needed would require a battery with a capacity of about 348 MW.

As noted for hydrogen, this analysis does not account for the extra energy needed to support the additional weight of the battery necessary for an aircraft of this size to achieve flight. A battery capacity of 348 MW would necessitate allocating over 112 tonnes of carrying capacity to the battery itself, in contrast to approximately 21 tonnes of conventional fuel. This weight surpasses the maximum take-off weight (MTOW) of a standard Boeing 737-800, which is approximately 79 tonnes, inclusive of passengers and baggage.[149]

Minimum range requirements

The minimum range requirement defines the average distance (in km) required for a medium-range flight. The threshold distance, 1,500km, reflects the distance of a 2-hour flight of 1,300km,[150] with a 15% range buffer to account for reserve requirements (Table 22). This was identified as a core operating requirement that will enable or limit technology uptake. Technology range capabilities for low emissions technologies were informed by their volumetric gravity density and literature.

Table 22: Minimum range requirements (single trip) – Aviation

Technologies	Medium-range flight	Results	Notes/assumptions
Threshold	*1,500km*		
Hydrogen combustion	>1,500km, reduced payload[151]		

[147] Adler EJ, Martins JRRA (2023) Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. Progress in Aerospace Sciences 141:100922. https://doi.org/10.1016/j.paerosci.2023.100922

[148] A 'C rate' is reflective of a [dis]charge capacity rate, where for instance, 1C is illustrative of a [disc]charge time of 1 hour, and 0.5C is illustrative of a [disc]charge time of 2 hours. See Table 2: de Vries R et al. (2024) Battery Performance Metrics for Large Electric Passenger Aircraft. *34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024).* <https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0636_paper.pdf> (accessed 23 June 2025).

[149] Boeing Commercial Airplanes (2024) Next-Generation 737 Airplane Characteristics for Airport Planning. *Document D6-58325-7 Rev B*. https://www.boeing.com/content/dam/boeing/boeingdotcom/commercial/airports/acaps/737NG_REV_B.pdf (accessed 23 June 2025).

[150] BITRE (2024) Domestic aviation activity, Statistical Report, BITRE, Canberra ACT.

[151] See, e.g. Su-ungkavatin P, Tiruta-Barna L, Hamelin L (2023) Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. Prog Energy Combust Sci 96,. doi:10.1016/j.pecs.2023.101073

Hydrogen fuel cells	>1,500km, reduced payload[151]		Possesses a higher gravimetric energy density, but lower volumetric energy density relative to CJF (by 4-fold). Subsequent payload capacity may be lost at the expense of additional on-board space required for fuel storage.
Synthetic fuels	>1,500km[152]		Applying a 4% fuel efficiency premium to the CJF reference.
Biofuels (HEFA)	>1,500km[152]		Applying a 4% fuel efficiency premium to the CJF reference.
Biofuels (FT)	As above		
Biofuels (AtJ)	As above		

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Transport (LCOT) was estimated to determine the viability of each technology considered. LCOT is defined as the average net present cost per unit of output (in c/passenger-km or c/tonne-km), over a vehicle's lifetime.

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 of new deployments 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 12. **Biofuels (FT, HEFA and AtJ) are projected to be the most cost competitive technologies.** A supplementary case study (Box 4) was conducted to assess the feasibility of technologies for a less energy intensive application.

Although biofuels have been identified as the lowest-cost technology, synthetic fuels (PtL) may fulfill 'drop-in' requirements where biogenic fuels are unavailable. As an alternative to drop-in fuels, hydrogen combustion, as it may offer a mid-range cost alternative. For these reasons, **PtL and hydrogen combustion are also included as Primary technologies,** acknowledging that range of solutions may be necessary for an effective transition.

This economic assessment is based on a Boeing 737-800 aircraft, operating at a typical frequency of 6,806km distance per day and load factor of 83% (as outlined in *Technical Appendix: Levelised cost analysis*). An asset lifetime of 15 years is assumed. This assessment does not capture the cost of establishing sufficient refuelling infrastructure. Establishing single or multi-fuel delivery, handling and storage infrastructure would require significant capital costs, and ongoing expenditure and investment in insurance, training and hazard assessments. These would need to be considered on a site-basis and therefore have not been incorporated into this analysis.

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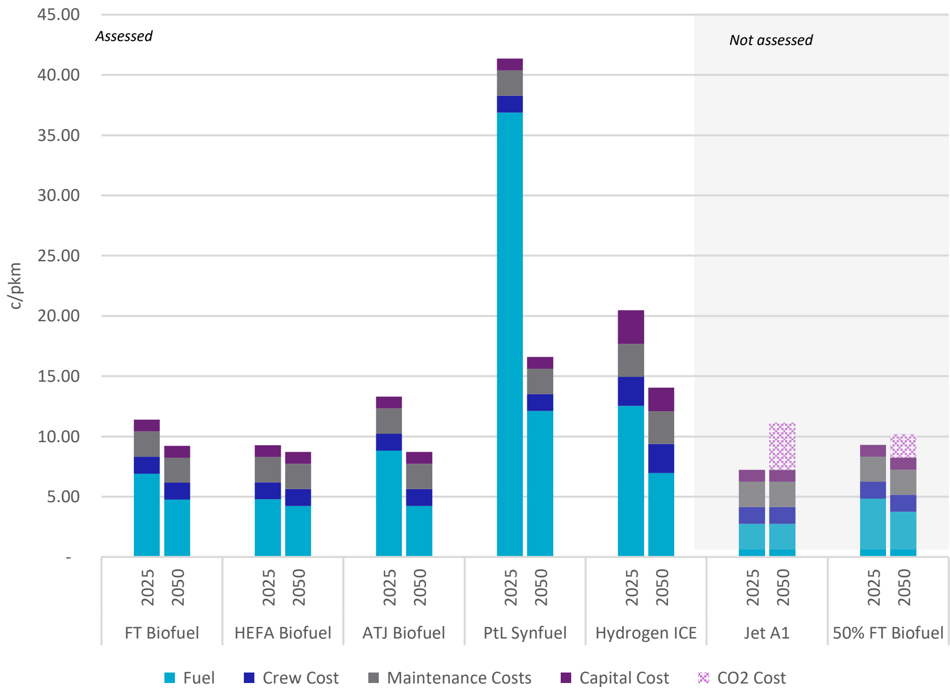
[152] Gaspar RMP, Sousa JMM (2016) Impact of alternative fuels on the operational and environmental performance of a small turbofan engine. Energy Conversion and Management 130, 81. doi:10.1016/j.enconman.2016.10.042

An absence of data has led to inconclusive determinations for hydrogen fuel cell aircraft.

Figure 12: Levelised cost of transport (c/pkm) – Passenger plane: 180 people, 2-hour flight



Note: Airlines face additional operating costs that are not captured here, such as airport fees and SG&A costs.

The relative cost-effectiveness of each technology is primarily driven by fuel costs, which in turn are a function of feedstock cost.[153] Standard Jet A1 fuel is a common and conventional kerosene-based commercial aviation fuel included as a technology benchmark, though it is not assessed. Jet A1 is estimated to remain the lowest cost technology in the near term (Figure 12).

Biofuels

Biofuels present as the lowest cost grouping in 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.

Biofuel costs for FT, HEFA, and AtJ fuelled aircraft are modelled to be higher than Jet A1 in 2025 but become the lowest cost mitigation solution in 2050 when accounting for a CO_2 emission cost. A lower blend ratio (50%) of FT biofuel can also offer a cost-effective mitigation solution in the near-term, falling within current allowable blending rates. Levelised costs for blends of biofuels and Jet A1 can be estimated from these results by interpolating the relevant 100% biofuel and 100% Jet A1 costs.

Biofuels also have comparable energy density to CJF, compared to the lower volumetric energy density than other mitigation solutions (i.e., hydrogen). This allows the aircraft to maintain a base level of flexibility, such as greater versatility of flight routes and compatibility with existing refuelling infrastructure. Biomass feedstock availability, however, may be a constraining factor for the uptake of biofuels.[154]

Synfuels (PtL)

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[153] Note that these can be highly variable and the effects of future demand from competing industries are not well understood.

[154] CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra; Braun M, Grimme W, Oesingmann K (2024) Pathway to net zero: Reviewing sustainable aviation fuels, environmental impacts and pricing. Journal of Air Transport Management 117,. doi:10.1016/j.jairtraman.2024.102580

PtL fuelled aviation meets the cost criterion. Despite PtL synfuel aircraft adopting similar capital, crew and maintenance costs as the biofuel alternatives, fuel costs render it more costly that Jet A1 fuel, biofuel and hydrogen solutions in the near term and long term. This is driven by the cost to obtain reactant materials, including renewable hydrogen and carbon dioxide via direct air capture (DAC). While higher cost than biofuels, PtL synfuel aircraft are the lowest cost non-biogenic 'drop in' mitigation solution in 2050; necessary where biofuel or biomass supply cannot meet 'drop-in' fuel demands.

Synfuel aircraft are costed to operate on fuels produced with CO_2 from DAC and hydrogen from PEM electrolysis. While the CO_2 input from DAC may be more costly compared to biogenic or point-sourced alternatives, it is essential for meeting large-scale synfuel production demands, though both pathways face supply constraints.

Hydrogen aviation

Hydrogen combustion aircraft meet the cost criterion. Hydrogen combustion aircraft are estimated to have higher capital and operating costs than the biofuel alternatives. Due to the reduced volumetric density of liquid hydrogen compared to Jet A1 fuel, the modelled hydrogen combustion aircraft has a seating capacity of 90 passengers. As such, the levelised cost of two 90-seat hydrogen combustion aircraft is compared to the cost of a singular aircraft with a 180-seat capacity, thereby increasing the capital, crew and maintenance costs compared to other technology types.

Hydrogen fuel cell technologies are rendered inconclusive given an absence of appropriate cost assumptions. Literature providing preliminary modelling shows fuel cell propulsion to be in the order of 30% higher compared to hydrogen combustion configurations.[155]

155 Project NAPKIN Consortium (2022) Making Zero-carbon Emission Flight a Reality in the UK Final Summary Report Project. Project NAPKIN: New Aviation, Propulsion, Knowledge and Innovation Network. <https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/about/future-flight-challenge/NAPKIN%20Report%20Pages%20221104.pdf>; Su-ungkavatin P, Tiruta-Barna L, Hamelin L (2023) Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. Prog Energy Combust Sci 96,. doi:10.1016/j.pecs.2023.101073

Box 4: Aviation supplementary case study: Short range, 60-minute flight, 18 passengers

Key messages

- **Technology options for the short-range use case remain consistent with medium-range analysis. 100% FT, HEFA and AtJ biofuels are the lowest cost options in the long-term, and a lower blend ratio (50%) of FT biofuel offering the least expensive alternative to Jet A1 fuel in the near-term.**
- **Hydrogen fuel cell aircraft are deemed technologically feasible for the range and recharging, and cost analysis found them to have a lower levelised cost than synthetic fuels in both 2025 and 2050.**
- **Though deemed unsuitable as the primary drivetrain, there is scope for batteries to be used for auxiliary power need, such as the cabin environmental control or the flight control systems, within hybrid electric-fuel configurations.[156]**

A supplementary case study was conducted to assess the feasibility of technologies for a less energy intensive application. For technology prioritisation, thresholds for range and refuelling durations were lowered to 600km and 15 minutes respectively, and the following ratings applied (Table 23).

Table 23: Technology analysis results

Technology type *Threshold*	Refuelling/recharging duration *15 minutes*		Range *600km*	
Conventional (Beechwood 1900D)	1-2 minutes		>600km	
Battery electric	16-127 minutes		Inconclusive[157]	
Hydrogen fuel cells	0.3-1 minutes		>600km[158]	
Synthetic fuels (PtL)	1-2 minutes		>600km[159]	
Biofuels (HEFA, FT, AtJ)	1-2 minutes		>600km	

Like for the medium-range use case, biofuel and synfuels comfortably meet the technical parameters required for flight operation. Hydrogen fuel cells were assessed in place of hydrogen combustion aircraft, due to higher energy efficiencies which position them as a more suitable solution for short range flights.[160]

For batteries, recharge times may be able to accommodate tight turnaround schedules necessitated by commercial flight schedules. Where flight schedules are less frequent and flights are less energy intensive (i.e., shorter flight paths or smaller plane sizes), batteries could meet operational demands.[161] Battery swapping has not been considered for this analysis, but could be another viable option.

The LCOT was conducted for a short-range passenger plane operating at a typical frequency and load factor (See *Technical Appendix: Levelised cost analysis*). Jet A1 is estimated to remain the lowest cost technology in the near term (Figure 13). Biofuel-powered aircraft are projected to be competitive in 2050 when accounting for a CO_2 emission cost.

Figure 13: Levelised cost of transport (c/pkm) – Passenger plane: 18 passenger, 1-hour flight

[156] Su-ungkavatin P, Tiruta-Barna L, Hamelin L (2023) Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. Prog Energy Combust Sci 96,. doi:10.1016/j.pecs.2023.101073

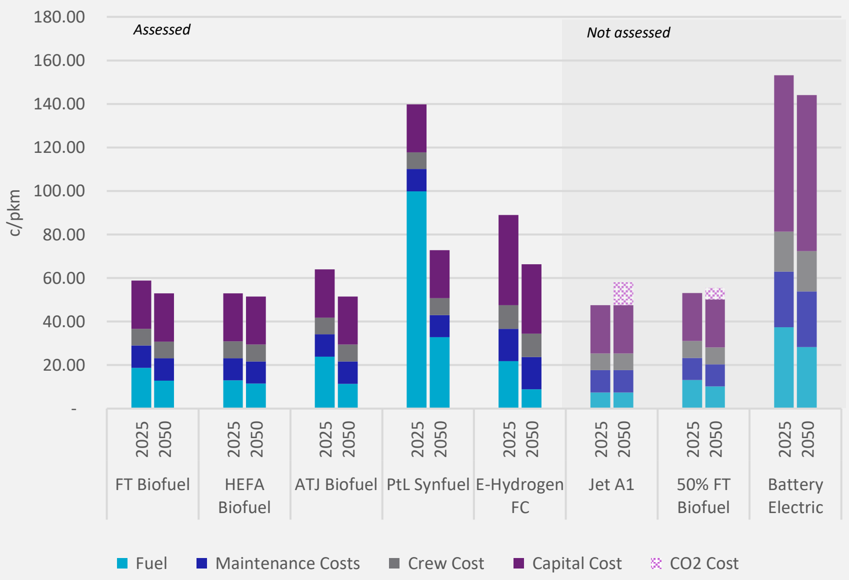
[157] Early-stage pre-demonstration trials indicate ranges up to 400km. See for example, https://vaeridion.com.

[158] Can always be met, given gravimetric energy density relative to CJF. See, e.g. Su-ungkavatin P, Tiruta-Barna L, Hamelin L (2023) Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems. Prog Energy Combust Sci 96,. doi:10.1016/j.pecs.2023.101073

[159] Applying a 4% fuel efficiency premium to the CJF reference. As per, Gaspar RMP, Sousa JMM (2016) Impact of alternative fuels on the operational and environmental performance of a small turbofan engine. Energy Conversion and Management 130, 81. doi:10.1016/j.enconman.2016.10.042

[160] Stralis, in collaboration with CSIRO and CQUniversity and under the Regional University Industry Collaboration program, is developing long-range hydrogen-electric propulsion systems for aviation, with plans to demonstrate a test flight from Gladstone to Brisbane. For more information see, https://www.csiro.au/en/news/All/News/2025/January/Research-to-help-hydrogen-electric-aircraft-take-off

[161]Based on Picchi Scardaoni M, Magnacca F, Massai A, Cipolla V (2021) Aircraft turnaround time estimation in early design phases: Simulation tools development and application to the case of box-wing architecture. Journal of Air Transport Management 96,. doi:10.1016/j.jairtraman.2021.102122



Note: Airlines face additional operating costs that are not captured here, such as airport fees and SG&A costs.

PtL synfuel is estimated to be the highest cost drop-in fuel technology, and slightly more expensive than hydrogen fuel cell aviation, due to the high costs of renewable CO_2 and H_2, driving up its fuel costs; but could meet demands where biogenic fuels are not available.

Battery electric aircraft are more expensive than other solutions in both 2025 and 2050. The battery electric aircraft is estimated to be the most expensive solution as the model assumes two planes are needed to meet the 18-passenger requirement, with each carrying nine passengers. The electricity price input for battery electric aircraft includes wholesale cost, a retail margin and a fast-charging infrastructure and operating cost components to reflect the likelihood that commercial aircraft will require dedicated fast charging infrastructure, driving up the energy cost.[162]

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.

[162] There are currently limited numbers of Electric or Hydrogen Fuel Cell aircraft in commercial operation, so the 2025 levelised costs for these technologies are indicative only. Given the emergent nature of these technologies, there is limited information available on capital costs. We have therefore assumed the same base aircraft capital cost for each propulsion technology in 2050. FCEV and electric aircraft are assumed to be initially produced in smaller quantities than conventional fuels, resulting in a 30% capital cost premium in 2025.

The technology analysis framework identified Biofuels, synthetic fuels and hydrogen combustion as *Primary technologies* for a medium-range passenger flight use case.

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the aviation 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 and energy efficiency solutions 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.

Figure 14: Auxiliary and energy efficiency technologies – Aviation

Biofuels
- Feedstock processing
- Distribution and storage infrastructure

Synfuels
- CO_2 capture and utilisation (CCU)
- Low emissions electricity generation and distribution
- Monitoring, reporting and verification (MRV)

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

Energy efficiency solutions
- Technology and componentry improvement
- Drag reduction and design
- Energy management solutions
- Lightweighting
- Traffic and logistics management technologies

Auxiliary technologies

Biofuels and synfuel solutions cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 24.

Table 24: Auxiliary technologies – Aviation

Primary technology	Auxiliary technology	Description
Biofuels	**Feedstock processing**	Conversion technologies and processing systems that refine biomass feedstocks into intermediates suitable for biofuel production.
	Distribution and storage infrastructure	Logistics, storage, and handling systems allowing the distribution and integration of biofuel supply chains.
Synfuels	**CO_2 capture and utilisation (CCU)**	Technologies for capturing CO_2 from industrial or atmospheric sources for utilisation (here, as a synthetic fuel)
	Low emissions electricity generation and distribution	Infrastructure required to produce and transport low emissions electricity to end-users. Refer to the *Electricity* technical appendix for further detail.
	Monitoring, reporting and verification (MRV)	Systems and frameworks that track and verify the renewable origin of electricity and CO_2. Here MRV systems can be used to ensure synthetic fuel production meets regulatory compliance and emissions accounting claims.
Hydrogen combustion	**Hydrogen liquefaction technologies**	Technologies involved in the process of cooling hydrogen gas to extremely low temperatures to convert it into its liquid state for storage or transport.
	Production, transportation, and storage infrastructure	Systems and networks required for hydrogen production, transmission and storage.

	Refuelling infrastructure	Facilities and systems, such as fuel storage tanks, pipelines, and refuelling vehicles, designed to supply aircraft with the necessary fuel efficiently and safely.

Energy efficiency solutions

For Aviation, there are a range of energy efficiency solutions that will also support emissions mitigation efforts. These solutions are outlined in Table 25.

Table 25: Energy efficiency solutions – Aviation

Energy efficiency solution	Description
Technology and componentry improvement	Improves energy efficiency by improving drivetrain/transmission efficiencies
Drag reduction and design	Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles
Energy management solutions	Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, and enhance battery life (where relevant)
Lightweighting	Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.
Traffic and logistics management technologies	Improves energy efficiency by optimising vehicle movement and operation.

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, 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 26. 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). Although identified as a primary technology component, RD&D opportunities related to feedstock processing and fuel production are discussed in more detail under the *Low Carbon Fuels* technical appendix.

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 26: Summary of RD&D opportunities – Aviation[163]

		Biofuels	Synfuels	Hydrogen combustion
Primary technologies		**Fuel production pathways**	**Fuel production pathways**	**Technologies**
	Commercial	HEFA	-	-
	Mature	AtJ	Fischer-Tropsch (FT), Methanol-to-jet (MtJ)	-
	Emerging	FT-SPK	-	H_2 turbofans, H_2 ICE
Primary RD&D		• Reduce fuel costs **(Target: $1.36-1.52/L, cf. $2.20-2.83/L)** through: - E.g. Improving feedstock yields and the efficiency of feedstock conversion pathways (for detailed RD&D opportunities, see *Low Carbon Fuels* technical appendix) • Modify biofuels to meet existing jet fuel specifications through: - E.g. Engineering fuels with desirable aromatic content - E.g. Increasing the blend ratios of biofuels • Modify engine and aircraft infrastructure to enable the direct use of pure biofuels	• Reduce fuel costs **(Target: $3.89/L, cf. $11.84/L)** through: - E.g. Improving the process efficiency and selectivity of converting FT crude into jet fuel (for detailed RD&D opportunities, see *Low Carbon Fuels* technical appendix) - E.g. Improving the yield of carbon capture technologies (for detailed RD&D opportunities, see *Carbon Management* technical appendix) • Modify synthetic fuels to meet existing jet fuel standards through: - E.g. Introducing new materials in fuel systems and engine redesign - E.g. Increasing the blend ratios of synthetic fuels	• Fundamentally redesign the aviation combustion engine to: - E.g. Enhance flame stabilisation and minimise flame blow-out - E.g. Minimise NOx emissions through the adoption of lean-burn technologies - E.g. Reduce concentrations of ambient aerosols in hydrogen exhaust to minimise water vapour • Develop advanced aircraft architecture and innovative storage solutions • Maintain durability and safety **(Target: 75,000 flight cycles, consistent with conventional)**
Auxiliary RD&D		• For biofuel production, distribution and storage RD&D opportunities, see the *Low Carbon Fuels* technical appendix	• Support emissions abatement through further lifecycle analysis and establishing sustainability safeguards • For synthetic fuel production RD&D opportunities, see the *Low Carbon Fuels* technical appendix	• Improve the efficiency and cost of hydrogen liquefaction **(Target: A$1.50-3/kg LH_2 at >100t/day, cf. A$3-5/kg LH_2 at <32t/day)**[164] • For hydrogen production, distribution and storage RD&D, see the *Low Carbon Fuels* chapter

cf. – Compare.

[163] 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.

[164] Spot price of $1 USD to $1.54 AUD (as at 18 June 2025). Al Ghafri SZS et al. (2022) Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Energy & Environmental Science 15(7). https://doi.org/10.1039/D2EE00099G; Banijamali SM et al. (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

5.6.1 Biofuels

HEFA, FT-SPK, and AtJ[165] pathways are the primary technological routes for aviation biofuel production. These pathways vary in their feedstock flexibility and processing complexity, with pathways optimised based on resource availability, conversion efficiency, and fuel performance characteristics. HEFA, the most commercially mature, relies on lipid-based feedstocks such as waste oils and tallow, undergoing hydro-processing to produce drop-in hydrocarbons. FT synthesis, while more feedstock-agnostic, undergoes biomass gasification to generate syngas, followed by catalytic conversion to liquid fuels. AtJ leverages alcohol intermediates (e.g., ethanol, methanol, butanol etc.), to yield synthetic kerosene.

This section discusses the use of biofuels in relative to the aviation subsector; for broader discussion related to the production of these fuels and their feedstocks, please refer to the *Low Carbon Fuels* technical appendix.

Sustainable aviation biofuels lack particular aromatic compounds (found in fossil-based jet fuels) that are important for sealing and lubricating aircraft fuel systems. To overcome this challenge, the primary strategy is to modify the biofuels so that they meet existing jet fuel standards. A secondary approach and lesser focus of the aviation industry is aircraft engine development and redesign to better accommodate pure aviation biofuels.

Primary technologies

Modifying sustainable aviation biofuels to meet existing jet fuel standards could enable their near-term deployment as a drop-in fuel.

RD&D is focused on adjusting the chemical composition of biofuels to comply with jet fuel standards. This includes strategies such as engineering fuels with improved aromatic content or increasing blend ratios.[166] Aviation biofuels are drop-in fuels that must currently be blended with CJF to achieve the required balance of paraffins, olefins, and aromatics for safe use in existing engines and infrastructure.[167] While current blend ratios are limited to 50%,[168] ongoing research aims to increase this blend ratio to further reduce flight related carbon emissions and support the use of new materials in fuel systems.

Reducing the cost of sustainable aviation biofuels through RD&D could enable its widespread adoption.

Alongside fuel modification, continued RD&D is needed to reduce fuel costs (Target: $1.36-1.52/L, cf. $2.20-2.83/L). Improvements in feedstock processing, fuel synthesis and upgrading techniques are needed to scale supply chains and reduce cost premiums associated with aviation biofuels. RD&D related to these developments is captured in the *Low Carbon Fuels* technical appendix.

[165] Either through ethanol (Ethanol-to-jet, EtJ), methanol (Methanol-to-jet, MtJ) or other alcohol intermediates.

[166] See, for example, Calderon OR, Tao L, Abdullah Z, Moriarty K, Smolinski S, Milbrandt A, Talmadge M, Bhatt A, Zhang Y, Ravi V, Skangos C, Tan E, Payne C (2024) Sustainable Aviation Fuel (SAF) State-of-Industry Report: State of SAF Production Process. <www.nrel.gov/publications.>

[167] Per criteria from the ASTM D1655 fuel standard. Shahriar MF, Khanal A (2022) The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel 325,. doi:10.1016/j.fuel.2022.124905;. ICAO, UNDP, GEF (2017) SUSTAINABLE AVIATION FUELS GUIDE TRANSFORMING GLOBAL AVIATION COLLECTION 4 OF 4; Dahal K, Brynolf S, Xisto C, Hansson J, Grahn M, Grönstedt T, Lehtveer M (2021) Techno-economic review of alternative fuels and propulsion systems for the aviation sector. Renewable and Sustainable Energy Reviews 151,. doi:10.1016/j.rser.2021.111564

[168] ASTM International (2023) ASTM D4054-22 Standard Practice for Evaluation of New Aviation Turbine Fuels and Fuel Additives. <https://www.astm.org/d4054-22.html>

Modifying engine and aircraft infrastructure could enable the direct use of pure biofuels, offering an alternative pathway to adoption.

While the dominant strategy focuses on modifying fuels to meet current jet fuel standards, an alternative and longer-term pathway involves adapting aircraft engines and fuel systems to operate with biofuels that have little or no aromatic content. This strategy will likely entail minor engine adaptations for optimised biofuel performance and could serve to eventually enable 100% biofuel-powered flights.[169]

Auxiliary technologies

The development of sustainable and scalable feedstock supply chains will underpin the production of aviation biofuels.

A robust biofuel industry will require dependable access to sustainable, low carbon feedstocks, with RD&D supporting feedstock production and provenance throughout feedstock supply chains. Research needs related to feedstock production, processing and transportation are captured in the *Low Carbon Fuels* technical appendix.

Enabling safe, reliable distribution of biofuels requires RD&D to improve material compatibility and fuel handling infrastructure.

Storage and distribution systems and infrastructure will require material compatibility with biofuels to prevent degradation and leakage.[170] Assessing the chemical compatibility of varying blends with existing system components, such as seals and gaskets, can enable safe and reliable biofuel use.

5.6.2 Synthetic fuels (Power-to-liquid (PtL))

Renewable electricity and water are electrolysed to produce hydrogen, which is then combined with CO_2 sourced from capture technologies to synthesise hydrocarbons. These hydrocarbons are transformed into synthetic fuels through a range of production processes, including Fischer-Tropsch (FT) or methanol-to-jet (MtJ).[171]

FT fuels are approved for commercial use by the International Civil Aviation Organisation, however the MtJ pathway is still undergoing the approval process to be accepted by the ASTM.[172] Over 50 power-to-X (PtX) pilot projects have begun worldwide, indicating increased interest in synthetic fuels.[173]

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[169] 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

[170] Biofuel blends have led to some engine issues to date; for example, O-ring seals contracting and causing potential fuel tank leakage. This may be mitigated by minor retrofitting of conventional engines (e.g. changes to O-ring seals) when using fuel blends. Graham JL, Striebich RC, Myers KJ, Minus DK, Harrison WE (2006) Swelling of nitrile rubber by selected aromatics blended in a synthetic jet fuel. Energy and Fuels 20, 759. doi:10.1021/ef050191x https://pubs.acs.org/doi/10.1021/ef050191x

[171] 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

[172] 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

[173]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

Primary technologies

Modifying synthetic fuels to meet existing jet fuel standards could enable their near term deployment as a drop-in fuel.

Similar to aviation biofuels, synthetic fuels are drop-in alternatives that need to be blended with CJF in ratios of up to 50% to maintain a balanced composition suitable for use in standard engines and infrastructure.[174] Research is ongoing to improve blend ratios to further reduce emissions and support 100% synthetic fuel operation. This includes research to enhance aromatic content, optimise hydrocarbon composition, and evaluate material compatibility across aircraft fuel systems. Innovations in engine design and materials may also support this transition, though modifications remain a secondary industry focus compared to drop-in fuel development.[175]

Reducing the costs of synthetic fuels will be central to improving their economic viability.

Research related to synthetic fuel production is primarily centred on driving down production costs (Target: $3.89/L, cf. $11.84/L); largely incurred by the high costs of renewable hydrogen and CO_2 feedstocks. These plants are capital intensive, and additional considerations such as access to capital grants, loans or tax incentives may be required to encourage local investment.[176] Continued research and innovation focused on improving process efficiency, increasing jet fuel selectivity from FT-crude, and lowering the energy and material requirements of PtL systems, are likely to play an ongoing role in synthetic fuel development.

RD&D related to PtL production are discussed within the *Low Carbon Fuels* technical appendix, including research opportunities for hydrogen production. CO_2 procurement is discussed in the *Carbon Management* technical appendix.

Auxiliary technologies

Ensuring PtL fuels achieve the desired emission abatement outcomes requires robust sustainability safeguards for its inputs and a better understanding of the emissions profile along the supply chain.

For PtL to deliver genuine emissions reductions, PtL production must adhere to strict sustainability criteria. Further development of PtL fuel production will require appropriate sustainability safeguards and provenance measures to ensure the use of electricity and CO_2 from renewable sources, including through the establishment of suitable monitoring, reporting and verification (MRV) frameworks.[177] Further lifecycle analysis and modelling is required to better understand, and consequently mitigate, emissions associated with PtL infrastructure development, its distribution, and the emission reduction potential of different pathways, in addition to ensuring the sustainability of PtL fuel production and fuel certification.

In addition to securing feedstock, the establishment and growth of a PtL supply chain in Australia will require an increase in refining capacity and storage infrastructure.

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[174] Per criteria from the ASTM D1655 fuel standard. Shahriar MF, Khanal A (2022) The current techno-economic, environmental, policy status and perspectives of sustainable aviation fuel (SAF). Fuel 325,. doi:10.1016/j.fuel.2022.124905;. ICAO, UNDP, GEF (2017) Sustainable Aviation Fuels guide: Transforming global aviation guide collection 4 OF 4; Dahal K, Brynolf S, Xisto C, Hansson J, Grahn M, Grönstedt T, Lehtveer M (2021) Techno-economic review of alternative fuels and propulsion systems for the aviation sector. Renewable and Sustainable Energy Reviews 151,. doi:10.1016/j.rser.2021.111564

[175] 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

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

[177] Khalifa R, Alherbawi M, Bicer Y, Al-Ansari T (2024) Fueling circularity: A thorough review of circular practices in the aviation sector with sustainable fuel solutions. Resources, Conservation and Recycling Advances 23. doi:10.1016/j.rcradv.2024.200223

The expansion of Australia's PtL supply chain is currently constrained by its refining capacity[178] and challenges associated with scaling the required storage and distribution infrastructure for alternative fuels in space constrained and regional airports[179]. Assessments of the adaptability of existing infrastructure and the development of tailored solutions will be required to optimise fuel storage, distribution and blending locations. The viability of PtL fuels is also influenced by the availability of cost effective, low emissions inputs, primarily renewable hydrogen and CO_2, with RD&D a crucial lever in improving their accessibility, sustainability and economic viability. The *Low Carbon Fuels* technical appendix outlines research areas for hydrogen production and storage and references possible distribution solutions. The *Carbon Management* technical appendix addresses opportunities to improve CO_2 sourcing and infrastructure. Notably, CO_2 storage is often needed between capture and fuel processing, with RD&D required to ensure the long-term safety and stability of storage sites.[180]

5.6.3 Hydrogen combustion

Hydrogen combustion in aviation involves the direct utilisation of hydrogen as a fuel source for jet engines, where it is burned in a controlled oxidisation process using combustion to generate thrust.

The use of hydrogen as a fuel in aviation requires complete redesign of aircraft, and airport facilities and procedures, as hydrogen's chemical properties differ significantly from conventional jet fuels. Liquid hydrogen (LH_2) systems are likely to be preferred over gaseous systems, due to the higher volumetric density of LH_2. These may more readily meet onboard energy capacity for commercial flights and enable more efficient storage and fuel handling at airports.

Primary technologies

Aircraft combustion systems must be completely redesigned to run on hydrogen fuel, necessitating extensive development and validation to ensure they operate safely and efficiently.

Hydrogen's distinctive combustion properties, including its higher flame velocity relative to kerosene, can lead to challenges such as flame blow-out and unstable combustion chamber operation. RD&D could enable a deeper understanding of hydrogen flame behaviour under different operating conditions, including high and varying altitudes, temperatures, pressures, air-fuel ratios and load. Mechanisms for enhancing flame stabilisation can be refined to prevent flame extinguishment. This may include improving the hydrogen-air mixing process through vortex-like flow, and studying flame patterns, such as the formation of spherical flame structures at the base of the flame to stabilise combustion.[181] Additionally, the severe space and weight constraints of aircraft burners further complicates the integration of new combustion technologies.[182]

Addressing NOx emissions and contrail formation could maximise climate benefits of hydrogen-fuelled propulsion and protect against harmful environmental impacts.

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178 CSIRO (2023) Sustainable Aviation Fuel Roadmap. CSIRO, Canberra.

179 Viva Energy Australia (2025) Market context and opportunity report – SAF infrastructure solutions for the future <https://arena.gov.au/assets/2025/07/Viva-Energy-SAF-Infrastructure-Solutions-for-the-Future-Market-context-and-opportunity-report.pdf>

180 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; IEA (n.d.) Direct Air Capture. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture> (accessed November 2023).

181 Takeno K, Kido H, Takeda H, Yamamoto S, Shentsov V, Makarov D, Molkov V (2024) Flame Stabilisation Mechanism for Under-Expanded Hydrogen Jets. Fire 7(2):48. https://doi.org/10.3390/fire7020048

182 Suda Y, Kato D, Tsuru T, Oda T, Ashida Y, Wirsum M (2024) NOx Emission Characteristics of a Low NOx Emission Burner for Hydrogen Aircraft under High Pressure and Temperature. International Journal of Gas Turbine Propulsion and Power Systems 15(6). https://doi.org/10.38036/jgpp.15.6_v15n6tp03

While it does not emit CO_2, hydrogen combustion can lead to the formation of NOx emissions and can produce more than four times as much water vapour compared to kerosene combustion.[183] Lowering flame temperatures is can reduce atmospheric thermal NOx emissions, with ongoing research underway to explore lean-burn technologies (e.g., changes to flame dynamics and thermochemical processes aimed at mitigating NOx emissions).[184] The water vapour emitted from hydrogen combustion can generate contrails at elevated altitudes and temperatures, which can contribute to cloud formation, affect weather patterns and trap heat in the Earth's atmosphere. Preliminary simulations indicate that reduced concentrations of ambient aerosols in hydrogen exhaust result in fewer and larger ice crystals, potentially decreasing the duration of contrails and their associated warming effect.[185] Thorough experimental validation is required to substantiate this hypothesis and explore techniques and technologies to minimise contrail formation.

Integrating cryogenic hydrogen storage into aircrafts creates engineering and material challenges that could be addressed through RD&D.

Cryogenic hydrogen requires about four and a half times as much volume for storage as Jet A1 fuel as a result of its low volumetric energy density.[186] Hydrogen propulsion requires significant volumes of cryogenic liquid hydrogen, which will likely cause significant redesign of aircraft architecture, including potential elongating fuselages or novel tank placements.[187] Although less hydrogen by weight is needed compared to kerosene for an equivalent amount of usable energy, the storage requirements for liquid hydrogen are stringent. Liquid hydrogen must be stored at temperatures below its boiling point of -253°C, which necessitates the use of advanced, highly insulated systems to maintain these conditions.[188] Industry is targeting to reduce the mass of LH_2 tanks by 50%, compared to current prototypes, using advanced materials.[189] LH_2-powered aircraft will need modified fuel delivery systems that include a heat exchanger to convert LH_2 to GH_2 before combustion, as well as redesigned fuel pipes, pumps, seals, and valves to manage the increased volumetric flow and cryogenic temperatures.[190] Pressure sensors and relief valves must be incorporated into these storage and delivery systems to prevent overpressure, which could result in the vessel's failure.[191]

Ensuring operational durability and safety is critical for commercial certification and long-term adoption.

To improve viability and align with current operational and maintenance schedules, hydrogen aircraft would benefit from achieving lifetimes comparable to that of conventional aircraft. For example, a Boeing 737-800

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[183] Khan MAHB, Brierley J, Tait KN, Bullock S, Shallcross DE, Lowenberg MH (2022) The Emissions of Water Vapour and NOx from Modelled Hydrogen-Fuelled Aircraft and the Impact of NOx Reduction on Climate Compared with Kerosene-Fuelled Aircraft. Atmosphere 13(10):1660. https://doi.org/10.3390/atmos13101660

[184] Schefer RW, White C, Keller J (2007) Chapter 9: Lean hydrogen combustion. *Sandia National Laboratories Report SAND2007-1524P*. https://www.osti.gov/biblio/1731098 (accessed 19 June 2025).

[185] DLR (2025) World first: In-flight measurements of contrails from hydrogen propulsion. <https://www.dlr.de/en/latest/news/2025/world-first-in-flight-measurements-of-contrails-from-hydrogen-propulsion> (accessed 19 June 2025).

[186] IATA (2022) Energy Transition. <https://www.iata.org/contentassets/f9f1f10a29524cf68326605e9982bb8d/energy-transition-hemant-mistry-gmd2022.pdf> (accessed 19 June 2025).

[187] Mukhopadhaya J, Rutherford D (2022) Performance analysis of evolutionary hydrogen-powered aircraft. <https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf> (accessed 19 June 2025). For example, see commentary on novel storage designs (composite conformal tanks): Netherlands Aerospace Centre (NLR) (2025) Research and Development more electric and hydrogen powered aerospace. https://www.nlr.org/wp-content/uploads/2025/06/E1841_v8_Research-and-Development-more-electric-and-hydrogen-powered-aerospace.pdf (accessed 20 June 2025).

[188] Mukhopadhaya J et al. (2022) Performance analysis of evolutionary hydrogen-powered aircraft. <https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf> (accessed 19 June 2025).

[189] Thomas J (2022) Liquid hydrogen energy storage for net zero aviation. <https://www.innovationnewsnetwork.com/liquid-hydrogen-energy-storage-for-aviation/25389/> (accessed 19 June 2025).

[190] Mukhopadhaya J et al. (2022) Performance analysis of evolutionary hydrogen-powered aircraft. <https://theicct.org/wp-content/uploads/2022/01/LH2-aircraft-white-paper-A4-v4.pdf> (accessed 19 June 2025).

[191] FlyZero (2022) Airports, Airlines and Airspace. <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf> (accessed 19 June 2025).

is able to complete up to 75,000 flight cycles in its lifetime.[192] Research can help to determine strategies and materials to mitigate degradation caused by temperature fluctuations, impurities in fuel and air, and repeated start and stop cycles, and fatigue from (de)pressurisation at take-off and landing.

Box 5: Hydrogen fuel cell aviation case study

Like hydrogen FCEVs in Section 1, hydrogen fuel cells in aviation operate by facilitating an electrochemical reaction between hydrogen and oxygen, producing electricity, water, and heat as by-products. This system converts chemical energy directly into electrical energy through the use of advanced membranes, catalysts, and electrode assemblies, which are integral in optimising energy output and efficiency.

Advancing fuel cell technology will require extensive RD&D to meet the energy demands of aviation.

The most prevalent type, proton exchange membrane (PEM) fuel cells, currently offer up to 3.5kWh/kg per stack using state-of-the-art technology before passive components are included.[193] This power density falls significantly short of the power requirements for commercial aviation. Industry aims to achieve fuel cell power densities of up to 16kWh/kg for high temperature PEM fuel cell stacks in 2050[194] by, for instance, RD&D exploring advanced membrane and catalyst materials, novel stack architectures and improved cell designs. Solid oxide fuel cells present an alternative technology, performing well in high-temperature and high-pressure conditions. However, researchers are investigating improvements to their gravimetric energy density (kW/kg), and methods to maintain gastight fuel sealing.[195] Please refer to Section *4.6.2* **Hydrogen fuel cell electric vehicles (Hydrogen FCEVs)** for additional discussion on fuel cell RD&D.

Additional balance of plant components, such as compressors, humidifiers, and heat exchangers, are required to ensure that the fuel cells operate under optimal conditions and to minimise degradation. However, these additional components add complexity and weight to the fuel cell system.[196] Compared to conventional aircraft, a fuel cell regional aircraft could experience an increase in take-off mass of 7.1% in 2040, before considering variations in aircraft architecture. This suggests that fuel cell propulsion may be less suitable for aircraft with high thrust requirements needs unless the mass can be sufficiently reduced through RD&D.[197]

Hydrogen fuel cell aviation will require similar storage, durability, safety and auxiliary technologies as those discussed for hydrogen combustion.

Auxiliary technologies

Production, transportation, and storage infrastructure for hydrogen are critical to support the use and demand of hydrogen aviation at airports efficiently and safely.

Large scale hydrogen production, liquefaction, transportation and storage infrastructure are required to facilitate the hydrogen demand from aircraft; refer to the *Low Carbon Fuels* technical appendix for detailed discussion. On-site airport storage and transportation systems, such as pipelines and cryo-tankers, are also crucial for the efficient and safe distribution of liquid hydrogen. RD&D is required to address a range of

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[192] Per US regulations: eCFR (2025) 14 CFR § 121.1115 - Fuel Tank Inerting Requirements. <https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-121/subpart-AA/section-121.1115> (accessed 19 June 2025). See also Boeing regulations with a limit of 100,000 cycles for the Boeing 737-800BCF model: FAA (2024) Draft Advisory Circular AC 25.XX-X, Cryogenic Liquid Hydrogen Fuel System Installations. <https://downloads.regulations.gov/FAA-2024-2315-0002/attachment_3.pdf> (accessed 19 June 2025).

[193] Karpuk S, Freund Y, Hanke-Rauschenbach R (2025) Potential of Hydrogen Fuel Cell Aircraft for Commercial Applications with Advanced Airframe and Propulsion Technologies. Aerospace 12(1):35. https://doi.org/10.3390/aerospace12010035

[194] FlyZero (2022) Fuel Cells Roadmap Report. <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-PPN-COM-0033-Fuel-Cells-Roadmap-Report.pdf> (accessed 19 June 2025).

[195] Schafer D, Kramer TJ, Roberts R, Gong M (2025) Investigation of Solid Oxide Fuel Cell Seals in Aerospace Applications. AIAA SciTech Forum. https://doi.org/10.2514/6.2025-0507

[196] Karpuk S et al. (2025) Potential of Hydrogen Fuel Cell Aircraft for Commercial Applications with Advanced Airframe and Propulsion Technologies. Aerospace 12(1):35. https://doi.org/10.3390/aerospace12010035

[197] ropedes C, Scheider J, Isikli E, Hoffmann M, Reuss F, Müller B, Müller T, Koch R (2022) Numerical and Experimental Analysis of Flame Propagation in Lean Premixed Hydrogen-Air Swirl Flames for Aero-Engine Applications. *Proceedings of the International Symposium on Air Breathing Engines (ISABE)*. <https://elib.dlr.de/188835/1/ISABE_2022_291_full.pdf> (accessed 19 June 2025).

challenges at scale including, for example, the vaporisation and constant subcooling of liquid hydrogen during transport.[198]

Airport refuelling infrastructure must be developed or modified to manage cryogenic hydrogen and meet aviation standard and efficiency standards.

Hydrogen aircraft refuelling is significantly more complex than refuelling conventional aircraft, given the additional requirements to maintain temperatures below liquid hydrogen's boiling point of -253°C, at significantly higher pressures than that of kerosene.[199] Researchers are focused on demonstrating high-flow handling and refuelling technologies,[200] and improving and demonstrating appropriate technologies and procedures for aircraft that can work in an operational context across the fuelling process steps, including (dis)connecting, purging, chill-down, and refuelling.[201]

5.6.4 Energy efficiency solutions

Further RD&D in solutions that reduce energy use in aviation transport will also support emissions mitigation efforts. The solutions outlined in Table 27 are technology-agnostic with the ability to improve energy efficiencies across a range of technology types and systems. While many of these solutions have been the focus of past research efforts they may evolve alongside advancements in materials, digital technologies and system innovations, offering incremental improvements in transport efficiency.

Table 27: Energy efficiency solutions RD&D opportunities - Aviation

Energy efficiency solutions	RD&D opportunities
Drag reduction and design *Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles.*	• Retrofit existing planes and improve new designs to reduce wake vortex and drag. o For example, wingtip devices designed using advanced computational fluid dynamics may enable airlines to save more than 4% in fuel, in addition to reducing noise and NO_x emissions.[202] • Design aircraft with improved aerodynamics to enhance energy efficiency and reduce air resistance.
Lightweighting *Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.*	• Production upgrades, such as incorporating advanced composite materials and low weight alloys with high strength, can be applied to the aircraft, cabin equipment, seating, and cargo containers.[203] • Retrofit options include applying advance material lightweight cabin interiors, and applying thinner chrome-free paint has the potential to reduce paint weight by 15% while providing additional aerodynamic benefit. [204]

[198] Krog HA, Jooss Y, Fyhn H, Nekså P, Hjorth I (2025) Large-scale LH2 pipeline infrastructure concept for airports. arXiv. https://doi.org/10.48550/arXiv.2506.09410

[199] Or -173°C for supercritical H_2. FlyZero (2022) Airports, Airlines and Airspace. <https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf> (accessed 19 June 2025).

[200] Airbus (2024) Innovative aviation liquid hydrogen project launched. <https://www.airbus.com/en/newsroom/press-releases/2024-05-innovative-aviation-liquid-hydrogen-project-launched> (accessed 19 June 2025).

[201] Mangold J, Silberhorn D, Moebs N, Dzikus N, Hoelzen J, Zill T, Strohmayer A (2022) Refueling of LH2 Aircraft—Assessment of Turnaround Procedures and Aircraft Design Implication. Energies 15(7):2475. https://doi.org/10.3390/en15072475

[202] Air Transport Action Group (2021) Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century. <www.bluesky-d2d.com> (accessed 20 May 2024).

[203] Bravo-Mosquera PD, Catalano FM, Zingg DW (2022) Unconventional aircraft for civil aviation: A review of concepts and design methodologies. Progress in Aerospace Sciences 131,. doi:10.1016/j.paerosci.2022.100813

[204] Air Transport Action Group (2021) Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century. <www.bluesky-d2d.com> (accessed 20 May 2024).

Componentry improvement *Improves energy efficiency by improving engine efficiencies.*	• Incorporate incremental engine efficiencies, such as geared turbofans and greater electrification of engine components (motors, power electronics, advanced fuel injectors) that optimise energy conversion and reduce losses.
Traffic and logistics management technologies *Improves energy efficiency by optimising vehicle movement and operation.*	• Implement advanced navigation systems such as required navigation performance and space-based navigation technologies like radar and ADS-B to track and control flights. This may also allow for optimisation of flight paths based on weather conditions e.g. winds. [205] • Predictive maintenance technologies that use machine learning (ML) and data analytics to monitor health of aircraft to prevent breakdowns, reduce downtime and optimise maintenance. • Develop algorithms for real-time traffic prediction and optimisation.
Energy management solutions *Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, enhancing battery life.*	• Electric or assisted taxiing can be incorporated to conserve fuel • Electrifying auxiliary systems such as flight control that coordinate (such as rudders, flaps and spoilers) and environmental control (such as de-icing systems and internal climate control).[206]

[205] Air Transport Action Group (2021) Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century. <www.bluesky-d2d.com> (accessed 20 May 2024).

[206] Tom L, Khowja M, Vakil G, Gerada C (2021) Commercial aircraft electrification—current state and future scope. Energies (Basel) 14,. doi:10.3390/en14248381;https://www.mdpi.com/1996-1073/16/4/1904 // 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

6 Rail

6.1 Executive summary

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

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

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.

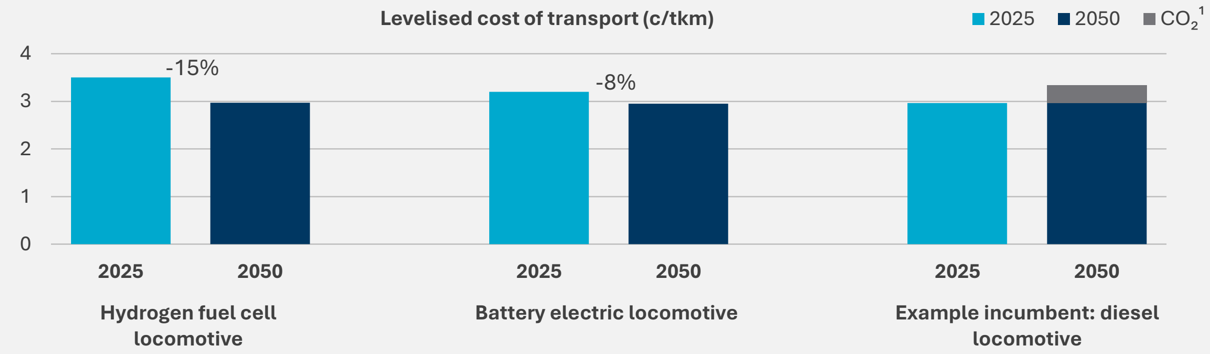
Auxiliary

- 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 FCEV 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 *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions. Note, c/tkm = cents/tonne – km.

6.2 Introduction

Rail transport plays a vital role in the movement of both people and freight. It is significantly less emissions intensive than other forms of domestic transportation, with rail freight generating 16 times less emissions compared to road freight and passenger rail generating 30% less emissions than road travel.[207] Given its lower emissions intensity relative to other forms of transportation, including road and aviation, encouraging a modal shift toward rail, in addition to direct subsector decarbonisation efforts, presents as a valuable opportunity to reduce transport-sector emissions.

In Australia, the rail subsector emitted 6.5 $MtCO_2e$ in 2023-2024, accounting for 5% of Australia's total transport emissions.[208] Freight operations dominate these emissions, contributing to 95% of the total.[209] Traction energy contributes to that vast majority of industry emissions (90%), where freight emissions are dominated by diesel use and passenger emissions are largely produced from electricity generation.[210]

Considering these statistics, the primary challenge for decarbonising domestic rail lies in freight services, particularly those linked to Australia's resource extraction industries. Australia's heavy haul operations are energy-intensive due to high-weight penalties which distinguishes Australian rail transport from many global operations, where decarbonisation trials largely focus on passenger applications.[211]

Like other non-road segments, rail assets have long asset lives where rail operators are required to make long-term investment decisions and replacement is economically challenging. Nearly half of Australia's diesel-powered rolling stock is due to be replaced in the next 8 to 13 years, making the availability of low emissions technologies within this window a determinant for the pace of decarbonisation.[212]

The remoteness of regional mining operations and route utilisation also complicates decarbonisation strategies. Land ownership structures can limit the opportunities for refuelling and energy supply which can restrict the technology solutions that can be adopted.[213] The viability of infrastructure-intensive solutions, such as overhead catenary rail, are context specific. For example, catenary systems could outperform battery-electric or fuel cell locomotives on shorter, high traffic routes where infrastructure costs are shared across a busy fleet and fuel costs eliminated (see Section 0).

Meanwhile, route specificity and train configuration flexibility present both challenges and opportunities. Rail freight operations are highly tailored to route characteristics, including gradients that enable energy efficiency measures such as regenerative braking. While some routes may impose inherent limitations, this specificity also creates opportunities for optimised, route-adapted solutions.[214]

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207 Australasian Railway Association (2024) Transitioning the rail industry and its supply chain: The critical path to decarbonise Australia's rail rollingstock.

208 BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

209 Based on unpublished BITRE statistics supplied to CSIRO.

210 Rail Industry Safety and Standards Board (2022) NATIONAL RAIL CARBON FOOTPRINT STUDY.

211 Australasian Railway Association (2024) Transitioning the rail industry and its supply chain: The critical path to decarbonise Australia's rail rollingstock.

212 Australasian Railway Association (2024) Transitioning the rail industry and its supply chain: The critical path to decarbonise Australia's rail rollingstock.

213 Knibbe R, Harding D, Cooper E, Burton J, Liu S, Amirzadeh Z, Buckley R, Meehan PA (2022) Application and limitations of batteries and hydrogen in heavy haul rail using Australian case studies. Journal of Energy Storage 56,. doi:10.1016/j.est.2022.105813

214 Knibbe R, Harding D, Burton J, Cooper E, Amir Zadeh Z, Sagulenko M, Meehan P, Buckley R (2023) Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives. Journal of Energy Storage 71,. doi:10.1016/j.est.2023.108090

These factors, combined with the cost of deploying zero emission alternatives and supporting infrastructure, can present significant decarbonisation challenges[215], creating clear opportunities for RD&D to support heavy rail transition to low emissions technologies.

This chapter presents an assessment of low emissions technologies for heavy freight rail to identify technically feasible and cost competitive solutions. This informs an exploration of RD&D opportunities that could support, and possibly accelerate, the deployment of these technologies.

6.2.1 Rail use case(s)

To explore low emissions technologies in the rail subsector, a single use case has been defined to reflect a short-range heavy haulage freight train on a 700km return journey (see Table 28). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

This use case is representative of an operational profile of a typical commodity Pilbara iron ore route, with a 350km one way trip (700km return journey).[216]

A supplementary case study was also conducted (see Box 7), to assess the feasibility of technology options for an application in which longer distances are required, therefore incurring higher energy demands. This case study reflects a long-range, 2800km freight return journey.

These use cases are illustrative and present requirements that technologies must be able to meet in order to service Australia's domestic rail industry. In reality, operations in Australia are diverse and require trains of varying sizes and configurations, over variable distances.

Table 28: Use case(s) – Rail

Use case(s)	Short-range haulage
Description:	**A short-range freight train on a 700km return journey with a 2000m train length.** The vast majority of rail services in Australia are for freight.[217] As a subsector, rail transport is responsible for 6.5 $MtCO_2e$, which equates to 32% of domestic non-road emissions.[218]

[215] Climate Change Authority (2024) Sector Pathways Review: Transport. <https://www.climatechangeauthority.gov.au/sites/default/files/documents/2024-09/2024SectorPathwaysReviewTransport.pdf>

[216] CSIRO (n.d.) Transport logistics – TraNSIT model <https://www.csiro.au/en/research/technology-space/it/transport-logistics-transit>

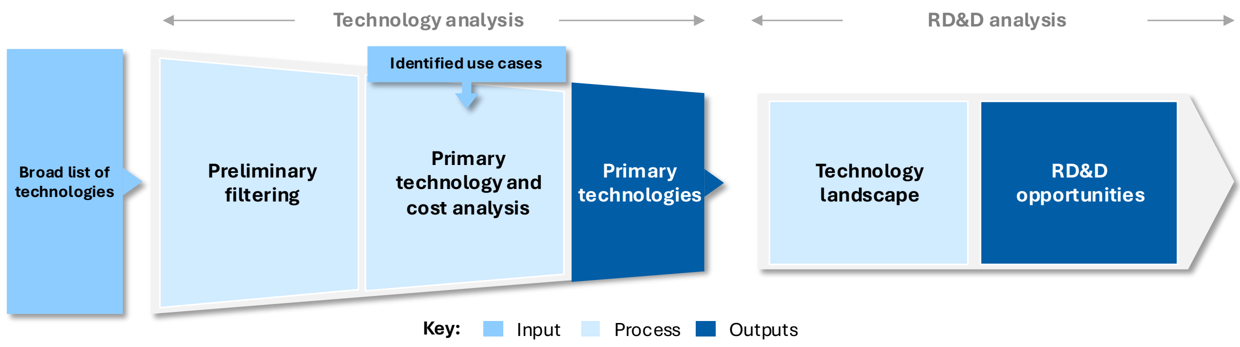
[217] Based on unpublished BITRE statistics supplied to CSIRO

[218] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

6.3 Methodology: Rail 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 decarbonisation for heavy rail freight. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 15).

Figure 15: Technology and RD&D analysis framework for rail



6.3.1 Broad technology list

A broad technology list was comprised of seven technologies was developed (Table 29). These technologies were then passed through two preliminary filters: technological maturity and abatement potential. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case(s).

Table 29: Technology categories – Rail

Technology category	Definition
Battery electric	Locomotives which employ battery-powered drivetrains which store and supply electrical energy.
Catenary electric	Locomotives which operate with an electric drivetrain that draws power from overhead wires, enabling continuous energy supply to the traction system.
Electric-LPG hybrid	Locomotives with integrate an electric drivetrain with liquid petroleum gas (LPG)-fuelled combustion engine.
Electromagnetic propulsion	Locomotives which employ an electromagnetic propulsion systems and linear motor technology, generating movement through electromagnetic forces without physical contact between the train and track. This includes both magnetic levitation and hyperloop variants.
Hydrogen combustion	Locomotives which employ an internal combustion engine fuelled by e-hydrogen, generally coupled with cryogenic liquid hydrogen storage to meet energy demands.
Hydrogen fuel cells	Locomotives which employ a hydrogen fuel cell system that generates electric power from e-hydrogen, driving an electric traction system. This is coupled with an onboard storage system, generally cryogenic, to meet energy demands.
Renewable diesel	Locomotives which employ renewable diesel, or HVO (hydrotreated vegetable oil), as a 'drop-in' hydrocarbon fuel equivalent to conventional diesel

6.3.2 Primary technology filters

Applications in non-road transportation are commonly grouped together due to their extreme performance requirements and high energy demands that are not typically faced by road transport vehicles. Technology assessments involved evaluating the technologies identified through preliminary filtering against three performance parameters for the defined used case (Table 30). These performance parameters were deemed to be core operational requirements that will enable or limit technology uptake, particularly in applications that are energy and cost intensive and require high utilisation rates.

The thresholds for range and refuelling duration were ascertained based on the characteristics of a train of equivalent length operating on diesel fuel. The range reflects typical route requirements in Australia's Pilbara region.[219] The threshold for refuelling duration reflects an estimated loading/unloading time for the use-case freight train, on the basis that replenishing times could be coupled with other operational procedures. This is particularly true for tender configurations, in which empty fuel wagons (tenders) can be replaced will pre-filled ones to minimise operational downtime.

Range and cost parameters are also influenced by the configuration of the train. Trains are typically configured with multiple locomotives and tenders to meet the energy requirements of a given route. For this reason, a 2000m train length has been imposed. Distances that require additional tenders do so at the expense of a cargo container, thereby reducing payload and increasing the cost of transport per tkm.

The lowest cost mitigation technologies able to meet these thresholds were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 0*

[219] BITRE (2024) Domestic aviation activity, Statistical Report, BITRE, Canberra ACT.

Primary technology analysis.

Table 30: Technology filtering criteria – Rail

Subsector	Rail
Use case(s)	**Short-range haulage**
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 meets or exceeds an abatement threshold of 90%, relative to an equivalent locomotive configuration operating on conventional diesel.
Primary technology filters	**Minimum range requirement** Technology can meet an acceptable distance threshold in a single trip.
	Refuelling/recharging duration Technology can meet an acceptable threshold refuelling duration, based on the time taken to refuel the use case train on conventional diesel.
	Levelised Cost of Transport (LCOT) in 2050 Technologies projected to be the most cost competitive by 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.

6.4 Technology analysis

This chapter outlines the process of identifying primary technologies for Australia's domestic rail sector. Following the technology analysis framework process, **battery electric and hydrogen fuel cell locomotives emerged as primary technologies for further RD&D exploration.** These technologies were able to best service the 700km rail haulage use case and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in rail decarbonisation, 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 rail transport subsector are provided in Table 31.

Table 31: Technology analysis results – Rail [220]

Legend: Meets criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering | 2. Primary technology analysis — Short-range freight: 700km return journey

Technologies	Maturity	Abatement potential[221]	Refuelling duration	Range requirement	LCOT (2050)	
Threshold	*TRL>3*	*90% decrease in emissions*	*≤4 hours*	*≥700km*	*c/t-km*	
Battery electric	TRL 8	92%	3.3 to >30 hours	>700km, payload slightly reduced	2.95	★
Catenary electric	TRL 8	92%	NA	>700km	4.43	
Electric-LPG hybrid	TRL 8	15-30%				
Electromagnetic propulsion	Not suitable for freight					
Hydrogen combustion	TRL 7-9	100%	15 minutes	>700km, payload slightly reduced	No data	
Hydrogen fuel cells	TRL 8	100%	15 minutes	>700km, payload slightly reduced	2.97	★
Renewable diesel	TRL 9	40-75%				

[220] Details for these figures, including sources/assumptions, are found in Table 33 (abatement potentials); Table 34 (Refuelling/recharging duration); Table 35 (Range); and under 'Levelised cost analysis' and *Technical Appendix: Levelised cost analysis* (LCOT).

[221] Emissions estimates encompass the full fuel cycle, where a conventional diesel ICE freight train has an emissions estimate of 90.9gCO_2/MJ. The abatement potential threshold is set to 95%, reflecting the availability of cost competitive low emissions technology solutions by 2050.

6.4.1 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

All technologies were found to meet this criterion across the designated use case, as they can be reasonably deployed in the Australian context.

Technological maturity

All technologies, with the exception of electromagnetic propulsion, were found to meet this criterion processing a TRL greater than 3 (Table 32).

Maturity ratings are informed by desktop research, drawing on the IEA Clean Energy Technology Guide.[222]

Electromagnetic propulsion systems employ magnetic fields to levitate, guide and/or propel a rail car. Here, Maglev and Hyperloop variants are considered.[223] While both systems have been deemed feasible for passenger transportation (Maglev TRL 9; Hyperloop TRL 4), these systems are considered less suitable for heavy freight applications that are less time sensitive and do not benefit from high service speeds, particularly where additional energy requirements to levitate high-weight goods are incurred.

Table 32: Technology maturities – Rail

Technology	TRL
Battery electric	• TRL 8
Catenary electric	• TRL 9
Electric-LPG hybrid	• TRL 8
Electromagnetic propulsion	*Not suitable for freight*
Hydrogen combustion	• TRL 7-9
Hydrogen fuel cells	• TRL 8
Renewable diesel	• TRL 9

Abatement potential

Key information – Abatement potential

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

[222] IEA. Clean Technology Guide, <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide> (accessed June 2024)

[223] Hyperloop combines magnetic levitation principles with vacuum technology and is sometimes considered a ‘fifth form of transportation’

- **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 *Appendix **A.4***.

The abatement potential was assessed against a diesel freight train with an emissions intensity of 90.9gCO_2e/MJ, obtained from the US Argonne National Laboratory's ICAO-GREET model.[224] A 90% abatement potential threshold was set for rail transport, reflecting both the expected availability of cost competitive low emissions technology solutions by 2050 and the challenges of decarbonising energy-intensive modes of transportation. This threshold also accounts for residual emissions in the grid, recognising that some fossil fuel capacity will likely remain in the long-term.

Greenhouse gas emissions considered include methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2). The emissions estimates are outlined in Table 33.

For hydrogen-fuelled assets, hydrogen electrolysis facilities are assumed to operate with a 60% utilisation factor in 2050: aligning with electricity generation from variable renewable energy (VRE). Only operating electrolysers when renewable generation assets are online can enable zero emissions hydrogen production and allow for cost savings compared to higher utilisation rates (see *Low Carbon Fuels* technical appendix).

For technologies that rely on electricity or electricity-derived fuels (i.e., hydrogen or synthetic fuels), efforts have been made to adjust grid-born electricity emissions to reflect a prospective 2050 grid intensity in which 5% of current electricity generation occurs from peaking gas and the remainder generated from renewable resources.[225] In the case of a hybrid-electric freight train, values were obtained from Cipek et al. (2019 and 2022).[226] Unlike the other transport subsectors, the ICAO-GREET model did not contain the rail technology options required.

Table 33: Abatement thresholds – Rail

Technology	Well-to-wheel emissions *gCO_2/MJ*	Abatement *Threshold: 90%*
Conventional diesel freight train	**90.9**	
Battery electric	7.4	92%
Catenary electric	7.4	92%
Electric-LPG hybrid	10.2-12.3	15-30%[227]
Electromagnetic propulsion	7.4	92%

[224] Argonne National Laboratory (2019) ICAO-GREET model. Accessed July 2024. https://greet.anl.gov/greet_icao.

[225] The emissions intensity (7.4gCO_2-e per MJ) is based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions.

[226] Cipek M, Pavković D, Kljaić Z, Mlinarić TJ (2019) Assessment of battery-hybrid diesel-electric locomotive fuel savings and emission reduction potentials based on a realistic mountainous rail route. Energy 173, 1154. doi:10.1016/j.energy.2019.02.144; Cipek M, Pavković D, Krznar M, Kljaić Z, Mlinarić TJ (2021) Comparative analysis of conventional diesel-electric and hypothetical battery-electric heavy haul locomotive operation in terms of fuel savings and emissions reduction potentials. Energy 232,. doi:10.1016/j.energy.2021.121097

[227] Cipek M, Pavković D, Kljaić Z, Mlinarić TJ (2019) Assessment of battery-hybrid diesel-electric locomotive fuel savings and emission reduction potentials based on a realistic mountainous rail route. Energy 173, 1154. doi:10.1016/j.energy.2019.02.144; Cipek M, Pavković D, Krznar M, Kljaić Z, Mlinarić TJ (2021) Comparative analysis of conventional diesel-electric and hypothetical battery-electric heavy haul locomotive operation in terms of fuel savings and emissions reduction potentials. Energy 232,. doi:10.1016/j.energy.2021.121097

Hydrogen combustion	-	100%
Hydrogen fuel cells	-	100%
Renewable diesel	-	40-75%[228]

Electric-LPG hybrid

Hybrid and plug-in hybrid electric vehicles do not meet the abatement criteria, due to the emissions associated with fossil fuel combustion.

Hybrid drivetrains are often discussed as a transitionary technology as fully electric drivetrains are developed. In the long-term hybrid locomotives will need to be replaced by fully electrified vehicles to entirely decarbonise the sector.

Renewable diesel

For renewable diesel production, first- or second-generation feedstocks are unlikely to achieve 90% abatement when considering both direct and indirect emissions, failing to meet the abatement criteria. Estimates sourced from Xu et al. (2022)[229] and Cai et al. (2022)[230] suggest renewable diesel synthesis from first-generation crops (canola, soybean) and second-generation sources (used cooking oil) can abate 40-55% and up to 75% of emissions respectively. In these analyses, tailpipe emissions are assumed to be zero, where the CO_2 emissions from combusting renewable diesel is offset by the CO_2 absorbed during plant growth.

Box 6: The impact of renewable diesel on rail haulage operations

Renewable diesel could significantly aid the short-term decarbonisation of existing Australian rail fleets, as longer-term solutions continue to be developed. While hydrogen and electric-based options emerge as desirable low emissions alternatives from an abatement perspective, infrastructure barriers and technical hurdles are limiting to nearer term adoption.

In applications such as rail where assets have long lifetimes, the decision to convert these locomotives to alternative fuels is limited. Renewable diesel is a compelling solution; complimenting long asset lifetimes due to its properties as a drop-in fuel that is compatible with existing technologies and related infrastructure. It can also be produced alongside other hydrocarbon fractions, such as those used to generate aviation biofuels.

Hybridised diesel/electric configurations offer greater potential. Hybrids trains are currently adopted within the rail industry and can further reduce energy use (via regenerative braking) and emissions compared to full renewable diesel locomotive trains.

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[228] For biofuels, when accounting for ILUC, 100% abatement is unlikely to be achieved. Emissions estimates for renewable diesel are highly variable, depending on feedstock, pathway and methodology. Range reflects widely cited estimates from literature: Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. doi:10.1039/d2se00411a; Jeswani HK, Chilvers A, Azapagic A (2020) Environmental sustainability of biofuels: A review: Environmental sustainability of biofuels. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 476,. doi:10.1098/rspa.2020.0351; Xu H, Ou L, Li Y, Hawkins TR, Wang M (2022) Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environmental Science and Technology 56, 7512. doi:10.1021/acs.est.2c00289

[229] Xu H, Ou L, Li Y, Hawkins TR, Wang M (2022) Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. Environmental Science and Technology 56, 7512. doi:10.1021/acs.est.2c00289

[230] Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. doi:10.1039/d2se00411a

6.4.2 Primary technology analysis

Key information – Primary technology analysis

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

- Refuelling/recharging duration: Technologies that meet an acceptable replenishing duration, based on the time taken refuel a conventional internal combustion engine (ICE) engine.
- Minimum range requirement (single trip): Technologies that meet an acceptable distance threshold in a single trip.
- Levelised cost of transport: 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.

Refuelling/recharging duration

This filter defines an acceptable refuelling/recharging time for technologies applied to the end-use case. This was identified as a core operating requirement that will enable or limit technology uptake, particularly in applications with high utilisation rates. The benchmark duration reflects an estimate of loading/unloading time for the use-case freight train, on the basis that replenishing times could be coupled with other operational procedures. This is particularly true for tender configurations, in which empty fuel wagons (tenders) can be replaced will pre-filled ones to minimise operational downtime. Estimates are sourced from Building Queensland (2017) and Juturna Consulting (2012) (Table 34).[231]

Table 34: Refuelling/recharging durations – Rail

Technologies *Threshold*	**700km return journey** *Approx. 4 hours*	
Battery electric	3.3 to >30 hours.[232] Highly dependent on charger capacity, number of charging stations and route characteristics.	
Catenary electric	Not applicable – constant supply of electricity via catenary system	
Hydrogen combustion	6 minutes – 2.25 hours	
Hydrogen fuel cells	As above	

Hydrogen-fuelled

Hydrogen locomotives, both fuel cell and combustion, offer operational benefits given they do not require track modifications and could be refuelled in a similar timeframe to conventional locomotives.[233]

[231] *1.8-3hrs,* see: Building Queensland (2017) TOWNSVILLE EASTERN ACCESS RAIL CORRIDOR DETAILED BUSINESS CASE, November 2017. <https://www.statedevelopment.qld.gov.au/__data/assets/pdf_file/0016/54601/TEARC-Detailed-Business-Case-1.pdf>; *3.5hr unloading,* see: Juturna Consulting (2012) MITEZ 50-YEAR FREIGHT INFRASTRUCTURE PLAN / FINAL REPORT / MAY 2012. Prepared for MITEZ. <https://www.infrastructureaustralia.gov.au/sites/default/files/2019-06/MITEZ_50_Year_Plan_2012.pdf>. *The refuelling time of a conventional diesel locomotive stands at ~15mins.* Barbosa FC (2022) Battery Electric Rail Technology Review - A Technical and Operational Assessment. Current Status, Challenges and Perspectives. <http://appliedmechanics.asmedigitalcollection.asme.org/JRC/proceedings-pdf/JRC2022/85758/V001T05A002/6892659/v001t05a002-jrc2022-78133.pdf>; Iden ME (2021) BATTERY ELECTRIC LOCOMOTIVES & BATTERY TENDERS: OPERATIONAL & INFRASTRUCTURE CHALLENGES TO WIDESPREAD ADOPTION. <http://nuclearengineering.asmedigitalcollection.asme.org/JRC/proceedings-pdf/JRC2021/84775/V001T07A003/6707511/v001t07a003-jrc2021-58378.pdf>

[232] For the size of energy required for this case study (33MWh), charging times could range from 33hours (single charger with 1MW power capacity) to 3.3hrs (2 chargers each with 5MW power capacity, target). These are simple estimates, approximated via a power-to-energy calculation which does not account for more complex factors like non-linear charging curves or energy losses.

[233] Ehrhart BD, Klebanoff LE, Mohmand JA, Markt C Study of Hydrogen Fuel Cell Technology for Freight Rail Propulsion and Review of Relevant Industry Standards.

Optimal fuel configurations for hydrogen trains are yet to be determined, but will influence the overall re-fuelling time. Due to the fuel storage capacity required for long distances and heavy haulage, liquified hydrogen (LH_2) may better suited compared to gaseous hydrogen refuelling and onboard storage, but low storage temperatures create additional operational challenges and incur processing and storage costs.[234]

The additional processing steps for hydrogen dispensing may marginally increase refuelling times compared to conventional fuels. Using current average flow rates (13.2kg/min),[235] which account for the controlled pressurisation of the tank through a cascading flow rates, the 1800kg of hydrogen could be replenished in approximately 2 hours and 15 minutes, far below the threshold established. Achieving higher flow rates could be achieved with RD&D, allowing hydrogen-powered locomotives to become competitive with diesel refuelling systems in the long term.[236] For example, in order to achieve a comparable refuel time of 15 minutes, a flow rate of 120kg/min would be required; broadly aligning with ambitions to achieve fuel rates of >100kg/min for heavy-duty applications.[237]

Battery electric

For the size of energy required for this case study (33MWh), charging times could range from 33hours (single charger with 1MW power capacity) to 3.3hrs (2 chargers each with 5MW power capacity, target). These are simple estimates, approximated via a power-to-energy calculation. While this provides a general sense of charging time, it does not account for more complex factors like non-linear charging curves or energy losses. Technology breakthroughs enabling higher charging capacities and operational strategies such as establishing multiple charging bays, rotating battery tenders and optimising routes for regenerative breaking can reduce these times substantially and improve the utilisation of the battery electric train.

Catenary electric

Although direct electrification via overhead catenary networks is a proven low emissions technology for passenger transport in high-traffic urban areas and heavy rail haulage in Australia[238], there are several logistical, economic and technical factors that challenge their adoption for isolated or single user networks. Most notably, high build out and maintenance costs associated with installing overhead electric rail infrastructure (i.e., transformers, cable or third rail, pantograph or third rail connector shoe) limit their feasibility on low- to medium-traffic corridors.[239] Overhead structures are also more susceptible to weather-related service disruptions and failure.[240]

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[234] Ding D, Wu XY (2024) Hydrogen fuel cell electric trains: Technologies, current status, and future. Applications in Energy and Combustion Science 17,. doi:10.1016/j.jaecs.2024.100255; Ling-Chin J, Giampieri A, Wilks M, Lau SW, Bacon E, Sheppard I, Smallbone AJ, Roskilly AP (2024) Technology roadmap for hydrogen-fuelled transportation in the UK. International Journal of Hydrogen Energy 52, 705. doi:10.1016/j.ijhydene.2023.04.131

[235] NREL (2022) Fast Flow Future for Heavy-Duty Hydrogen Trucks Expanded Capabilities at NREL Demonstrate High-Flow-Rate Hydrogen Fueling for Heavy-Duty Applications. <https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html> (accessed March 2025)

[236] Wolfe S et al. (2023) Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia. CSIRO and GHD Advisory.

[237] 1,800kg of LH_2 fuel is required for this end-use case. A flow rate of 150-300kg/min would refuel the train in approximately 6-12mins. Refuelling rate based on: Ehrhart BD, Anleu GB, Mohmand JA, Baird AR, Klebanoff LE SANDIA REPORT Refueling Infrastructure Scoping and Feasibility Assessment for Hydrogen Rail Applications. <https://classic.ntis.gov/help/order-methods>; Ling-Chin J, Giampieri A, Wilks M, Lau SW, Bacon E, Sheppard I, Smallbone AJ, Roskilly AP (2024) Technology roadmap for hydrogen-fuelled transportation in the UK. International Journal of Hydrogen Energy 52, 705. doi:10.1016/j.ijhydene.2023.04.131

[238] For example, 2,100km of Aurizon's Central Queensland Coal Network (CQCN) is electrified. < https://www.aurizon.com.au/news/2024/aurizon-secures-funding-to-develop-next-generation-freight-trains-using-renewable-energy>

[239] Barbosa F (2023) Battery only electric traction for freight trains - A technical and operational assessment, 238(3), 322-337. DOI: 10.1177/09544097231160613

[240] Rahman FAA, Kadir MZAA, Osman M, Amirulddin UAU (2020) Review of the AC Overhead Wires, the DC Third Rail and the DC Fourth Rail Transit Lines: Issues and Challenges. IEEE Access 8, 213277. doi:10.1109/ACCESS.2020.3040018

Minimum range requirement

The minimum range requirement defines the average distance (in km) required for the short-range freight end-use case. The threshold distance, 700km, aligns with reported average distances by major mining companies and known haulage routes.[241]

Trains are typically configured with multiple locomotives and tenders to meet the energy requirements of a given route. The modular, and therefore, scalable configuration of freight trains ensures that range requirements can always be met regardless of the propulsion system. For this reason, while all technologies meet the range parameter, a 2000m train length has been imposed in determining the unit cost of transport. Distances that require additional tenders do so at the expense of a cargo container, thereby increasing the cost of transport per tkm due to reduced payload.

All technologies meet this criterion. Though battery electric and catenary experience payload reductions of around 1%, this is deemed to be negligible and unlikely to drastically influence rail operations (Table 35).

As discussed under *Refuelling/recharging duration*, the operation of catenary electric trains will be dependent on the rollout and maintenance of sufficient network infrastructure along the entire distance of the journey route. The feasibility of this will be route-dependent, and subject to the local conditions and route economics (See *Levelised cost analysis*).

Table 35: Range capabilities – Rail

Technologies	700km return journey	Results
Threshold	*700km*	
Battery electric	>700km. Can always be met, using battery tender configurations.[242] For the designated use case, a payload reduction of 1% were observed.	
Catenary electric	Unlimited, infrastructure dependant.	
Hydrogen combustion	>700km. Can always be met, using hydrogen tender configurations. For the designated use case, a payload reduction of 1% were observed.	
Hydrogen fuel cells	>700km.[243] Can always be met, using hydrogen tender configurations.	

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Transport (LCOT) was estimated to determine the viability of each technology considered. LCOT is defined as the average net present cost per unit of output (in c/passenger-km or c/tonne-km), over a vehicle's lifetime.

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.*

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[241] Knibbe R, Harding D, Burton J, Cooper E, Amir Zadeh Z, Sagulenko M, Meehan P, Buckley R (2023) Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives. Journal of Energy Storage 71,. doi:10.1016/j.est.2023.108090; RailwayPro (2022) Hitachi expands Rio Tinto's automated rail network. <https://www.railwaypro.com/wp/hitachi-expands-rio-tintos-automated-rail-network/> (accessed June 2024).

[242] Aurizon (2024) Aurizon secures funding to develop next-generation freight trains using renewable energy. Media release 8/3/24. <https://www.aurizon.com.au/news/2024/aurizon-secures-funding-to-develop-next-generation-freight-trains-using-renewable-energy> (accessed June 2024); Barbosa F (2023) Battery only electric traction for freight trains – A technical and operational assessment. doi.org/10.1177/095440972311606.

[243] Source suggests up to 1000km before requiring refuelling or additional tenders. Kang D, Yun S, Kim B (2022) Review of the Liquid Hydrogen Storage Tank and Insulation System for the High-Power Locomotive. Energies *15*(12). doi.org/10.3390/en15124357

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 of new deployments 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 16. **Battery electric locomotives and hydrogen fuel cell locomotives were projected to be the most cost competitive,** distinguished by a cost differential in LCOT relative to other assessed technologies, suggesting areas of promise for further RD&D activity**.** A supplementary case study was conducted to assess the feasibility of technologies for a longer haul haulage route, see Box 7.

The economic assessment calculates the total cost of transport for a mainline freight train. The composition of the train (i.e., number of locomotives, tenders and cargo wagons) varies depending on the drivetrain and reflects varied fuel and energy requirements. Trains with an electric component, that can take advantage of regenerative breaking, were assumed to have reduced energy needs relative to a conventional diesel train. Sole hydrogen and electrically powered trains require tenders to account for the lower volumetric energy densities of the respective fuels. A train length of 2000m is imposed, with each additional fuel tender replacing a cargo wagon and therefore reducing payload.

The train is assumed to travel an average annual distance of 127,750km per year, with an asset lifetime of 20 years. This assessment does not capture the cost of refuelling infrastructure, except in the case of the catenary electric train.

For renewable diesel and battery electric vessels, sufficient data was available for cost analysis. Though these technologies did not meet the earlier abatement potential and range requirement filters, respectively, cost analysis has been conducted, for reference only.

A conventional diesel train has been analysed and is included as a technology benchmark – though it is not assessed. Diesel is estimated to remain the lowest cost technology in the near term (Figure 16).[244]

While it does not meet preliminary filtering due to non-zero emissions intensity, battery-diesel hybridised locomotives were also included as a second reference case. This solution was found to offer a competitive levelised cost in the short-term, owing to increased energy efficiency and reduced fuel consumption from regenerative braking, which offsets the increase in capital cost.

Battery electric

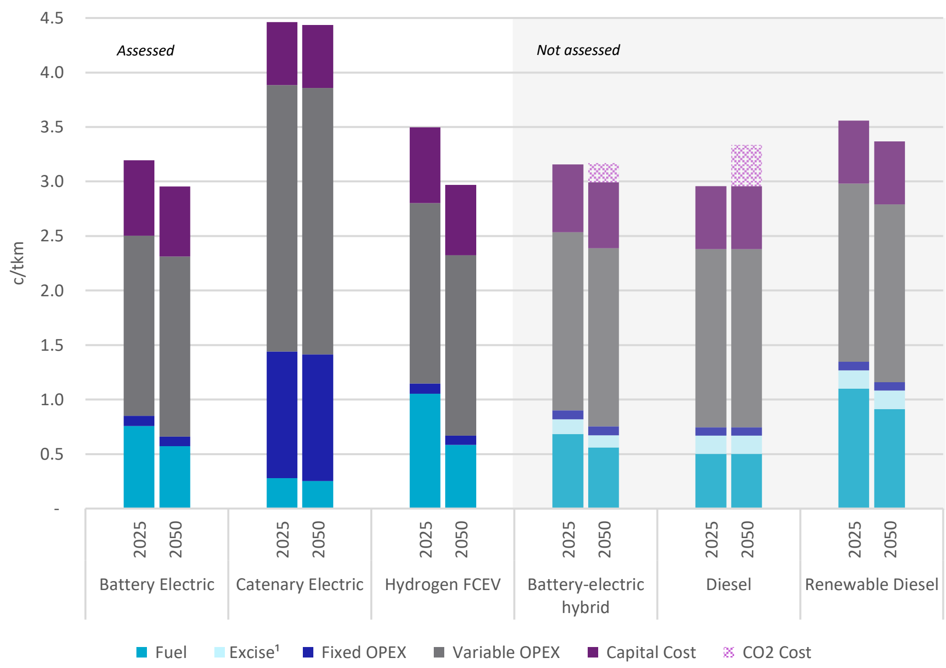
The battery electric train meets the criterion. It presents as the lowest cost technology in 2050 (alongside the hydrogen fuel cell train), distinguished by a cost differential in LCOT.

Lower levelised costs are attributable to projected reductions in capital and fuel costs out to 2050. However, this configuration requires additional battery storage tenders. This reduces freight carrying capacity (by ~1%), which increases their levelised costs per tonne-km.

Though fuel costs for battery electric configurations are higher than catenary electric configurations to account for the fast-charging infrastructure required, overall levelised cost remains low.

[244] It is assumed that the train makes its return journey unloaded. Refer to Table 30 for detailed operating assumptions.

Figure 16: Levelised cost of transport (c/tkm) – Rail, 700km return journey



Note: 1. Fuel excise is typically claimed back via a fuel tax credit for this use case. The perceived cost of diesel and hybrid configurations would therefore not include this component, reducing their levelised cost. 2. Variable operational costs include labour, maintenance of locomotives and tenders as well as Fixed Track Access Charges (FTAC) that contribute to maintenance of the track and associated infrastructure.

Catenary electric

The catenary electric train does not meet the criterion, presenting the highest levelised cost of technologies analysed.

Despite lower fuel costs compared to battery electric configurations, catenary electric was found to be most costly in the near and long-term. This is related to the increased capital and operational costs associated with the installation and maintenance of the catenary system, which were found to outweigh any fuel cost savings for this use case. As the capital and operational costs of catenary infrastructure can be shared across a fleet of trains, a catenary electric train's levelised costs could be reduced if route utilisation increases. This analysis assumed a single-track operation with a utilisation rate of 4 trains per day. Catenary electric is modelled to become competitive at 12 trains per day.

Hydrogen fuel cell

The hydrogen fuel cell train meets the criterion, presenting as the lowest cost technology in 2050 (alongside battery electric), distinguished by a cost differential in LCOT.

Similar to the battery electric train, lower levelised costs are driven by projected reductions in capital and fuel costs (particularly for hydrogen). The lower volumetric energy density of the fuel, relative to diesel, sees hydrogen fuel cell trains require additional fuel storage tenders. Like battery electric, this reduces their freight carrying capacity by ~1%, thereby increasing levelised costs per tonne-km.

Hydrogen combustion

Cost analysis was unable to be conducted for a hydrogen combustion train due to a lack of sufficient data. While hydrogen combustion locomotives could present fewer near-term upfront costs by retrofitting diesel combustion locomotives, over the long-term it is expected that hydrogen fuel cell systems would be the preferred drivetrain for hydrogen fuel. Fuel cells offer higher efficiencies serving to minimise payload trade-offs and regenerative braking potential, reducing overall energy requirements.[245]

Box 7: Rail supplementary case study: Long-range, 2800km freight return journey

Key messages

- For all technologies, the LCOT reduces on a per tonne-km basis as journey length increases.
- Technology analysis concludes that unlike in the short-range assessment, battery-electric trains are unsuitable for long-distance rail haulage due to large charging demands and larger numbers of battery tenders to meet energy requirements, which in turn incur additional capex and opex costs and reduce payloads.
- Hydrogen FCEVs are projected to be cost competitive in the long-term, albeit with some payload losses compared to conventional technologies. Hybrids are projected to be a feasible and cost competitive solution in the near-term; however, the abatement potential is limited (see *6.4.1*).
- Cost analysis was unable to be conducted for a hydrogen combustion train due to a lack of sufficient data. While hydrogen combustion locomotives could present fewer near-term upfront costs by retrofitting diesel combustion locomotives, over the long-term it is expected that hydrogen fuel cell systems would be the preferred drivetrain for hydrogen fuel.

A supplementary case study was conducted to analyse the feasibility of technologies for more energy-intensive applications. For technology analysis, the refuelling threshold was not adjusted (as train size was held constant) and the range was increased to 2800km. The following ratings in Table 36 were applied.

Table 36: Technology analysis results

Technology *Threshold>*	Refuelling/recharging duration *Approx.4 hours*		Range *≥2,800km*	
Battery electric	>4 hours. For the size of energy required for this case study (132MWh), a charging system would require 33MW power capacity (i.e., approx. 7x 5MW chargers).[246] Chargers of this scale are yet to be developed and would require incur significant infrastructure costs (not captured in LCOT).		>2,800. Can always be met using tenders.[247] Significantly reduced payload (20% reduction).	
Catenary electric	Unlimited, infrastructure dependant		>2,800, infrastructure dependant	
Hydrogen combustion	30 minutes[248]		>2,800, can always be met using tenders	
Hydrogen fuel cell	30 minutes		>2,800, can always be met tenders.[249] Reduced payload (6% reduction).	

For refuelling/recharging, the size of the battery system required would not be able to be recharged in the (un)loading window without developments in charging power and may be prohibited by cost barriers. Like for the short-range case, the scalable configuration of the train always allows for range requirements to be met for hydrogen and battery-powered locomotives. However, high energy requirements amplify payload losses associated with the addition of fuel tenders at the expense of cargo.

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[245] Ding D, Wu XY (2024) Hydrogen fuel cell electric trains: Technologies, current status, and future. Applications in Energy and Combustion Science 17,. doi:10.1016/j.jaecs.2024.100255

[246] Please note, these are simple estimates, approximated via a power-to-energy calculation which provides a general sense of charging time but does not account for more complex factors like non-linear charging curves or energy losses. Technology breakthroughs enabling higher charging capacities and operational strategies such as establishing multiple charging bays, rotating battery tenders and optimising routes for regenerative breaking can reduce these times substantially.

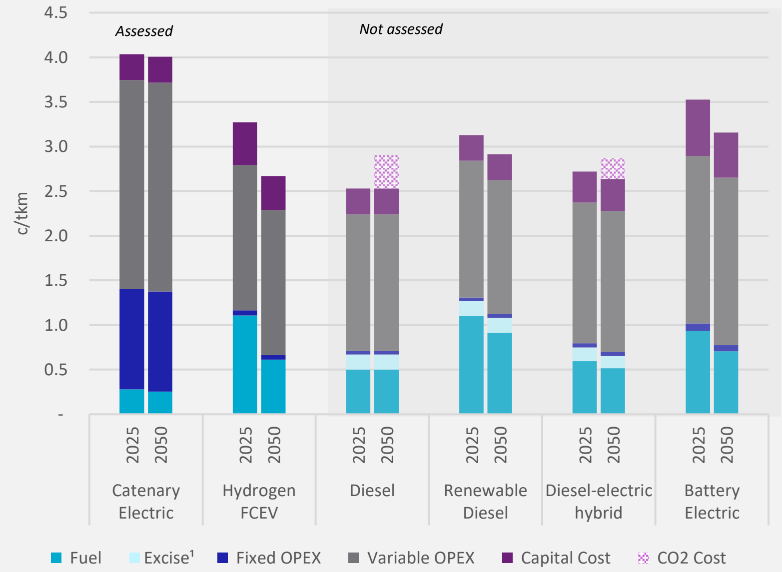
[247] Payload reduction as per cost analysis.

[248] 7,200kg of LH_2 fuel is required for this end-use case. A flow rate of 300kg/min would refuel to the train in approximately 24mins. Ehrhart B, Anleu G, Mohmand J, Klebanoff L, Baird A (2021) Current Efforts in Hydrogen for Rail. International Hydrail Conference June 2021. <https://www.osti.gov/servlets/purl/1874683>; Ling-Chin J, Giampieri A, Wilks M, Lau SW, Bacon E, Sheppard I, Smallbone AJ, Roskilly AP (2024) Technology roadmap for hydrogen-fuelled transportation in the UK. International Journal of Hydrogen Energy 52, 705. doi:10.1016/j.ijhydene.2023.04.131.

[249] Payload reduction as per cost analysis.

The LCOT is measured on a per tonne-km basis (c/tkm), and diesel is estimated to remain the lowest cost technology in the near term (Figure 17). Hydrogen fuel cell configurations are estimated to be the lowest cost technology in 2050.

Figure 17: Levelised cost of transport (c/tkm) – Rail, 2800km return journey



Note: 1. Fuel excise is typically claimed back via a fuel tax credit for this use case. The perceived cost of diesel and hybrid configurations would therefore not include this component, reducing their levelised cost. 2. Variable operational costs include labour, maintenance of locomotives and tenders as well as Fixed Track Access Charges (FTAC) that contribute to maintenance of the track and associated infrastructure.

The LCOT results also reflect the suitability of power modes with a higher volumetric density for long distances; whereby LH_2 (8.5MJ/L) is a more efficient fuel carrier compared to Li-ion batteries (0.83-3.6MJ/L). As such, fewer additional tenders will be required for hydrogen fuel cell trains than for battery electric leaving more cargo capacity per train and reducing levelised costs. As fuel costs are a key driver in levelised cost differentiation between the technologies, this benefit, coupled with the reduced costs of hydrogen fuel drives the competitiveness of hydrogen fuel cell trains out to 2050.

Battery electric is estimated to not be the second most costly technology for this end-use case in both 2025 and 2050. The large number of battery tenders required creates additional capital and maintenance costs, while reducing payload capacity, thereby increasing costs per tonne-km.

6.5 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 Battery electric locomotives and hydrogen fuel cell locomotives as *Primary technologies* for a short-range haulage use case.

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the rail 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 and energy efficiency solutions identified for analysis are outlined in Figure 18 below. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Figure 18: Technology landscape identification - Non-road, Rail

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

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

Auxiliary technologies

Battery electric locomotives and hydrogen fuel cell locomotives cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 37.

Table 37: Auxiliary technologies – Rail

Primary technology	Auxiliary technology	Description
Battery electric locomotive	**Low emissions electricity generation and distribution**	Infrastructure required to produce and transport low emissions electricity to end-users. Refer to the *Electricity* technical appendix for further detail.
	Energy storage and charging systems	Technologies that allow for energy flows to be managed between rail, grid and energy storage systems. This also includes charging systems that transfer electricity to the on-board drivetrain at sufficient power output.
	Tools to optimise train configurations	Computational models and algorithms to establish train configures that meet energy demands of tailored routes, and can assist in train design and optimisation
Hydrogen fuel cell locomotives	**Liquid hydrogen dispensing**	Dispenser nozzle that safely transfers liquid hydrogen from storage tanks to the onboard storage with appropriate pressure control and temperature management.
	Hydrogen storage and distribution	The infrastructure and technologies required to store liquefied hydrogen and distribute it to refuelling stations.
	Tools to optimise train configurations	Computational models and algorithms to establish train configures that meet energy demands of tailored routes, and can assist in train design and optimisation

Energy efficiency solutions

For rail transport, there are a range of energy efficiency solutions that will also support emissions mitigation efforts. These solutions are outlined in Table 38.

Table 38: Energy efficiency solutions – Rail

Energy efficiency solution	Description

Technology and componentry improvement	Improves energy efficiency by improving drivetrain/transmission efficiencies
Drag reduction and design	Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles
Energy management solutions	Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, and enhance battery life (where relevant)
Lightweighting	Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.
Traffic and logistics management technologies	Improves energy efficiency by optimising vehicle movement and operation.

6.6 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, 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 39. 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: all cost-related targets have been obtained from literature and reflect aspirational costs required to make a technology cost competitive, agnostic of country-specific RD&D. While converted into Australian currency, these figures assume large impacts from economies of scale which may not represent Australia's capacity for manufacturing. Elsewhere, Levelised Cost forecasts have been determined, referring to 2050 costs or assumptions, as calculated via CSIRO levelised cost analysis during technology analysis.

Table 39: Summary of RD&D opportunities – Rail [250]

		Battery electric locomotive		Hydrogen fuel cell locomotive	
		Battery cell			
Primary technologies		Metal-ion	Metal-S	Fuel cells	On-board storage
	Commercial	Li-ion	-	Proton exchange membrane (PEM) fuel cell	Liquid hydrogen tanks
	Mature	-	-	Solid oxide fuel cell (SOFC)	-
	Emerging	Li solid state	Li-S	-	-
Primary RD&D		• Reduce battery cell costs **(Target**: **$117/kWh, cf. $229/kWh)** through: - E.g. Improving energy densities **(Target: Li-ion >300Wh/kg, cf. 200-300Wh/kg)** - E.g. Optimising high energy and high power material combinations • Improve thermal stability of batteries through: - E.g. Improving the thermal stability of electrodes - E.g. Adopting a battery/thermal management system		• Reduce fuel cell costs **(Target: $240/kW, cf. $1031/kW)** through: - E.g. Improving fuel cell efficiency **(Target: 55% beginning-of-life, 50% end-of-life)** - E.g. Improving the durability of fuel cell membranes and catalysts • Verify less technologically mature fuel cells under heavy haulage conditions	• Reduce storage costs through: - E.g. Improving system lifespan **(Target: 5000 cycles)** - E.g. Minimising boil-off **(Target: below 0.1%)**
Auxiliary RD&D		• Develop electric locomotive supply equipment through: - E.g., Developing fast charging systems **(Target: >5MW[4])** • Optimise rail operations for electric locomotives through: - E.g. Integrating rail-to-grid battery energy storage systems - E.g. Optimising the configuration of locomotives, tenders and wagons for specific routes and applications		• Support adoption through the development of hydrogen refuelling infrastructure: - E.g. Develop faster fill rates **(Target: >100kg/min)** • For Hydrogen distribution and storage RD&D opportunities, see *Low Carbon Fuels* technical appendix	

[250] 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.

6.6.1 Battery electric locomotives

Battery electric locomotives employ battery-powered drivetrains which store and supply electrical energy. They can operate by themselves or with other locomotives and be recharged with electrical power from stationary recharging infrastructure.[251]

The onboard power demands of heavy haulage rail systems far exceed those required for road transport. This performance challenge is amplified by ownership structures, where freight companies often do not own land at destination locations or along rail corridors; necessitating that round-trip energy capacity be carried on-board where mid-point refuelling is not practical.[252] Therefore, the adoption of electric locomotives will require the development of large, cost effective battery systems and advanced electric locomotive supply equipment. As such, these things are the primary focus in the following RD&D discussion.

Primary technologies

Developing large, cost-effective battery systems ($/kWh) could improve the commercial viability of electric locomotives and help these systems meet the power demands of heavy haulage rail.

Based on the cost analysis conducted in this technical report, a 700km return journey has a system energy requirement of 33.1MWh for a battery electric train, across 2 locomotives. If 2035 Li-ion cell-level target estimates of $75-150/kWh (cf. $150-290)[253] are met, this battery system would cost between $2.5-5 million. Using a median value, this equates to a total cost of approximately $5.8million for each battery electric locomotive, compared to $5.1million for each diesel locomotive.[254]

Improving battery cell energy densities and optimising material combinations could enhance battery performance while reducing system costs. In the near-term, Li-ion systems are expected to remain a critical solution for battery-powered locomotives due to their commercial maturity, with the use of high-energy materials offering potential to improve energy to mass ratios. For rail, LFP ($LiFePO_4$) has been identified as a promising Li-ion chemistry due to lower costs and higher cycling stability; however, there are a number of high-energy materials (NMC or NCA) and high-power materials (LFP or LTO) that could be combined to optimise material combinations further.[255] High-energy materials have high energy densities, allowing for longer ranges and running time per charge. High-power materials are optimised for power density, allowing them to deliver charge quickly, making them suitable for applications requiring rapid energy inputs and outputs such as acceleration and regenerative breaking.

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[251] Iden M.E (2021) Battery Electric Locomotives & Battery Tenders: Operational & infrastructure challenges to widespread adoption. Proceedings of the 2021 Joint Rail Conference JRC2021.

[252] NMC – Nickel Manganese Cobalt, NCA – Nickel Cobalt Aluminium, LFP – Lithium Iron Phosphate, LTO – Lithium Titanate Oxide. Knibbe R, Harding D, Cooper E, Burton J, Liu S, Amirzadeh Z, Buckley R, Meehan PA (2022) Application and limitations of batteries and hydrogen in heavy haul rail using Australian case studies. Journal of Energy Storage 56,. doi:10.1016/j.est.2022.105813

[253] Annegret Stephan, Tim Hettesheimer, Christoph Neef, Thomas Schmaltz, Steffen Link, Maximilian Stephan, Jan Luca Heizmann, Axel Thielmann (2023) Alternative Battery Technologies Roadmap 2030+. doi:10.24406/publica-1342; Slowik P, Isenstadt A, Pierce L, Searle S (2022) Assessment of light-duty electric vehicle costs and consumer benefits in the United States in the 2022–2035 time frame, the International Council on Clean Transport. Where required, cost targets are converted from EUR to AUD by applying a conversion rate of 1AUD=0.61EUR and USD to AUD by applying a conversion rate of 1AUD=0.66USD, representing annual average exchange rates from Feb 2023 – Feb 2024.

[254] The diesel locomotive cost assumes the energy requirement for the journey is 42.7MWh.

[255] Knibbe R, Harding D, Cooper E, Burton J, Liu S, Amirzadeh Z, Buckley R, Meehan PA (2022) Application and limitations of batteries and hydrogen in heavy haul rail using Australian case studies. Journal of Energy Storage 56,. doi:10.1016/j.est.2022.105813; Knibbe R, Meehan P (2022) Decarbonising Australian railway fleets with batteries. <https://mechmining.uq.edu.au/article/2022/02/decarbonising-australian-railway-fleets-batteries>; Barbosa F (2023) Battery only electric traction for freight trains - A technical and operational assessment. DOI: 10.1177/09544097231160613

Performance jumps could also be achieved through next-generation alternative Li-based chemistries. Notably, Li-based solid state and Li-S have achieved over 500Wh/kg in lab-based demonstrations. Others, like metal-air batteries, offer even higher capacities, however these batteries are at low maturity (TRL 1-2), and not investigated further here.[256]

RD&D to enhance the thermal stability of batteries could make them safer and more practical for use in large scale electric locomotives.

Like other BEVs, battery electric locomotives have safety challenges related to high-voltage systems and thermal runaway, necessitating RD&D to mitigate these risks particularly under high cycling conditions. RD&D focused on improving the thermal stability of electrodes or improving battery management systems to avoid explosion, gassing and intoxication[257] and enhance thermal management,[258] are potential opportunities for advancement.

Auxiliary technologies

RD&D to advance electric locomotive supply equipment and optimise rail operations, could play a significant role in supporting the successful electrification of trains.

Developing ultra-fast charging systems of >5MW capable of efficient charging with minimum battery degradation, could prove to be a major lynch point for driving electric locomotive adoption.[259] Moreover, integrating and optimising rail-to-grid energy storage systems that provide real-time energy management, could provide significant energy efficiency improvements.[260] Lastly, developing advanced modelling and simulation tools could effectively optimise the configuration of locomotives, tenders and wagons for specific routes and applications or serve to identify trade-offs between energy capacity and payloads.[261]

6.6.2 Hydrogen fuel cell locomotives

Hydrogen fuel cell locomotives employ a hydrogen fuel cell system that generates electric power from e-hydrogen, to drive an electric traction system. This is coupled with an onboard storage system, generally cryogenic, to meet energy demands.

Two fuel cell types are considered candidates for heavy rail haulage, due to their properties and performance: PEM fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs).[262] PEMFCs are technologically mature with high-

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[256] Wang MJ, Kazyak E, Dasgupta NP, Sakamoto J (2021) Transitioning solid-state batteries from lab to market: Linking electro-chemo-mechanics with practical considerations. Joule 5, 1371. doi:10.1016/j.joule.2021.04.001; Duffner F, Kronemeyer N, Tübke J, Leker J, Winter M, Schmuch R (2021) Post-lithium-ion battery cell production and its compatibility with lithium-ion cell production infrastructure. Nat Energy 6, 123. doi:10.1038/s41560-020-00748-8

[257] Batteries Europe (2023) Research and Innovation Roadmap on Battery Technologies Powering Europe’s Green Revolution: Paving the Way to a More Resilient and Sustainable Battery Industry.

[258] Olabi AG, Maghrabie HM, Adhari OHK, Sayed ET, Yousef BAA, Salameh T, Kamil M, Abdelkareem MA (2022) Battery thermal management systems: Recent progress and challenges. International Journal of Thermofluids 15,. doi:10.1016/j.ijft.2022.100171

[259] Barbosa FC (2022) Battery Electric Rail Technology Review - A Technical and Operational Assessment. Current Status, Challenges and Perspectives. *Proceedings of the 2022 Joint Rail Conference. 2022 Joint Rail Conference*. ASME. DOI: 10.1115/JRC2022-78133; Batteries Europe (2023) Research and Innovation Roadmap on Battery Technologies Powering Europe’s Green Revolution: Paving the Way to a More Resilient and Sustainable Battery Industry.

[260] IEA. Clean Technology Guide, <https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide> (accessed June 2024)

[261] Knibbe R, Harding D, Burton J, Cooper E, Amir Zadeh Z, Sagulenko M, Meehan P, Buckley R (2023) Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives. Journal of Energy Storage 71,. doi:10.1016/j.est.2023.108090.

[262] Knibbe R, Harding D, Burton J, Cooper E, Amir Zadeh Z, Sagulenko M, Meehan P, Buckley R (2023) Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives. Journal of Energy Storage 71,. doi:10.1016/j.est.2023.108090 Ding D, Wu XY (2024) Hydrogen fuel cell electric trains: Technologies, current status, and future. Applications in Energy and Combustion Science 17,. doi:10.1016/j.jaecs.2024.100255

power densities, however they face high production costs due to the use of platinum catalysts. Comparatively, SOFCs have higher operating temperatures and can recuperate waste heat to achieve higher operating efficiencies. However, their volumetric density is lower than PEMFCs and there is a lack of commercial demonstration of SOFCs in mobile applications. There is a clear need for RD&D to enhance the technical and economic viability of hydrogen fuel cell locomotives. These challenges are the primary focus of the following RD&D discussion.

Primary technologies

Reducing hydrogen fuel cell and storage costs, will require targeted RD&D to overcome key technical barriers.

Meeting target fuel cell costs ($240/kW, cf. $1031/kW) will depend on improving both fuel cell efficiency and durability. For example, improving the efficiency of PEM fuel cells (target: 55% beginning of life, 50% end of life) while reducing costs could be achieved by developing novel cell membranes and non-platinum catalysts. RD&D in these areas could help realise the potential of hydrogen fuel cells in heavy rail haulage applications, where high payloads and long distances make battery based alternatives less viable.

In terms of reducing the cost of hydrogen storage, examples include improving the lifespan of storage systems (target: 5000 cycles) or minimising hydrogen boil off (target: below 0.1%). These RD&D efforts could help spread capital costs over more operational cycles, reduce fuel waste and lower refuelling frequency. For greater detail on improving the economic viability of hydrogen storage systems, refer to the *Low Carbon Fuels* technical appendix.

Verifying the potential of hydrogen fuel cells under heavy haulage conditions, could accelerate the development and deployment of hydrogen based locomotives.

Demonstrating high temperature fuel cells, such as solid oxide fuel cells, in real world settings could help validate performance and identify new RD&D opportunities. While PEM fuel cells are more commercially mature, many of their key performance parameters (such as quick start-up times) are better suited to light rail applications. RD&D is therefore needed to improve existing systems and to explore alternative fuel cell technologies that might be better suited to the demands of heavy haulage rail.

Auxiliary technologies

RD&D to develop advanced hydrogen refuelling infrastructure, could play a significant role in supporting the successful deployment of hydrogen fuel cell trains.

For freight locomotives, the hydrogen tank capacity is around 20 times higher than for heavy road transport.[263] Therefore, depending on the application and its energy demand, achieving LH_2 fill rates of >100kg/min will be important. RD&D focused on establishing liquid hydrogen refuelling facilities with high flow rates similar to conventional diesel pumps presents is a clear opportunity that could encourage technology adoption.

Similar to battery electric trains, RD&D to optimise the configuration of hydrogen locomotives, tenders and wagons for specific routes and applications could significantly improve operational efficiencies.

As hydrogen fuel cells operate best under continuous conditions, hybrid systems (i.e., battery-hydrogen fuel cell systems), are common in rail studies. In these configurations, batteries provide a buffer for excess power

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[263] US DOE (2024) Multi-Year Program Plan. Hydrogen and Fuel Cell Technologies Office.<https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf>; Ehrhart B, Anleu G, Mohmand J, Klebanoff L, Baird A (2021) Current Efforts in Hydrogen for Rail. International Hydrail Conference June 2021. <https://www.osti.gov/servlets/purl/1874683>

supply and demand and allow for regenerative braking which can greatly reduce net energy storage requirements.[264] Developing advanced modelling and simulation tools to optimise configurations, verified by field tests, will be important for balancing locomotives, energy storage units and regenerative braking capacity.[265]

The feasibility and viability of hydrogen fuel cell trains will be heavily influenced by the production, storage and distribution of hydrogen for operational use.

For details on hydrogen based RD&D opportunities, refer to the *Low Carbon Fuels* technical appendix.

6.6.3 Energy efficiency solutions

Further RD&D in solutions that reduce energy use in rail transport will also support emissions mitigation efforts. The solutions outlined in Table 40 are technology-agnostic with the ability to improve energy efficiencies across a range of technology types and systems. While many of these solutions have been the focus of past research efforts, they may evolve alongside advancements in materials, digital technologies and system innovations, offering incremental improvements in transport efficiency.

Table 40: Energy efficiency RD&D opportunities – Rail

Theme	RD&D opportunities[266]
Drag reduction and design *Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles.*	• Design vehicles with improved aerodynamics to enhance energy efficiency and reduce air resistance. Including by implementing drag reduction structures such as nose fairings, air deflectors, skirts etc. • Modelling systems to analyse airflow and optimise train configurations including car spacings, arrangement of locomotives, and the use of distributed power systems on aerodynamic drag.
Lightweighting *Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.*	• Develop advanced composite materials and alloys with high strength and low weight
Technology and componentry improvement *Improves energy efficiency by improving drivetrain/transmission efficiencies.*	• Electric drivetrain components (motors, power electronics) that optimise energy conversion and reduce losses.

[264] Fragiacomo P, Piraino F, Genovese M, Flaccomio Nardi Dei L, Donati D, Migliarese Caputi MV, Borello D (2022) Sizing and Performance Analysis of Hydrogen- and Battery-Based Powertrains, Integrated into a Passenger Train for a Regional Track, Located in Calabria (Italy). Energies 15,. doi:10.3390/en15166004

[265] Zhang B, Lu S, Peng Y, Wu C, Meng G, Feng M, Liu B (2022) Impact of On-Board Hybrid Energy Storage Devices on Energy-Saving Operation for Electric Trains in DC Railway Systems. Batteries 8,. doi:10.3390/batteries8100167; Murray-Smith D (2022) Simulation models in hybrid train design: Issues of fitness for purpose. <https://www.globalrailwayreview.com/article/132743/simulation-models-in-hybrid-train-design-issues-of-fitness-for-purpose/> (accessed June 2024).

[266] DCCEEW (n.d.) Rail Transport. <https://www.energy.gov.au/business/sector-guides/transport/rail-transport>; Cole C, Sun Y, Wu Q, Spiryagin M (2024) Exploring hydrogen fuel cell and battery freight locomotive options using train dynamics simulation, 238(3). DOI: 10.1177/09544097231166477; Knibbe R, Harding D, Burton J, Cooper E, Amir Zadeh Z, Sagulenko M, Meehan P, Buckley R (2023) Optimal battery and hydrogen fuel cell sizing in heavy-haul locomotives. Journal of Energy Storage 71,. doi:10.1016/j.est.2023.108090; Ling-Chin J, Giampieri A, Wilks M, Lau SW, Bacon E, Sheppard I, Smallbone AJ, Roskilly AP (2024) Technology roadmap for hydrogen-fuelled transportation in the UK. International Journal of Hydrogen Energy 52, 705. doi:10.1016/j.ijhydene.2023.04.131; Riabov I, Goolak S, Kondrtieva L, Overianova L (2023) Increasing the energy efficiency of the multi-motor traction electric drive of an electric locomotive for railway quarry transport. Engineering Science and Technology, an International Journal. doi: 10.1016/j.jestch.2023.101416

Traffic and logistics management technologies *Improves energy efficiency by optimising vehicle movement and operation.*	• Predictive maintenance technologies that use ML and data analytics to monitor health of locomotives and freight cars to prevent breakdowns, reduce downtime and optimise maintenance. • Develop algorithms for real-time traffic prediction and optimisation
Energy management solutions *Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, enhancing battery life.*	• Develop and refine advanced regenerative braking systems, particularly those optimised for heavy haulage. • Optimise integration of energy storage systems with regenerative braking systems to more efficiently re-use recovered energy. • Advanced simulation/modelling and energy management systems to optimise the use of regenerative braking, including real-time monitoring of rail train dynamics, track conditions and energy requirements.

7 Shipping

7.1 Executive summary

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 LPG infrastructure. Shipping infrastructure compatibility and strict handling requirements will drive technology preference.

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

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

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 subsector. 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.

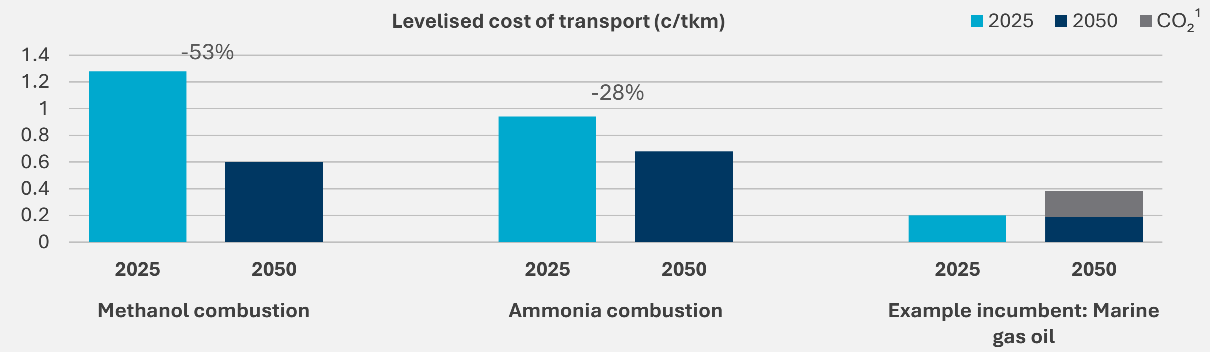
Auxiliary

- Deploying these technologies depends on 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 *Levelised cost analysis* and *Technical Appendix: Levelised cost analysis* for assumptions. Note, c/tkm = cents/tonne – km.

7.2 Introduction

In 2023, the International Maritime Organisation (IMO) adopted the 2023 IMO Greenhouse Gas (GHG) Strategy, targeting net-zero emissions for international shipping by or around 2050.[267] As part of this strategy, countries that register ships must pay a carbon price per tCO_2e on any emissions over an established baseline.[268] Those that do not comply, risk having their ships barred from ports, prevented from working with compliant organisations or excluded from international trade.[269] Achieving net zero presents significant challenges for the shipping sector, particularly in deep-sea operations, where high energy demands and reliance on fossil fuels, particular heavy oil, make the transition to low emissions alternatives both technically and economically complex. The global scale of shipping across these operations further compounds these challenges, requiring coordinated efforts across industry, infrastructure and regulatory frameworks.

In Australia, domestic shipping services account for 1% of Australia's total transport emissions, emitting 2 $MtCO_2e$ in 2023-2024.[270] Although shipping makes up a smaller share of overall domestic transport emissions relative to the other sectors, Australia's role in global trade is significant and contributes substantially to global international trade emissions. In 2020, Australia accounted for 14% of global sea freight, contributing to 4% of global CO_2 emissions.[271] Decarbonising the maritime sector will be essential for not only reducing emissions, but also for supporting enabling and facilitating new green export industries.[272]

Like other non-road transport sectors, the long asset lifespans of maritime vessels (often exceeding 25 years), contribute to slow fleet turnover and make transitions challenging. As such, there is growing interest in retrofitting existing ships and deploying dual-fuel engines as transitional solutions to reduce emissions while maintaining operational viability.

Decarbonising deep-sea shipping remains particularly challenging due to the need for high energy density fuels that can sustain multi-week voyages without refuelling. Long-haul operations require alternative fuels capable of delivering comparable energy performance to conventional marine fuels. Several low emissions pathways are being explored, including a broad array of biofuels, synthetic fuels, hydrogen (and derivatives); however, each present distinct challenges related to fuel production, distribution and vessel compatibility, each of which introduce cost and logistical challenges. The infrastructure requirements for alternative fuels are particularly complex, relying on extensive refuelling networks at ports to support new energy carriers.

Overcoming these hurdles will require substantial investment, technological advancements, as well as supportive policy frameworks to coordinate and incentivise adoption.

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[267] IMO (n.d.) IMO's work to cut GHG emissions from ships. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx (accessed March 2025)

[268] European Commission (2025) Landmark agreement towards achieving net-zero emissions from global shipping by 2050. <https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_25_1037/IP_25_1037_EN.pdf>; Bush D (2025) IMO approves historic carbon price agreement. Lloyd's List. <https://www.lloydslist.com/LL1153160/IMO-approves-historic-carbon-price-agreement>.

[269] European Commission (2025) Landmark agreement towards achieving net-zero emissions from global shipping by 2050. <https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_25_1037/IP_25_1037_EN.pdf>; Bush D (2025) IMO approves historic carbon price agreement. Lloyd's List. <https://www.lloydslist.com/LL1153160/IMO-approves-historic-carbon-price-agreement>.

[270] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

[271] DITRDCA (2023) Australia's Maritime Context and Emission Reduction Initiatives. September 2023. <https://www.infrastructure.gov.au/sites/default/files/documents/mernap-background-presentation.pdf> (accessed March 2025)

[272] DITRDCA (2023) Maritime Emissions Reduction National Action Plan - Scoping paper for Consultative Group. June 2023. <https://www.infrastructure.gov.au/sites/default/files/documents/scoping-paper-final.pdf> (accessed March 2025)

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

7.2.1 Shipping use case(s)

To explore low emissions technologies in the shipping subsector, a single use case has been defined to reflect a deep-sea Panamax class freight vessel, capable of a 12,100 km journey (Table 41). Through the technology analysis framework, the technologies explored by this study meet select criteria associated with this use case.

This use case is representative of a multi-stop domestic shipping (as part of an international shipping route), critical for allowing Australia to continue to contribute to international trade via sea routes.

A supplementary case study was also conducted (see Box 8), to assess the feasibility of technology options for an application in which longer distances are required, therefore incurring higher energy demands. This case study reflects an operational profile for short-sea ferrying over a 100 km journey.

These use cases are illustrative and present requirements that technologies must be able to meet in order to service Australia's shipping subsector. In reality, operations in Australia are diverse and require vessels of varying size and carrying capacity, over variable distances.

Table 41: Use case(s) – Shipping

Use case(s)	Deep-sea shipping
Description:	**A deep-sea Panamax class freight vessel on a 12,100km journey.** The vast majority of shipping services in Australia are for freight.[273] As a subsector, domestic shipping is responsible for 2 $MtCO_2e$, which equates to 9% of Australia's domestic non-road emissions.[274]

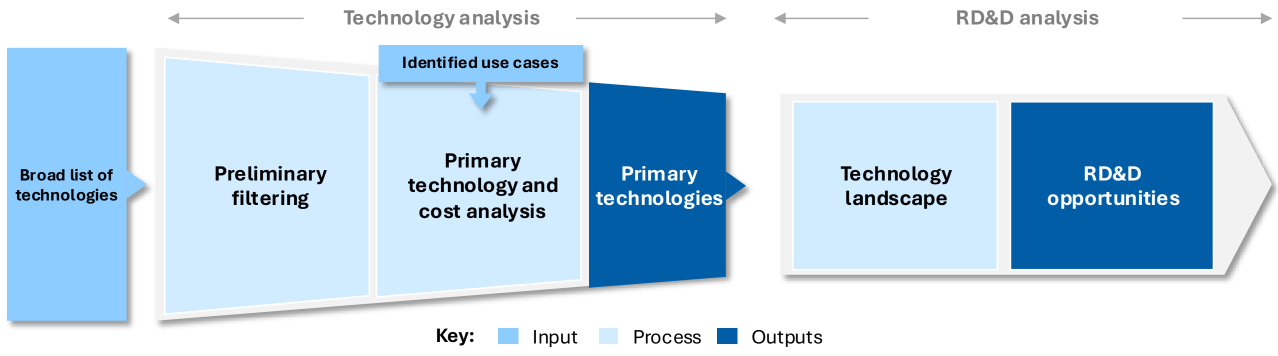
7.3 Methodology: Shipping inputs and criteria

The methodology is comprised of several steps. Technology analysis was performed to first determine prospective technologies with the potential to contribute to decarbonisation for the designated use case. This underpinned RD&D analysis, designed to identify broad workstreams that could drive impactful technological progress (Figure 19).

[273] Based on unpublished BITRE statistics supplied to CSIRO.

[274] BITRE (2025) Australian Infrastructure and Transport Statistics Yearbook 2024. <https://www.bitre.gov.au/sites/default/files/documents/australian-infrastructure-and-transport-statistics--yearbook-2024--january-2025.pdf> (accessed 25 March 2025).

Figure 19: Technology and RD&D analysis framework for shipping



7.3.1 Broad technology list

A broad technology list comprised of eight technologies was developed (Table 42). These technologies were then passed through four preliminary filters: relevance to Australia, technological maturity, abatement potential and safety. The technologies that satisfied the preliminary filters were then assessed against the performance parameters for the relevant use case(s).

Table 42: Technology category definitions – Shipping

Technology category	Definition
Ammonia combustion	Vessels which employ combustion engines adapted for ammonia. As a low emissions solution, it is assumed that the vessel operates on e-ammonia as a fuel, produced with electrolytic hydrogen via the Haber-Bosch synthesis.
Biofuels (FAME; HVO)	Vessels which employ standard combustion engines that operate on liquid biofuels, including fatty acid methyl ester (FAME) or hydrotreated vegetable oil (HVO).
Battery electric	Vessels which operate using battery-powered drivetrains which store and supply electrical energy.
Fossil fuels with OCCUS	Vessels which employ standard combustion engines operating on fossil fuels, coupled with on-board carbon capture, utilisation and storage (OCCUS) systems to capture and store carbon emissions during combustion.
Hydrogen combustion	Vessels which employ a combustion engine adapted for hydrogen, generally coupled with cryogenic liquid hydrogen storage.
Hydrogen fuel cells	Vessels which employ a hydrogen fuel cell to drive an electric drivetrain. Hydrogen is generally stored in cryogenic liquid form and vaporised to gaseous hydrogen for use in the fuel cell.
Methanol combustion	Vessels which employ combustion engines adapted for methanol use. To be considered a low emissions technology solution, low emissions methanol is required for operation. [275]
Nuclear propulsion	Vessels equipped with nuclear reactors that use nuclear fission to generate heat for driving propulsion systems.

[275] Methanol engines are agnostic to the methanol used to fuel them, with low emissions methanol able to be produced synthetically (i.e., e-methanol, with electrolytic hydrogen and CO_2 from direct air capture/point source) or from biomass (i.e., biomethanol, with renewable hydrogen and carbon from biogenic sources).

7.3.2 Additional preliminary filtering criteria

An additional preliminary filter has been adopted for shipping: *Safety* (Table 43).

A core challenge area for the shipping sector relates to managing safety risks, particularly those related to toxicity, flammability and explosion risks in confined, on-board environments. These safety risks not only relate to on-board personnel, but also those involved in bunkering procedures. Environmental and ecosystem safety must also be considered, in the advent of fuel spillage or leakage.

The safety filter identifies technologies that possesses standard and manageable safety risks. Safety ratings have been qualitatively assessed relative to the shipping industry standard of being 'as low as reasonably practical' (ALARP) across the handling, bunkering and onboard use of these technologies.[276] These ratings draw upon the National Fire Protection Association (NFPA) Hazard Identification system, which identifies the degree of severity of the health, flammability, instability, and specific hazards associated with hazardous materials.

7.3.3 Primary technology filters

Applications in non-road transportation are commonly grouped together due to their extreme performance requirements and high energy demands that are not typically faced by road transport vehicles. To assess potential mitigation technologies, relative to a Panamax class vessel operating on marine diesel oil (MDO) fuel, two performance filters were adopted: **range and cost** (Table 43)**.** These performance parameters, were deemed to be core operational requirements that will enable or limit technology uptake, particularly given the energy and cost intensive nature of the subsector.

The threshold for range was informed by the distance to many of Australia's trading partners, principally those in the Asia Pacific (APAC) region. Though, longer range capabilities to access more distant regions and ports or enable greater maritime flexibility.

Unlike other non-transport subsectors, refuelling duration was not assessed. Berthing times generally exceed 30hrs, allowing sufficient time for refuelling across most technology systems. The average berthing time across major Australian container ports was approximately 45hrs in 2021/22.[277]

The lowest cost mitigation technologies able to meet the minimum range requirement for a single trip, were progressed for further RD&D opportunity analysis. Further details on the selected parameters are provided in *Section 7.4.2 Primary technology analysis* .

Table 43: Use cases and technology filtering criteria – Shipping

Subsector	Shipping
Use case(s)	**Deep-sea shipping**
Preliminary filtering criteria	**Relevance to Australia** Technology can be reasonably deployed and assist in decarbonisation efforts under Australian conditions.

[276] CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra; Together in Safety (2022) Future Fuel Risk Assessment. <https://togetherinsafety.info/wp-content/uploads/2022/06/Future-Fuels-Report.pdf>

[277] ACCC (2022) Container stevedoring monitoring report 2021-2022. December 2022. ACCC, Canberra ACT.

	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 meets or exceeds an abatement threshold of 90%, relative to a vessel of the same class operating on marine diesel oil (MDO).
	Safety Technology possesses standard and manageable safety risks, characterised as being 'as low as reasonably practical' (ALARP). *Additional criteria considered due to heighted risks to personnel and marine environments associated with alternative marine fuels, compounded with confined on-board spaces on vessels.*
Primary technology filters	**Minimum range requirement** Technology can meet an acceptable distance threshold in a single trip.
	Levelised Cost of Transport (LCOT) 2050 Technologies projected to be cost competitive by 2050, distinguished by a cost differential in LCOT relative to other assessed technologies.

7.4 Technology analysis

The chapter outlines the process of identifying primary technologies for deep sea shipping. Following the technology analysis framework process, **ammonia and methanol combustionemerged as primary technologies for further RD&D exploration.** These technologies were able to service the needs of the deep-sea shipping use case and satisfy all criteria. The other technologies assessed by the framework but not identified as *Primary technologies* could still play a role in shipping decarbonisation, for specific use cases, and over time RD&D can lead to new technologies worthy of consideration. The results of the technology analysis are provided in Table 44.

Table 44: Technology analysis results – Shipping[278]

Legend: Meets criteria | Meets with caveats | Does not meet | ★ Primary technology | Not assessed further

1. Preliminary filtering					2. Primary technology analysis: Deep-sea freight: 12,100 km journey		
Technologies	**Relevance to Australia**	**Maturity**	**Abatement potential[279]**	**Safety**	**Range**	**LCOT (2050)**	
Threshold		*TRL >3*	*90% decrease in emissions*	*As low as reasonably possible (ALARP)*	*>12,000km*	*c/t-km*	
Ammonia combustion		TRL 4-6	Near 100%	High toxicity	>12,100, payload reduced (-6%)	0.68	★
Biofuels (FAME; HVO)		TRL 9	36-84%				
Battery electric		No data for long distance	92%	Higher flammability than conventional	Not suitable for long distance. If battery system is scaled, payloads reduced by 17%		
Fossil fuels with OCCUS	Geo-dependent (CCS)	TRL 5-6	74%				
Hydrogen combustion		TRL 4-5	100%	Higher flammability than conventional	>12,100, payload reduced (-14%)	1.06	
Hydrogen fuel cells		TRL 6-8 (Small to medium vessels)	100%	Higher flammability than conventional	>12,100, payload reduced (-11%)	0.98	
Methanol combustion		TRL 9	100%		>12,100, payload reduced (-4%)	0.60	★
Nuclear propulsion		TRL 4-5	100%		>12,100	1.07	

278 Details for these figures, including sources/assumptions, are found in Table 46 (abatement potentials); Table 47 (safety); Table 48 (range) and under 'Levelised cost analysis' and *Technical Appendix: Levelised cost analysis* (LCOT).

279 Emissions estimates encompass the full fuel cycle (CO_2, N_2O and CH_4), where a medium-speed bulk-foreign vessel operating on MDO has an emissions estimate of 91.9gCO2e/MJ. The abatement potential threshold is set to 95%, reflecting the availability of cost competitive low emissions technology solutions by 2050.

7.4.1 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

All technologies were found to meet this criterion for the designated use case, as they can be reasonably deployed in the Australian context. For fossil fuel-powered systems with OCCUS, a 'meets with caveats' rating was determined.

For these vessels, the value chain ends with the utilisation of the captured CO_2 or its permanent geological storage in deep, underground formations. For the latter, 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 categories were found to meet this criterion, possessing a TRL greater than 3 (Table 45).

Maturity ratings are informed by desktop research, drawing on the IEA Clean Energy Technology Guide.[280] Please note, all maturity ratings reflect the readiness of the vessel, not the readiness of fuel synthesis pathways.

For battery electric vessels, the technology was deemed to meet the criteria with caveats. Small battery electric vessels have a TRL of 8-9, however, no reliable data was obtained for the maturity of long-distance shipping. It is expected that scaling these systems to the range required for deep sea shipping would present a number of technical challenges, including overcoming weight and payload penalties, in order to be effectively deployed in these applications.

Table 45: Technology maturities – Shipping

Technology	TRL
Ammonia combustion	• TRL 4-6
Biofuels (FAME; HVO)	• TRL 9
Battery electric	*No data for long distance; TRL 9 in short sea applications.*
Fossil fuels with OCCUS	• TRL 5-6
Hydrogen combustion	• TRL 4-5
Hydrogen fuel cells	• TRL 6-8 (Small to medium vessels) ○ **Proton exchange membrane (PEM):** TRL 8

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

	○ **Solid oxide fuel cell (SOFC):** TRL 7 ○ **Molten carbonate fuel cell (MCFC):** TRL 7 ○ **High-temperature PEMFC:** TRL 6
Methanol combustion	• TRL 9
Nuclear propulsion	• TRL 4-5

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 *Appendix **A.4**.*

Abatement potential was assessed based on a medium-speed vessel for international bulk-commodity shipping. The abatement potential was assessed against a vessel operating on marine diesel oil (MDO), with an emissions intensity of 91.87 gCO_2e/MJ. A 90% abatement potential threshold was set for shipping, reflecting both the expected availability of cost competitive low emissions technology solutions by 2050 and the challenges of decarbonising energy-intensive modes of transportation. This threshold also accounts for residual emissions in the grid, recognising that some fossil fuel capacity will likely remain in the long-term.

Greenhouse gas emissions considered, include methane (CH_4), nitrous oxides (N_2O) and carbon dioxide (CO_2). The emissions estimates (in CO_2 equivalents), as outlined in (Table 46), draw upon the US Argonne National Laboratory's GREET model which assesses life cycle emissions and environmental impact of given fuel and technology options. Specifically, the RD&D GREET Marine Module[281] was adopted, which allows for life cycle analysis of a set of conventional and alternative marine fuels.

For hydrogen vessels, hydrogen electrolysis facilities are assumed to operate with a 60% utilisation factor in 2050: aligning with electricity generation from variable renewable energy (VRE). Only operating electrolysers when renewable generation assets are online can enable zero emissions hydrogen production and allow for cost savings compared to higher utilisation rates (see *Low Carbon Fuels* technical appendix).

For technologies that rely on electricity or electricity-derived fuels, efforts have been made to adjust grid-born electricity emissions to reflect a prospective 2050 grid intensity in which 5% of current electricity generation occurs from peaking gas and the remainder generated from renewable resources.[282]

These principles similarly apply to synthetic fuels. The CO_2 component is assumed to be sourced from direct air capture (DAC), ensuring that combustion emissions are offset by prior capture. Hydrogen is produced via the process above during periods of surplus renewable generation.

[281] Argonne National Laboratory (2023) RD&D GREET Marine Module. Accessed July 2024. https://greet.anl.gov/greet_marine

[282] The emissions intensity (0.0307$kgCO_2$-e per kWh or 7.4gCO_2-e per MJ) is based on a prospective 2050 grid intensity in which 5% of electricity generation occurs from peaking gas, with the remainder generated from renewable resources and assumed to produce no direct emissions.

Table 46: Abatement thresholds – Shipping

Technology	ILUC *gCO_2e/MJ*	Biogenic CO_2 *gCO_2e/MJ*	Well-to-pump *gCO_2e/MJ*	Pump-to-wake *gCO_2e/MJ*	Well-to-wake *gCO_2e/MJ*	Abatement *Threshold: 90%*
Conventional MDO (0.5% sulphur)	-	-	13.2	78.7	**91.9**	
Ammonia combustion	-	-	-	Near 0	**Near 0**	Near 100%
Battery electric	-	-	-	7.4	**7.4**	92%
Hydrogen combustion	-	-	-	-	**-**	100%
Hydrogen fuel cells	-	-	-	-	**-**	100%
Fossil fuels with OCCUS	*Breakdown unavailable via GREET*				**23.9**	74%[283]
Methanol combustion	-	-	-	-	**-**	100%
Nuclear propulsion	-	-	-	-	**0**	100%
Biofuels						
1. FAME	1. 25.8	1. -76.3	1. 31.7	1. 76.3	1. **57.5**	1. 37%
2. HVO	2. NA	2. -73.7	2. 14.5	2. 73.7	2. **14.5**	2. 84%
3. Biomethanol	3. NA	3. -70.7	3. 12.6	3. 70.7	3. **12.6**	3. 86%

Ammonia combustion

e-ammonia combustion was deemed to meet the criteria with caveats, on the basis that while no CO_2 emissions are produced, there is potential for N_2O emissions.

Biofuels

Biofuels do not meet the criteria, with abatement potential estimated to be 37-84%. These figures account for ILUC impacts from feedstock production, where relevant.

Fossil fuels with OCCUS

OCCUS systems are currently unable to capture 100% of direct emissions from a ship's operations. Because of this limitation, fossil fuel pathways that rely on OCCUS do not meet the criteria set by this filter. For example, Mærsk McKinney Møller Center (2022) estimates that an OCCUS system with an 82% capture rate could achieve a 74% reduction in emissions relative to a conventional ship.[284]

Safety

The safety criterion identifies technologies that possesses standard and manageable safety risks (Table 47). Safety ratings have been qualitatively assessed relative to the shipping industry standard of being 'as low as reasonably practical' (ALARP) across the handling, bunkering and onboard use of these technologies.[285] These ratings draw upon the National Fire Protection Association (NFPA) Hazard Identification system, which

[283] Assumes 74% reduction with a capture rate of 82%. See Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[284] Mærsk Mc-Kinney Møller Center (2022) The role of onboard carbon capture in maritime decarbonization. <https://cms.zerocarbonshipping.com/media/uploads/publications/The-role-of-onboard-carbon-capture-in-martime-decarbonization.pdf> (accessed 10 May 2023).

[285] CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra; Together in Safety (2022) Future Fuel Risk Assessment. <https://togetherinsafety.info/wp-content/uploads/2022/06/Future-Fuels-Report.pdf>

identifies the degree of severity of the health, flammability, instability, and specific hazards associated with hazardous materials.[286]

Conventional marine fuels, such as marine diesel oil (MDO) and very low sulphur fuel oil (VLSFO), are known to have carcinogenic effects, are flammable and may pose an explosion risk.[287] However, these risks are well-understood, can be managed, and fall within the allowed safety specifications outlined by the International Maritime Organisation (IMO), and are therefore considered ALARP.[288]

Table 47: Safety – Shipping

Technologies	Safety	Results
Threshold	*Standard and manageable safety risks present - ALARP*	
Ammonia combustion	High toxicity	
Biofuels (FAME; HVO)	Standard and manageable safety risks present	
Battery electric	Higher flammability than conventional	
Fossil fuels with OCCUS	Standard and manageable safety risks present	
Hydrogen combustion	High flammability	
Hydrogen fuel cells	High flammability	
Methanol combustion	Standard and manageable safety risks present	
Nuclear propulsion	Standard and manageable safety risks present	

Ammonia combustion

The use of ammonia as a fuel poses high toxicity that could present risks to crew and marine ecosystems in the event of leakage and exposure. As per the NFPA Hazard Identification system, ammonia receives a '3' toxicity rating (i.e., 'extremely dangerous'). This is higher than for convention marine fuels, which receive a 'normal' or 'slightly hazardous' rating.[289]

While handling procedures are well-understood, further work is required to adapt existing standards of practice to maritime safety, including bunkering and on-board activities.

Battery electric

Batteries present safety issues related to fire risks from electrical faults and thermal runaway.[290] While these have been incorporated into mitigation strategies and regulations for onboard use on small vessels, the inherent risk was still deemed to be higher than conventional engine systems.

Hydrogen-fuelled

Hydrogen poses inherent safety risks owing to its chemical nature, including a low flashpoint, high flammability, ability to diffuse quickly, lack of odour, and near-invisible flame.[291] Further, high pressure

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[286] https://www.nfpa.org/codes-and-standards/nfpa-704-standard-development/704

[287] BP Australia (2021) Safety Data Sheet: BP Marine Fuel Oil IF 40. <https://www.bp.com/content/dam/bp/country-sites/en_au/australia/home/products-services/data-sheets/bp-marine-fuel-oil-if-40.pdf>

[288] International Maritime Organisation (n.d.) International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) <https://www.imo.org/en/ourwork/safety/pages/igf-code.aspx> (accessed May 2023); International Maritime Organisation (n.d.) Bulk Carrier Safety. https://www.imo.org/en/OurWork/Safety/Pages/BulkCarriers.aspx (accessed May 2023)

[289] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.

[290] CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra.

[291] CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra.

hydrogen storage can present an explosion risk. As per the National Fire Protection Association (NFPA) Hazard Identification system, hydrogen receives a '4 of 4' rating, indicating fire hazard below 22°C. This is higher than for conventional marine fuels, which receive a '2' rating (i.e., fire hazard above 37°C).[292]

However, it is expected that these risks can be managed with appropriate standards and operating procedures, and further RD&D as the hydrogen industry continues to develop.

Nuclear propulsion

Compared to other technology systems, nuclear propulsion eliminates flammability and explosion risks but introduces radiological safety concerns related to reactor operation and containment. These risks are highly regulated by bodies such as the IMO[293] and the International Atomic Energy Agency (IAEA)[294], and have been effectively managed in military navies and select civilian vessels internationally through robust containment systems, shielding and operational protocols. While not covered by the NFPA system, nuclear safety is considered ALARP for onboard use where stringent standards are applied. Wider commercial use would require expanded regulatory frameworks and public acceptance.

7.4.2 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.

- **Minimum range requirement (single trip):** Technologies that meet an acceptable distance threshold in a single trip.
- **Levelised cost of transport**: 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.

Minimum range requirement (single trip)

The minimum range requirement defines the average distance (in km) required for the deep-sea freight use case. The threshold distance, 12,100km, was informed by the distance to many of Australia's trading partners in the APAC region, as well as meet domestic shipping needs. Many of these international ports can be reached with a vessel range of 10,000-15,000km, however, ships will require longer range capabilities to access more distant regions and ports. This was identified as a core operating requirement that will enable or limit technology uptake, particularly in applications requiring long route durations.

For the range requirement, the drivetrain of all mitigation solutions can be scaled to meet the distance threshold imposed. For battery and fuel cell technologies, the battery or fuel cell system has been sized to ensure it can deliver the energy required for the journey distance. For combustion engines, sufficient on-board fuel storage for the journey distance is assumed. Where the solutions have a lower energy density compared to MDO, the size of the drivetrain and fuel storage will be at the expense of cargo space, reducing the effective payload.

Payload reductions of ~5% and below were regarded as inevitable in the switch to alternative technology options and were deemed to meet the criteria. Mitigation solutions with payload reductions above this range

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[292] Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore; Yang M, Ng C, Liu M (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore

[293] International Maritime Organisation (n.d.) Safety regulations for different types of ships. <https://www.imo.org/en/OurWork/Safety/Pages/RegulationsDefault.aspx>

[294] International Atomic Energy Agency (2024) Transport security. <https://www.iaea.org/topics/transport-security> (accessed June 2024)

were determined to meet the criterion with caveats and are subject to the willingness of shipping operators to concede more impactful capacity losses.

All technologies are deemed to be able to provide meet the range requirements for conventional fuels across both end-use cases. However, meeting these range requirements may require operational trade-offs due to the lower volumetric density of the alternative low emissions alternatives (Table 48). This may be at the expense of payload capacity or flexibility as additional refuelling stops may be required if additional fuel storage cannot be integrated into the vessel design. These impacts may be compounded or reduced by the efficiency of alternative engines and propulsion systems, which dictate the range a vessel may travel based on fuel consumption.[295]

Table 48: Minimum range requirement, single trip – Shipping

Technologies	12,100km journey *Threshold: 12,100km*	Results
Ammonia combustion	>12,100, payload reduced Requires 3x the fuel tank volume of MGO to store equivalent energy, resulting in a 6% payload capacity loss (as per the cost analysis case study)	
Battery electric	Up to 1,100km. Please note, theoretical maximums of 12,100km could be achieved if battery system is sufficiently scaled. If scaled, battery system results in an 17% payload capacity loss (as per the cost analysis case study)	
Hydrogen combustion	>12,100, payload reduced Requires 4.5x the fuel tank volume of MGO to store equivalent energy, resulting in a 14% payload capacity loss (as per the cost analysis case study)	
Hydrogen fuel cells	>12,100, payload reduced Requires 4.5x the fuel tank volume of MGO to store equivalent energy, resulting in an 11% payload capacity loss (as per the cost analysis case study)	
Methanol combustion	>12,100, payload reduced Requires 2.4x the fuel tank volume of MGO to store equivalent energy, resulting in a 4% payload capacity loss (as per the cost analysis case study)	
Nuclear propulsion	>12,100	

Battery electric

Like other battery electric technologies, the size of the battery system can be scaled to meet the energy demands of a given application. In the costed battery electric use case, this would equate to a 6,600MW battery system which would result in a 17% payload reduction. It is unlikely that such a significant reduction in carrying capacity would be tolerated by shipping operators, particularly for long distance, international routes, and the practicality of employing a battery of this size would push current vessels designs beyond safe operating limits.[296]

Recent trials and demonstrations of battery electric vessels fall far short of the minimum range threshold imposed by this criterion, even where innovative solutions such as en route battery swapping are employed.

[295] Integr8 Fuels, Research and Advisory (2020) Integ8: VLSFO Calorific Calue, Pour Point and Competitiveness with LSMGO. <https://shipandbunker.com/news/world/662089-integr8-vlsfo-calorific-value-pour-point-and-competitiveness-with-lsmgo> (accessed May 2023)

[296] Kersey J, Popovich, N, Phadke, A (2022) Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping. *Nat Energy* **7**, 664–674. https://doi.org/10.1038/s41560-022-01065-y

Projects typically target shorter-distance operations, such as ferrying;[297] though, distances of up to 1100km are reported to be achieved for cargo vessels.[298]

Nuclear propulsion

Nuclear-powered ships can operate for extended periods of time, often years, due to high enrichment of uranium fuel. As a result, range limitations will be governed by personnel, maintenance and logistics rather than fuel depletion.

Levelised cost analysis

Key information – Levelised cost analysis

The Levelised Cost of Transport (LCOT) was estimated to determine the viability of each technology considered. LCOT is defined as the average net present cost per unit of output (in c/passenger-km or c/tonne-km), over a vehicle's lifetime.

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 of new deployments 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 20. **Methanol and ammonia combustion were projected to be the most cost competitive**, distinguished by a cost differential in LCOT relative to other assessed technologies; suggesting areas of promise for further RD&D activity**.** A supplementary case study was conducted to assess the feasibility of technologies for a short range ferry, Box 8.

The economic assessment calculates the total cost of transport for a new single deep-sea 5,000 TEU freight vessel, using a low speed two stroke engine over a 12,100km distance. The vessel is assumed to travel an annual distance of 278,000km with four days allowed in port between each trip and an asset lifetime of 25 years.[299]

As a low emissions solution, ammonia vessels are assumed that the vessel operates on e-ammonia as a fuel, produced with electrolytic hydrogen via the Haber-Bosch synthesis. Similarly, methanol vessels are costed to operate on e-methanol produced with CO_2 from DAC and hydrogen from PEM electrolysis. While this is likely a more costly input, in comparison to point source CO_2 or biomethanol production, large-scale production is likely to be reliant on DAC. It is recognised, however, that these pathways could meet a portion of production demand, however, both face supply limits.

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[297] For example, the world's largest battery electric ferry was launched in May 2025 by InCat Tasmania. The Royal Institution of Naval Architects (2023) Incat Tasmania building world's largest battery electric ship. <https://rina.org.uk/publications/the-naval-architect/incat-tasmania-building-worlds-largest-battery-electric-ship/> (accessed January 2025).

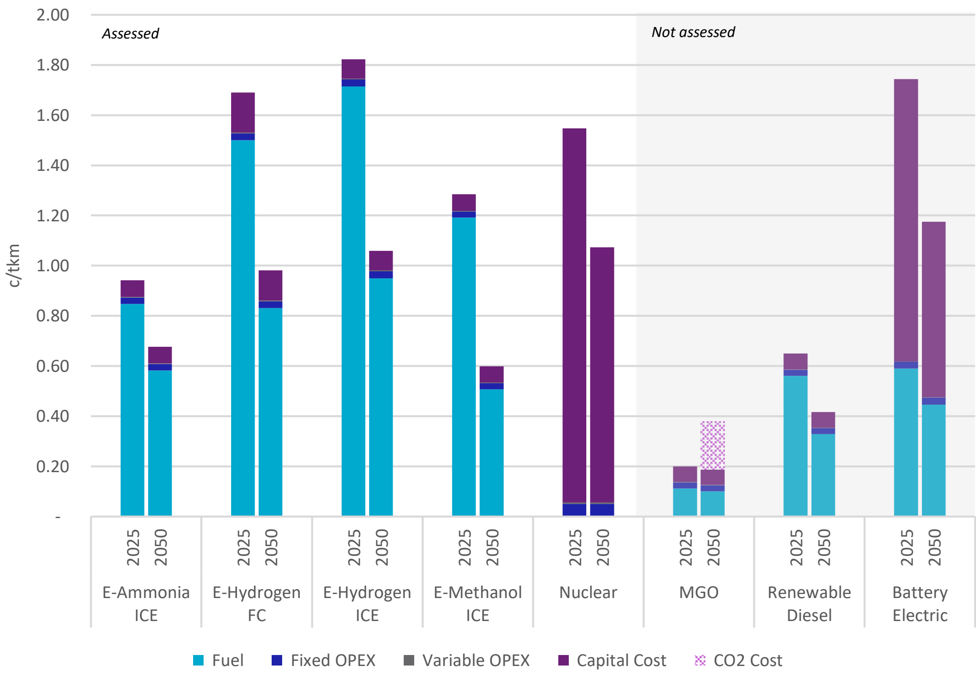
[298] See, for example, Sustainable Ships (2023) COSCO 700 TEU Full Electric Container Ship. <https://www.sustainable-ships.org/stories/2023/cosco-700-teu-full-electric-container-ship> (accessed January 2025).

[299] Long asset lifetimes, here assumed to be 25 years, will limit technology adoption for new commissions.

This assessment does not capture the cost of establishing sufficient refuelling infrastructure. Establishing single or multi-fuel delivery, handling and storage port infrastructure would require significant capital costs, and ongoing expenditure and investment in insurance, training and hazard assessments. These would need to be considered on a site-basis, and therefore has not been incorporated into this analysis.

Additional technologies include renewable diesel and battery electric vessels. These technologies did not meet the earlier abatement potential and range requirement filters, respectively. However, as sufficient cost data was available, cost analysis has been conducted for reference only.

Figure 20: Levelised cost of transport (c/tkm) – Deep-sea freight



Due to the high utilisation of the ship and the large energy demands, the relative competitiveness of each technology option is mainly driven by its fuel price. Fuel storage requirements also impact the levelised costs in several ways. The capital and operational costs of onboard fuel tanks and associated equipment contribute to total capital and operating costs. The additional space required to store fuels with a lower volumetric energy density also leads to a reduction in cargo capacity, increasing levelised costs per tkm.

MGO, a common and conventional marine fuel, is included as a technology benchmark – though it is not assessed. MGO is estimated to remain the lowest cost technology in both the near term and long term, even when accounting for a CO_2 emission cost (Figure 20). This is driven by an expectation for much higher fuel and capital costs associated with alternative mitigation solutions, and aligns with commentary from the European Maritime Safety Agency, suggesting that renewable fuels will find it difficult to compete with the prices of conventional fossil fuels without government intervention.[300]

Sufficient data was available to analyse battery electric systems, though they were deemed unable to meet the range requirement. This technology option was found to be the highest cost, both in 2025 and 2050. The very high capital cost of this technology is driven by the large amount of battery capacity required, resulting in an 17% payload reduction.

[300] DNV-GL (2019) ASSESSMENT OF SELECTED ALTERNATIVE FUELS AND TECHNOLOGIES MARITIME.

Ammonia combustion

Ammonia combustion meets the criteria on the basis that it is the second lowest-cost assessed technology in 2050.

Modelled cost reductions between 2025 and 2050 are primarily driven by reductions in future hydrogen costs. Ammonia combustion is modelled to be more cost effective than hydrogen-powered vessels as the fuel possess a higher volumetric energy density, leading to a smaller reduction in cargo capacity relative to hydrogen. Additional infrastructure required to ensure safe storage and refuelling of e-ammonia at ports could increase the cost of this technology, however, this is not captured here.

Methanol combustion

Methanol combustion is modelled to have a higher levelised cost than ammonia combustion in 2025, but becomes the lowest cost technology in 2050. Though presenting higher 2025 costs than ammonia, methanol could be a nearer-term solution with preferred handling and infrastructure compatibility.

Cost reductions out to 2050 are a result of projected decreased in fuel production inputs (renewable H_2 and CO_2). Methanol combustion and fuel cell levelised costs could reduce further if CO_2 from a biogenic source is used rather than CO_2 from direct air capture.

Hydrogen-fuelled

Hydrogen-fuelled vessels did not meet the criterion, presenting higher cost than hydrogen-derived fuels.

Both combustion engines and fuel cells were considered for hydrogen-powered ships and are assumed to use liquid hydrogen fuel given its higher volumetric energy density compared to compressed hydrogen gas. Liquid hydrogen is more expensive than gaseous hydrogen due to the liquefaction process required, further driving up fuel costs. The improved efficiencies of the fuel cell drive train were found to offset the higher capex cost compared to the combustion system, resulting in marginally lower overall costs.

Nuclear propulsion

Nuclear-powered vessels did not meet the criterion, presenting higher costs than other assessed technologies in 2050.

The capital expenditure required for nuclear-powered vessels is an order of magnitude higher than the other low emissions technologies evaluated (assumed at $3.4 billion in 2025 and declining to $2.3 billion in 2050).[301] This analysis adopts a commonly used proxy approach, drawing on capex from land-based nuclear power plants and scaling them for marine applications. It excludes vessel-specific design requirements and does not account for decommissioning expenses occurred at the end of operational life. For reference, decommissioning costs for land-based reactors are estimated between $1.6-1.8million per MWe, with limited residual value expected from nuclear-powered ships at retirement.[302]

Nuclear fuel (here 5% enriched uranium), taken as $2560/kg, offers extremely high energy density and long core lifetimes, eliminating the need for regular bunkering and substantially reduce fuel-related opex costs. As a result, variations in the cost of nuclear fuel have negligible impacts on overall levelised cost results on a per kilometer basis compared to the other technologies assessed.

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[302] European Maritime Safety Agency (2024), Potential Use of Nuclear Power for Shipping, EMSA, Lisbon <https://www.emsa.europa.eu/publications/reports/item/5366-potential-use-of-nuclear-power-for-shipping.html>

Box 8: Shipping supplementary case study: short-sea ferries and harbour craft, 100 km journey

Key messages

- **Battery electric vessels are modelled to be the lowest cost mitigation technology in 2050. For shorter ranges (or less energy intensive operations), payload reductions are less impactful; however, operational strategies, such as more frequent recharging, may need to be factored into some operating procedures.**
- **E-methanol ICE vessels are modelled to be the next most competitive technology after battery electric vessels in 2050, however high e-methanol fuel costs make them less viable in the near term.**

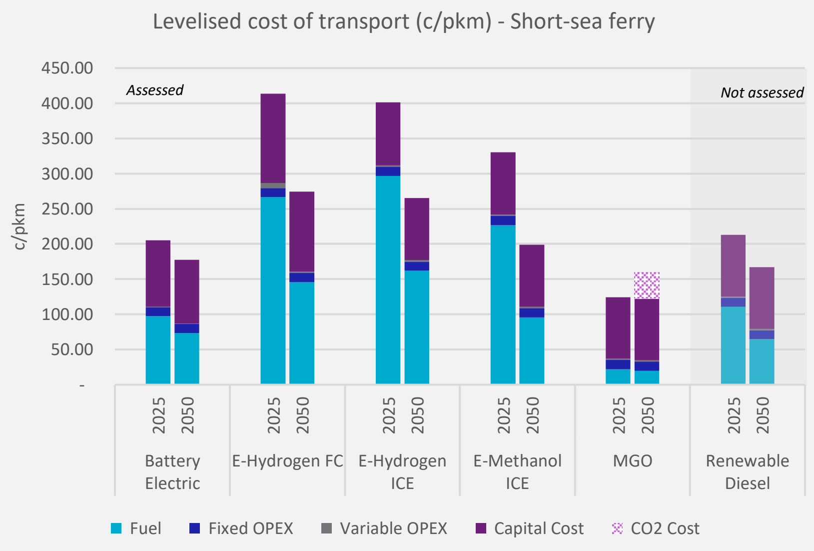
A supplementary case study has been conducted to assess the feasibility of technologies for less energy -intensive applications. This additional end-use case for the shipping segment is defined by a short-sea ro-pax ferry operating at a typical frequency and load factor.[303]

During preliminary filtering, final results presented similar to the deep-sea case. There was one exception; the inability of e-ammonia combustion engines to meet the safety criteria, due to toxicity concerns stemming from the lack of sufficient ventilation onboard smaller vessels.

For preliminary technology analysis, the range threshold was lowered to 100km, aligning with popular inter-state passenger ferry routes and servicing harbour craft that assist in single-port or single-region activities.[304] All technologies met this criterion.

The LCOT is measured on a per passenger-km (c/pkm) basis, and MGO is estimated to remain the lowest cost technology in the near term and long-term (Figure 21).

Figure 21: Levelised cost of transport (c/pkm) – Short-sea ferry



As fuel costs make up a smaller proportion of total costs in short-sea shipping, the cost gap is not as large between MGO and emission mitigation technologies as in deep-sea shipping. Battery electric vessels are much more competitive in the short-sea end-use case, particularly in the near term. The lower range requirement leads to lower battery capital costs compared to deep-sea. E-Methanol ICE vessels are modelled to be the next most competitive technology after battery electric vessels in 2050, however high e-methanol fuel costs make them less viable in the near term.

Despite the lower volumetric densities of alternative solutions, analysis assumes payload reductions are negligible at this range; however, where present, they may be overcome with more frequent refuelling/recharging.

[303] Ro-pax ferries are "roll-on, roll off" ferries that are capable of transporting passengers and vehicles.

[304] This distance accounts for inner-city ferry networks or river cruises such as in Sydney, Melbourne and Brisbane; popular port ferrying activities (e.g., Melbourne-Portarlington-Geelong or Mornington Peninsula-Bellarine Peninsula in Victoria; Cape Jervis-Kangaroo Island in South Australia; Fremantle-Rottnest Island in Western Australia).

7.5 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 Ammonia and methanol combustion engines as *Primary technologies* for a deep-sea shipping use case.

Although not explored further, the other low emissions technologies evaluated in this report could still contribute to achieving Australia's long-term energy transition objectives, or meeting the requirements of other use cases in the in the shipping 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 and energy efficiency solutions identified during analysis are outlined in Figure 22. These technologies formed the basis for identifying RD&D opportunities that could drive impactful technological progress.

Figure 22: Technology landscape identification - Non-road, Shipping

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

Energy efficiency solutions

- Lightweighting and drag reduction design
- Technology and componentry improvement
- Energy management solutions
- Traffic and logistics management technologies

Auxiliary technologies

Ammonia and methanol combustion technologies cannot exist in isolation and their successful use and deployment is dependent on a range of auxiliary technologies, summarised in Table 49.

Table 49: Auxiliary technologies – Shipping

Primary technology	Auxiliary technology	Description
Ammonia combustion	**Ammonia storage and bunkering**	Infrastructure and technologies for the safe storage, handling, and refuelling of ammonia as a maritime fuel, ensuring compliance with safety, regulatory, and operational requirements.
Methanol combustion	**Methanol storage and bunkering**	Infrastructure and technologies for the safe storage, transfer, and refuelling of methanol in maritime applications, addressing fuel compatibility, safety standards, and logistical integration with port infrastructure.

Energy efficiency solutions

For shipping transport, there are a range of energy efficiency solutions that will also support emissions mitigation efforts. These solutions are outlined in Table 50.

Table 50: Energy efficiency solutions – Shipping

Energy efficiency solution	Description
Technology and componentry improvement	Improves energy efficiency by improving drivetrain/transmission efficiencies.
Drag reduction and design	Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles
Energy management solutions	Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, and enhance battery life (where relevant)
Lightweighting	Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.
Traffic and logistics management technologies	Improves energy efficiency by optimising vehicle movement and operation.

7.6 RD&D opportunity analysis

Key information – RD&D opportunities

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, 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 51. 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). Though identified as a primary technology component, RD&D opportunities related to fuel production are discussed in more detail under the *Low Carbon Fuels* technical appendix.

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 51: Summary of RD&D opportunities – Shipping[305]

		Ammonia combustion			Methanol combustion		
		Engine	**On board storage**	**Fuel production pathways**	**Power systems**	**On board storage**	**Fuel production pathways**
Primary technologies	**Commercial**	-	Ammonia storage tanks	*See Low Carbon Fuels technical appendix for hydrogen and NH_3 production technologies.*	Two-stroke ICE	Methanol storage tanks	*See the Low Carbon Fuels technical appendix for hydrogen production and methanol synthesis technologies.* *See the Carbon Management technical appendix for CO_2 capture technologies.*
	Mature	-	-		-	-	
	Emerging	Two-stroke ICE	-		-	-	
Primary RD&D		• Fuel cost reductions **(Target: $1.30/kg, cf. $1.90/kg)** through: - E.g. Improving fuel production pathways, see *Low Carbon Fuels* technical appendix • Develop combustion engines optimised for Ammonia's unique chemical properties - E.g. Developing engines with high compression ratios for better ignition - E.g. Developing engines with embedded N_2O emissions reduction technologies • Redesign onboard storage systems to improve the safety and efficiency of fuel storage - E.g. Retrofitting MGO tanks to accommodate ammonias lower energy density and increased volume requirements - E.g. Adopting advanced materials that prevent leakage and degradation			• Fuel cost reductions **(Target: $1.30/L, cf. $3.07/L)**, achieved through: - E.g. Improving fuel production pathways, see *Low Carbon Fuels* technical appendix - E.g. Improving carbon capture technologies, see *Carbon Management* technical appendix • Improve the performance of methanol propulsion systems through: - E.g. Improving the energy and fuel economy of ICEs. - E.g. Improving the efficiencies of methanol fuel cells **(Target: >20%)** • Redesign onboard storage systems to improve the safety and efficiency of fuel storage - E.g. Retrofitting MGO tanks to accommodate methanol's lower energy density and increased volume requirements - E.g. Adopting established safety systems such as overfill alarms or automatic shutdown		
Auxiliary RD&D		• Expand and optimise ammonia production, storage and distribution infrastructure • Optimise operations for ammonia bunkering, while maintaining safety through: - E.g. Increasing ammonia flow rates - E.g. Adopting safety systems such as pressure testing and temperature stabilisation			• Expand and optimise methanol with production, storage and distribution, including leveraging compatibility with existing MGO bunkering infrastructure		

cf. – Compare.

[305] 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. For further detail regarding (1) hydrogen production forecast please refer to the *Low Carbon Fuels* technical appendix, and (2) CO_2 forecast, please refer to the *Carbon Management* technical appendix.

7.6.1 Ammonia combustion vessels

Ammonia combustion systems can be retrofitted into existing vessels and use conventional LPG infrastructure, positioning this solution as an attractive technology option for many offtakers. However, the uptake of ammonia will require a variety of changes to vessel design, componentry to manage emissions, and safety systems. In addition, achieving fuel cost reductions will be critical for driving greater adoption.

Primary technologies

Since fuel is the biggest driver of technology costs, research to lower the cost of e-ammonia production could reduce costs for all technologies that use ammonia as a fuel.

Current processing pathways for e-ammonia production are energy-intensive and require costly inputs of electrolytic hydrogen. Reducing cost of e-ammonia production (target $1.30/kg, c.f., $1.90/kg) could be an adoption lever, with RD&D presenting opportunities to improve the energy efficiency and lower emissions of synthesis pathways. Research opportunities related to these considerations are discussed further in the *Low Carbon Fuels* technical appendix.[306]

Developing engines to overcome ammonia's unique chemical properties, could help increase its adoption as a fuel.

Currently, ammonia engines are only available in simple configurations at prototype-level. Technical challenges, such as a high autoignition temperature, high heat of vaporisation, and high minimum ignition energy can make compression ignition of direct liquid ammonia injection challenging and create engineering difficulties, resulting in unstable combustion.[307] Given the high cost of green ammonia production (see *Levelised cost analysis*), research to increase engine efficiencies will also serve to improve the operational economics of adoption.

Optimising emissions reduction technologies and their integration will also be a factor. Despite emitting zero carbon emissions upon combustion, there is potential for other greenhouse gases to be liberated during the combustion process including NO_x and N_2O (a GHG with 300-fold the warming potential of CO_2). This requires engines to embed effective emissions reduction technologies to reduce their exposure to the atmosphere.[308]

To ensure safe and efficient operation with fuels like ammonia, vessels will need to redesign on-board fuel storage systems.

While ammonia storage options are mature, RD&D to enhance engine and storage system efficiencies offers potential to minimise spatial requirements for fuel storage. Ammonia possess a volumetric density around a third that of conventional fuels (12.7 MJ/L, c.f., 36.6MJ/L for MGO), with re-design efforts presenting opportunities to increase onboard energy capacity and mitigate potential cargo losses at the expense of

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[306] McKinlay CJ, Turnock SR, Hudson DA (2021) Route to zero emission shipping: Hydrogen, ammonia or methanol?. International Journal of Hydrogen Energy 46, 28282. doi:10.1016/j.ijhydene.2021.06.066

[307] Kumar L, Sleiti AK (2024) Systematic review on ammonia as a sustainable fuel for combustion. Renewable and Sustainable Energy Reviews 202,. doi:10.1016/j.rser.2024.114699; MAN Energy Solutions (2023) MAN B&W two-stroke engine operating on ammonia. <https://www.man-es.com/docs/default-source/marine/tools/man-b-w-two-stroke-engine-operating-on-ammonia.pdf>

[308] DNV GL (2019) Comparison of Alternative Marine Fuels; Chrobak U (2021) The world's forgotten greenhouse gas. BBC. https://www.bbc.com/future/article/20210603-nitrous-oxide-the-worlds-forgotten-greenhouse-gas; MAN Energy Solutions (2023) MAN B&W two-stroke engine operating on ammonia. <https://www.man-es.com/docs/default-source/marine/tools/man-b-w-two-stroke-engine-operating-on-ammonia.pdf>

onboard fuel storage.[309] Alternately, these efforts could reduce the frequency of bunkering, with the potential to extend voyage times and increase operational costs.[310]

Ammonia is also a highly toxic substance, with only relatively low levels of exposure sufficient to cause loss of consciousness. Due to its toxicity and caustic nature, safety performance could be enhanced through the development of advanced materials that both improve volumetric and gravimetric storage capacity and that buffer against corrosion and leakage to prevent degradation over time.[311] While existing protocols for ammonia as a fertiliser exist, new safety systems and strategies are necessary for its use as a marine fuel to manage safety and ecological risks. This could include onboard safety monitoring systems, mitigation solutions following leaks (such as water curtains and ventilation systems), and buffer zone requirements for onshore storage.

Auxiliary technologies

Ensuring that delivery and refuelling infrastructure is able to meet operational needs, including safety, will be an underlying consideration for technology adoption.

Ammonia can leverage established LPG storage and delivery infrastructure, reducing barriers to implementation.[312] For example, ammonia is extensively used as a fertiliser input for the agricultural sector and has established reliable facilities for production, handling, storage and distribution.[313] Sufficient volumes of refrigerated storage tanks for bunkering would need to be deployed at location, while ensuring adhering to safety parameters in the event of ammonia leakage and dispersion.[314]

Seafaring vessels possess extremely large stores of fuel to meet high energy demands and RD&D could play an important role in improving and optimising bunkering flow rates, while minimising safety risks.[315] To meet high fuel carrying capacities, increasing flow rates can help to minimise disruptions to existing bunkering schedules and operating procedures. Compared to fuel rates used to fill ammonia as cargo, flow rates for ammonia

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309 Yang M, Ng C, Liu M (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore; Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.; Integr8 Fuels, Research and Advisory (2020) Integ8: VLSFO Calorific Calue, Pour Point and Competitiveness with LSMGO. <https://shipandbunker.com/news/world/662089-integr8-vlsfo-calorific-value-pour-point-and-competitiveness-with-lsmgo> (accessed May 2023); DNV-GL (2019) ASSESSMENT OF SELECTED ALTERNATIVE FUELS AND TECHNOLOGIES MARITIME; See also, Kim K, Roh G, Kim W, Chun K (2020) A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. Journal of Marine Science and Engineering 8,. doi:10.3390/jmse8030183; Yang M, Lam JSL (2023) Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective. Transportation Research Part D: Transport and Environment 117,. doi:10.1016/j.trd.2023.103666

310 Svanberg M, Ellis J, Lundgren J, Landälv I (2018) Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews 94, 1217. doi:10.1016/j.rser.2018.06.058

311 McKinlay CJ, Turnock SR, Hudson DA (2021) Route to zero emission shipping: Hydrogen, ammonia or methanol?. International Journal of Hydrogen Energy 46, 28282. doi:10.1016/j.ijhydene.2021.06.066 ; Balci G, Phan TTN, Surucu-Balci E, Iris Ç (2024) A roadmap to alternative fuels for decarbonising shipping: The case of green ammonia. Research in Transportation Business and Management 53,. doi:10.1016/j.rtbm.2024.101100; Morlanés N, Katikaneni SP, Paglieri SN, Harale A, Solami B, Sarathy SM, Gascon J (2021) A technological roadmap to the ammonia energy economy: Current state and missing technologies. Chemical Engineering Journal 408,. doi:10.1016/j.cej.2020.127310

312 Svanberg M, Ellis J, Lundgren J, Landälv I (2018) Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews 94, 1217. doi:10.1016/j.rser.2018.06.058

313 CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra. See also e.g. Morgan E, Manwell J, McGowan J (2014) Wind-powered ammonia fuel production for remote islands: A case study. Renewable Energy 72, 51. doi:10.1016/j.renene.2014.06.034; Zamfirescu C, Dincer I (2009) Ammonia as a green fuel and hydrogen source for vehicular applications. Fuel Processing Technology 90, 729. doi:10.1016/j.fuproc.2009.02.004; Zamfirescu C, Dincer I (2008) Using ammonia as a sustainable fuel. Journal of Power Sources 185(1). doi: 10.1016/j.jpowsour.2008.02.097.

314 Ng CKL, Liu M, Lam JSL, Yang M (2023) Accidental release of ammonia during ammonia bunkering: Dispersion behaviour under the influence of operational and weather conditions in Singapore. Journal of Hazardous Materials 452,. doi:10.1016/j.jhazmat.2023.131281

315 Yang M, Lam JSL (2024) Risk assessment of ammonia bunkering operations: Perspectives on different release scales. Journal of Hazardous Materials 468,. doi:10.1016/j.jhazmat.2024.133757; Yang M, Lam J (2023) Operational and economic evaluation of ammonia bunkering – Bunkering supply chain perspective. Transportation Research Part D: Transport and Environment. doi: 10.1016/j.trd.2023.103666.

bunkering are expected to be lower and encompass a wider range due to more stringent safety protocols and additional operating procedures (i.e., purging fuel lines, pressure testing, temperature stabilisation) that must be conducted for safe handling.[316]

7.6.2 Methanol combustion vessels

Methanol-fuelled vessels use internal combustion engines to convert chemical energy in methanol into propulsion and onboard power. However, the deployment of methanol as a marine fuel presents unique operational and engineering challenges. Methanol's lower volumetric energy density requires larger storage volumes, affecting vessel design and payload. Its corrosive nature demands specialised materials across engines, storage systems, and port infrastructure. The high cost of e-methanol production also places pressure on fuel efficiency and onboard system performance. There are opportunities to improve methanol production economics, optimise shipboard systems and support safe and scalable integration across global ports.

Primary technologies

Since fuel is the biggest driver of technology costs, research to lower the cost of e-methanol production could reduce costs for all technologies that use methanol as a fuel.

The production of e-methanol is costly, requiring a source of electrolytic hydrogen and renewable CO_2 (obtained from biogenic sources, direct air capture (DAC) or point source emissions). Reducing the cost of e-methanol production (target: $1.30/L, cf. $3.07/L) could be an adoption lever, with RD&D presenting opportunities to improve the cost proposition of synthesising e-methanol and its key inputs. Opportunities for hydrogen production can be found in the *Low Carbon Fuels* technical appendix, while those for carbon capture technologies can be found in the *Carbon Management* technical appendix.

Improving the performance of methanol-fuelled propulsion systems, including operational efficiencies, could also reduce costs.

For ICE-based propulsion, improving the engine efficiencies and fuel economy of ICE vessels can reduce overall operating costs for ship owners. Methanol two-stroke engines are commercially available (CRI 4), with many offtakers also adopting dual-fuelled methanol-diesel builds to bridge the transition until the bunkering of methanol, and other renewable fuels, is more widely available at ports.

For emerging methanol-based fuel cells, RD&D to increase operational efficiencies could also support cost reductions. Methanol fuel cells are less mature (TRL 5)[317] than combustion engines, with our levelised cost analysis suggesting they may be more cost effective for the given use case (i.e., large vessels travelling long distances), where greater energy and fuel storage requirements would exacerbate payload reductions. Current direct methanol fuel cells (DMFCs) have high theoretical energy conversion efficiencies, but efficiencies achieved in operational cells are much lower (20%).[318] Increasing efficiencies of indirect methanol fuel cells (RMFC/IMFCs) which convert methanol to hydrogen for use can also support cost reductions.

To ensure safe and efficient operation with fuels like methanol, vessels will need to re-design on-board fuel storage systems.

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[316] ABS (2024) Ammonia Bunkering: Technical and Operational Advisory. June 2024. <https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/ammonia-bunkering-advisory.pdf>

[317] Ovrum E, et al. (2022) Maritime forecast to 2050. DNV. <https://www.dnv.com/maritime/publications/maritime-forecast-2022/index.html>

[318] IMO (2021) Sub-committee on carriage of cargoes and containers, 7th session (CCC 7), 6–10 September 2021. [Meeting summary] <https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/CCC-7th-session.aspx> (accessed 10 May 2023); Tronstad T, et al. (2017) Study on the use of fuel cells in shipping. EMSA. https://www.emsa.europa.eu/publications/item/2921-emsa-study-on-the-use-of-fuel-cells-in-shipping.html.

While methanol storage options are mature, RD&D to enhance engine and storage system efficiencies offers potential to minimise spatial requirements for fuel. Methanol has volumetric density of around half that of conventional fuels (16.2MJ/L compared to 36.6MJ/L for MGO), requiring ships to have storage tanks capable of carrying more than twice as much fuel as conventional tanks to achieve an equivalent energy capacity. [319] Re-design efforts present opportunities to increase onboard energy capacity and mitigate potential cargo losses at the expense of onboard fuel storage. Alternately, these efforts could reduce the frequency of bunkering, with the potential to extend voyage times and increase operational costs.[320]

To ensure the safe storage and handling of methanol as a marine fuel and meet the IMO's International Code of Safety for Ships using Gases or other Low-flashpoint Fuel (international standard), there are well established engineering procedures to address safety risks.[321] Additional monitoring systems are also required compared to conventional fuels, including overfill alarms, automatic shutdown, monitoring of ventilation and gas detection; however, these are largely mature and as such no RD&D opportunities were identified.[322]

Auxiliary technologies

Ensuring that delivery and refuelling infrastructure is able to meet operational needs, including safety, will be an underlying consideration for technology adoption.

The compatibility of methanol with existing infrastructure allows methanol bunkering processes to remain similar to that of conventional marine fuels and eases some of the complications associated with multi-fuel adoption in ports.[323] Although existing infrastructure and expertise support their use, meeting increased consumption would require an appropriate increase in production, storage and distribution capacity.[324]

Given the corrosive nature of methanol, bunkering equipment, including hoses, transfer pumps and bulk storage facilities may need to adopt new materials to avoid corrosion of carbon steel over time.[325]

7.6.3 Energy efficiency solutions

Further RD&D in solutions that reduce energy use in shipping will also support emissions mitigation efforts.

There are several solutions that are well-established and easy-to-implement, for example, wind-assisted propulsion systems (i.e., kites and rotor sails).[326] Given their maturity, specific RD&D opportunities have not

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[319] Yang M, Ng C, Liu M (2022) Ammonia as a marine fuel. Nanyang Technological University, Singapore; Thepsithar P (2020) Alternative fuels for international shipping. Nanyang Technological University, Singapore.; Integr8 Fuels, Research and Advisory (2020) Integ8: VLSFO Calorific Calue, Pour Point and Competitiveness with LSMGO. <https://shipandbunker.com/news/world/662089-integr8-vlsfo-calorific-value-pour-point-and-competitiveness-with-lsmgo> (accessed May 2023)

[320] Svanberg M, Ellis J, Lundgren J, Landälv I (2018) Renewable methanol as a fuel for the shipping industry. Renewable and Sustainable Energy Reviews 94, 1217. doi:10.1016/j.rser.2018.06.058

[321] International Maritime Organization (2016) Methanol as marine fuel: environmental benefits, technology readiness, and economic feasibility. <https://www.unclearn.org/wp-content/uploads/library/5.pdf>; McKinlay CJ, Turnock SR, Hudson DA (2021) Route to zero emission shipping: Hydrogen, ammonia or methanol?. International Journal of Hydrogen Energy 46, 28282. doi:10.1016/j.ijhydene.2021.06.066

[322] International Maritime Organization (2016) Methanol as marine fuel: environmental benefits, technology readiness, and economic feasibility. <https://www.unclearn.org/wp-content/uploads/library/5.pdf>;

[323] CSIRO (2023) Co-design process: Australia–Singapore initiative on low-emissions technologies for maritime and port operations. CSIRO, Canberra.

[324] DNV-GL (2019) ASSESSMENT OF SELECTED ALTERNATIVE FUELS AND TECHNOLOGIES MARITIME.

[325] Liu M, Li C (2021) Methanol as a marine fuel. Nanyang Technological University, Singapore

[326] IEA (2024) ETP Clean Energy Technology Guide. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide (accessed 24 October 2024).; DNV Maritime Forecast to 2050 report

been identified. Some estimates suggest that implementing measures to improve energy efficiency, could see improvements of between 20-30%.[327]

The solutions outlined in Table 52 are technology-agnostic with the ability to reduce energy use across a range of technology types and systems. While many of these solutions have been the focus of past research efforts they could evolve alongside advancements in materials, digital technologies and system innovations, offering incremental improvements in transport efficiency.

Table 52: Energy efficiency RD&D opportunities – Shipping

Energy efficiency solutions	RD&D opportunities
Drag reduction and design *Improves energy efficiency as less energy is required to accelerate and maintain speed in more aerodynamic vehicles.*	• Streamlined hulls and structural modifications that minimise friction and leverage hydrodynamic principles.[328] • Air lubrication systems, that inject air along the flat bottom area of a ship to reduce frictional drag.[329]
Lightweighting *Improves energy efficiency as less energy is required to accelerate and maintain speed in lighter vehicles.*	• Advanced composite and low weight materials.[330]
Componentry improvement *Improves energy efficiency by improving drivetrain/transmission efficiencies.*	• Improved engine components to increase durability, reduce weight and enhance engine and thermal efficiencies. • Integration of waste heat recovery systems. • Incorporation of complementary systems, such as wind propulsion.
Traffic and logistics management technologies *Improves energy efficiency by optimising vehicle movement and operation.*	• Automated vessel and digitalisation platforms to optimise vessel speed, routes, port scheduling, and delivery of port services such as bunkering.
Energy management solutions *Improves energy efficiency by employing advanced hardware and software solutions that optimise energy usage, balance power demands, enhancing battery life.*	• Optimisation of waste heat recovery energy systems. • Electrification and secondary fuel sources for on-ship use.

[327] Hydrogen Europe (2021) TECHNO-ECONOMIC ASSESSMENT OF LOW-CARBON HYDROGEN TECHNOLOGIES FOR THE DECARBONISATION OF SHIPPING.

[328] Xu K, Su X, Bensow R, Krajnovic S (2022) Drag reduction of ship airflow using steady Coanda effect. Ocean Engineering 266,. doi:10.1016/j.oceaneng.2022.113051

[329] DNV (2024) Maritime Forecast to 2050. <https://www.dnv.com/maritime/publications/maritime-forecast>

[330] Halim RA, Kirstein L, Merk O, Martinez LM (2018) Decarbonization pathways for international maritime transport: A model-based policy impact assessment. Sustainability (Switzerland) 10,. doi:10.3390/su10072243

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.
Alcohol-to-jet conversion (AtJ)	Commonly referred to by its acronym AtJ, alcohol-to-jet (AtJ) is a biofuel typically produced using carbohydrate, waste and residue feedstocks. These are converted into alcohols (e.g. ethanol) and subsequently put through chemical processes such as dehydration, oligomerisation and hydrogeneration to create jet fuel.
Artificial intelligence / Machine learning (AI/ML)	Commonly referred to by its acronym AI/ML, artificial intelligence refers to the stimulation of human intelligence in machines that programmed to think and learn like humans and machine learning is a subset of AI that involves the development of algorithms and statistical models that enable computers to learn from and make predictions or decisions based on data.
B100	B100 refers to pure, or neat, biodiesel in an unblended form.
Batteries: Flow	Rechargeable batteries, where two chemical components are dissolved in liquids and pumped through the system on either side of a membrane. They store and release energy through reversible oxidation and reduction reactions.
Batteries: Metal-ion	Rechargeable batteries that utilise the movement of ions (such as lithium or sodium) between electrodes through an electrolyte to store and release electrical energy. Examples include Li-ion and Na-ion.
Battery swap	A technology that is used in electric vehicles and allows for the quick exchange of a depleted battery pack with a fully charged one.
Biofuel	Liquid fuels derived from biomass or waste feedstock, including ethanol, biodiesel and bio-jet fuels. They can be classified as conventional and advanced biofuels according to the combination of feedstock and technologies used to produce them and their respective market maturity. If additional sustainability criteria are met, biofuels may also be referred to as a biogenic low carbon liquid fuel (LCLF) or, in aviation, sustainable aviation fuel (SAF).
Biogenic	Biogenic refers to substances, materials, or processes that originate from living organisms or biological activity, typically involving carbon from renewable sources like plants, animals, or 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.
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.

Bunkering	Bunkering refers to the process of supplying fuel to ships. This includes the logistics of loading and distributing the fuel among the ship's tanks.
Catenary electric	Locomotives which operate with an electric drivetrain that draws power from overhead wires, enabling continuous energy supply to the traction system.
Conventional jet fuel (CJF)	Commonly referred to by its acronym CJF, conventional jet fuel is a type of fuel specifically designed for use in aircraft powered by gas-turbine engines. It is typically a mixture of hydrocarbons, including normal and iso-paraffins, cycloparaffins, and aromatics. The most commonly used types are Jet A and Jet A1.
Cryopump	A type of vacuum pump that traps gases and vapours by condensing them on a cold surface at very low temperatures.
Deep-sea shipping	Refers to the maritime transport of goods on intercontinental routes, crossing oceans.
Direct air capture (DAC)	Commonly referred to by its acronym DAC, direct air capture is a technology that captures CO_2 directly from the atmosphere for use or storage.
Direct methanol fuel cells (DMFC)	Commonly referred to by its acronym DMFC, direct methanol fuel cells are a type of proton-exchange membrane fuel cell that uses methanol as the fuel and a special proton-conducting polymer as the membrane (PEM).
Distributed Energy Resources (DER)	Commonly referred to by its acronym DER, distributed energy resources are small scale units of local generation connected to the grid at the distribution level. These resources can include solar panels, wind turbines, energy storage systems etc.
Drop-in fuel	Drop-in fuels are a synthetic and completely interchangeable substitute for conventional petroleum-derived hydrocarbons, meaning they do not require adaptations to existing engines, fuel systems or networks.
E10	A type of fuel blend that consists of 10% ethanol and 90% gasoline.
E-fuels	E-fuels are liquid fuels produced through the synthesis of hydrogen and carbon dioxide using renewable electricity, typically through processes like Fischer-Tropsch or methanol synthesis. May also be referred to as ‘electro fuels’ or ‘power-to-liquid fuels.’
Electric vehicle (EV)	Commonly referred to by its acronym EV, electric vehicles are vehicles that employ batteries arranged in a battery pack and combined with inverters and electric motor to convert electrical energy into mechanical energy.
Electric-LPG generator	An Electric LPG (liquefied petroleum gas) generator is a type of generator that uses LPG as its fuel source to produce electricity.
Electromagnetic propulsion	A method of accelerating an object by using electrical currents and magnetic fields.
Emerging small modular reactors (SMR)	Commonly referred to by its acronym SMR, small modular reactors are a type of compact nuclear reactor (generally <300 MW) that are factory-fabricated and scalable.
Fatty acid methyl ester (FAME)	Commonly referred to by its acronym FAME, fatty acid methyl esters are chemical compounds formed by the esterification of fatty acids with methanol.
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) synthesis	Commonly referred to by its acronym FT, Fischer-Tropsch synthesis is biofuel typically produced using carbohydrate, waste and residue feedstocks. These are gasified into syngas and then catalytically converted into fuel.
Fission	A nuclear reaction in which an atomic nucleus splits into two smaller nuclei, releasing a large amount of energy, used in nuclear reactors.
Hydrogen fuel cell electric vehicle (hydrogen FCEV)	Commonly referred to by its acronym FCEV, hydrogen fuel cell electric vehicles are vehicles which employ a hydrogen fuel cell system that generates electric power from e-hydrogen, driving an electric traction system.
Full fuel cycle	Refers to directly radiative emissions released from vehicle fuel combustion, including upstream emissions from fuel supply, conversion and processing, and from power generation for electricity.
Gas-cooled fast reactors (GFRs)	Commonly referred to by its acronym GFRs, gas-cooled reactors are a type of nuclear reactor that uses gas (typically helium or carbon dioxide) as a coolant and operates with fast neutrons.
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)).
High temperature gas-cooled reactor (HTGR)	Commonly referred to by its acronym HTGR, high temperature gas cooled reactors are a type of nuclear reactor that uses helium gas as a coolant and graphite as a moderator.
High temperature PEMFC	A high temperature proton exchange membrane fuel cell (HT-PEMFC) is a type of fuel cell that operates at elevated temperatures, typically between 120°C and 200°C. They use a mineral acid based electrolyte e.g., phosphoric acid.
High-level waste (HLW)	Commonly referred to by its acronym HLW, high-level waste refers to highly radioactive waste resulting from used nuclear fuel or reprocessing, requiring long-term isolation and shielding due to its heat and radioactivity.
Hydrogenated vegetable oil (HVO)	Commonly referred to by its acronym HVO, hydrogenated vegetable oil is a type of fat produced by adding hydrogen to liquid vegetable oils to make them more solid at room temperature.
Hydroprocessed esters and fatty acids (HEFA)	Commonly referred to by its acronym HEFA, hydro-processed esters and fatty acids are biofuels typically produced using waste fats and oils, which are hydrotreated.
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 that 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.
Internal combustion engine (ICE)	Commonly referred to by its acronym ICE, an internal combustion engine is a type of engine in which the combustion of fuel occurs within a confined space called a combustion chamber. This process generates high-pressure gases that expand and move mechanical components, such as pistons or turbines, to produce power.

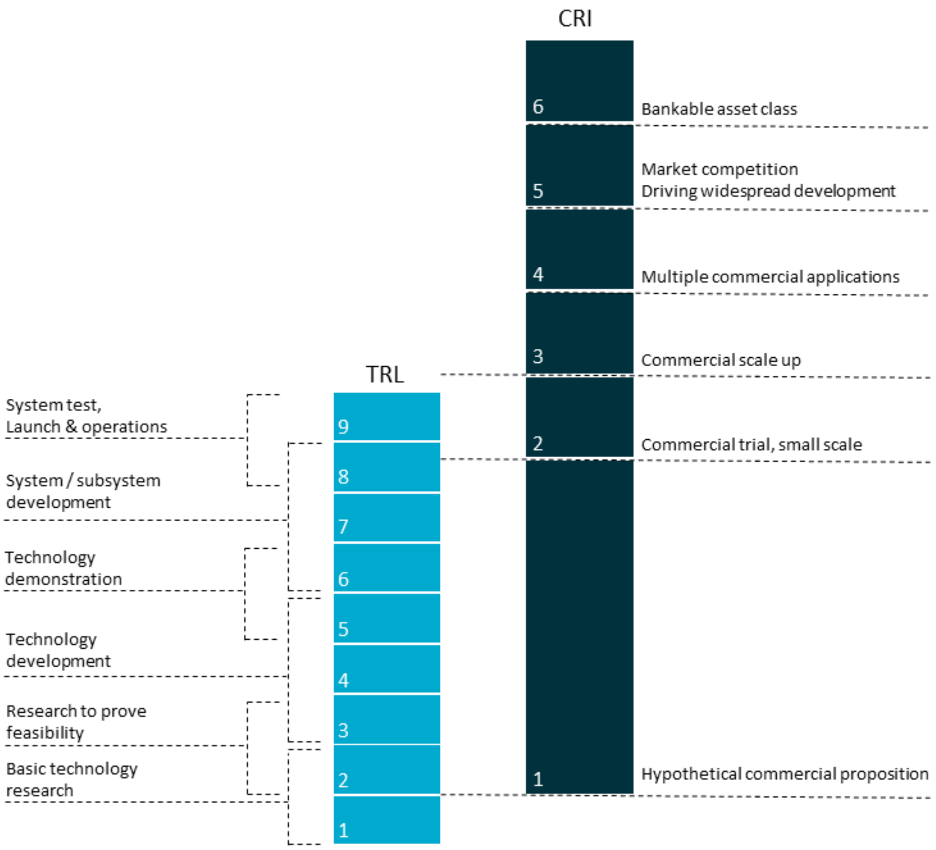
Isotopes	Atoms of the same element with different numbers of neutrons; some isotopes are radioactive and used as fuel or by-products in nuclear reactions.
Lead-cooled fast reactors (LCFRs)	Commonly referred to by its acronym LCFRs, lead-cooled fast reactors are a type of nuclear reactor that uses liquid lead as a coolant and operates with fast neutrons.
Lightweighting	The process of reducing the weight of a component or assembly, often to improve efficiency, performance, and sustainability. This concept is widely used in industries such as automotive, aerospace, and manufacturing.
Liquefied petroleum gas (LPG)	Commonly referred to by its acronym LPG, liquified 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 natural gas (LNG)	Commonly referred to by its acronym LNG, liquified natural gas vehicles employ an internal combustion engine fuelled by liquefied natural gas (LNG).
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.
Low-level waste (LLW)	Commonly referred to by its acronym LLW, low-level waste refers to waste with lower levels of radioactivity, such as contaminated tools or protective clothing, typically requiring less stringent disposal method that high-level waste (HLW).
Marine diesel oil (MDO)	Commonly referred to by its acronym MDO, marine diesel oil is a type of distillate fuel oil used primarily in marine engines. It is a blend of heavy gas oil and light gas oil, making it suitable for medium to high-speed marine diesel engines.
Marine Gas Oil (MGO)	Commonly referred to by its acronym MGO, marine gas oil is a type of distillate fuel oil used primarily in marine vessels. It is produced by distilling crude oil and consists mainly of lighter hydrocarbons.
Mechanical onsite compression	The process of compressing gases, such as natural gas or hydrogen, directly at the location where they are produced or used. This method involves using mechanical compressors to increase the pressure of the gas.
Methanol-to-jet (MtJ)	Commonly referred to by its acronym MtJ, methanol-to-jet is a process that converts methanol into jet fuel, providing a sustainable alternative to conventional aviation fuels. It is a type of biofuel.
Microreactors	Microreactors are a type of nuclear reactor (typically <10 MW) designed for rapid deployment, portable use, and autonomous operation in remote or off-grid locations.
Modular shielding	Radiation shielding components that are designed in modular units, allowing easier transport, assembly, and customization in nuclear systems.
Molten carbonate fuel cell (MCFC)	Commonly referred to by its acronym MCFC, molten carbonate fuel cells are a type of high-temperature fuel cell that operates at temperatures around 600°C to 700°C. It uses a molten carbonate salt mixture as its electrolyte.
Molten Salt Reactor (MSR)	Commonly referred to by its acronym MSR, molten salt reactors are a type of nuclear reactor that uses molten salt mixtures as both a coolant and fuel solvent.

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.
Nickel cobalt aluminium (NCA)	Commonly referred to by its acronym NCA, nickel cobalt aluminium is used in reference to a type of lithium-ion battery chemistry that uses nickel, cobalt, and aluminium as the primary materials in the cathode.
Nickel manganese cobalt (NMC)	Commonly referred to by its acronym NMC, nickel manganese cobalt is used in reference to a type of lithium-ion battery chemistry that uses nickel, manganese, and cobalt as the primary materials in the cathode.
Non-mechanical onsite compression	Methods of compressing materials or structures without using mechanical devices like compressors or hydraulic presses. Instead, these methods rely on natural forces or manual techniques to achieve compression, e.g., gravity based compression.
Nuclear propulsion	Nuclear powered ships use onboard reactors to generate heat, which is converted into mechanical or electrical energy for propulsion and onboard systems.
Onboard carbon capture, utilisation and storage (OCCUS)	Commonly referred to by its acronym OCCUS, onboard carbon capture utilisation and storage refers to the technologies and processes used to capture carbon dioxide (CO_2) emissions directly from the exhaust gases of ships during their operation.
Power-to-liquid (PTL)	Commonly referred to by its acronym PtL, power-to-liquid is a process that involves the production of fuels using non-biogenic feedstocks, such as hydrogen and carbon dioxide, along with renewable energy sources.
Pressurised water reactors (PWRs),	Commonly referred to by its acronym PWR, pressurised water reactors are a type of nuclear reactor where water under high pressure is used as both a coolant and neutron moderator.
Proliferation	The spread of nuclear weapons or weapons-usable material and technology; a key concern in nuclear energy development and international policy.
Pyrolysis	A thermochemical treatment in which an organic (carbon-based material) is exposed to high temperature in the absence of oxygen, causing its chemical and physical separation into different molecules.
Regenerative braking	The process where kinetic energy is recovered during braking and converted into electrical energy which is then stored in a battery or energy storage system.
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.
Short-sea shipping	Refers to vessel movement over relatively short distances, as opposed to the intercontinental cross-ocean deep sea shipping. In the context of this report, it generally refers to domestic intra-port services; however, in less dispersed geographies (such as Europe) it may be encompass routes between country routes.
Sodium-ion (Na-ion)	Commonly referred to as Na-ion, a sodium-ion is a positively charged ion formed when a sodium atom loses one electron.
Sodium-cooled fast reactors (SFRs)	Commonly referred to by its acronym SFRs, sodium-cooled fast reactors are a type of nuclear reactor that uses liquid sodium as a coolant and operates with fast neutrons.

Solid oxide fuel cell (SOFC)	Commonly referred to by its acronym SOFC, a solid oxide fuel cell is an electrochemical device that generates electricity directly from the oxidation of a fuel.
Steam turbine propulsion (shipping)	A propulsion method where steam produced by heating water drives a turbine connected to a propeller or other mechanism. For a nuclear vessel, the heat is provided by a nuclear reactor.
Synthetic fuels	A liquid or gaseous fuel obtained from syngas (a mixture of carbon monoxide and hydrogen) via a gas-to-liquid process. Synthetic fuels may be derived from biogenic or fossil fuel feedstocks (i.e., coal) but are considered a low emissions fuel when the production of syngas and gas-to-liquid processes draw on renewable resources and inputs. Within the AusTIMES model, the term 'synthetic fuel' encompasses synthetic kerosene and synthetic diesel. While e-Fuels and biofuels may be classified as synthetic fuels depending on their synthesis pathway, they are discussed independently as 'e-Fuels' and 'biofuels' throughout this report.
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.
Thorium	A naturally occurring radioactive element that can be used as an alternative nuclear fuel, particularly in molten salt or breeder reactors.
TRi-structural ISOtropic (TRISO)	A type of advanced nuclear fuel particle with multiple protective layers that contain radioactive materials even under extreme conditions, used in high-temperature reactors.
Turbo electric propulsion	A system where a turbine (powered by steam or gas) generates electricity that drives electric motors for ship propulsion.
Underground hydrogen storage (UHS)	Commonly referred to by its acronym UHS, underground hydrogen storage is where hydrogen is compressed and injected into geological or engineered subsurface structures including salt caverns, depleted gas fields, aquifers or excavated caverns.
Uranium	A naturally occurring radioactive element used as fuel in most nuclear reactors. The isotope Uranium-235 (U-235) is the most common fuel for nuclear reactors due to its fissile nature, meaning it can sustain a nuclear reaction. As the natural concentration of U-235 is too low to efficiently support this reaction in most commercial reactors, enrichment is required to increase the proportion of U-235.
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.
Very high temperature reactor (VHTR)	Commonly referred to by its acronym VHTR, very high temperature reactors are a type of nuclear reactor that operates at extremely high temperatures (~1000°C), typically using helium as a coolant.
Very low sulfur fuel oil (VLSFO)	Commonly referred to by its acronym VLSFO, very low sulfur fuel oil is a type of marine fuel with a sulfur content of 0.5% or less by weight.
Well-to-tank (WTT)	Commonly referred to by its acronym WTT, well-to-tank is 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 23: Technology Readiness Levels and Commercial Readiness Index[331]



331 Adapted from ARENA (2014) Commercial Readiness Index. <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf>

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,[332] publications from domestic[333] and international[334] government bodies, and prominent literature from Australian research centres (e.g., ClimateWorks Australia,[335] Net Zero Australia,[336] and the CSIRO[337]).

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

		Subsector	Criteria
Energy supply	Electricity	Electricity generation	Levelised cost
		Electricity storage	Discharge duration Levelised cost

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

[333] 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)>

[334] 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).

[335] 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).

[336] 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).

[337] 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>

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

A.3.3 Aviation refuelling methodology and assumptions

The Total Usable Energy (TUC) of a conventional aircraft (Boeing 737-800) was calculated by multiplying the conventional fuel mass of Jet A1 fuel by its gravimetric density for Total Energy Capacity (TEC), which is then multiplied by the conventional energy efficiency to arrive at the conventional TUC.

$$TUC\ (kWh) = Fuel\ mass\ (kg) \times Gravimetric\ energy\ density\ (kWh/kg)\ \times Engine\ efficiency\ (\%)$$

The TUC was utilised as a consistent standard for all technologies to match, to determine refuelling across different alternative aviation technologies.

For each of the conventional, hydrogen combustion and hydrogen fuel cell technologies, the consequent approach included deriving TEC by dividing TUC by the engine efficiency of each respective technology, reflecting the energy output relative to the engine's performance.

TEC for each technology was derived by dividing TUC by their respective engine efficiencies, reflecting energy output relative to performance.

$$TEC\ (kWh) = \frac{TUC\ (kWh)}{Engine\ Efficiency\ (\%)}$$

From TEC, the mass of fuel required is calculated by dividing it by the energy density (measured in kWh/kg). Refuelling time is then estimated by dividing the fuel mass by the fill rate (kg/min) and adjusting for a 15% battery minimum to account for reserve requirements.

$$Fuel\ mass\ (kg) = \frac{TEC\ (kWh)}{Gravimetirc\ energy\ density\ (kWh/kg)}$$

$$Refuelling\ time\ (min) = \frac{Fuel\ mass\ (kg)}{Fill\ rate\ (kg/min)} \times (1 - 0.15)$$

A distinct approach was adopted for battery electric aviation, given its specific charging characteristics and requirements. TEC is immediately divided by the charge rate, factoring in the same 15% battery minimum and a conversion of hours to minutes.

$$Recharging\ time\ (min) = \frac{TEC\ (kWh)}{Charge\ rate\ (kW)} \times 60 \times (1 - 0.15)$$

This approach ensures that energy requirements and operational timelines are systematically compared while accommodating the varied properties of each technology. This analysis does not account for variations in weight requirements due to technological changes, nor does it account for additional processing that may be required for alternative fuels (e.g. temperature regulation for cryogenic hydrogen).

Table 54 provides key intermediary calculations; and Table 55 notes key assumptions used in this methodology.

Table 54: Refuelling / recharging rates by technology – Aviation, medium-range flight

Calculation	Unit	Conventional	Biofuels / synfuels	Hydrogen combustion	Hydrogen fuel cell	Electric battery
Total usable energy	kWh	***88,085***	*Assumed equivalence to conventional*	**88,085**	**88,085**	**88,085**
Total energy capacity	kWh	*251,670*		195,744	125,835	96,796
Mass of fuel	kg	*20,924*		4,967	3,775	112,423
Refuelling time – upper bound	mins	*24.6*		14.1	10.7	1,316.4
Refuelling time – lower bound	mins	*8.6*		3.5	2.7	169.7

Refuelling assumptions

Table 55: Key levelised cost assumptions – Aviation, medium-range flight, refuelling

Assumption	Units	Figure	Notes
Fuel tank size – Boeing 737-800	L	26,025[338]	Used as conventional alternative for primary use case.
Fuel tank size – Beechwood 1900D	L	2, 519[339]	Used as conventional alternative for secondary use case.
Density – Jet A1 fuel	Kg/L	0.80	In line with levelised cost assumptions.
Gravimetric energy density			
Conventional (Jet A1 – LHV)	kWh/kg	12.03	In line with levelised cost assumptions.

[338] Boeing (2023) 737-800BCF Converted Freighter. <https://www.boeing.com/content/dam/boeing/boeingdotcom/commercial/services/assets/brochure/737_800BCF.pdf> (accessed 23 June 2025).

[339] Airport Technology (2002) Raytheon BK 1900 Project. <https://www.airport-technology.com/projects/raytheon_bk_1900/?cf-view> (accessed 23 June 2025).

Hydrogen – HHV (Hydrogen combustion)	kWh/kg	39.41	In line with levelised cost assumptions.
Hydrogen – LHV (fuel cell)	kWh/kg	33.33	In line with levelised cost assumptions.
Battery	kWh/kg	0.86[340]	na
Engine efficiency			
Conventional (Boeing 737-800)	%	35%[341]	Assumes best today per conventional, for typical cruise conditions (Mach 0.78-0.8, at optimal altitude). Reflective of a CFM56-3 Engine.
Hydrogen combustion	%	45%[342]	na
Hydrogen fuel cell	%	70%[343]	Assumes use of a reversible fuel cell.
Electric battery	%	91%[340]	Per the nominal scenario in 2050 from the source.

Refill / recharge rates		Minimum	Maximum	
Liquid fuels	L/min	900[344]	3,213[345]	Minimum rate assumes 1 nozzle point at 50 PSIG. Maximum rate assumes 2 nozzle points.
Hydrogen[344]	Kg/min	300	1,200[345]	Minimum rate assumes 1 nozzle point using a 6-inch inner diameter pipe, similar to current infrastructure. Maximum scenario reflects a scenario from literature, given proper precautions and technological advancements.
Electricity	kW	3,750[346]	29,089[347]	Minimum rate reflects current state-of-the-art charging output available to heavy duty vehicles of 3.75 MW. Maximum rate derived from a future plane with a 15.4 MW battery that is assumed to have a 'C rate' of 1.7, and incorporates charging efficiency of about 90%.

[340] Tiede B, O'Meara CA, Jansen R (2022) Battery Key Performance Projections based on Historical Trends and Chemistries. *2022 IEEE/AIAA Transportation Electrification Conference and Electric Aircraft Technologies Symposium (ITEC+EATS)*. https://ntrs.nasa.gov/citations/20220009109 (accessed 23 June 2025).

[341] Korba P, Balli O, Caliskan H, Al-Rabeei S, Kale U (2023) Energy, exergy, economic, environmental, and sustainability assessments of the CFM56-3 series turbofan engine used in the aviation sector. Energy 269:126765. https://doi.org/10.1016/j.energy.2023.126765

[342] Adler EJ et al. (2023) Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts. Progress in Aerospace Sciences 141:100922. https://doi.org/10.1016/j.paerosci.2023.100922; Campe R (2019) Hydrogen co-combustion in ICE. *ICCT ZEV Workshop*, San Francisco, July 2019. <https://theicct.org/sites/default/files/2_Campe_H2_combustion_ICE_PUBLIC.pdf> (accessed 23 June 2025); Stępień Z (2021) A Comprehensive Overview of Hydrogen-Fueled Internal Combustion Engines: Achievements and Future Challenges. Energies 14(20):6504. https://doi.org/10.3390/en14206504

[343] U.S. Department of Energy (2024) Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan 2024. <https://www.energy.gov/sites/default/files/2024-05/hfto-mypp-2024.pdf> (accessed 23 June 2025).

[344] Babuder D et al. (2025) Operational performance in sustainable aviation: an in-depth analysis of turnaround times of future commercial narrowbody liquid hydrogen aircraft. International Journal of Sustainable Aviation 11(1):1-38. https://doi.org/10.1504/IJSA.2025.145735

[345] Boeing Commercial Airplanes (2024) Next-Generation 737 Airplane Characteristics for Airport Planning. *Document D6-58325-7 Rev B*. https://www.boeing.com/content/dam/boeing/boeingdotcom/commercial/airports/acaps/737NG_REV_B.pdf (accessed 23 June 2025).

[346] Jentzsch R, Danieli M (2024) Megawatt Charging System: Charging at 3.75 MW – The Next Step in Electromobility. *Vector Informatik*. https://cdn.vector.com/cms/content/know-how/_technical-articles/Megawatt_Charching_System_MCS_202411_TechnicalArticle_EN.pdf (accessed 23 June 2025).

[347] A 'C rate' is reflective of a [dis]charge capacity rate, where for instance, 1C is illustrative of a [disc]charge time of 1 hour, and 0.5C is illustrative of a [disc]charge time of 2 hours. See Table 2: de Vries R et al. (2024) Battery Performance Metrics for Large Electric Passenger Aircraft. *34th Congress of the International Council of the Aeronautical Sciences (ICAS 2024)*. <https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0636_paper.pdf> (accessed 23 June 2025).

A.4 Abatement potential data repository

Table 56: Abatement potential sources and assumptions – Transport

Subsector	Abatement threshold		Emissions data		Source
	Threshold	Explanation	Direct emissions	Indirect emissions	
Road transport	90%	Technologies are compared against a *relative abatement threshold*, compared to a conventional petrol internal combustion engine (ICE) vehicle train, with an emissions intensity of 236.7gCO2e/km. Threshold reflects the availability of low emissions technology solutions by 2050, and accounts for residual emissions in the grid, recognising that some fossil fuel capacity will likely remain (i.e., peaking plants).	Full fuel cycle	Includes ILUC for biofuels	Biofuels derived from Xu et al. (2022) and Cai et al. (2022).[348] RD&D GREET Fuel-Cycle model[349]
Aviation	*60%*	Technologies are compared against a *relative abatement threshold*, compared to an aircraft operating on conventional jet fuel, with an emissions intensity of 85.1gCO2e/GJ. Threshold reflects the availability of solutions by 2050, that do not compete with food production.	Full fuel cycle	Includes ILUC for biofuels	ICAO-GREET model (2019)[350]
Rail	90%	Technologies are compared against a *relative abatement threshold*, compared to a diesel freight train with an emissions intensity of 90.9gCO2e/GJ. Threshold reflects the availability of low emissions technology solutions by 2050, accounting for residual emissions in the grid and the challenges of decarbonising energy-intensive modes of transportation.	Full fuel cycle	Includes ILUC for biofuels	ICAO-GREET model (2019)
Shipping	90%	Technologies are compared against a *relative abatement threshold*, compared to medium-speed vessel for international bulk-commodity shipping operating on Marin Diesel Oil with an emissions intensity of 91.9gCO2e/GJ. Threshold reflects the availability of low emissions technology solutions by 2050, accounting for residual emissions in the grid and the challenges of decarbonising energy-intensive modes of transportation.	Full fuel cycle	Includes ILUC for biofuels	ICAO-GREET model (2019)

348 Emissions intensities from these sources were converted from kgCO2/MJ to kgCO2/kg fuel using an energy density of 39.36 MJ/kg. Xu H et al. (2022); Cai H, Prussi M, Ou L, Wang M, Yugo M, Lonza L, Scarlat N (2022) Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy and Fuels 6, 4398. https://doi:10.1039/d2se00411a

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