Dear Committee Secretary

I refer to the recent enquiry announced into the transition of electric vehicles.

Please find attached a recent study we completed considering various zero emission powertrain and energy source alternatives.

We provide the study report as a submission to the Committee as it explores various matters relating to electric vehicles.

We would welcome the opportunity to discuss any aspect of the attached with the Committee.

Cheers

Craig

craig allen
director
[redacted]

Xseed
Regenerating resources to live locally

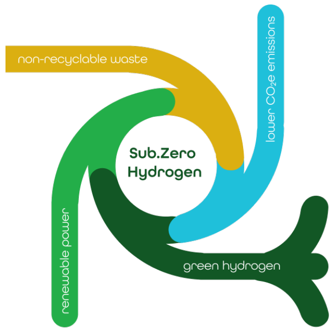
Sub.Zero® hydrogen lowers the decarbonised Total Cost of Ownership of truck and bus pathways in Australia

Author: Craig Allen | Director - Xseed Solutions | 16 February 2024

Executive Summary

Introduction

Hugging Australia's coastlines, 95% of Australia's population live within 50 km of its' beaches, in an area representing just 5% of Australia's land mass, slightly larger than Sweden. Across that area Australia has over 121,000 km of national highways and arterial roads, more than eight times Sweden's major road network. A unique infrastructure challenge when evaluating alternative models to embark on a decarbonisation transition.



Based on this report's key findings we expect hydrogen produced from waste (Sub.Zero H_2) to be the more favourable environmental and economic decarbonisation operating and capital cost emissions reduction pathway. Sub.Zero H_2 delivery is capable to be actioned with today's technology for zero waste outcomes to provide both localised Sub.Zero hydrogen, fast charge power and e-methanol to the truck and bus network - capable to reduce up to 11% pa of Australia's Greenhouse Gas (GHG) emissions.

Climate benefits from a more targeted vehicle and infrastructure focus

This paper provides a unique, comprehensive Australian Total Cost of Ownership (TCO) and lifecycle analysis from energy and fuel production and distribution through to alternative powertrains across various truck classes and use cases.

Our findings advocate for the following outcomes:

- **Sub.Zero hydrogen from Resources, Energy and Chemical Hubs (REC Hubs) or Consortium Resources, Energy and Chemical Hubs (C-REC Hubs), provide the lowest carbon intensity outcomes.** The technology pathway provides additional vehicle choice flexibility and efficient energy carrier options (i.e., Sub.Zero methanol) with Sub.Zero H_2 to fuel combinations of battery electric and hydrogen fuel cell vehicles. Operating as micro-grids, grid dependency risks are minimised to accelerate real net zero GHG reductions in transitioning away from fossil fuels. Thus, enabling the decarbonisation of road transport - a hard to abate sector.
- **Light commercial vehicles, rigid trucks, and long-haul trucks (500km) provide the most effective TCO outcomes near term.** A tangible, opportunistic pathway for business and government to transition away from diesel. Decarbonising this sub-sector efficiently reduces Australia's GHG emissions by up to 5%. All enabled:
    - with fuel pricing equivalence with diesel, based on net energy parity;
    - with the powertrain capability to utilise battery electric or hydrogen infrastructure or extend that with micro-grid recharging;
    - by the convergence of TCO and infrastructure outcomes by 2030; and
    - yielding relatively higher GHG intensity reductions vs passenger vehicles.

  Australia currently has an estimated 73,000 passenger electric vehicles reducing Australia's GHG emissions by up 212,000 t CO_2e. Transitioning the similar number of light commercial vehicles would abate 330,000 t CO_2e, rising to over 660,000 t CO_2e using Sub.Zero H_2 as the fuel source to recharge the vehicles. **A three times greater climate positive outcome.**
- **Hydrogen fuel-cell powertrains utilising Sub.Zero hydrogen infrastructure reduces to be cost competitive by 2027.** By 2030, long haul articulated vehicles (i.e., tractor trailers) TCO outcomes are expected to be lower than diesel. Given the higher relative GHG benefits, from a more concentrated and impactful number of vehicles affected, it is a business sub-sector worthy of government policy and investment to stimulate actions today. Also benefiting before 2030 are the anticipated technology advancements for the high proportion of articulated trucks at over 40 t GCM and road trains in Australia. This will enable extension of the decarbonisation pathway to multi-combination trailer fleets for productive long haul freight movements across regional Australia.

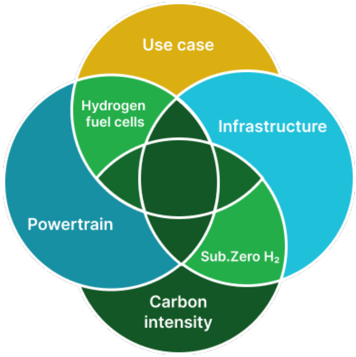
More than a Hydrogen Hub producing a single product, **REC Hubs,** *Resources, Energy and Chemical Hubs* (REC Hubs), are circular economy Sub.Zero H_2 manufacturing resource hubs producing ultra-low carbon hydrogen, electricity, chemicals, and related resources.

C-REC Hubs, Consortium Resources, Energy and Chemical Hubs (C-REC Hubs), are circular economy Sub.Zero H_2 production resource hubs, majority owned by organisations consuming the ultra-low carbon hydrogen, electricity , chemicals, and resources produced.

Decarbonised Total Costs of Ownership

This report addresses the following four key criteria as part of assessing the economic and environmental outcomes of each alternative pathway being:

- Use case — Long haul | Regional | Urban
- Infrastructure — Islanded | Hubs | REC-Hubs | C-REC Hubs
- Powertrain — Diesel | Battery electric | Hydrogen fuel cell
- Carbon intensity — High | Low | Ultra-low



Carbon negative Sub.Zero H_2, as an ultra-low carbon intensive fuel and energy source, provides a powerful and unique decarbonisation accelerator to replace diesel. Especially with an integrated infrastructure eco-system from production to distribution with localised battery electric and hydrogen refuelling stations.

Attaining carbon intensity reductions well below that of diesel and grid electricity at 0.33 and 0.65 kg CO_2e per kWh respectively comes at a cost. Adopting Sub.Zero H_2 pathways moderates that cost increase, and accelerates cumulative CO_2e reduction savings, lowering GHG abatement outcomes at more than twice that of traditional renewable energy pathways of solar, wind and/or electrolysis hydrogen.

Progressing Sub.Zero H_2 eco-systems on a shared C-REC Hub basis, enables participating organisations and governments to benefit from lowered cost and GHG reduction outcomes. A Sub.Zero H_2 C-REC Hub pathway further reduces the incremental operating and capital cost differential, accelerating businesses' transition to net or real zero, as compared to islanded and hub battery electric or electrolysis hydrogen infrastructure.

Infrastructure ▽	Diesel	Battery electric	Hydrogen	◁ Energy Source
C-REC Hub		Sub.Zero Hydrogen	Sub.Zero Hydrogen	Ultra Low
REC Hub		Sub.Zero Hydrogen	Sub.Zero Hydrogen	Ultra Low
Hub	Diesel	Renewable Network Grid	Electrolysis Hydrogen	Low (High - Diesel)
Islanded		Renewable Micro Grid	Electrolysis Hydrogen	Low
Powertrain ▷	Diesel	Battery electric	Hydrogen Fuel Cell	△ Carbon Intensity

Figure 1 – Criteria pathways assessed for decarbonised TCO outcomes

Highlighting the benefits of Sub.Zero H_2 pathways, Table 1 summarises the incremental Total Cost of Ownership (TCO) $ per kg CO_2e of the marginal abatement outcomes as compared to the current predominate use of diesel across various road freight, bus and coach vehicle classes and use cases:

Table 1. Summary of 2024 TCO per CO_2e marginal abatement outcomes (vs diesel) of road transport use cases.

TCO $ per kg CO_2e - Marginal abatement cost/(benefit)	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Battery electric via Islanded in 2024	0.98	1.11	0.93	0.25	1.21	2.33	0.87
Battery electric via Hub in 2024	1.86	1.92	1.71	1.37	3.57	7.38	1.76
Battery electric via REC Hub in 2024	0.35	0.43	0.36	(0.01)	0.28	0.46	0.37
Battery electric via C-REC Hub in 2024	0.24	0.32	0.25	(0.09)	0.17	0.36	0.29
Sub.Zero H_2 via REC Hub in 2024	0.66	0.76	0.70	0.57	0.81	0.94	1.04
Sub.Zero H_2 via C-REC Hub in 2024	0.44	0.54	0.48	0.40	0.59	0.73	0.87
Electrolysis H_2 via Islanded in 2024	3.13	3.06	2.67	2.99	6.47	12.71	3.55
Electrolysis H_2 via Hub in 2024	2.24	2.45	2.27	1.67	3.19	4.42	2.44

***Note:** **H_2** is hydrogen; **BE** is battery electric; **Hub** is either a Hydrogen Hub or Renewable Energy Hub; **REC Hub** is a Resources, Energy and Chemical Hub; **C-REC Hub** is a Consortium Resources, Energy and Chemical Hub.*

Under three cents - regenerating waste into a valuable resource

In addition to these climate positive GHG outcomes, this report highlights four key TCO findings as part of road freight and bus use cases:

1. Regional battery electric trucks, utilising Sub-Zero H_2 stations, yields the lowest incremental 2024 TCO increase to diesel at up to $0.32 per km.
2. Regional vehicles, utilising Sub.Zero H_2 C-REC Hub stations with hydrogen or fast charge flexibility results in a TCO at least 83% below that of BE Hub facilities.
3. Long haul hydrogen fuel cell trucks, utilising Sub.Zero H_2 C-REC Hub stations results in an average TCO 25% below that of electrolysis hydrogen facility options.
4. Within 6 years, long-haul ZEV utilising Sub.Zero H_2 C-REC Hubs are expected to be $0.09 to $0.15 per km lower than diesel.

Table 2. Summary of reducing Sub.Zero H_2 C-REC Hub TCO incremental cost (vs diesel) - as powertrain costs decline.

Incremental TCO $ per km	**Long-haul tractor trailers**			**Regional rigid vehicles**			**Buses /**
	500 km	**800 km**	**1,000 km**	**Heavy**	**Medium**	**Light**	**coaches**
Sub.Zero H_2 via C-REC Hub in 2030	**(0.09)**	**(0.15)**	**(0.15)**	**0.29**	**0.23**	**0.21**	**0.50**
2030 vs 2024 (x) times	↓ 11.0x	↓ 8.5x	↓ 7.6x	↓ 1.2x	↓ 1.9x	↓ 0.8x	↓ 2.9x
Sub.Zero H_2 via C-REC Hub in 2024	0.91	1.13	1.00	0.65	0.68	0.39	1.96

Table 3. Summary of incremental 2024 TCO (as compared to diesel) of alternative hydrogen use case pathways.

Incremental TCO $ per km	**Long-haul tractor trailers**			**Regional rigid vehicles**			**Buses /**
in 2024	**500 km**	**800 km**	**1,000 km**	**Heavy**	**Medium**	**Light**	**coaches**
Sub.Zero H_2 via C-REC Hub	**0.91**	**1.13**	**1.00**	**0.65**	**0.68**	**0.39**	**1.96**
vs REC Hub	↓ 33%	↓ 29%	↓ 32%	↓ 31%	↓ 27%	↓ 22%	↓ 16%
Sub.Zero H_2 via REC Hub	1.37	1.59	1.47	0.94	0.93	0.50	2.35
REC Hub vs Electrolysis H_2 hubs	↓ 25%	↓ 21%	↓ 21%	↓ 32%	↓ 35%	↓ 50%	↓ 19%
Electrolysis H_2 via Hub	1.84	2.01	1.85	1.38	1.44	1.01	2.90
Electrolysis H_2 via islanded	2.57	2.50	2.17	2.47	2.91	2.90	4.20

Table 4. Summary of incremental TCO of Battery Electric (BE) technology solutions (as compared to diesel).

Incremental TCO $ per km	**Long-haul tractor trailers**			**Regional rigid vehicles**			**Buses /**
in 2024	**500 km**	**800 km**	**1,000 km**	**Heavy**	**Medium**	**Light**	**coaches**
Sub.Zero BE via REC Hub	**0.73**	**0.90**	**0.76**	**(0.02)**	**0.32**	**0.25**	**0.83**
Sub.Zero BE vs BE via Hub	↓ 60%	↓ 51%	↓ 54%	↓ 102%	↓ 83%	↓ 87%	↓ 64%
Battery Electric (BE) via Hub	1.80	1.86	1.65	1.27	1.89	1.95	2.31

The powerful combination of Sub.Zero H_2 REC Hub technology and Zero Emission Vehicle (ZEV) powertrains enables many Australian use cases to transition away from fossil fuels and deliver up to 11% pa in Australian GHG reductions. Today's actions, with current technology implementable by 2027, can see Australian companies delivering significant GHG reductions of Australian road freight. Excluding the two highest cost scenarios (ie. battery electric and electrolysis hydrogen), we model the average road freight TCO increase over diesel at $0.84 per km, anticipated to reduce with economies of scale within six years to less than $0.24 per km.

All sectors benefit, none more so than agriculture. In transporting cattle over 1,000 km from regional Australia to the coast or bananas and avocados south from Queensland, it is estimated today this represents a transport cost increase per 250g of produce item of less than three cents – reducing further as scale and technology advances into 2030.

Introduction

Australia's vast road network accommodates over 4.7 million buses, articulated and rigid trucks and light commercial vehicles to connect the country's 27 million people. Consuming over 15 billion litres of diesel annually, the Australian government reports this sub-sector emits 42 million t CO_2e annually, with cars only marginally higher at 45 million t CO_2e annually.

Australians share a common decarbonisation technology pathway to Europe utilising emerging ZEVs to replace harder to abate diesel dependant freight trucks and passenger buses. The International Council on Clean Transport (ICCT) has released a series of comprehensive papers, most recently the paper *A total cost of ownership comparison of truck decarbonisation pathways in Europe* (2023) authored by Hussein Basma and Felipe Rodríguez. That paper's key findings were that in Europe 2030 battery electric vehicles were expected to be the most cost-effective decarbonisation pathway, followed by hydrogen fuel-cell trucks sometime before 2040.

Based on these European findings: *Is there also a positive impact for Australian pathways given Australia's electricity carbon intensity at 0.650kg CO_2e/kWh as compared with the average carbon intensity of Europe's 27 country electricity network at 0.251 kg CO_2e / kWh, below that of diesel at 0.334 kg CO_2e / kWh?*

Can Australia gain a strategic advantage utilising its' abundance of local resources, solar, wind, and waste to yield more advantageous environmental outcomes despite its large distances within the same timeframe?

Yes, and yes. For Australia, this report's findings are that today's battery electric vehicles provide the lowest incremental alternative TCO outcome for rigid truck vehicles in regional and urban areas. In combining ultra-low Sub.Zero H_2 and REC Hub infrastructure choices, with either battery electric or hydrogen fuel cell powertrains, it is estimated that this provides the lowest TCO and highest GHG reduction outcomes today, reducing up to 11 times further by 2030. For Australia, this enables it to deliver low cost TCO and GHG reductions 5 to 10 years before those identified for Europe by Basma and Rodríguez.

Despite Australian road transport contributing 21% to Australia's total CO_2e GHG emissions, Australia is yet to introduce any comprehensive policies to stimulate the road freight and the passenger bus sectors to decarbonise. Currently, both sectors are heavily reliant on diesel engine technology with less than 0.25% of Australia's truck and bus fleet classified as low carbon intensive vehicles. Australian electric passenger car transition is at 0.48%.

Internationally the most advanced zero emission powertrains are battery electric and hydrogen fuel cell trucks and buses – collectively Zero Emission Vehicles. Fuelled by renewable electricity, ZEVs can provide GHG emission reductions with low carbon intensity outcomes. ZEVs powered by hydrogen, produced efficiently from landfill waste (Sub.Zero H_2), is capable to reduce Australia's total GHG even further, up to 11% annually.

That is, diverting Australia's landfill waste, not depleting Australia's scarce water resources, to manufacture green hydrogen to fuel and charge ZEVs also lowers costs, GHG emissions and reduces biodiversity impacts. Comparing electrolysis to Sub.Zero hydrogen, it is estimated that it takes over 2,000 kg of water to produce 100 kg of hydrogen using electrolysis, whereas diverting 1,000 kg of waste is capable to produce similar quantities of hydrogen, whilst utilising one-sixth of the renewable energy. Sub.Zero H_2 production uses less water, less land usage, less renewable energy is consumed and the eco-system solution has lower GHG emissions. Four compelling reasons to consider a waste to hydrogen fuel and energy manufacturing pathway for the transport sector.

Sub.Zero
- Less water
- Less land usage
- Less renewable energy used
- Lower GHG emissions

Waste to hydrogen is capable to power 80% of road freight transport

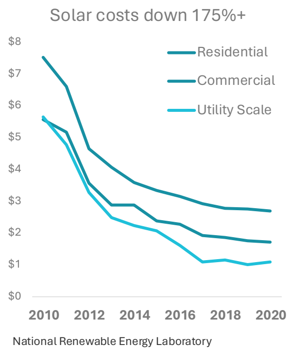
Australian households dispose of 10 million tpa waste to landfill each year. Despite Australian businesses' best recycling efforts, a further 12 million tpa of business waste is disposed of to landfill. This is at a time that when government household waste from landfill diversion targets by 2030 of 70% to 80% exist and go unactioned. The Australian Government reports that Australians are disposing more waste to landfill than ever, well below these aspirational net zero diversion targets.

Empirical studies show on average this level of Australian household and business waste to landfill is capable to manufacture 2.2 million tpa of Sub.Zero hydrogen. This domestically, manufactured hydrogen source is capable to be a substitute for an estimated 12 billion litres of diesel annually.

Yearly, around 15 billion litres of diesel, or 50% of all Australian diesel sold, is estimated to be consumed by registered buses, light commercial vehicles, and articulated and rigid trucks. That is, Australians regenerating and recycling its household and business landfill waste are capable to domestically manufacture sufficient hydrogen to fuel and charge 80% of its bus and road freight transport fleet.

We analyse the benefits that utilising circular economy principles, and today's technology, to establish Sub.Zero H_2 REC Hubs enables participants. This approach advances decarbonisation pathways at the lowest TCO per km and lowest TCO per CO_2e by 2030 for most scenarios analysed in this model.

The upfront capital investment is higher than the status quo. That was the case with solar, which has reduced 175% to 400% in per kWh for alternative use cases with wider adoption over 10 years. Basma & Rodríguez, 2023 anticipate similar powertrain advancements into 2030 that contribute to a lowering of TCO outcomes into 2027 and 2030.



Given the price sensitive nature of agricultural and road freight sectors consuming 67% of Australian diesel, the adoption of new technologies and infrastructure is likely to be influenced by three factors:

1. The TCO of zero emission vehicles, trucks and buses powertrains;
2. The TCO of low carbon production, refuelling and recharging infrastructure; and
3. The attainable level of GHG reductions from the pathways adopted.

This analysis acknowledges the comprehensive work of the ICCT, Basma and Rodríguez and others noted. We have endeavoured to leverage and extend that work to assess the decarbonised TCO of trucks, buses, and low carbon infrastructure delivery in Australia, to:

- Localise the analysis for Australian circumstances, incorporating updates to a number of the operating financial and cost inputs;
- Extend the TCO analysis to incorporate the TCO of establishing islanded vs common user production and refuelling infrastructure (colloquially referred to as "Hubs");
- Analyse the TCO between its operating and capital expenditure cost elements;
- Incorporate a measure of carbon intensity of alternative solutions, assessed using a TCO per CO_2e metric; and
- Extend the analysis to include Sub.Zero hydrogen produced from waste.

This paper addresses the issues in five sections for Australia:

1. After introducing the scope of the analysis, we focus on the most relevant Australian vehicle classes and powertrain technologies.
2. The second section focuses on the total cost of ownership methodology adopted for various use cases.
3. In the third section, we present the TCO analysis results.
4. The fourth section provides some insights on the carbon intensity outcomes from alternative solutions.
5. Finally, we provide a summary of key findings from the analysis.

The paper also includes an extensive list of appendices summarising the main data and assumptions used to quantify the capital and operating TCO elements and carbon intensities.

Scope of analysis

Given Australia's unique environment and adjacency to one of the world's most precious resources the Great Barrier Reef, what are the key economic constraints inhibiting Australia regenerating and recycling its waste resources to manufacture hydrogen to enable the road transport sector to transition away from fossil fuels.

In a circular economy sense, described as "Waste to Hydrogen to X", technology exists today to manufacture hydrogen from waste. Arguably more efficiently and with greater biodiversity benefits than utilising scarce water resources to produce hydrogen using electrolysis, or other alternatives that simply burn our waste to produce electricity.

The TCO and carbon intensity analysis presented in this paper covers:

1. **Use cases:** Urban, regional, and long-haul truck and bus classifications, summarised in Table 5, mainly:
    a. long-haul tractor trailers operating with Gross Combination Mass (GCM) up to 42.5 tonnes in three primary modes:
        i. Up to 500 km per day, typically drayage vehicles with predictable routes that return daily to depots;
        ii. Up to 800 km per day, reflecting Australia's longer distances, where trucks may return to its home depot on occasion; and
        iii. Averaging 1,000 km per day, with intra or inter-state routes where the vehicles don't return to its home depot at the end of each day.
    b. rigid trucks operating in regional and urban delivery networks, and
    c. passenger buses operating across urban and regional networks; and
2. **Infrastructure:** Production, refuelling or recharging infrastructure in various forms:
    a. **Islanded** – dedicated single site production and distribution infrastructure for battery electric or electrolysis hydrogen as summarised in Table 8;
    b. **Hubs** – ranging from current diesel infrastructure through to utilising grid renewable electricity for battery electric recharges or electrolysis hydrogen production servicing multiple distribution sites;
    c. **REC Hubs** – are practical examples of circular economy principles and zero waste outcomes, where waste resources are regenerated or recycled to manufacture Sub.Zero resources and products. All capable to be used by the waste provider and/or others through two ownership models:
        i. **REC Hub** – owned and operated by a third party and providing resources on an arm's length basis to Sub.Zero resource users;
        ii. **C-REC Hub -** common user infrastructure majority owned by a consortium providing and/or utilising a majority of the resources, benefiting from lower externalities to produce Sub.Zero resources (eg. hydrogen and/or methanol).
        Both REC Hub ownership models are capable to be operated on a hub to point or point to point distribution basis to multiple DC fast charge and hydrogen refuelling stations.
3. **Powertrains:** Diesel, battery electric, and hydrogen fuel cell powertrains.
4. **Carbon intensity:** Covering four main fuel / energy sources (1) diesel; (2) renewable electricity; (3) electrolysis hydrogen; and (4) Sub.Zero hydrogen.

Table 5. Summary of various vehicle use cases.

	Chassis type	GCM tonnes	GVM tonnes	Power unit rating kW	Fuel system sizing km	Registered vehicles '000	Australian GHG kt CO_2e pa
Articulated tractor-trailer	Tractor	42.5	> 15.0	350	500 / 800 / 1,000 km	120	13,000
Regional heavy rigid vehicle	Rigid	22.5	15.0	300	300 km	575	9,000
Urban medium rigid vehicle	Rigid	10.4	7.2	250	230 km		
Urban light commercial vehicle	Rigid	3.8	3.5	140	250 km	3,952	18,000
Bus / coach	Rigid	19.0	11.0	250	300 km	98	2,000

Australia has a unique truck classification system to Europe, North America, and other Asian markets which has been used for this paper. Given the current battery electric and hydrogen tractor GCM data limitations at around 40 t, this report's TCO scenarios does not consider the various materially higher tractor trailer combinations utilised in Australia to enhance productivity, including the B double, B triple, and road train combinations. It is estimated that these combinations with GCM well over 40 t compromise around 64% of total Australian articulated tractor-trailer combinations. It is anticipated that powertrain technology advancements modelled that suitable tractors with the required fuel cell power and hydrogen storage capacity would be available before 2030.

This paper acknowledges and utilises the technical specifications, pricing, cost, and consumption outcomes of many of the various powertrains developed using detailed vehicle technology analysis described in various ICCT publications (Basma, Beys, et al., 2021; Basma & Rodríguez, 2022; Basma & Rodríguez, 2023). Where more specific, or localised Australian data or reports are available, that information has been used to enhance the reflection of local Australian operating conditions.

Total cost of ownership approach

The Total Cost of Ownership approach adopted for this analysis evaluates the capital expenditure costs of the powertrains, vehicles, and infrastructure separate from the operating costs of the vehicles.

Table 6. Summary of Total Cost of Ownership elements.

<table>
<tr><th colspan="7">Total Cost of Ownership</th></tr>
<tr><th colspan="3">Capital Expenditure</th><th colspan="4">Operating Expenditure</th></tr>
<tr><td>Vehicle retail price</td><td>Vehicle residual value</td><td>Infrastructure</td><td>Energy and fuel</td><td>Insurance</td><td>Labour</td><td>Maintenance</td></tr>
<tr><td colspan="2">Basma and Rodríguez (2023)</td><td colspan="2">Energy and fuel alternatives</td><td colspan="3">Modified for known Australian conditions</td></tr>
</table>

As an emerging sector we have incorporated two infrastructure aspects to the TCO analysis:

1. ZEV owners and operators entering into longer term *Vehicle As A Service* (VAAS) style agreements incorporating costs or fees for the vehicle and/or a long term fuel or energy contracts.
2. Islanded infrastructure developments where dedicated solar, battery, hydrogen or other renewable energy production, distribution or dispensing approaches are adopted. This early-mover approach provides a threshold assessment to be used to analyse and present the operating and capital cost modifications arising from participating in more complete hub arrangements utilising battery electric, electrolysis hydrogen, or Sub.Zero H_2 as the primary fuel or energy sources.

For comparability of this analysis to VAAS style agreements, whether as islanded or hub infrastructure, a five-year ownership, service, or leasing period is adopted. With vehicle capital expenditure and pro-rata infrastructure expenditure treated as a year one cost and residual vehicle values treated as a year five recovery.

Each of these costing analyses are compared based on 2024, 2027 and 2030 cost profiles to:

- Diesel vehicles of similar capability, with the diesel infrastructure costs already incorporated in the diesel fuel costs; and
- Zero emission vehicles based on forecast retail prices and operating costs.

All costs are discounted on an Australian business pre-tax cost of debt basis of 9.5% pa.

Retail price and residual value

Publicly available information has been used to inform and localise the retail prices of diesel vehicles in Australia. Australian vehicles are sourced from Europe, North America, and Asian manufacturers and are often assembled in Australia as left-hand drive vehicles.

For battery electric and hydrogen fuel cell vehicles, the retail prices presented as part of the meta-study conducted by ICCT, as detailed in Sharpe and Basma (2022), Xie et al (2023) and Basma and Rodríguez (2023), have been used as a reference once converted to Australian dollars. Where comparable data is available, it was observed that Australian vehicles retail at a premium to comparable calculated retail prices. That Australian premium, where identified, has been included in the calculated retail price of each vehicle class. The retail prices are summarised in Appendix C, Table C1.

Table 7. Summary of primary alternative power train components' direct manufacturing costs

		2024	2027	2030
Energy battery	$ / kWh	343	235	183
Power battery	$ / kWh	608	459	360
Fuel cell system	$ / kW	1,231	599	449
Hydrogen fuel tank	$ / kg	1,880	1,459	1,257
Electric drive	$ / kW	90	45	34

Note: The data reported in Xie et al. (2023) is expressed in 2022 USD. It is converted to 2024 AUD based on the current foreign exchange rate of USD 1.00 = AUD 1.49.

Table 7 summarises the main alternative truck powertrain components as:

- **Energy battery,** designed to store a higher amount of energy and are optimised for low rates of charge and discharge for battery-electric vehicles.
- **Power battery**, as part of hybrid and fuel-cell powertrains, used for short-term high-power purposes, being optimised to have a high charge and discharge rate.
- **Fuel cell system**, comprising the (1) fuel cell stack, or fuel cell units, generates the electric power, and (2) the balance of plant manages the inputs and outputs of the fuel cell stack.
- **Hydrogen fuel tank,** based on 700 bar Type IV hydrogen storage tanks. These are illustratively at 10% higher costs than 350 bar hydrogen storage tanks.
- **Electric drive** comprising the inverter, the gearbox, and the electric motor.

To ensure consistency of analysis the estimated residual value of the vehicles using the bottom-up approach described in Basma et al. (2023) and Mao et al. (2021). That work assesses the battery, hydrogen tank, and fuel cell stack residual values as calculated based on its lifetime and frequency of charge/discharge cycles during the five-year ownership period. The residual values are summarised in Appendix C, Table C1.

Infrastructure

In 2022, Australia had around 3,000 public electric vehicle charging points and less than 10 islanded hydrogen refuelling stations. More recently, ARENA has financially supported the development of around six low carbon islanded depots and stations that are capable to be used as references for determining the infrastructure costs required for islanded low carbon depots and stations.

Diesel refuelling and depots are relatively frequent in higher population areas with its infrastructure cost already embedded in the diesel price per litre used as part of operating costs.

The illustrative infrastructure estimates included for islanded depot facilities or new islanded facility developments typically include charger station units, installation, solar, battery, substation and associated civil works. Islanded electrolysis hydrogen refuelling stations include charger refuelling units, installation, electrolysers, hydrogen storage, solar, battery, substation and associated civil works. Sub.Zero refuelling stations are less capital intensive, comprising charger refuelling units, installation, hydrogen storage, and associated civil works. The inclusion of methanol reformer units is dependent on whether Sub.Zero hydrogen or Sub.Zero methanol is adopted as the energy carrier.

Individual Sub.Zero H_2 infrastructure and REC Hub costs will vary with the specific range of equipment incorporated as part of any specific planned development. Hydrogen is a very versatile energy carrier. Hydrogen and CO_2 provides even greater versatility and optionality for REC Hub designs and inclusions. Given the current known technical and cost parameters, we have sought to estimate and provide a common infrastructure facility cost for a mid-range Sub.Zero H_2 REC Hub configuration.

CSIRO (2023) provided a cross reference for the assessment of the operating and capital costs of islanded electrolysis hydrogen facilities. Data points and outcomes from the IRENA (2020) and CER (2023) reports were used to estimate and validate the operating and capital costs of a hub electrolysis hydrogen plant and renewable power infrastructure capable to produce the equivalent hydrogen volumes to the modelled Sub.Zero H_2 REC Hubs.

Based on the ARENA, IRENA and CER publicly available information, the pro-rata infrastructure cost per vehicle has been included as part of the TCO capital element, with Table 8 summarising the key outcomes. The identified operating costs from these reports for electrolysis hydrogen facilities was used as the operating costs for islanded and hub electrolysis hydrogen facilities included in Table 9.

For each infrastructure facility the plant average lives have been assessed based on the currently available information as to refinery, solar panels, electrolyser, battery, HPAG and balance of plant assessments. It is noted from these reports that batteries and electrolysers have an effective life between 9 to 12 years, we've modelled 12 years. HPAG technology is between 20 and 25 years, we've modelled 20 years.

Table 8. Summary of parameters of islanded and Sub.Zero infrastructure.

	Infrastructure	Plant average life (years)	$'000 / vehicle	$'000 / vehicle pa	Vehicle capacity pa	Developer
Diesel	Hub	20	12	0.6	-	Various
Electrolysis H_2	Hub	12	536	182.5	718	IRENA report
Battery electric	Hub	12	459	38.3	60	Global Express
Electrolysis H_2	Islanded	12	2,191	182.5	15	Viva Energy
Battery electric	Islanded	12	459	38.3	60	Global Express
Battery electric	C-Hub	12	1,533	44.7	60	BCC Metro
Electrolysis H_2	C-Hub	12	536	182.5	718	IRENA report
Sub.Zero H_2	REC Hub	20	258	12.9	718	Boson Energy

Energy and fuel costs

Currently, Australian hydrogen and electric battery refuelling and recharging is in its infancy. Nevertheless, the analysis considered in this paper utilises Australian outcomes based on publicly available data for (1) diesel, (2) electricity, (3) electrolysis hydrogen produced from renewable electricity, and (4) Sub.Zero hydrogen manufactured from the thermochemical treatment of waste.

Historical **diesel** fuel retail prices were sourced from the Australian Institute of Petroleum (2024). The twelve-month national diesel price to 30 June 2023, adjusted to include an average cost for the use of Adblue, CO_2e cost of diesel emissions at an average Australian carbon price, excluding GST and the available $0.20 per litre diesel fuel rebate for on road vehicles over 4.5 t GVM. It is noted that Australian diesel prices have risen an average of 6% over the last 16 years, with a fluctuation in pricing during periods +/- 20%.

Grid renewable electricity pricing was sourced from wattever.com.au, based on the average of current tariff and daily supply pricing for businesses from five large electricity retailers across Australia, including an adjustment for Green Power or renewable energy tariff pricing. Publicly accessible **electric vehicle charging tariff** pricing was sourced from whichcar.com.au. In determining the electricity charging cost for each vehicle option, the following considerations were adopted:

- Long-haul trucks travelling 500 km would be able to utilise depot charging infrastructure with renewable electricity sourced from the grid;
- Long-haul trucks travelling up to 800 km would be able to recharge 80% at depots utilising grid electricity and 20% from publicly accessible electric charge rechargers;
- Long-haul trucks travelling up to 1,000 km daily would be able to recharge 50% at depots utilising grid electricity and 50% from publicly accessible electric charge rechargers;
- Regional and urban rigid vehicles would be able to recharge 50% at depots utilising grid electricity and 50% from publicly accessible electric charge rechargers; and
- Buses would rely on accompanying depot recharging infrastructure with renewable electricity sourced from the grid.

Currently, Australia does not have an active **hydrogen** from electrolysis retail market or refuelling network. Accordingly, we have estimated the retail price of publicly available green hydrogen by reference to retail green hydrogen pricing outcomes in Europe, South Korea, Japan, and California. For islanded and Hub electrolysis hydrogen production costs, we have utilised the hydrogen production costs estimated by CSIRO (2023).

Sub.Zero hydrogen retail pricing has been estimated with reference to two scenarios:

1. **Sub.Zero H_2 via REC Hub** – Retail pricing equating to a diesel net energy parity equivalent on a VAAS equivalent contractual basis.
2. **Sub.Zero H_2 via C-REC Hub** – The Sub.Zero H_2 REC Hub retail pricing outcome adjusted for currently modelled rebates, dividends, or other distributions attributable to part or full ownership of Sub.Zero H_2 C-REC Hub. This is intended to approximate the average scenario outcome of the operating costs of Sub.Zero H_2.

2027 and 2030 pricing outcomes for each fuel and energy product have been forecasted based on relevant CPI inflationary factors, incorporating the view that renewable energy prices will decline to 2030.

In general, relative to diesel pricing, future Sub.Zero H_2 pricing is anticipated to:

- be less volatile, with lower risks, enabling the entry of longer-term supply contracts;
- have lower cost bases and production costs with declining forecast costs matching lower future renewable energy costs; and
- provide lower variable price risks given the offset in part by CPI movements of labour and operating costs.

Table 9. Summary of unweighted fuel and energy retail prices in Australia

Energy Source	Infra-structure	Year		Artic 6 tractor-trailer	Regional heavy rigid vehicle	Urban medium rigid vehicle	Urban light commercial vehicle	Bus / coach
Diesel	Hub	2024	$ / l	1.87	1.87	1.87	2.05	1.87
		2030	$ / l	2.65	2.65	2.65	2.91	2.65
Battery electric	Hub	2024	$ / kWh	0.57	0.57	0.57	0.57	0.57
		2030	$ / kWh	0.64	0.64	0.64	0.64	0.64
Battery electric	Islanded	2024	$ / kWh	0.29	0.29	0.29	0.29	0.29
		2030	$ / kWh	0.33	0.33	0.33	0.33	0.33
Battery electric via Sub.Zero H_2	C-REC Hub	2024	$ / kWh	0.17	0.17	0.17	0.17	0.17
		2030	$ / kWh	0.19	0.19	0.19	0.19	0.19
Electrolysis H_2	Hub	2024	$ / kg	12.99	13.39	13.52	13.46	13.40
		2030	$ / kg	14.62	15.08	15.23	15.15	15.08
Electrolysis H_2	Islanded	2024	$ / kg	3.86	3.86	3.86	3.86	3.86
		2030	$ / kg	4.35	4.35	4.35	4.35	4.35
Sub.Zero H_2	REC Hub	2024	$ / kg	10.45	10.45	10.45	10.45	10.45
		2030	$ / kg	11.77	11.77	11.77	11.77	11.77
Sub.Zero H_2	C-REC Hub	2024	$ / kg	3.32	3.32	3.32	3.32	3.32
		2030	$ / kg	3.74	3.74	3.74	3.74	3.74

Labour, maintenance, and insurance

Australia's Fairwork *Road Transport and Distribution Award 2023* provides a minimum framework for salary and wages costs for the road transport sector. The most recent award provides a comprehensive framework for road transport driver pay and working hour conditions operating various vehicle combinations. The outcomes in this paper are presented as driver labour costs, inclusive of superannuation, payroll tax, allowances, and benefits, inclusive of rest break hours on a $ per hour basis for each of the vehicle use cases outlined.

We have used the average annual insurance costs as a percentage of the retail price of the vehicles as presented by Basma and Rodríguez (2023). These percentages were broadly consistent with other empirical Australia reports and data points identified.

Table 10. Summary of Australian-average labour and insurance costs for different truck classes

		Artic 6 tractor-trailer	Regional heavy rigid vehicle	Urban medium rigid vehicle	Urban light commercial vehicle	Bus / coach
Labour	$ / hr		37.20	36.75	36.10	37.20
- 500 km	$ / hr	37.62				
- 800 km	$ / hr	37.74				
- 1,000 km	$ / hr	37.74				
Insurance	%	2.14	2.73	2.35	2.35	2.73

Australia's *Transport Assessment and Planning Guidelines* report provides details based on the average of the PPI for diesel road freight and auto parts as at June 2013, uplifted for Australia's CPI indexation to September 2023 for this analysis. The maintenance cost data for different battery electric and hydrogen fuel cell truck classes and power train technologies are adopted from Basma and Rodríguez, (2023), as shown in Table 11.

Table 11. Summary of Australian-average maintenance costs for different truck classes

		Artic 6 tractor-trailer	Regional heavy rigid vehicle	Urban medium rigid vehicle	Urban light commercial vehicle	Bus / coach
Diesel	$ / 100km	30.01	18.43	17.24	8.03	48.73
Battery electric	$ / 100km	21.45	21.45	17.03	12.15	67.68
Hydrogen fuel cell - 2024	$ / hr	29.97	29.91	25.55	17.82	62.27
Hydrogen fuel cell - 2030	$ / hr	22.32	22.32	17.90	12.78	48.73

Results and discussion

We provide an overview of the key findings of the analysis and a detailed TCO and carbon intensity analysis for the nominated vehicles, powertrains, use cases, and infrastructure choices.

Summary of key findings

In all cases utilising Sub.Zero H_2 provides the highest GHG abatement levels - reducing CO_2e emissions towards or below net zero ambitions. Tables 12 and 13 summarises the incremental TCO per kg CO_2e relative to the current diesel baselines in 2024 and 2030.

For context, on a pro-rata weight basis the incremental higher cost of transporting your 250 g beef or avocado product 1,000 km from the producer, or the same item 50 km from your local distribution centre, is between $0.026 and $0.006 - that is under three cents per item.

Table 12. Summary of incremental 2024 TCO per kg CO_2e abated (vs diesel) of various scenarios

TCO $ per kg CO_2e - Marginal abatement cost/(benefit)	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Battery electric via Islanded in 2024	0.98	1.11	0.93	0.25	1.21	2.33	0.87
Battery electric via Hub in 2024	1.86	1.92	1.71	1.37	3.57	7.38	1.76
Battery electric via REC Hub in 2024	0.35	0.43	0.36	(0.01)	0.28	0.46	0.37
Battery electric via C-REC Hub in 2024	0.24	0.32	0.25	(0.09)	0.17	0.36	0.29
Sub.Zero H_2 via REC Hub in 2024	0.66	0.76	0.70	0.57	0.81	0.94	1.04
Sub.Zero H_2 via C-REC Hub in 2024	0.44	0.54	0.48	0.40	0.59	0.73	0.87
Electrolysis H_2 via Islanded in 2024	3.13	3.06	2.67	2.99	6.47	12.71	3.55
Electrolysis H_2 via Hub in 2024	2.24	2.45	2.27	1.67	3.19	4.42	2.44

Table 13. Summary of incremental 2030 TCO per kg CO_2e abated (vs diesel) of various scenarios

TCO $ per kg CO_2e - Marginal abatement cost/(benefit)	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Battery electric via Islanded in 2030	0.38	0.40	0.34	0.07	1.24	2.22	0.05
Battery electric via Hub in 2030	1.55	1.45	1.33	1.32	4.39	7.77	1.05
Battery electric via REC Hub in 2030	0.04	0.07	0.06	(0.15)	0.21	0.38	(0.13)
Battery electric via C-REC Hub in 2030	(0.08)	(0.05)	(0.07)	(0.25)	0.06	0.27	(0.23)
Sub.Zero H_2 via REC Hub in 2030	0.18	0.15	0.15	0.39	0.52	0.70	0.44
Sub.Zero H_2 via C-REC Hub in 2030	(0.06)	(0.10)	(0.10)	0.22	0.27	0.50	0.25
Electrolysis H_2 via Islanded in 2030	2.49	1.95	1.63	2.74	7.24	12.65	2.55
Electrolysis H_2 via Hub in 2030	1.11	0.93	0.87	1.19	2.68	3.68	1.29

Total Cost of Ownership

The TCO analysis for 2024 and 2030 for each of the vehicle classes, powertrain and infrastructure combinations is summarised in Tables 14.1 and 14.2 respectively. The tables outline the TCO, inclusive of capital and operating costs, of the various decarbonisation pathways in $ per km in comparison to the current predominate diesel TCO reference point.

Table 14.1. Summary of 2024 TCO, operating and capital expenditure by vehicle and fuel/energy source

Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2024	1.67	1.59	1.45	1.56	1.32	1.19	2.84
Battery electric via Islanded in 2024	2.62	2.67	2.36	1.80	1.96	1.80	3.98
Battery electric via Hub in 2024	3.47	3.45	3.10	2.83	3.21	3.13	5.15
Battery electric via REC Hub in 2024	2.40	2.49	2.21	1.54	1.64	1.43	3.67
Battery electric via C-REC Hub in 2024	2.17	2.26	1.98	1.41	1.51	1.38	3.49
Sub.Zero H_2 via REC Hub in 2024	3.05	3.18	2.92	2.50	2.25	1.69	5.19
Sub.Zero H_2 via C-REC Hub in 2024	2.59	2.72	2.45	2.21	2.00	1.58	4.80
Electrolysis H_2 via Islanded in 2024	4.24	4.09	3.63	4.03	4.23	4.08	7.05
Electrolysis H_2 via Hub in 2024	3.51	3.59	3.30	2.94	2.76	2.19	5.74

Table 14.2. Summary of 2030 TCO, operating and capital expenditure by vehicle and fuel/energy source

Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2030	1.75	1.66	1.52	1.68	1.35	1.22	3.11
Battery electric via Islanded in 2030	2.03	1.95	1.76	1.74	1.85	1.75	3.17
Battery electric via Hub in 2030	2.89	2.72	2.49	2.78	3.09	3.08	4.34
Battery electric via REC Hub in 2030	1.81	1.77	1.61	1.49	1.53	1.38	2.86
Battery electric via C-REC Hub in 2030	1.62	1.58	1.41	1.36	1.41	1.34	2.65
Sub.Zero H_2 via REC Hub in 2030	2.04	1.89	1.75	2.20	1.79	1.52	3.98
Sub.Zero H_2 via C-REC Hub in 2030	1.66	1.51	1.37	1.97	1.59	1.44	3.61
Electrolysis H_2 via Islanded in 2030	3.31	2.87	2.53	3.79	3.81	3.94	5.85
Electrolysis H_2 via Hub in 2030	2.45	2.24	2.06	2.60	2.26	2.01	4.49

Tables 15.1 and 15.2 summarise the operating expenditure components respectively of each of these decarbonisation pathways. Tables 15.1 and 15.2 summarise the capital expenditure components respectively of each of these decarbonisation pathways.

Table 15.1 Summary of 2024 TCO, operating expenditure only by vehicle and fuel/energy source

Operating Element of Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2024	1.27	1.18	1.10	1.21	1.14	1.02	1.84
Battery electric via Islanded in 2024	1.27	1.28	1.16	0.98	1.10	1.02	1.74
Battery electric via Hub in 2024	1.27	1.36	1.31	1.06	1.19	1.03	1.74
Battery electric via REC Hub in 2024	1.30	1.30	1.18	0.99	1.11	1.02	1.76
Battery electric via C-REC Hub in 2024	1.07	1.07	0.95	0.86	0.98	0.97	1.58
Sub.Zero H_2 via REC Hub in 2024	1.59	1.52	1.44	1.37	1.39	1.16	2.17
Sub.Zero H_2 via C-REC Hub in 2024	1.14	1.06	0.98	1.08	1.14	1.05	1.78
Electrolysis H_2 via Islanded in 2024	1.17	1.10	1.01	1.10	1.16	1.06	1.81
Electrolysis H_2 via Hub in 2024	1.76	1.69	1.61	1.47	1.48	1.20	2.30

Table 15.2 Summary of 2030 TCO, operating expenditure only by vehicle and fuel/energy source

Operating Element of Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2030	1.31	1.21	1.14	1.33	1.16	1.06	2.01
Battery electric via Islanded in 2030	1.17	1.17	1.08	0.97	1.07	1.00	1.69
Battery electric via Hub in 2030	1.17	1.23	1.20	1.06	1.15	1.01	1.69
Battery electric via REC Hub in 2030	1.19	1.19	1.10	0.99	1.08	1.01	1.71
Battery electric via C-REC Hub in 2030	1.00	1.00	0.90	0.85	0.96	0.96	1.50
Sub.Zero H_2 via REC Hub in 2030	1.40	1.30	1.23	1.24	1.29	1.11	2.02
Sub.Zero H_2 via C-REC Hub in 2030	1.02	0.92	0.85	1.02	1.08	1.03	1.65
Electrolysis H_2 via Islanded in 2030	1.05	0.95	0.88	1.03	1.09	1.03	1.68
Electrolysis H_2 via Hub in 2030	1.50	1.41	1.33	1.31	1.34	1.14	2.12

Tables 15.1 and 15.2 above highlights that:

- the average TCO operating cost component of each alternative is often at or less that the current diesel operating costs,
- a variety of battery electric powertrain and fuel / energy combinations lower the current diesel operating costs for regional rigid vehicles, and
- for long-haul transport Sub.Zero H_2 C-REC Hub combinations are 15% to 25% below diesel operating costs.

Table 16.1. Summary of 2024 TCO, capital expenditure only by vehicle and fuel/energy source

Capital Element of Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2024	0.40	0.41	0.35	0.35	0.18	0.16	1.00
Battery electric via Islanded in 2024	1.35	1.38	1.19	0.82	0.86	0.79	2.24
Battery electric via Hub in 2024	2.20	2.09	1.79	1.77	2.03	2.11	3.41
Battery electric via REC Hub in 2024	1.11	1.19	1.02	0.55	0.53	0.41	1.91
Battery electric via C-REC Hub in 2024	1.11	1.19	1.02	0.55	0.53	0.41	1.91
Sub.Zero H_2 via REC Hub in 2024	1.45	1.65	1.48	1.13	0.86	0.53	3.02
Sub.Zero H_2 via C-REC Hub in 2024	1.45	1.65	1.48	1.13	0.86	0.53	3.02
Electrolysis H_2 via Islanded in 2024	3.07	2.99	2.61	2.93	3.08	3.03	5.23
Electrolysis H_2 via Hub in 2024	1.75	1.91	1.69	1.47	1.28	1.00	3.44

Table 16.2. Summary of 2030 TCO, capital expenditure only by vehicle and fuel/energy source

Capital Element of Total Ownership Cost $ / km	Long-haul tractor trailers			Regional rigid vehicles			Buses / coaches
	500 km	800 km	1,000 km	Heavy	Medium	Light	
Diesel via Hub in 2030	0.45	0.45	0.38	0.36	0.20	0.17	1.10
Battery electric via Islanded in 2030	0.86	0.78	0.69	0.77	0.77	0.75	1.48
Battery electric via Hub in 2030	1.72	1.49	1.29	1.72	1.94	2.07	2.65
Battery electric via REC Hub in 2030	0.62	0.58	0.52	0.50	0.44	0.38	1.15
Battery electric via C-REC Hub in 2030	0.62	0.58	0.52	0.50	0.44	0.38	1.15
Sub.Zero H_2 via REC Hub in 2030	0.64	0.59	0.52	0.95	0.51	0.41	1.96
Sub.Zero H_2 via C-REC Hub in 2030	0.64	0.59	0.52	0.95	0.51	0.41	1.96
Electrolysis H_2 via Islanded in 2030	2.26	1.92	1.65	2.75	2.72	2.91	4.17
Electrolysis H_2 via Hub in 2030	0.95	0.84	0.73	1.29	0.92	0.88	2.37

All combinations in Tables 16.1 and 16.2 have a higher TCO capital cost relative to diesel powertrain baseline, where:

- for regional and urban transport Sub.Zero H_2 battery electric combination increases are $0.28 per km below islanded battery electric capital alternatives;
- the more advanced powertrain solutions that currently exist for regional and urban road transport, yield the lowest TCO declines into 2030; and
- for long-haul transport, 2024 Sub.Zero H_2 REC Hub combinations increases are between $0.61 and $1.13 per km, lowering on average six-fold to $0.14 and $0.19 per km by 2030 with anticipated powertrain technology and capacity advancements.

Carbon intensity analysis

Pivotal to all decarbonisation strategies is analysing the carbon intensity of the alternative strategies to ensure that the chosen actioned pathway delivers real net zero objectives. In transitioning away from fossil fuels across the Australian road transport sector the current carbon intensities of the grid electricity network and diesel usage at 0.650 and 0.334 kg CO_2e per kWh respectively, as compared to the European electricity comparison of 0.251 kg CO_2e per kWh, provide a centre piece for Australian strategy selection and outcomes.

Certainly, the singular focus of utilising dedicated renewable energy or electrolysis hydrogen refuelling stations as a powertrain energy source, with estimated carbon intensities at 0.10 and 0.21 kg CO_2e per km, respectively assists in providing that sought after outcome.

On the Australian pathway to achieving real net zero outcomes, Sub.Zero resources, including hydrogen and methanol as efficient energy carriers, provide an even higher environmental advantage. This accelerates the overall declines in GHG emissions across many hard to abate sectors – road transport, energy and micro-grids, chemicals, agriculture, shipping, waste, etc. Delivering higher GHG abatement outcomes and an estimated absolute carbon intensity reduction of up to 2.1 kg CO_2e per km, 103% lower than alternatives - provides the foundation for a compelling environmental business case for Sub.Zero developments.

This is particularly the case with the incremental 2030 TCO of Sub.Zero C-REC Hub scenarios less than diesel in all long-haul scenarios. Battery electric heavy rigid and bus use cases yielded similar abatement savings of $0.23 to $0.25 per kg CO_2e. Electrolysis hydrogen scenarios were 3 to 12 times less effective than Sub.Zero hydrogen infrastructure cases modelled.

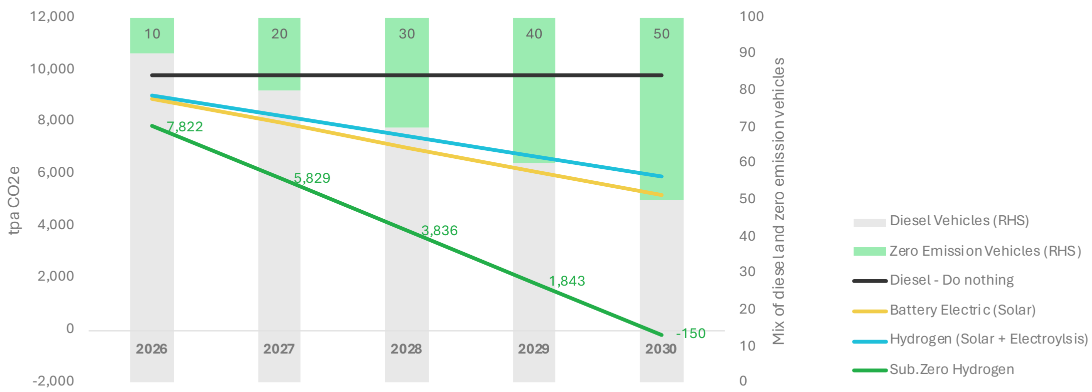
Case Example: Freight company accelerating its decarbonisation pathway

To illustrate the potential, we have modelled a use case with freight organisation owning 100 Artic 6 long haul vehicles. The trucks operate on a drayage basis within 500km of its depot enabling alternative ZEV powertrains to refuel at the depot 100% of the time. We estimate the annual GHG footprint of that freight organisation averaging 9,815 tpa CO_2e.

Strategically, from 2026 the freight organisation plans to replace 10% of its diesel vehicles, ie 10 vehicles a year, as either battery electric or hydrogen fuel cell vehicles. It intends to utilise dedicated renewable energy or electrolysis hydrogen refuelling stations. This pathway results in a decline to 5,178 to 5,890 tpa CO_2e respectively by 2030, an encouraging 40% to 47% reduction in absolute GHG emissions within five years.

We estimate utilising Sub.Zero hydrogen, either for battery electric or hydrogen fuel cells powertrains, the freight organisation, having transitioned only 50% of its fleet by 2030, abates higher GHG emissions. In this case, the organisation achieves a real net zero emission outcome by 2030 of negative 150 tpa CO_2e. **A real zero outcome by 2030!**

Figure 2. Summary of GHG abatement outcomes with a 10% diesel to ZEV fleet transition from 2026



Hydrogen is an energy carrier, a versatile tangible product that forms the basis of many of our everyday products – X (anything). A holistic Waste to Hydrogen to X strategic outcome is consistent with both circular economy and waste hierarchy principles. That is, repurposing, regenerating, or recycling discarded products to manufacture a suite of new products with different functions, at a materially higher value. Maintaining resources at their highest possible value for the longest time – the circular economy.

Largely biogenic CO_2 is captured during the hydrogen manufacturing process to be utilised in an additive, economically positive downstream process. That is, Waste to Hydrogen manufacturing lowers supplementary CO_2 to the environment and avoids the need for new carbon to be added from fossil fuels. The manufacture of waste into a valuable resource that adds economic and environmental value enabling users to transition towards real zero outcomes.

TCO and carbon intensity

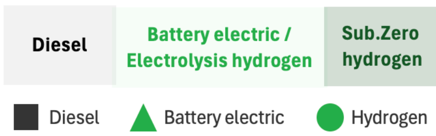
Figures 3.1 to 3.7 below summarise the 2024 TCO and GHG outcomes for each of the modelled road transport use cases.

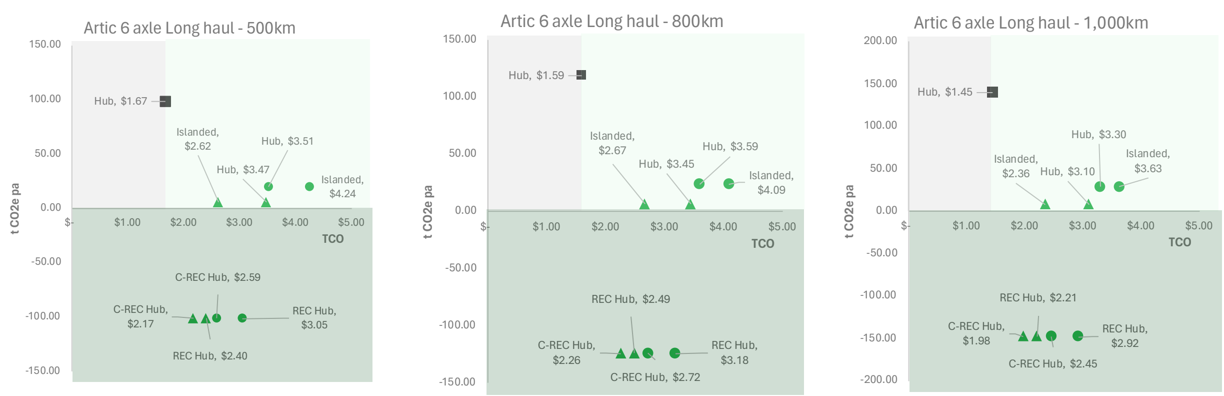
Both battery electric and electrolysis hydrogen pathways reduce emissions as compared to diesel powertrains; both require renewable energy to achieve that outcome. Extending Australia's electricity supply network inefficiently to road transport, a non-traditionally supplied electricity sector, further stretches Australia's electricity infrastructure upgrade plans.

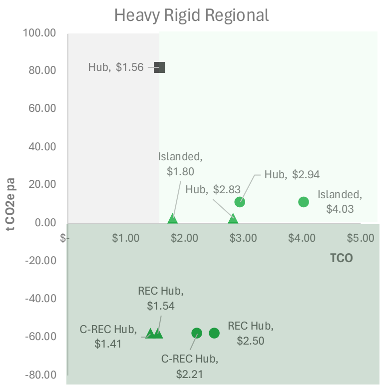
In all cases, electrolytic hydrogen TCO outcomes, using scarce water resources, are significantly above alternative pathways.

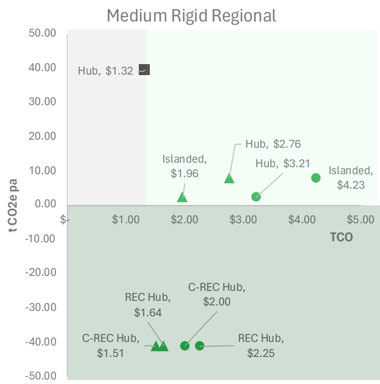
Utilising one of Australia's currently untapped resources, landfill waste, to produce hydrogen is modelled as being competitive with battery electric pathways and over time significantly lowers the higher cost of long-haul hydrogen. Both outcomes well suited for Australia's vast land mass and decentralised population centres to connect with regional Australia.

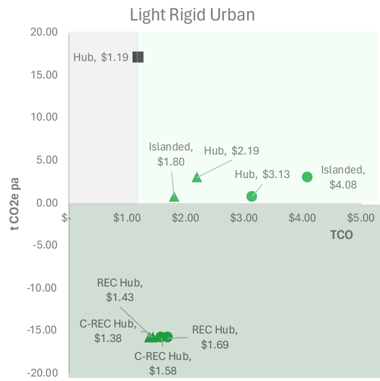
Figures 3.1 to 3.7. Summaries of 2024 TCO and t CO_2e outcomes for various use cases

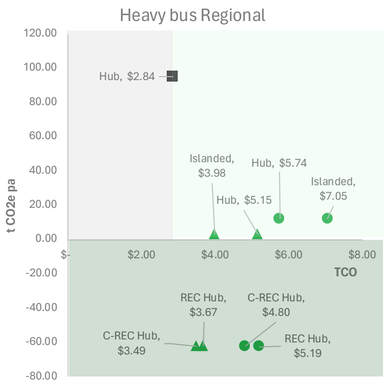












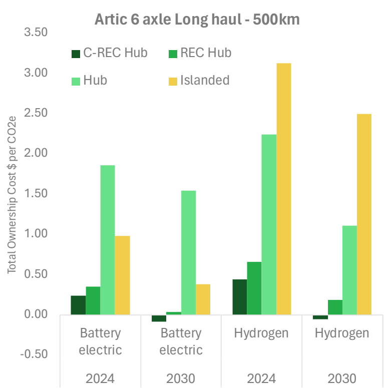
Total ownership cost analysis

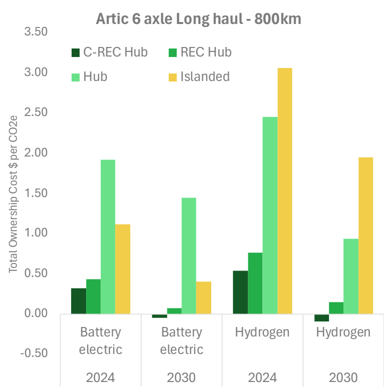
Figures 4.1 to 4.7 below summarise the modelled TCO outcomes between 2024 and 2030 for battery electric and hydrogen delivered through alternative infrastructure platforms.

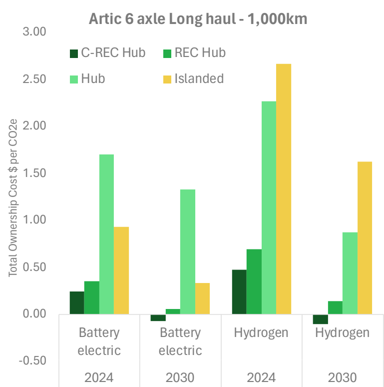
Each highlight that TCO outcomes decrease into 2030 largely driven by powertrain technology advancements.

The modelling also highlights that overall TCO increases can be moderated with Sub.Zero H_2 C-REC Hub pathways, to achieve the higher absolute and relative GHG emission reductions as highlighted above in Figures 3.1 to 3.7.

Figures 4.1 to 4.7. Summaries of incremental TCO outcomes for various use cases







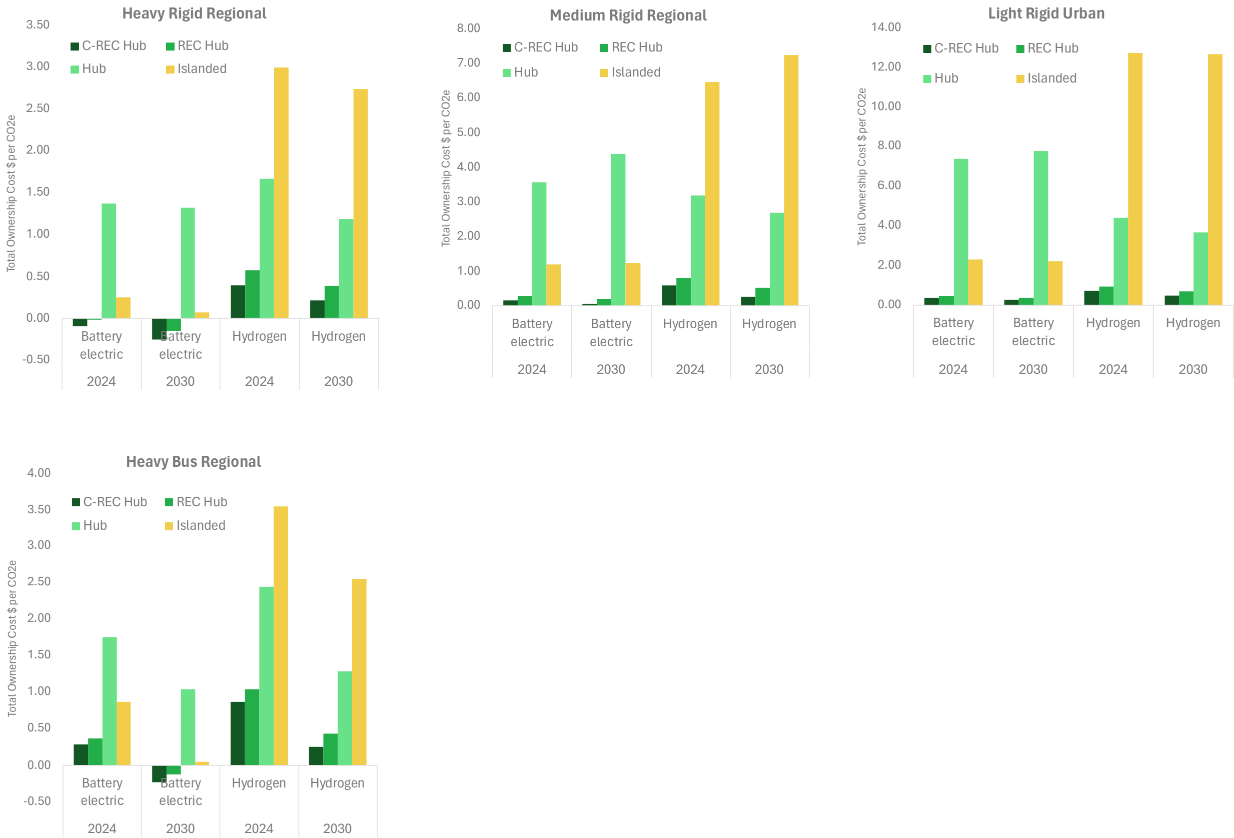
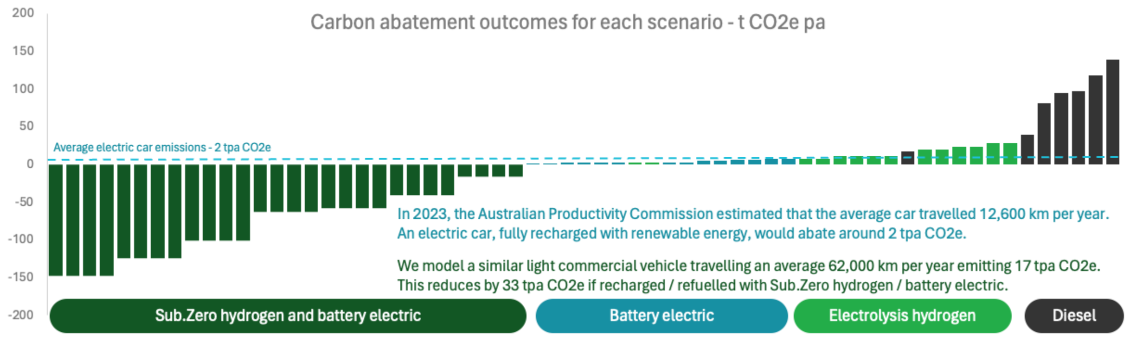


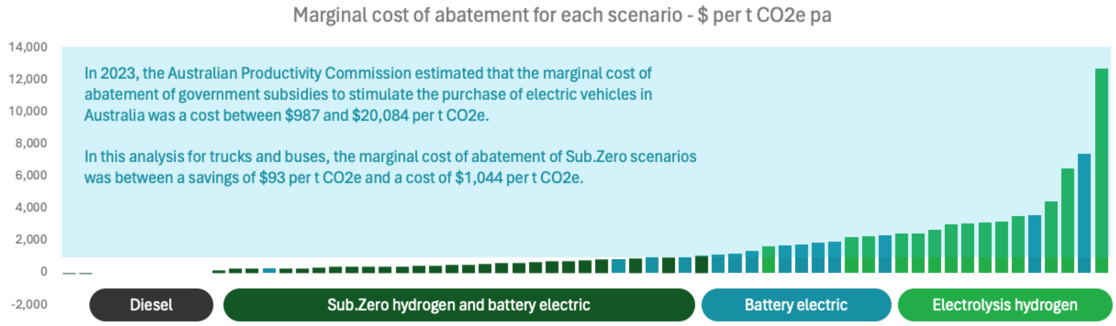
Figure 5 illustrates the annual t CO_2e emissions for each of the scenarios modelled, ranging from sub-zero t CO_2e outcomes for each of the Sub.Zero energy sources, through to significant diesel emissions. To provide some perspectives of the impact of the analysis, we contrasted this to passenger cars. In 2023, the Australian Productivity Commission estimated the average passenger car travelled 12,600 km per year. An electric passenger car, fully recharged with renewable energy, would abate around 2 tpa CO_2e. We modelled a similar light commercial vehicle travelling an average 62,000 km per year emitting 17 tpa CO_2e. This reduces by 33 tpa CO_2e if recharged or refuelled with Sub.Zero hydrogen or battery electric energy sources.

Figure 5. Carbon emissions (t CO_2e) for each 2024 scenario



Further to this the Australian Productivity Commission estimated that the marginal cost of abatement of government subsidies to stimulate the purchase of electric passenger vehicles in Australia was a cost between $987 and $20,084 per t CO_2e. In this analysis for trucks and buses, the marginal cost of abatement of Sub.Zero scenarios ranged between a savings of $94 per t CO_2e and a cost of $1,044 per t CO_2e. Figure 6 illustrates the TCO $ per t CO_2e emissions for each of the scenarios modelled, with a majority of Sub.Zero TCO $ per t CO_2e scenarios less than the current government abatement subsides for passenger electric cars.

Figure 6. TCO $ per t CO_2e for each 2024 scenario



Introducing tighter emissions standards, to lower the capital purchase of ZEVs beyond passenger cars, for early movers in agricultural and road transport sectors is long overdue.

Enabling and actioning coordinated government policy to focus on diverting 100% of landfill waste, to fuel 24% of our road vehicles to lower 48% of the road transport's CO_2e emissions further reduces government net zero targets from 43% to well above 50%.

Class-specific analysis

Do you remember the Pareto Principle? 80% of outcomes result from 20% of the causes.

2030 is less than six years away. Australia has less than 800,000 light vehicle, trucks, and buses. That is, one-sixth of road freight vehicles contribute to 57% of the road freight transport sector's GHG emissions.

The principle of a four times positive impact from a focused plan provides an instrumental freight transport decarbonisation target. In embarking on a decarbonisation strategy and policy agenda for Australia's agriculture and road transport sectors that:

1. Focus on those 800,000 vehicles to reduce Australian GHG by 9.1% pa, diverting 14.4 million tpa of landfill waste transitioning Australian's away from 7.2 billion litres of diesel; plus
2. Extend the reach to 75% of light commercial vehicles, each emitting twice the emissions than passenger cars, to cumulatively reduce Australian GHG potentially up to 11% pa, benefiting from the regeneration of all household and business landfill waste transitioning Australia away from 17.7 billion litres of diesel.

With Sub.Zero resources providing an additional carbon intensity benefit we specifically focus on the three alternative TCO Sub.Zero H_2 C-REC Hub outcomes as compared to diesel in four classes: (1) regional heavy and medium rigid trucks; (2) long haul articulated trucks; (3) urban light commercial vehicles; and (4) buses / coaches.

Regional heavy and medium rigid trucks

The regional heavy and medium rigid truck class accounts for 12% of registered trucks and buses, contributing an estimated 22% to the sub-sector's GHG emissions. Battery electric truck powertrain technologies are most advanced in this class facilitating a near term adoption pathway to reduce 2% to 3% pa of Australia's GHG emissions.

The incremental 2024 TCO of $0.23 to $0.64 per km for the islanded battery electric infrastructure model is adversely impacted by the relatively high land use requirements to accommodate both solar renewable energy and longer recharge times for dedicated battery electric infrastructure upgrades.

The alternative Sub.Zero H_2 C-REC Hub battery electric model yields significantly lower TCO outcomes, plus delivers a higher CO_2e abatement outcome to yield 2024 TCO savings of $0.15 per km up to an incremental 2024 TCO of up to $0.32 per km over current diesel use cases. The flexibility to utilise hydrogen fuel cell trucks remains an attractive option with C-REC Hub resulting in an incremental 2024 TCO of $0.65 to $0.68 per km, modelled to decline to $0.23 to $0.29 per km by 2030.

An encouraging use case for many regional higher frequency freight organisations. Coupling waste regeneration with resultant hydrogen or battery electric use provides many positive circular economy options for hard to abate sectors utilising vehicles including cement, construction, agriculture, food retail, and ambulances in health care.

Long-haul articulated trucks

120,000 long haul articulated trucks accounts for 2.5% of total registered trucks and buses yet is estimated to contribute an estimated 31.0% to the sub-sector's GHG emissions – 2.8% of Australia's total GHG emissions.

The incremental 2024 TCO per CO_2e of $1.84 to $2.57 per km for islanded and hub electrolysis hydrogen infrastructure respectively approach is potentially adversely impacted by a range of factors. These include being one of the highest TCO cost outcomes, its' high water use requirements, and isolated equipment issues to maintain reliable fuel supply.

Incremental Sub.Zero and hydrogen fuel cell 2024 TCO outcomes vs diesel range to $0.76 per km per CO_2e. Modelled technology advancements by 2030 are anticipated to reduce that to $0.15 per km per CO_2e for REC Hubs. Incremental TCO per CO_2e for C-REC Hubs use cases are less than the cost of diesel.

Average TCO operating expenditure vs diesel are often lower using Sub.Zero resources. Impacting the total powertrain choice in this sub-sector is the balance between higher labour costs and longer delivery times associated with battery electric trucks, offsetting higher purchase costs of hydrogen fuel cell trucks. The largest component of the incremental 2024 TCO increase is in the ZEV powertrain capital expenditure.

Basma and Rodríguez model that the current higher retail purchase costs of battery electric and hydrogen fuel cell trucks to narrow within the next 6 years, with the incremental capital cost increases less than \$0.20 per km by 2030. Combined with operating cost savings, this lowers Sub.Zero H_2 C-REC Hub 2030 TCO results to \$0.09 to \$0.15 per km below 2030 diesel TCO outcomes.

Light commercial vehicles

With the recent emergence of hydrogen fuel cell light commercial vehicles, and battery electric powertrains more widely anticipated in the next few years, this sub-sector provides an optimistic pathway to transition 4% to 5% pa of Australia's GHG emissions from diesel.

At retail price points similar to many passenger cars, and with emission reduction outcome 1.5 times that attributable to passenger vehicles, we would anticipate many significant benefits on focusing on expanding this sub-sector's ZEV base.

Operating costs compared to diesel for battery electric and hydrogen are similar, it is the incremental capital cost associated with the vehicles and infrastructure establishment that requires bridging. The higher incremental electricity infrastructure costs for battery electric or electrolysis hydrogen may curtail advancement of these specific pathways. However, incremental Sub.Zero H_2 2024 TCO outcomes at \$0.19 to \$0.50 per km are encouraging pricing point outcomes, modelled to decline to the lower end of this TCO range by 2030.

Buses

Australia currently has 223 registered ZEV buses, less than 0.3% of the total Australian bus registrations which in total contribute 2 million t CO_2e, equivalent to the emissions from 680,000 passenger cars.

With lower TCO operating costs vs diesel in most cases. Outcomes of the various bus powertrain technology alternatives being trialled are often the most advanced of each of the truck classes in terms of vehicle decarbonisation pathways.

The inhibiting factor relates back to the TCO capital cost increases largely attributable to ZEV powertrains of up to \$1.00 per km for battery electric buses and \$2.00 per km for hydrogen fuel cell buses, a function of the lower vehicle utilisation as compared to other sub-sectors. The electrolysis hydrogen incremental 2024 TCO of \$4.20 per km is unlikely to reduce given the high-cost impact of the islanded hydrogen infrastructure.

By 2030, the model expects lower TCO costs than diesel for battery electric bus and Sub.Zero infrastructure combinations, with Sub.Zero hydrogen providing the lower TCO outcomes for bus operators operating beyond back to station recharging capabilities. These outcomes provide all bus operators fleet choice flexibility between battery electric and hydrogen fuel cell, particularly if adopting the dual functionality provided by Sub.Zero H_2 C-REC Hubs.

Regenerating resources to live locally.

The EU has embarked on building ZEV refuelling stations every 300 km by 2030. Multiple ZEV powertrains are currently available, or will be available, within the next 2 years. Waste to Hydrogen to X technologies, including Sub.Zero hydrogen, exists today to action and deliver zero waste, climate positive local councils and numerous, multi-tiered government policies.

Currently, the pieces of the puzzle are actionable in Australia to resolve both aspects of the admired "chicken or the egg" dilemma of infrastructure and users for many sectors including waste, agriculture, healthcare, and road freight transport.

Prioritise Australian resources, incorporating our landfill waste, to enable a circular economy hydrogen and e-methanol highway. This underpins a climate positive eco-system connecting regional and urban Australia - stimulating extensive "live local" domestic Hydrogen to X manufacturing growth opportunities.

Legalities

Citation

Xseed Solutions (2024) Sub.Zero® hydrogen lowers the decarbonised Total Cost of Ownership of truck and bus pathways in Australia. Xseed Solutions, Brisbane. Authored by Craig Allen.

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Acknowledgements

Xseed Solutions provides specialist innovative technology solutions enabling Waste to Hydrogen to X (W2X) infrastructure solutions for sustainable transport and renewable energy in Australia and New Zealand.

Xseed Solutions would like to acknowledge the assistance and input of the parties set out in References.

Glossary

ABS, refers to the Australian Bureau of Statistics.

ARENA, refers to the Australian Renewable Energy Agency.

Artic 6 axle, is a single articulated vehicle with 6 axles.

B double, refers to a prime mover (tractor) towing two semi-trailers utilising "B" type couplings.

B triple, refers to a prime mover (tractor) towing three semi-trailers utilising "B" type couplings.

bar, refers to a measure of pressure, being 100 kPa.

Capex, means Capital Expenditure.

CO_2e, Carbon dioxide equivalent, a measure used to standardise the emissions from various greenhouse gases to determine their individual and total contributions to global warming.

C-REC Hubs, Consortium Resources, Energy and Chemical Hubs, are circular economy Sub.Zero H_2 production resource hubs, majority owned by organisations consuming, the ultra-low carbon hydrogen, electricity , chemicals, and resources produced.

CUI, refers to Common User Infrastructure.

CPI, refers the Australian All Indexes Consumer Price Index.

CER, refers to the Australian Clean Energy Regulator.

CSIRO, refers to the Commonwealth Scientific and Industrial Research Organisation – Australia's national science agency.

Electrolysis hydrogen, refers to the process of using renewable energy to split water into hydrogen and oxygen.

EU, refers to the European Union.

Gasification, refers to the thermochemical process that converts organic or fossil-based carbonaceous materials at high temperatures (>700°C) without combustion, into carbon monoxide, hydrogen, and carbon dioxide.

GHG, Greenhouse gas, means the gases in the atmosphere that raise the surface temperature of the Earth, namely carbon dioxide, methane, and nitrous oxide.

GVM, Gross Vehicle Mass, means the maximum weight of the loaded vehicle.

GCM, Gross Combination Mass, is the weight of the vehicle and trailer mass.

H_2, hydrogen, a colourless, odourless, tasteless, flammable chemical element

HPAG, Hydrogen capable Plasma Assisted Gasification developed by Boson Energy.

Hub, refers to a network of producers, consumers and connective infrastructure located in close proximity. Currently, the term often refers to electrolysis hydrogen hub. Aligned with circular economy principles, the term extended to REC Hubs and C-REC Hubs.

Islanded, or micro-grids, refers to the production and consumption of electricity without connection to a distributed electricity network or grid.

IRENA, International Renewable Energy Agency.

kWh, stands for kilowatt hour, with 1 kilowatt hour the amount of energy it takes to run a 1,000 watt (or 1kWh) equipment for 1 hour.

Opex, Operating Expenditure.

Powertrains, comprise the main components of the vehicle that generate power and deliver that power to the road surface.

PPI, means producer pricing index.

REC Hubs, Resources, Energy and Chemical Hubs, are circular economy Sub.Zero H_2 manufacturing resource hubs producing ultra-low carbon hydrogen, electricity, chemicals, and related resources.

Sub.Zero® hydrogen (Sub.Zero® H_2), is hydrogen manufactured from landfill waste utilising Boson Energy's Hydrogen capable Plasma Assisted Gasification (HPAG) technology.

TCO, Total Cost of Ownership, is the total operating and capital expenditure related to a vehicle, including associated infrastructure.

VAAS, Vehicle As A Service, refers to the supply of hydrogen, renewable energy, or methanol on a five year supply basis, contractually with or without the supply of the ZEV.

W2X, Waste to Hydrogen to X, describes the eco-system where waste to processed into hydrogen and the hydrogen manufactured is capable to be used across multiple applications (X).

ZEV, Zero Emission Vehicle, refers to (1) electric vehicles with rechargeable batteries (battery electric) and/or (2) electric vehicles that use electricity generated by a fuel cell powered by hydrogen (hydrogen fuel cell) powertrains.

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Appendix A: Truck and bus energy and fuel consumption

Table A1. Summary of average operational truck fuel/energy consumption for truck classes in 2024 and 2030

Technology	Truck Class	2024	2030
Diesel (LDE / 100km)	Artic 6 (500 km)	30.70	23.20
	Artic 6 (800 km)	30.70	23.20
	Artic 6 (1,000 km)	30.70	23.20
	Heavy rigid	28.60	25.74
	Medium rigid	16.89	12.67
	Light commercial	8.30	7.47
	Bus	40.65	36.59
Battery Electric (kWh / 100km)	Artic 6 (500 km)	138.00	101.00
	Artic 6 (800 km)	141.00	103.00
	Artic 6 (1,000 km)	141.00	108.00
	Heavy rigid	77.70	71.00
	Medium rigid	81.00	65.00
	Light commercial	32.44	24.66
	Bus	110.00	113.00
Hydrogen Fuel Cell (kg / 100km)	Artic 6 (500 km)	8.32	6.13
	Artic 6 (800 km)	8.41	6.16
	Artic 6 (1,000 km)	8.53	6.18
	Heavy rigid	5.31	3.69
	Medium rigid	4.62	3.37
	Light commercial	2.00	1.40
	Bus	7.00	6.00

Appendix B: Truck and bus energy storage system sizing

Table B1. Battery electric battery size in kWh for nominated truck classes.

Truck Class		2024	2030
Artic 6 (500 km)	kWh	760	405
Artic 6 (800 km)	kWh	1,000	680
Artic 6 (1,000 km)	kWh	1,000	870
Heavy rigid	kWh	360	280
Medium rigid	kWh	250	200
Light commercial	kWh	140	100
Bus	kWh	340	454

Table B2. Hydrogen powered truck fuel tank sizes for nominated truck classes.

Truck Class		2024	2030
Artic 6 (500 km)	kg	45	33
Artic 6 (800 km)	kg	73	54
Artic 6 (1,000 km)	kg	80	67
Heavy rigid	kg	16	11
Medium rigid	kg	11	9
Light commercial	kg	6	6
Bus	kg	27	35

Appendix C: Vehicle retail price

Table C1. Summary of the vehicle's estimated retail prices, residual values, and residual percentage (what is BEV and FCV?)

Truck Class	Technology	Retail price 2024 $'000	Residual value 2024 $'000	Residual % 2024 %	Retail price 2030 $'000	Residual value 2030 $'000	Residual % 2030 %
Artic 6 axle (500 km)	Diesel	259	73	28	284	74	26
	BEV	608	134	22	327	95	29
	FCV	821	181	22	350	112	32
Artic 6 axle (800 km)	Diesel	319	86	27	345	90	26
	BEV	774	124	16	394	126	32
	FCV	1,128	203	18	400	132	33
Artic 6 axle (1,000 km)	Diesel	319	86	27	345	90	26
	BEV	774	108	14	421	143	34
	FCV	1,149	161	14	416	137	33
Heavy Rigid	Diesel	201	54	27	202	53	26
	BEV	246	73	24	211	57	35
	FCV	553	122	24	426	60	32
Medium Rigid	Diesel	89	34	27	96	34	26
	BEV	176	55	22	138	47	34
	FCV	314	70	22	168	55	33
Light commercial	Diesel	66	18	28	66	17	26
	BEV	89	20	22	81	25	31
	FCV	127	18	14	92	26	28
Bus	Diesel	430	69	16	470	75	16
	BEV	750	120	16	444	98	22
	FCV	1,250	225	18	836	217	26

Appendix D: Truck annual mileage

Table D1. Summary of annual kilometres travelled for each truck class in the first five years

Truck Class		Five-year annual average	Year 1	Year 2	Year 3	Year 4	Year 5
Artic 6 (500 km)	km	95,722	95,722	95,722	95,722	95,722	95,722
Artic 6 (800 km)	km	116,002	116,002	116,002	116,002	116,002	116,002
Artic 6 (1,000 km)	km	136,282	136,282	136,282	136,282	136,282	136,282
Heavy rigid	km	86,000	86,000	86,000	86,000	86,000	86,000
Medium rigid	km	70,000	70,000	70,000	70,000	70,000	70,000
Light commercial	km	62,000	62,000	62,000	62,000	62,000	62,000
Bus	km	70,000	70,000	70,000	70,000	70,000	70,000