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Why batteries trump hydrogen for buses

Hydrogen is the wrong technology to decarbonise Australian public transport

Electrifying Australia's buses should be a priority for state governments for air quality and climate reasons. Battery-powered electric buses are a mature technology and are commercially available. Hydrogen fuel cell buses are expensive, require more infrastructure, and do not deliver real-world reductions in emissions. Current trials of hydrogen buses should be abandoned, and resources directed to acquiring battery electric models.

Discussion paper

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Acknowledgement of Country

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Contents

Glossary

BEB – battery-electric bus.

BEV – battery-electric vehicle, including buses, cars, etc.

Blue hydrogen – hydrogen produced from fossil fuels, usually natural gas, along with an attempt to mitigate emissions through carbon capture and storage.

CCS – carbon capture and storage.

CFB – conventionally-fuelled bus, generally powered by diesel.

FCEB – fuel-cell electric bus, effectively powered by hydrogen.

FCEV – fuel-cell electric vehicle, including buses and cars that are effectively powered by hydrogen.

Fuel cell – an electrochemical unit that transforms hydrogen into electricity, producing only water and heat as byproducts.

GHG – greenhouse gas

Green hydrogen – hydrogen produced by water electrolysis, powered by predominantly renewable electricity.

Grey hydrogen – hydrogen produced from methane gas, by a process known as "steam reformation".

ICE – internal combustion engine.

ZEB – zero-emission bus, powered by batteries or hydrogen fuel cells, does not emit greenhouse gases during use.

ZEV – zero-emission vehicle, i.e. a car, bus, etc that does not produce greenhouse gas emissions during use.

Summary

In 2023 the transport sector produced 21% of Australia's greenhouse gas emissions. Without policy change, by 2030 it will be the largest contributor to the country's overall emissions. While they are only one part of that sector, Australia's buses nevertheless present a significant opportunity for decarbonisation.

Most of Australia's bus fleet is publicly owned and/or funded. As such, the pace of transition towards electric buses will be determined primarily by the ambition of state and territory governments. If these governments will not deliver the rapid electrification of their bus fleets, it appears very unlikely that they will be able to deliver on their promises to significantly reduce fossil fuel usage across their entire economies.

At present, the decarbonisation of Australia's bus fleet is focused on two competing technologies: electric buses that run on battery power (BEBs), and those powered by hydrogen fuel cells (FCEBs). However, the choice between these technologies is clear, because BEBs have several key advantages over FCEBs:

- FCEBs are between 15 and 32 times more expensive to run than BEBs;
- If run on green hydrogen—which is produced from water with renewable electricity, thus producing no greenhouse gases—FCEBs use more than three times more renewable electricity than BEBs;
- If they are run on hydrogen produced from fossil fuels, FCEBs produce significantly more greenhouse emissions than BEBs: the latter produce between 22.8% and 98.8% less CO_2-equivalent than the former.

In summary, FCEBs are dramatically more expensive than BEBs, and will not reduce emissions as much. Hydrogen buses are being trialled in South Australia, NSW, Tasmania and Victoria. These trials are a distraction from the rapid rollout of electric buses and should be scrapped immediately.

Hydrogen buses are a costly dead end, as shown by numerous failed hydrogen bus trials around the world. Meanwhile, BEBs have proven time and again to be an ideal, mature technology to drive the decarbonisation of public transport. They should be rolled out in Australia without further delay.

Introduction

In 2023, the transport sector produced 21% of Australia's greenhouse gas emissions, and in the absence of policy change, by 2030 it will be the largest contributor to the country's emissions.[1]

The national bus fleet alone was responsible for 2.7 million tonnes of CO_2 emissions in 2020,[2] and buses present a significant opportunity for decarbonisation for two key reasons.[3]

First, transitioning away from conventional diesel buses will have the added benefit of greatly improving air quality, especially in Australia's cities. Diesel powered buses emit not just greenhouse gasses, but a range of other major air pollutants. While just 0.5% of Australia's registered vehicles are buses,[4] they account for 3%-4% of nitrogen oxide emissions, 2%-4% of sulphur dioxide emissions and 2%-6% of PM_{10} particulate pollution.[5]

A recent report estimates $3 billion worth of additional annual health costs, resulting from bus emissions, for the Sydney-Newcastle-Wollongong region alone.[6] Meanwhile, the NSW EPA reports air pollution leads to 520 premature deaths in Sydney each year.[7] The NSW Government estimates that $1 billion–$2 billion in environmental and health costs could be saved in the state over 30 years by transitioning the bus fleet from diesel to electric.[8] Health and air quality issues alone provide a strong case for electrification of buses.

Second, the bus fleet is largely either owned by, or largely providing services to, state and territory governments. This means that these governments can direct the decarbonisation process—and as such, the pace of transition towards a decarbonised bus fleet will be

[1] DCCEEW (2023) *Australia's emissions projections 2023*, p. 20, https://www.dcceew.gov.au/sites/default/files/documents/australias-emissions-projections-2023.pdf

[2] Australian Bureau of Statistics, Survey of Motor Vehicle Use, Australia 12 Months ended 30 June 2020; 93090DO001_2021 Motor Vehicle Census, Australia, 2021; Comparative Assessment of Zero Emission Electric and Hydrogen Buses in Australia David A. Hensher Edward Wei Camila Balbontin; authors' calculations.

[3] Quicke and Parrott (2022) *Next stop: Zero emissions buses by 2030*, https://australiainstitute.org.au/report/next-stop-zero-emissions-buses-by-2030/; Denniss, Quicke, Parrott (2023) *Stuck in the Slow Lane: Electrification of buses in Australia*, https://australiainstitute.org.au/report/stuck-in-the-slow-lane/

[4] Australian Bureau of Statistics, op cit.

[5] BTRE (2005) *Health impacts of transport emissions in Australia: Economic costs,* https://www.bitre.gov.au/sites/default/files/wp_063.pdf

[6] Electric Vehicle Council (2019) *Submission: NSW Upper House Inquiry into electric buses in regional and metropolitan public transport networks in NSW,* https://electricvehiclecouncil.com.au/wp-content/uploads/2021/07/2019-Submission-to-NSW-Parliament-on-buses-1.pdf

[7] NSW Government (2016) *Clean air for NSW*, https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Air/clean-air-for-nsw-consultation-paper-160415.pdf

[8] NSW Government (2021) *Zero Emission Buses: Our Transition Strategy*, https://www.transport.nsw.gov.au/projects/current-projects/zero-emission-buses

determined primarily by the ambition of these governments. If state and territory administrations will not deliver the rapid decarbonisation of their bus fleets, it appears very unlikely that they will be able to deliver on their promises to significantly reduce fossil fuel usage across their entire economies.

There is a ready-made solution to the question of how to decarbonise Australia's bus fleet: electric buses. Battery-powered electric buses (BEBs) are a mature technology, already being rolled out around the world. The leading example of this is the Chinese city of Shenzhen, which operates an entirely battery-powered fleet of over 16,000 buses. This remarkable rollout was achieved in just five years, with BEB numbers increasing from 277 in 2012 to encompass the city's entire fleet of 16,359 by the end of 2017.[9] The city also has 20,000 electric taxis. The benefits have been dramatic: Shenzen has gone from being one of the worst cities in China in terms of air quality to being one of the best.[10]

There are more than 500,000 BEBs in operation across China as a whole.[11] Elsewhere, the US has established a $US5 billion fund to roll out electric school buses over five years from 2021, with 2,277 BEBs already on order, delivered or operating, and another 5,982 committed.[12] The UK has 2,776 BEBs in service, including 159 recently delivered in Oxford.[13] Europe already has thousands of BEBs on its roads, and is expected to reach at least 66,000 by 2030.[14]

In response to these issues and this context, Australian state and territory governments have begun developing strategies, targets and policies for their bus fleets (Table 1). These plans vary in their ambition and detail: the ACT is aiming to roll out a full fleet of zero-emission buses by 2040, whereas Tasmania has no policy for transitioning its bus fleet.[15]

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[9] Lu, Xue and Zhou (2018) *How Did Shenzhen, China Build World's Largest Electric Bus Fleet?* https://www.wri.org/insights/how-did-shenzhen-china-build-worlds-largest-electric-bus-fleet

[10] Weidenbach (2021) *Spotlight: Shenzhen has Transformed to One of China's Cities with the Lowest Air Pollution Rate*, https://www.climatescorecard.org/2021/06/spotlight-shenzhen-has-transformed-to-one-of-chinas-cities-with-the-lowest-air-pollution-rate/

[11] Victoria State Government – Department of Transport and Panning (2023) *Zero Emission Bus Transition: Consultation Paper*, p. 8, https://engage.vic.gov.au/ZEBtransition

[12] Freehafer, Lazer and Zepka (2023) *The State of Electric School Bus Adoption in the US*, https://www.wri.org/insights/where-electric-school-buses-us

[13] Topham (2024) Oxford becomes UK's electric bus capital as 159 vehicles join fleet, *The Guardian*, https://www.theguardian.com/world/2024/jan/14/oxford-becomes-uk-electric-bus-capital-159-vehicles-join-fleet

[14] ING (2021) *All aboard Europe's electric bus revolution*, https://think.ing.com/articles/all-aboard-europes-electric-bus-revolution-290921

[15] Tasmania is developing an Emissions Reduction and Resilience Plan for its transport sector. This Plan was due late 2023 but has not yet been released. The draft transport plan had no specific target for rolling out zero-emission buses. Tasmanian Government – Department of State Growth (2023) *Emissions Reduction and*

Table 1: Zero emission bus strategies, states and territories

State/Territory	Policy	Targets
NSW	*Zero Emissions Buses Transition Strategy*	Zero emissions buses in Greater Sydney by 2035; Outer Metropolitan by 2040; and Regional NSW by 2047.
Victoria	*Zero Emissions Bus Transition* (consultation)	TBC. Proposed introduction of ZEBs from 2025.
ACT	*Zero-Emission Transition Plan for Transport Canberra*	ZEBs by 2040.
QLD	*Zero Emission Bus Program*	New buses in south-east Queensland to be ZEBs from 2025, and from 2025-30 across regional Queensland.
SA	*Electric Vehicle Action Plan*	100% electric bus fleet by 2050
WA	*State Electric Vehicle Strategy*	No target; 130 BEBs to be made locally.
Tasmania	None	None
NT	*Electric Vehicle Strategy Implementation Plan*	Investigating feasibility of ZEBs.

Source: NSW Government (2021) *Zero Emissions Buses Transition Strategy*; Victoria State Government (2023) *Zero Emission Bus Transition*; ACT Government (2020) *Zero-Emission Transition Plan for Transport Canberra*; Queensland Government (2023) *Zero Emission Bus Program*; Government of South Australia (2020) *South Australia's Electric Vehicle Action Plan: Lowering energy costs whilst cutting pollution*; Government of Western Australia (2024) *Electric Vehicle (EV) Strategy*; Northern Territory Government (2021) *Electric Vehicle Strategy Implementation Plan.*

These policy developments are welcome. But even in the states that have ambitious targets for electric bus rollouts, such as NSW and Victoria, progress has been slow. In the latest census there were less than 200 electric buses in Australia, out of a total of over 100,000 buses—a share of 0.2%.[16]

Concerningly, several states and local jurisdictions have walked back commitments to BEB procurement, shifting to a focus on "zero emissions vehicles". These are defined as vehicles with zero greenhouse gas emissions from the tailpipe, which broadens the scope of acquisitions to include hydrogen fuel-cell electric buses (FCEBs) as well as BEBs. This subtlety is important, because it says nothing about the climate impact of producing the electricity

Resilience Plan – Transport: Consultation draft, https://recfit.tas.gov.au/emissions_reduction_and_resilience_plans/transport

[16] Denniss, Quicke and Parrott (2023) *Stuck in the slow lane*, p. 5.

that powers the buses. If BEBs are powered by emission-free renewable electricity, then both their charging and their operation produces no emissions. However, this is not the case for hydrogen.

While it is possible to produce “green” hydrogen from electrolysis of water—a process that is emissions-free if powered by renewable electricity—doing so is expensive and difficult. This means that using green hydrogen for FCEBs is currently far too expensive to offer a viable alternative to BEBs—and this will most likely remain the case, as any future supplies of green hydrogen will be in high demand for “hard-to-abate” applications such as producing green iron and steel for export. Such sectors will be key sources of demand, and the fact that there is already a mature, cheap option for the electrification of bus travel makes buses a wasteful use of possible future green hydrogen supplies.

In any case, the prospect of there ever being sufficient green hydrogen to power Australia’s buses seems fanciful. For perspective, Australia currently produces 450 tonnes of green hydrogen per year. Considering that the Australian bus fleet travelled a collective 2.4 billion km in 2021, we find that a full fleet of FCEBs would result in demand for 222,450 tonnes of hydrogen—nearly 500 times the country’s entire annual green hydrogen output.

In addition, Australia’s plans to export green hydrogen and its derivatives around the world make the use of green hydrogen in FCEBs even more unlikely—if Australia is really to become a “renewable energy superpower”, it will not do so by using its green hydrogen output to power its buses.

This means that if Australia was to use FCEBs, they would have to run on hydrogen produced by other methods—and those methods, unlike renewables-powered electrolysis, are absolutely not emissions-free. “Grey” and “blue” hydrogen are both produced from fossil fuels, so while FCEBs that run on cells powered by these sources of hydrogen will produce no emission from their tailpipes, they will still be responsible for the emission of greenhouse gases into the atmosphere.

Finally, in addition to their climate impact, FCEBs are also unreliable. Experience from around the world has demonstrated consistently the technical difficulties and high costs of hydrogen buses. The FCEBs that ran at the 2020 Tokyo Olympics were plagued by high capital and fuel costs.[17] The French city of Montpellier cancelled an order for 51 hydrogen buses when it found they would be at least six times more expensive to run than BEBs.[18]

[17] Harding (2021) ‘High costs dog Tokyo’s hydrogen buses’, *Financial Times*¸ https://www.ft.com/content/2b9dd655-6b64-416c-a83f-1fe1002da7d5

[18] Collins (2022) ‘French city drops order for 51 hydrogen buses after realising electric ones six times cheaper to run’, *ReCharge*, https://www.rechargenews.com/energy-transition/french-city-drops-order-for-51-hydrogen-buses-after-realising-electric-ones-six-times-cheaper-to-run/2-1-1143717?zephr_sso_ott=mwK3PC

And in the German city of Weisbaden, hydrogen buses were retired just one year after they were delivered, due to high running costs and unreliable filling infrastructure.[19]

This paper argues that FCEB trials in Australia should be abandoned, and no further trials undertaken. BEBs are cheaper, more efficient, will deliver significantly lower emissions, and require less in the way of costly new infrastructure. They should be rolled out rapidly around the country.

[19] Collins (2022) 'German city to retire its one-year-old hydrogen fuel-cell buses after €2.3m filling station breaks down', *Hydrogen Insight*, https://www.hydrogeninsight.com/transport/german-city-to-retire-its-one-year-old-hydrogen-fuel-cell-buses-after-2-3m-filling-station-breaks-down/2-1-1375568

“Zero-emission buses”: BEBs and FCEBs, explained

Battery-electric buses

The main alternative to conventional diesel buses are battery-electric buses (BEBs). Their wheels are driven by electric motors that draw their power directly from onboard batteries. As such, they are “zero-emission vehicles”, producing no emissions during operation.

The degree to which BEBs produce greenhouse gas emissions is determined by the carbon-intensity of the electricity with which they are charged. If charged by entirely renewable energy, a BEB produces no emissions in either charging or operation. As such, as the grid transitions to renewable energy, the climate impact of BEB operation decreases, and when operated via an entirely renewable grid, BEBs become emission-free. A UK study found that if the carbon intensity of electricity is reduced in line with Paris Agreement targets, operating an electric bus in 2050 will produce 35.5 times less carbon than a conventionally fuelled bus.[20]

Importantly, even while being charged from a grid with significant fossil fuel electricity generation, BEBs *still* offer a significant emission saving over conventionally fuelled buses (CFB). Based on Australia’s current energy mix, in which fossil fuels still make up 67% of generation, BEBs would more than halve total lifecycle emissions from buses.[21] Much of this improvement is due to the inefficiency of the internal combustion engines in CFBs, compared with more-centralised large-scale electricity generation. CFBs are also unable to benefit from regenerative braking, particularly relevant in bus operations.

To put this plainly, the fact that BEBs are more efficient than their conventionally fuelled counterparts means that they already represent a vast improvement in terms of greenhouse emissions—and this improvement will only become larger as the amount of renewable energy in the grid increases. In the states and territories that are already predominantly powered by renewables—Tasmania, the ACT, and South Australia—BEBs represent an even higher emissions saving right now.

[20] Logan et al (2020) “Electric and hydrogen buses: Shifting from conventionally fueled cars in the UK”, in *Transportation Research Part D: Transport and Environment*, Vol 85 Issue 1, https://doi.org/10.1016/j.trd.2020.102350

[21] DCCEEW (2023) *Australian Energy Update* 2023, https://www.energy.gov.au/sites/default/files/Australian%20Energy%20Update%202023_0.pdf; Hensher, Wei and Balbontin (2022) Comparative assessment of zero emission electric and hydrogen buses in Australia, *Transport Research Part D*, https://doi.org/10.1016/j.trd.2021.103130

Fuel-cell electric buses

A competing technology with BEBs is Fuel-Cell Electric Buses (FCEBs). Both BEBs and FCEBs are “electric”, in that their wheels are driven by electric motors, and have similar powertrains. FCEBs, however, store energy in the form of hydrogen, which is then transformed into electricity by an onboard “fuel cell”. That electricity is used to keep a small battery charged. Storing and transforming hydrogen into electricity in this way involves many more steps than simply charging the battery of a BEB. The extra onboard components and technologies required to operate the fuel cell make hydrogen buses markedly more unreliable and costly than BEBs.

FCEBs are often considered “zero-emissions vehicles”, because the only byproduct produced by fuel-cells is water. But, like BEBs, the extent to which these vehicles represent an improvement in lifecycle emissions is influenced by several factors.

First, hydrogen can be produced in a variety of ways – including coal gasification, steam methane reforming, or electrolysis – only one of which is “green”. It is highly likely that a “zero-emissions” hydrogen bus will run on hydrogen made by burning fossil fuels. Second, FCEBs require access to a network of hydrogen transport and filling stations, which does not currently exist and would need to be constructed. This network itself would involve significant cost and energy consumption that needs to be considered.

Is hydrogen a fossil fuel?

Despite being framed as an exciting new fuel source to power the world to a net zero economy, hydrogen has been produced and used at an industrial scale for a century. It is primarily produced via the use of fossil fuels. Understanding the different methods of hydrogen production, and their associated greenhouse gas emissions, is important when considering if FCEBs are truly "zero-emission vehicles".

FOSSIL HYDROGEN: GREY, BLACK, BROWN AND BLUE

Fossil fuels are hydrocarbons, i.e. compounds of hydrogen and carbon. As such, they provide a ready source of hydrogen, so long as that hydrogen can be liberated from the compounds in which it is held. All the various forms of fossil hydrogen—grey, black, brown and blue, with the colours referring to various production processes—rely on the processing of fossil fuels to extract the hydrogen held within. All of these processes produce greenhouse gas emissions. All these processes release greenhouse gases into the atmosphere.[22] Currently, 99.9% of all hydrogen produced globally is fossil hydrogen.[23]

Grey hydrogen is produced from either natural gas, via a process called "steam reformation", or from oil via "partial oxidation". Brown and black hydrogen both use coal as feedstock—either brown or black coal, respectively—and use the process of "coal gasification". Steam reformation is the most common method used around the world, and involves reacting methane with high temperature steam, producing hydrogen, carbon monoxide and carbon dioxide.[24]

The other form of fossil hydrogen is "blue" hydrogen. Blue hydrogen is also produced from natural gas, using the same process as grey hydrogen. The difference is that the blue hydrogen process aims to capture the emissions generated in the production process and store them (usually in a geological reservoir)—a process known as "carbon capture and storage" (CCS). The problem is that CCS does not yet exist commercially, or at scale. A meta-analysis of the CCS literature has found that these projects around the world "have been shown to emit more CO_2 than they sequester".[25]

[22] Bridges and Merzian (2019) *Hydrogen and Climate: Trojan Horse or Golden Goose?*, https://australiainstitute.org.au/report/hydrogen-and-climate-trojan-horse-or-golden-goose/

[23] IEA (2023) *Global Hydrogen Review*, p. 64, https://www.iea.org/reports/global-hydrogen-review-2023

[24] US Government - Office of Energy Efficiency & Renewable Energy (n.d.) *Hydrogen Production: Natural Gas Reforming*, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

[25] Sekera and Lichtenberger (2020) 'Assessing Carbon Capture: Public Policy, Science, and Societal Need', *Biophysical Economics and Sustainability*, https://link.springer.com/article/10.1007/s41247-020-00080-5

This helps to explain why just 0.6% of all hydrogen produced globally in 2022 was "blue"—made from fossil fuels with CCS—even though hydrogen is often considered "blue" even if only *some* greenhouse gas (GHG) is captured.[26]

Recent research into the warming potential of methane (CH_4), the fossil gas used most often to produce grey/blue hydrogen, casts further doubt on the emissions reduction potential of blue hydrogen. This work shows that reductions in CO_2 emissions are more than offset by CH_4 emissions—and CH_4 is more than 80 times more potent as a greenhouse gas as CO_2.[27]

Even if we optimistically assume that CCS will be developed at scale, these methane emissions might well mean that blue hydrogen never offers an emissions reduction over the use of diesel. Researchers have found that, due to leakages and emissions of CH_4, "the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat, and some 60% greater than burning diesel oil for heat".[28] It has been found that blue hydrogen—even assuming functional CCS—could result in emissions reductions of as little as 9% compared with conventional grey hydrogen.[29]

GREEN HYDROGEN

Hopes that hydrogen might contribute to a net zero economy (including by reducing GHG emissions from buses) thus rely on the prospects of "green" hydrogen, which is extracted from water (H_2O) via electrolysis. The electric current splits water molecules into hydrogen and oxygen, a process that produces no greenhouse gases. If this process is powered by renewable energy, such as wind and solar, it is completely emissions-free.

However, this method produced only 0.1% of global hydrogen in 2022.[30] We consider the reasons for this, and the prospects of green hydrogen, in more detail below, but suffice it to say for now that if they eventuate at all, green hydrogen supplies will be limited—and therefore expensive.

In summary, then, hydrogen buses do not really run on hydrogen, and will not do for the foreseeable future. Rather, they run on fossil fuels—through a series of convoluted, inefficient, and costly additional processes.

[26] Campbell (2023) *The Con of Carbon Capture and Storage*, https://australiainstitute.org.au/post/the-con-of-carbon-capture-and-storage/; IEA (2023) Global Hydrogen Review, p. 64

[27] UNEP (2022) *What's the deal with methane?* https://www.unep.org/news-and-stories/video/whats-deal-methane; Editorial (2021) 'Control methane to slow global warming — fast', *Nature*, https://doi.org/10.1038/d41586-021-02287-y

[28] Howarth and Jacobson (2021) How green is blue hydrogen?, *Energy Science and Engineering*, https://doi.org/10.1002/ese3.956

[29] Ibid

[30] IEA (2023) *Global Hydrogen Review*, p. 64

FCEBs vs BEBs: cost analysis

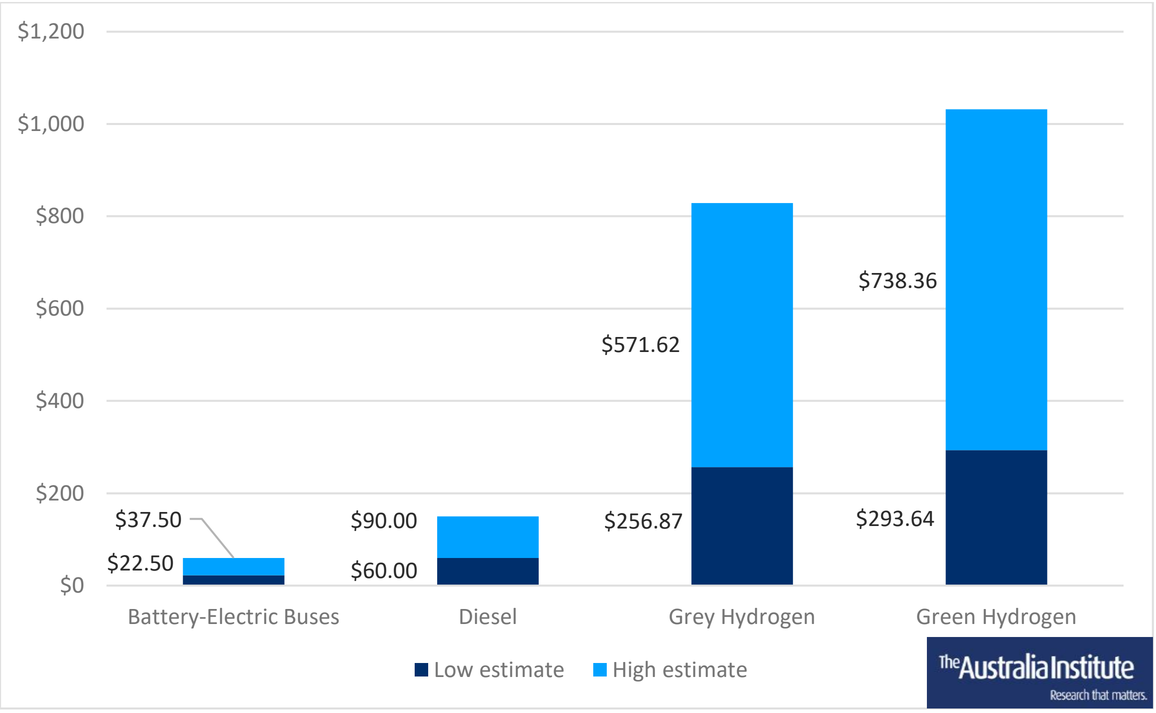
OVERALL COST

If Australia persists with FCEBs, it is almost certain to encounter the same high costs encountered in other international trials.

Hensher, Wei and Balbontin (2022) compared current costs for diesel buses, FCEBs, and BEBs in Australia. They found that at current prices, BEBs represent a 75% saving over the life of the vehicle compared to the cost of a new diesel fuelled bus.[31] This is driven partly by savings from the cost of fuel, and partly by drastically reduced maintenance costs.

FCEBs, by contrast, were found to cost 15 times *more* to fuel and BEBs—and even more to run. These costs are illustrated in Figure 1 below, which compares the fuel/energy costs of running BEBs, CFBs and FCEBs on a per-kilometre basis.

Figure 1: Battery, Diesel and Hydrogen fuel/energy costs per 100km



Source: BEB and Diesel derived from Hensher, Wei and Balbontin (2022) 'Comparative assessment of zero emission electric and hydrogen buses in Australia'; hydrogen price from Soria and Weeks (2024) *Logistical woes and high pump prices stall California H2 market development* and Schelling (2023) *Green Hydrogen to Undercut Gray Sibling by End of Decade*

[31] Hensher, Wei and Balbontin (2022) *Comparative assessment of zero emission electric and hydrogen buses in Australia*, https://ses.library.usyd.edu.au/download, p. 5.

The costs for BEB charging and CFB diesel fuel in Figure 1 were compiled from market prices, by Hensher, Wei and Balbontin (2022). The costs for grey hydrogen were taken from the Californian market; the low estimate was drawn from 2021 prices (before Russia's invasion of Ukraine pushed up global gas prices), while the high estimate came from January 2024. California is used as an example as it is the most mature market globally, including a relatively established distribution network. Only using at-cost production prices for hydrogen—as Hensher, Wei and Balbontin do—artificially deflates the running costs of a hydrogen bus network.

Per-kilometre costs for buses powered by green hydrogen were derived by subtracting average costs for grey hydrogen production from Californian market prices. This leaves a remainder, which is comprised of distribution costs (reflecting the size and complexity of the necessary distribution infrastructure). Finally, the current average green hydrogen production costs from Schelling (2023) are added to this derived distribution cost.

Current hydrogen fuel costs for FCEBs are at least 15 times higher—and potentially up to 25 times higher—than electricity costs for charging BEBs. The bulk of that cost comes from the costs of distributing hydrogen, but that price would be even higher if FCEBs ran on green hydrogen—and the use of green hydrogen would be necessary for any meaningful emissions saving. Current prices mean that the costs of operating FCEBs using green hydrogen would be up to 32 times higher than that of operating BEBs.

INFRASTRUCTURE AND MAINTENANCE COSTS

Whether hydrogen is produced from fossil fuels or renewable energy, using it to fuel a bus fleet requires storage infrastructure and distribution systems. After being produced, hydrogen needs to be either compressed or liquified at the point of production. It would then be transported to refuelling stations or bus depots, as a liquid or in a compressed form. That transport might theoretically be via pipeline[32] – but the costs of building extensive pipeline infrastructure mean trucks are the most likely distribution method. Those trucks then decant hydrogen into on-site storage. Various configurations of compression, liquefaction, and regassification are possible. With hydrogen on site at refuelling locations, FCEBs could fill their on-board storage tanks as required.

It is important to emphasise, then, that a proper analysis of the costs of a hydrogen bus network should not be limited to the costs of hydrogen production; it must also include the establishment and maintenance of such a distribution network. The cost and reliability of refuelling have derailed hydrogen bus projects in Japan and France, and are insufficiently

[32] Raj et al (2024) Evaluating hydrogen gas transport in pipelines: Current state of numerical and experimental methodologies, *International Journal of Hydrogen Energy*, https://www.sciencedirect.com/science/article/pii/S0360319924014137

considered in Australian trials and research. The Californian market provides a useful example.

Hydrogen filling stations deliver hydrogen in either a liquid or a compressed form, and require extensive high-power compression, storage systems and/or refrigeration equipment. This means that hydrogen filling stations do not entirely remove the load off the power grid, compared to BEB charging (discussed further below).

California has almost two decades of experience with hydrogen vehicles, but sales have struggled, with less than 18,000 fuel cell electric vehicles (FCEVs) on the roads. Users have only 55 fuelling stations across the state (compared to 8,161 stations selling gasoline and 5,305 selling diesel).[33] [34] The average price of hydrogen across the state at the bowser was US$33.48/kg on Jan 4, 2024. That price has risen 112% in the past two years.[35]

The price consumers pay for hydrogen in the Californian market is significantly higher than the production cost, which is around US$1-3/kg.[36] This enormous markup—between 10 and 30 times the production price—is a result of the cost and complexity of a hydrogen distribution network. And yet, despite the retail price of hydrogen jumping so dramatically, it remains unprofitable: in 2024 Shell announced it would withdraw from the market, closing its seven hydrogen refuelling stations, and cancelling its planned investment in 48 more.[37]

Building a hydrogen-refuelling network would involve significant cost. These costs are captured indirectly by the price of hydrogen in the Californian market but are likely much higher as refuelling infrastructure has typically run at a loss, to encourage the purchase of FCEVs. Small localised trials of FCEVs, as seen across Australia, fail to capture the costs and complexities of wider adoption of this technology.

Hydrogen bus trials around the world have also repeatedly shown that these buses have very high maintenance costs. A Canadian trial in 2010 found maintenance costs were

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[33] Sharma (2024) 'California's Hydrogen Economy Dealt A Hammer Blow By Shell's Exit', *Forbes*, https://www.forbes.com/sites/gauravsharma/2024/02/11/californias-hydrogen-drive-dealt-a-hammer-blow-by-shells-exit/?sh=6deaa9197fbc

[34] California Energy Commission (n.d.) *California Retail Fuel Outlet Annual Reporting (CEC-A15) Results*, https://www.energy.ca.gov/data-reports/energy-almanac/transportation-energy/california-retail-fuel-outlet-annual-reporting

[35] Soria and Weeks (2024) *Logistical woes and high pump prices stall California H2 market development*, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/012324-logistical-woes-and-high-pump-prices-stall-california-h2-market-development

[36] IEA (2021) *Global Hydrogen Review 2021*, https://www.iea.org/reports/global-hydrogen-review-2021/executive-summary; Schelling (2023) *Green Hydrogen to Undercut Gray Sibling by End of Decade*, https://about.bnef.com/blog/green-hydrogen-to-undercut-gray-sibling-by-end-of-decade/

[37] Sharma (2024) 'California's Hydrogen Economy Dealt A Hammer Blow By Shell's Exit'

$1.35/km—twice as high as diesel buses.[38] The failed French trial also found maintenance costs and downtime increased the cost of hydrogen buses.[39] In comparison, BEBs have been found to have only 20% of the maintenance costs of conventionally fuelled buses.[40]

Of all possible technologies for fuelling buses, green hydrogen—the only form of hydrogen that could conceivably rival the emission reductions that could be achieved by simply deploying BEBs—is *the most expensive*. When distribution costs are considered, all forms of hydrogen—including grey—are more expensive than BEBs.

FUTURE COSTS

One possible response to the above analysis might be that as green hydrogen expands, and fuel-cell technology matures, costs of operating FECBs will come down.

There are multiple problems with relying on such an argument. First and foremost, decarbonisation of public transport is an urgent priority, making current costs more important for decision making. Second, a significant proportion of hydrogen costs emerge from the complex refuelling infrastructure required to run FCEBs—an infrastructure that currently does not exist. And third, there is little reason to expect green hydrogen will expand quickly enough to meet the demand of the bus fleet or reduce in cost—especially when we consider the many probable competing sources of demand for this future fuel.

While Australia currently produces 494,300 tonnes of grey hydrogen per year,[41] it only produces 450 tonnes of green hydrogen annually.[42] To travel 100km, a FCEB requires 9kg of hydrogen.[43] The Australian bus fleet travelled a collective 2.4 billion km in 2021.

This means that if Australia's bus fleet was suddenly replaced by FCEBs, those buses would require 222,450 tonnes of hydrogen to travel as far as they did in 2021. This is almost half of

[38] CBC (2014) 'BC Transit's $90M hydrogen bus fleet to be sold off, converted to diesel', *CBC News*, https://www.cbc.ca/news/canada/british-columbia/bc-transit-s-90m-hydrogen-bus-fleet-to-be-sold-off-converted-to-diesel-1.2861060?fbclid=IwAR2lUxa45yFYgVoZ1rD6cKyzaz4Zoy6X10YQfdq7gFk9IBMArvSeThw0Cmg#:~:text=According%20to%20Burnaby's%20Ballard%20Power,kilometre%20for%20diesel%2Dpowered%20buses

[39] Martin (2023) French city that pioneered hydrogen buses will opt for battery-electric in future due to ongoing problems and high costs, *Hydrogen Insight*, https://www.hydrogeninsight.com/transport/french-city-that-pioneered-hydrogen-buses-will-opt-for-battery-electric-in-future-due-to-ongoing-problems-and-high-costs/2-1-1551821?fbclid=IwAR2RZkD-HL1fped1AuJ7ldr3z8SJA5dD3_6mb9He9GmCT8RcvbRa6VZpaHE

[40] National Renewable Energy Laboratory (2020) *Financial Analysis of Battery Electric Transit Buses*, https://www.nrel.gov/docs/fy20osti/74832.pdf

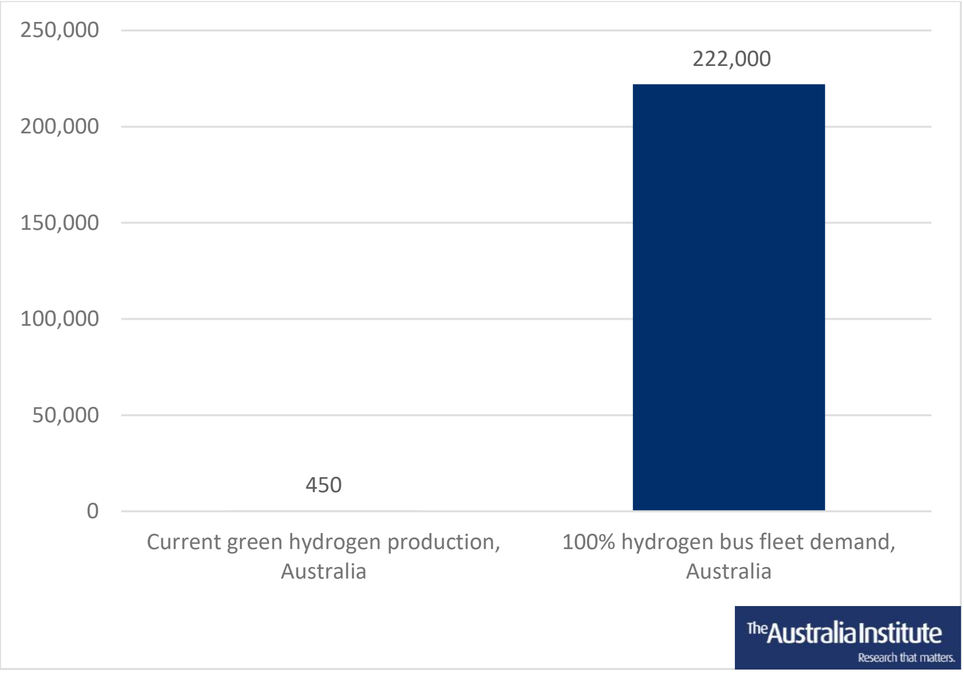
[41] DCCEEW (2023) *State of Hydrogen*, p. 10, https://www.dcceew.gov.au/sites/default/files/documents/state-of-hydrogen-2022.pdf

[42] CSIRO (2024) *Hydrogen Map*, https://www.csiro.au/en/maps/hydrogen-projects

[43] Hensher, Wei and Balbontin (2022) Comparative assessment of zero emission electric and hydrogen buses in Australia

Australia's entire annual total hydrogen production, and nearly 500 times more than the amount of green hydrogen it currently produces in a year. Figure 2 below illustrates this.[44]

Figure 2: Hydrogen supply and demand, Australia, tonnes



Sources: DCCEEW (2022) State of Hydrogen, p. 10; CSIRO (2024) Hydrogen Map; ABS (2020) Survey of Motor Vehicle Use; ABS (2021) Motor Vehicle Census, Australia.

Even if Australia's entire green hydrogen output was directed to its bus fleet, a close examination of proposed green hydrogen developments across Australia shows that it is highly unlikely that the country would ever produce enough green hydrogen for an entirely fuel cell-powered bus fleet.

Just as importantly, there will be many competing demands for those projected green hydrogen supplies—especially from hard-to-abate sectors. Green hydrogen will be central to decarbonising the agricultural sector, due to the critical role that hydrogen plays in fertiliser production. It will also be needed as a chemical feedstock, for shipping, for aviation, and possibly for the production of green steel.[45] And, indeed, supply *ought* to be directed to sectors where there are fewer alternatives to fossil-fuel use. The fact that there is already a mature, cheap option for electrification of bus travel makes buses a poor—even wasteful—use for future supplies of green hydrogen.

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[44] ABS (2020) *Survey of Motor Vehicle Use*, https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release; ABS (2021) *Motor Vehicle Census, Australia*, https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/latest-release

[45] DCCEEW (2023) *State of Hydrogen*.

In any case, the most important competing demand on future supplies of green hydrogen is likely to be the export market. Green hydrogen and its derivatives, such as ammonia and methanol, form the central plank in the plan to make Australia into a “renewable energy superpower”.[46] If the heroic projections of future green hydrogen production on which this plan is based come to pass, much of Australia’s hydrogen output will be secured by global trading partners, with Germany and Japan leading the way.[47] Of the 48 hydrogen projects listed on the Department of Industry, Science and Resources’ (DISR) *Resources and Major Projects List: 2023*, only 14 are green hydrogen projects that expect to supply the domestic market.[48]

Another way to gauge future green hydrogen supplies is the Hydrogen Production Tax Incentive, announced in the 2024–25 federal budget. This policy will provide a $2 incentive per kilogram of renewable hydrogen produced between 2027–28 and 2040–41.[49] While this subsidy will be demand driven, the government estimates that the program will cost $670 million per year to 2035, and $1.1 billion per year from 2034–35 until 2040–41 (Figure 3). This means the government expects green hydrogen production around the country will be 335,000 tonnes per year in 2030, rising to 550,000 by 2040.[50]

This output would be enough to effectively replace current uses of fossil hydrogen with green hydrogen, but there would be little to none left over to drive “renewable energy superpower” exports, to facilitate decarbonisation in other domestic sectors—or to fuel buses.

[46] Bowen (2023) ‘Message from the Minister’, in DCCEEW, *State of Hydrogen 2022*, https://www.dcceew.gov.au/energy/publications/state-of-hydrogen-2022

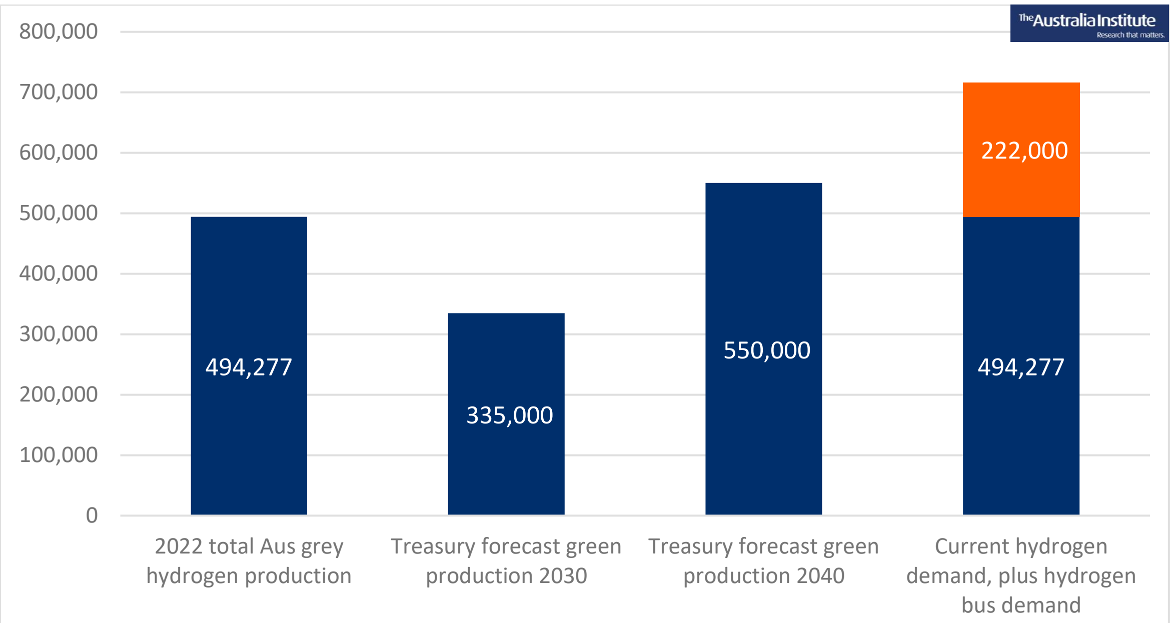
[47] ARENA (2022) *Australia signs hydrogen export deal with Japan*, https://arena.gov.au/blog/australia-signs-hydrogen-export-deal-with-japan/; Macdonald-Smith (2024) ‘Germany’s $660m pitch for Australia’s green hydrogen’, *Australian Financial Review*, https://www.afr.com/companies/energy/germany-s-660m-pitch-for-australia-s-green-hydrogen-20240118-p5ey7m

[48] DISA (2023) *Resources and Energy Major Projects List*, https://www.industry.gov.au/publications/resources-and-energy-major-projects-2023

[49] Commonwealth Government (2024) *Budget Paper No. 2: Budget measures*, p68

[50] Kohler (2024) *Market failures and political failures, made in Australia*, https://www.thenewdaily.com.au/finance/2024/05/27/alan-kohler-market-failures-australia

Figure 3: Current and projected hydrogen production, Australia, tonnes



Sources: DCCEEW (2023) *State of hydrogen 2022*; Commonwealth Gov (2024) *Budget Paper No. 2*

The *National Hydrogen Strategy 2024* is slightly more ambitious, with a "base target" of 500,000 tonnes of green hydrogen production in 2030, rising to 5 million tonnes by 2040.[51] Waiting till hypothetical hydrogen supply becomes available in 2040, when a cheaper, mature alternative technology is available today is, however, a poor way to meet current emissions reduction targets. Advice to government from the Climate Change Authority indicates that the best decarbonisation pathway for light rigid trucks *and buses* is to go from ICEs straight to BEVs.[52]

It is worth noting that the National Hydrogen Strategy contains the word 'buses' just once in its 104-pages.

Even if the supply of green hydrogen increases exponentially, demand is likely to keep pace with this increase, leaving the prospects for cheap, green hydrogen buses to languish. And in the absolute best-case scenario, if cheap green hydrogen somehow magically did become plentiful, the costs and complexities of refuelling infrastructure would remain terminal.

In reality, the many sources of demand will necessarily push up prices, and limit available supply. Green hydrogen is currently a far more expensive fuel than diesel for buses, and is likely to remain so for decades to come. At the same time, a new BEB already costs only a quarter of what a new diesel bus would do over the lifetime of the vehicle. In terms of cost, hydrogen is a dead end.

[51] DCCEEW (2024) *National Hydrogen Strategy 2024*, p. 43, https://www.dcceew.gov.au/energy/publications/australias-national-hydrogen-strategy

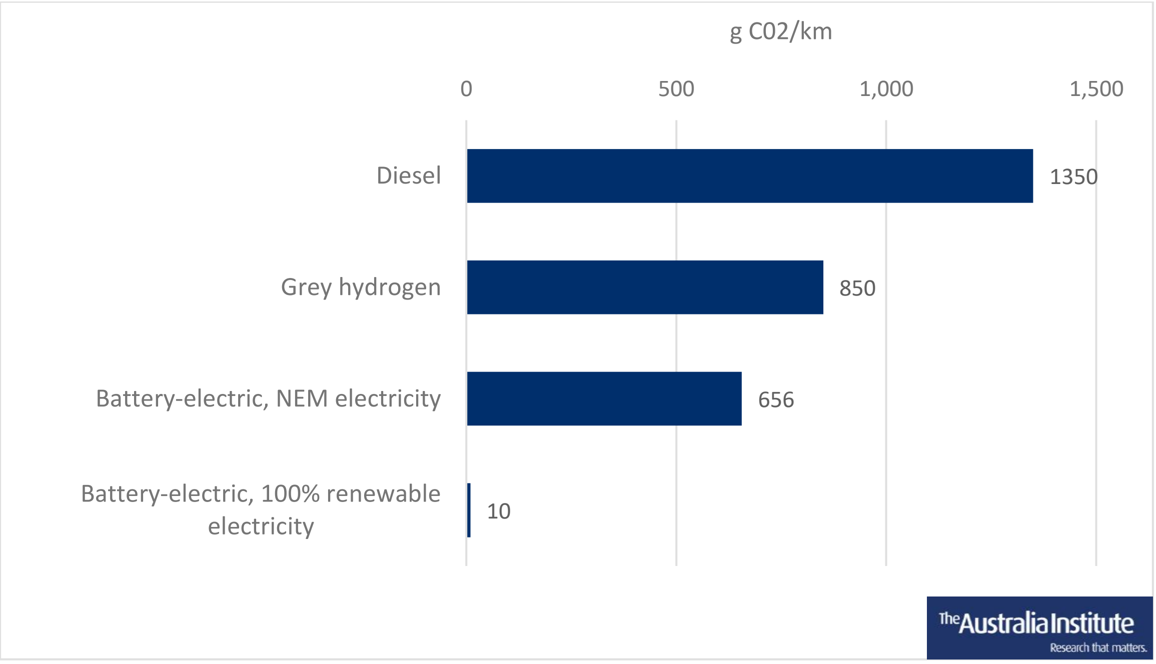
[52] Climate Change Authority (2024) *Sector Pathways Review*, p. 47 *https://www.climatechangeauthority.gov.au/sector-pathways-review*

Hydrogen vs battery-electric buses: Emissions

As discussed above, a supply of green hydrogen sufficient to run a hydrogen bus fleet is not currently available, and is unlikely to emerge. This means that FCEBs would need to run on fossil hydrogen. Proponents of CCS laud the potential of blue hydrogen—but even if sufficient supply of that form of hydrogen could be sourced, the ongoing non-viability of CCS means that emissions reductions from blue hydrogen cannot be guaranteed.[53]

As such, for the purpose of comparing emissions reduction potential of FCEBs and BEBs, it is appropriate to assume FCEBs will run on grey hydrogen. In this case, these so-called "zero-emissions vehicles" will fail to offer a meaningful reduction in emissions.

Figure 4: Life cycle emissions of different buses, per kilometre



Sources: Hensher, Wei and Balbontin (2022); Garcia (2022) 'Life cycle CO_2 footprint reduction comparison of hybrid and electric buses for bus transit networks', *Applied Energy*, p. 8, https://doi.org/10.1016/j.apenergy.2021.118354

As seen in Figure 4 above, while grey hydrogen offers a reduction in emissions compared to diesel, BEBs represent a greater emissions reduction today—and this emissions advantage only increases as the electricity grid is further decarbonised. The emissions intensities of diesel, grey hydrogen, and NEM-charged BEBs are drawn from Hensher, Wei and Balbontin

[53] Howarth and Jacobson (2021) How green is blue hydrogen?, *Energy Science and Engineering*, https://doi.org/10.1002/ese3.956

(2022), whereas that of BEBs running on 100% renewable energy are drawn from Garcia (2022). In these analyses, FCEBs fuelled by grey hydrogen emit 850g CO_2/km, representing a 37% reduction in emissions compared to diesel. But BEBs charged by grid electricity in Australia (which in 2022–23 had a 36.8% share of renewables) already offer a greater emissions reduction: 51%.

As the proportion of the grid powered by renewable sources increases—as it is projected to do, given the federal target of 82% renewable energy by 2030[54]—the carbon intensity of BEBs will continue to fall. For example, in South Australia—where 70% of electricity is generated from renewable sources—a BEB charged from the grid today has a carbon intensity of just 306.7 CO2/km.[55] This puts the per-capita emissions of a BEB passenger in SA at 7.6g CO_2/km, compared to 224g CO_2/km for the driver of a Toyota Hilux.[56]

Carbon emissions from the production of the bus itself add 10g CO_2/km (0.25 CO_2/km per person), representing a 99% reduction in emissions on diesel, and a 98.8% reduction compared with grey hydrogen.

Hydrogen buses will necessarily rely on grey hydrogen for fuel, undermining entirely the purported emissions reduction goals of introducing FCEBs. Hydrogen is more expensive, less efficient, and worse for the climate than battery-electric buses. The only possible argument for using hydrogen in buses is for long-distance coach travel between towns and cities, but only 12% of bus trips in Australia are interstate.[57] The vast majority of Australians live in cities, and a small minority of long-distance bus routes should not be used as cover for the widespread adoption of an inappropriate technology.

Even the limited use of FCEBs for long-distance travel ought to be rigorously examined, especially considering the cost of establishing refuelling infrastructure. Meanwhile, developments in “battery swapping” may quickly answer questions of range *and* recharging time, as they have with battery-electric trucks.[58]

[54] DCCEEW (2024) *Powering Australia*, https://www.dcceew.gov.au/energy/strategies-and-frameworks/powering-australia

[55] Authors calculations, derived from Hensher, Wei and Balbontin (2022) and Garcia (2022). The carbon intensity of full-renewable BEBs was subtracted from the carbon intensity of a BEB charged by the NEM in 2022, leaving the energy intensity of fossil fuel charging. The remainder was then adjusted from a 36.8% share of renewables to a 70% share.

[56] Australian Government (n.d.) *Green Vehicle Guide: 2020 Toyota Hilux*, https://www.greenvehicleguide.gov.au/Vehicle/ViewMatchingVariants?vehicleDisplayId=30615

[57] Bus Industry Conference (2020) *Bus Operations – 2020 Fast Facts*, https://bic.asn.au/industry-stats/2020-bus-operations-stats/

[58] Cui, Xie and Niu (2023) *China is propelling its electric truck market by embracing battery swapping*, https://theicct.org/china-is-propelling-its-electric-truck-market-aug23/; Siemens (n.d.) *Safe battery change on electric buses*, https://www.siemens.com/global/en/products/automation/industrial-controls/media/safe-battery-swapping.html

Given all of this, it is unsurprising that researchers have found that “given the current market prices for electricity and hydrogen in Australia, BEBs offer the best prospects for emission reductions and cost savings”.[59] Professor David Cebon of Cambridge University has been even more acerbic. He has said that adopting hydrogen buses will be “destructive from the point of view of emissions … destructive from the point of view of the energy transition… [and] destructive in terms of finances and the economy because you have to subsidise [FCEBs] in order to make them financially viable”.[60]

[59] Hensher, Wei and Balbontin (2022) ‘Comparative assessment of zero emission electric and hydrogen buses in Australia’, p. 13.

[60] Cebon, in Ore (2023) ‘Victoria warned against ‘very inefficient’ hydrogen buses after trial announced’, *The Guardian Australia*, https://www.theguardian.com/australia-news/2023/nov/24/victoria-warned-against-very-very-inefficient-hydrogen-buses-after-trial-announced

Hydrogen vs battery-electric buses: Efficiency

Another key limitation of FCEBs is the inherent inefficiencies involved, which have significant implications for land use and energy demand. When a BEB is charged by renewable energy, through the grid, almost all the energy captured by those solar cells or wind turbines makes its way to the engines that drive the wheels. Some energy is lost: the rate of energy loss through transmission in Australia is approximately 10%, and EVs use roughly 85% of the energy they draw from the grid.[61]

But the efficiency losses involved with an FCEB running on green hydrogen are much, much worse. In general, it takes three times as much energy to run a green hydrogen bus than it does a BEB. This is because of large efficiency losses through the process of electrolysis, compression, transportation of fuel, and the generation of electricity by the on-board fuel cell. As a result, research from Cambridge University has shown that 100kWh of renewable electricity will result in only 23kWh of energy available to drive a hydrogen bus.[62]

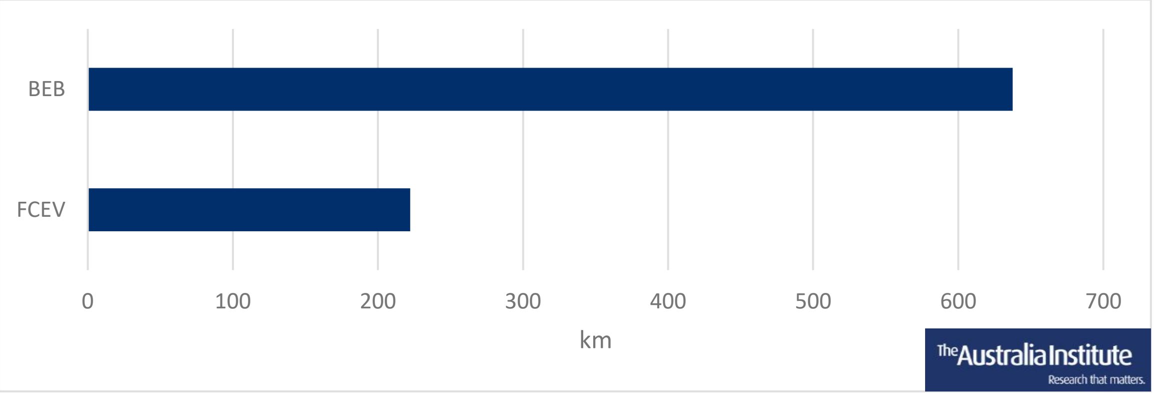
For example, Canberra's Mugga Lane solar farm has a capacity of 13 MW, so around 5 minutes of strong sunshine can generate 1MWh of energy. If all that energy was put toward powering a BEB, 10% would be lost in transmission, and the bus would transform 85% of the remaining power. A BEB requires 120kWh of charge to travel 100km, so the charge it received from the solar farm would allow it to travel 638km.

Producing 1kg of green hydrogen production requires 50kWh of solar power, so if a green hydrogen facility was installed next to the Mugga Lane solar farm, the same 1MWh of energy would allow for the production of around 20kg of hydrogen gas (H_2). Producing and transporting that hydrogen would result in energy loss through electrolysis (25%), H_2 compression (10%), H_2 transport (20%), and then within the onboard fuel-cell (50%). A FCEB requires 9kg of hydrogen to travel 100km. As a result of these losses, that same amount of solar power would result in only 222km of travel (Figure 4).

[61] AEMO (2024) *Loss factors and regional boundaries*, https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/market-operations/loss-factors-and-regional-boundaries; Lovell (2020) 'EVs: Are they really more efficient?', *Australian Energy Council*, https://www.energycouncil.com.au/analysis/evs-are-they-really-more-efficient/

[62] Cebon (2020) 'Long-haul lorries powered by hydrogen or electricity?', *Centre for Sustainable Road Freight*, https://www.csrf.ac.uk/blog/long-haul-lorries-powered-by-hydrogen-or-electricity/

Figure 4: Estimated distance travelled, 1MWh of solar power



Sources: Hensher, Wei and Balbontin (2022) 'Comparative assessment of zero emission electric and hydrogen buses in Australia', *Transportation Research Part D*; AEMO (2024) *Loss factors and regional boundaries*; European Parliament (2020) *The potential of hydrogen for decarbonising steel production*, https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2020)641552

Put simply, it takes around three times as much renewable energy to run a green hydrogen bus fleet than a BEV fleet run on renewable energy.

To put this in perspective, if you were to generate sufficient green hydrogen to power the entire Australian bus fleet, you would need 4.1GW of wind power capacity dedicated entirely to hydrogen production. That is 46% of all the wind power already installed in Australia.[63] On the other hand, a full fleet of BEBs would require just one third of that renewable energy capacity, dramatically reducing demands on energy infrastructure.

The complexity of the required FCEB infrastructure further undermines the efficiency of hydrogen use, and dramatically increases the cost of running such buses (detailed above). These factors also make the logistics of such a system very challenging. For example, the CSIRO considered the number of trucks that would be needed to supply hydrogen refuelling stations, compared to the existing standard for diesel. A standard diesel tanker carries 56,000L of fuel, with an energy content of 2,128GJ. A tanker carrying compressed hydrogen, carrying 1,344kg of fuel, has an energy content of 162GJ.[64] This means it would take 14 tanker loads of hydrogen to transport the same amount of energy as one diesel tanker. Having 14 times as many fuel tankers on Australian roads is a significant and unnecessary extra demand on road infrastructure. It also helps to explain the enormous cost of refuelling infrastructure, as reflected in Californian market prices.

Arguably the CSIRO's estimate understates the problem, however. B-double diesel trucks generally carry 69,000L, rather than 56,000L; existing compressed gas trucks have both a lower capacity, and lower pressure, than the CSIRO suggests. Considering these factors,

[63] Australian Trade and Investment Commission (2024) *Wind Energy*, https://www.globalaustralia.gov.au/industries/net-zero/wind-energy

[64] CSIRO (2023) *Hydrogen vehicle refuelling infrastructure: Priorities and opportunities for Australia*, p. 31, https://www.csiro.au/en/about/challenges-missions/hydrogen/hydrogen-vehicle-refuelling-infrastructure

hydrogen haulage is likely to require 24 to 29 trucks to move the same amount of fuel as a single diesel truck.

Not only does this dramatically increase the number of trucks on Australia's roads, but it also presents a challenge for sequencing and decanting this fuel at stations/depots concurrently with buses that require refuelling, often in tight, off-peak time windows. If these trucks were to run on hydrogen themselves, the efficiency of this system would be further eroded. This has been left out of the scope of analysis, to focus on buses, but hydrogen trucking is similarly highly inefficient, with poor prospects.[65]

Hydrogen refuelling stations also require extensive compressors and/or refrigeration, further undermining the efficiency of this technology, and increasing its cost.[66] The energy requirements of compression are significant, at 2.43kWh/kg, resulting in 540.5GWh of energy load in compression each year for a hydrogen bus fleet—more power than it takes to run 100 hospitals.[67] [68] In this way, unlike BEVS, a hydrogen bus fleet does not even relieve pressure on the grid.

[65] Williamson (2023) *Hydrogen for long-distance trucking makes no sense, says expert*, https://thedriven.io/2023/04/03/hydrogen-for-long-distance-trucking-makes-no-sense-says-expert/
[66] *Ibid*, p. 37.
[67] Bauer et al (2019) 'Energetic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen', *International Journal of Hydrogen Energy*, https://doi.org/10.1016/j.ijhydene.2019.01.087
[68] Burch, Anstey and McGain (2021) 'Renewable energy use in Australian public hospitals', *Medical Journal of Australia*, https://doi.org/10.5694/mja2.51197

Conclusion

Decarbonisation of Australia's transport system is a crucial step on the way to addressing climate change. Public transport decarbonisation is a powerful policy tool available to governments—state, territory, and federal—to drive this transition. The trials of hydrogen buses taking place in several jurisdictions are, however, a dead end in terms of both policy and technology—and neither Australia nor the world can afford such diversions at this point. Hydrogen buses are expensive to operate, and wasting time with them is expensive because it delays the rapid roll-out of BEBs.

Unlike FCEBs, fleets of BEBs already exist at scale, and they are being rolled out widely across Europe, China, India, and the United States. These buses are economically viable, commercially available, and offer meaningful emissions reduction—in other words, they are everything that FCEBs are not. FCEBs are more expensive than BEBs and are unlikely to produce promised emissions reductions. Hydrogen fuel cell technology has not matured, and even in Japan where it is being pushed hardest by governments, it is struggling.

Green hydrogen is far too expensive and scarce a resource to be used to power buses, especially as harder-to-abate sectors will be key sources of demand. In the absence of green hydrogen, blue hydrogen may seem promising—but is also extremely expensive, and importantly, its reliance on carbon capture and storage has meant that it has constantly failed to deliver promised emissions reductions.

Without access to green or blue hydrogen, a FCEB fleet in Australia would have to rely on grey hydrogen, a fuel that is comprehensively worse than BEBs via all key metrics. Grey hydrogen FCEBs are more costly than BEBs, offer much lower emissions reductions, and are far less efficient to operate.

Given how challenging the decarbonisation of Australia's energy grid is already proving, it would be simply bad policy to choose a wantonly inefficient technology like FCEBs for transportation. Doing so would make the decarbonisation of energy harder, and exacerbate shortages of labour, materials, and clean energy products.[69]

This all begs the question: why are state and territory governments wasting time and money on hydrogen bus trials? Government decisions to drive particular technologies through subsidy and procurement do not have to be "economically rational", narrowly defined, but

[69] Gittins (2023) 'How full employment has changed the economy', *Sydney Morning Herald*, https://www.smh.com.au/business/the-economy/how-full-employment-has-changed-the-economy-20231217-p5es04.html

these choices do reveal priorities. Why would a government's priority be to support hydrogen, against all available evidence?

Given the fact that grey and blue hydrogen production rely on natural gas as a feedstock, one possible explanation is that hydrogen is being used as a "trojan horse", to boost demand for natural gas.[70] Gas companies have invested considerable amounts in natural gas production and distribution infrastructures in Australia—$473 billion since 2010—and want a return on their investments. [71] These companies fear electrification, and they are looking to secure their profits in the future. Encouraging a reliance on hydrogen helps solve that problem.

Government subsidies are being poured into grey hydrogen projects with promises that one day, hydrogen could be produced with renewables. The government-owned Kurri Kurri power station is an example: it will run on natural gas until it can run on hydrogen. FCEB trials seem to represent the same tactic with buses: they encourage governments to trial and procure buses that run on dirty grey hydrogen, on the vague promise that one day soon, that grey hydrogen could be substituted for green hydrogen. Maybe. In the meantime, gas profits keep rolling in.

Perhaps this helps to explain why the South Australian government is trialling hydrogen buses, which it claims "showcase[s] a clean, green public transport future",[72] especially considering the close links between the South Australian Government and influential gas company, Santos.[73]

Meanwhile, BEBs present as a mature and cost-effective technology. Perhaps most importantly, BEBs become more and more attractive, as the carbon-intensity of grid electricity drops. With a national target for 82% renewable energy by 2030, the case for hydrogen will only get worse. A rapid roll-out of electric buses is needed and makes sense.

Electrifying bus fleets is an easy first step that state governments can take toward achieving their net zero goals. If state governments are unable, or unwilling, to take such a simple step, this does not simply demonstrate a lack of interest in reducing transport sector

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[70] Bridges and Merzian (2019) *Hydrogen and Climate: Trojan Horse or Golden Goose*, https://australiainstitute.org.au/report/hydrogen-and-climate-trojan-horse-or-golden-goose/

[71] APPEA (2022) *Key Statistics 2022*, https://www.appea.com.au/wp-content/uploads/2022/06/APPEA_KS22_final.pdf

[72] Government of South Australia (2023) 'SA accelerates towards zero-emission public transport with train and bus trials', Media Release, 30th August, https://www.premier.sa.gov.au/media-releases/news-items/sa-accelerates-towards-zero-emission-public-transport-with-train-and-bus-trials

[73] Bermingham (2022) 'Premier Peter Malinauskas vows no conflicts over brother Rob's Santos job', *The Advertiser*, https://www.adelaidenow.com.au/news/south-australia/premier-peter-malinauskas-vows-no-conflicts-over-brother-robs-santos-job/news-story/a58f8d98cc44b90bc43bf98899a3e390?amp

emissions. It suggests that state governments' commitments to net zero emissions are more symbol than substance.

Trialling different technologies is not responsible acquisition policy. It is a costly and unnecessary delay from rolling out a full fleet of BEBs. Framing FCEBs as a viable alternative is disingenuous, and cuts against both first-principle analysis and current research. It presents a danger of investing in the wrong infrastructure and thus creating inefficient path-dependencies. It also delays the immediate, rapid roll-out of BEBs, which represent far better value for money, make far more progress toward net zero goals, and ought to be the policy priority.[74]

Hydrogen buses are not only a waste of time and money, although they are certainly both of those things; they are also a dangerous dead end, both as technology and policy.

[74] Denniss, Quicke, Parrott (2023) *Stuck in the slow lane: Electrification of buses in Australia*, https://australiainstitute.org.au/report/stuck-in-the-slow-lane/