Comparative Assessment of Zero Emission Electric and Hydrogen Buses in Australia

David A. Hensher
Edward Wei
Camila Balbontin

Institute of Transport and Logistics Studies (ITLS)
The University of Sydney Business School, Sydney NSW Australia 2006
David.Hensher@sydney.edu.au
Edward.Wei@sydney.edu.au
Camila.Balbontin@sydney.edu.au

24 September 2021 (revised 8 November 2021)

Abstract
The pace of direct electrification vs indirect electrification for public transit bus fleets is accelerating internationally. Clear targets have been established by transport policymakers to achieve a zero-emission bus target as early as 2030 in some jurisdictions. Two prominent choices are battery-driven electric buses and fuel-cell electric buses. We draw on evidence on these current and future developments to provide an assessment of the two types of technology on emission reduction, capital, maintenance and energy costs, and other aspects. We apply a decision support system to compare a number of scenarios for different electrification plans of bus fleets using Australian data. Comparing scenarios such as slow versus fast take up and different mixtures of energy technologies in future zero emission fleets provides evidence on the reductions in carbon dioxide emissions and costs in converting a diesel bus fleet to a fully green, at tailpipe, fleet.

Keywords: Zero Emission Bus; electrification of bus fleet; electric bus, fuel-cell electric bus; decision support system; carbon dioxide emissions; operating cost of a transit bus

Acknowledgements: The paper was based on research partially funded by BusVic. We thank Dr Chris Lowe, the Executive Director for his support. Neil Wang, CEO of Futon Australia, provided the very latest estimates of the depot refit costs as well as the cost of hydrogen and reviewed the range of costs we have allowed for in the Decision Support System. We thank four referees for the extensive and extremely useful comments and suggestions.

Declaration of interest: There is no conflict of interest.

Author Contributions: David A. Hensher: Conceptualisation, methodology, writing – original preparation; Edward Wei: Data curation, modelling, original preparation, writing, editing; Camila Balbontin: reviewing and editing.

Introduction
Given the backdrop of the Paris Agreement to limit global warming to well below 2 degrees Celsius, preferably to 1.5 degrees Celsius, compared to pre-industrial levels, the introduction and rollout of zero-emission buses (ZEBs)[1] in many countries are starting to gather momentum. It is not a matter of whether such a transition is necessary, but how the change should be best implemented. Many governments have either defined a timetable or are working on the plan to achieve full electrification of diesel bus fleets.

---

[1] A zero-emission bus (ZEB) refers to zero emissions at the tailpipe.

For example, the EU started a program in 2013 called ZeEUS to test and facilitate the adoption of electric buses focusing on urban bus system networks. There are over 4,000 battery-electric city buses registered in Europe with a further 3,500 plus electric coaches. Top countries with ZEB fleets include the Netherlands, the UK, France, Poland, Sweden, Spain and Austria (CTI 2021). Over 3,000 ZEBs have been confirmed or are in operation in North America (Sustainable Bus 2021). In Asia, according to MarketWatch (2021), by May 2020, China had about 420,000 ZEBs, close to 99% of the total global ZEB fleet. ZEBs account for about 15% of China's total bus fleet.

The objective of this paper is to provide an update on the latest developments in battery electric buses (BEBs), driven by an electric motor to obtain energy from on-board batteries, and fuel cell (hydrogen) electric buses (FCEBs) that use compressed hydrogen gas as a fuel to generate electric power via a highly efficient energy converter, and together with the financial and environmental implications of adopting a specific technology, we implement a new decision support system to identify the change in carbon dioxide (CO_2) emissions, capital and operating costs under various transition plans away from diesel to mixtures of BEBs and FCEBs, both being ZEBs at the tailpipe. The findings provide guidance to both bus operators and regulators in not only tracking reductions in CO_2 emissions but also the cost outlays in bus and depot changes (including training and maintenance procedures) that will be required in the transition to ZEBs, which signals a challenge under negotiated or tendered contracts for adjusting contract prices or providing grants to funs new buses and depot reconfiguration to accommodate charging of ZEBs.

Australia has commenced the transition to ZEBs. Australia currently ranks 22nd in greenhouse gas emissions globally and transportation accounts for about 17% of the total emissions. Australia's per capita transport emissions are 45% higher than the Organisation for Economic Cooperation and Development (OECD) average level (Climate Council 2017). Globally, transportation contributes 22% of total CO_2 emissions more than the Australian level (Mohamed et al. 2018). Diesel driven heavy-duty vehicles, including buses, also account for most air pollutants, such as 45% of nitrogen oxides and 75% of particulate matters (Li 2016). Internationally, the public transport sector has a metropolitan modal share varying from a low of 10% in countries such as Australia to over 70% in China, with the private car being the main alternative (Climate Council 2017). There are generally, at least, three pathways to reduce emissions in transport: 1) shifting Internal Combustion Engine cars to electric vehicles; 2) shifting more transport requirements to public and active transport to reduce car use and passenger movements overall, and 3) electrification of public transport from diesel and gas-based to electric-based. The pathway is the focus of this paper and the other two pathways are something we have discussed in many other papers on topics such as road pricing reform, mobility as a service (MaaS) etc. Pathways 1 and 3 are strongly linked to the de-carbonisation and climate change agendas. As technology-based solutions, they offer greater prospects than pricing reforms, given the latter is not supported politically in many countries.

For buses, shifting car drivers to public transport buses and electrification of bus fleets are two primary strategies. Compared to passenger cars, a bus uses 60% less fuel to move 100 passengers over typical metropolitan distances of 10 to 40 kms. A 10% passenger shift from cars to buses has been estimated to reduce carbon emissions by over 400,000 tonnes a year (OzeBus 2020). On electrification of bus fleets, besides achieving the zero-emission objective, it is widely agreed that the total cost of ownership of a BEB will continue to decline, driven by the reduction in battery price and continued lower energy consumption by electric buses compared to diesel buses. In a recent cost-benefit analysis by Quarles et al. (2020) for the US market, they predict that the battery-electric bus fleet, including the required charging infrastructure, will be cost-competitive to the diesel bus fleet by 2030.

There are two leading technologies for ZEBs, both generating zero tailpipe emissions. The majority of ZEBs will be battery-driven electric buses using rechargeable batteries. The second type is hydrogen fuel cell electric buses, which use compressed hydrogen gas to generate electric power via a fuel cell, a highly efficient energy converter. Some other technologies are targeting partial electrification for low emission buses. For example, Transdev, a multinational bus operator, is testing a hydrogen unit called HYDI which can be installed on existing diesel buses to cut down the use of diesel. Low emission buses also include plug-in hybrid electric, which is usually not considered by state governments or bus operators.

In this paper, we only focus on ZEBs to align with the complete electrification of the bus fleet achieving the zero-emission tailpipe target. At the outset it is important to note that we have not included the cost of building new renewable energy generation sources since we do not believe that this is an issue for the bus operator except in ensuring they obtain adequate electricity supply. Our paper focusses on the transition costs and emissions of the bus operator with no expectation that they have to pay for grid upgrade which benefit many customers, and what matters is the availability of supply and its associated prices and we have accommodated this with a range available in the slider in the Decision Support System. On the matter of the volume and reliability of energy supply, many plans are in place and we have to assume they will deliver on depot requirements. We have been advised that the electricity energy suppliers are able and committed to provide the upgrades required into the bus depots. We realise that this is a priority issue and that this will be a challenge, but that this upgrade will not be passed on as an expense to the bus operators except through the negotiated peak and off-peak tariff. Transgrid, a major energy supplier in Australia, as an example, will leverage its current activity with Transit Systems in Sydney to investigate the role of stationary and on-board batteries in providing demand response and frequency services to the grid as potential optimizations for future projects and to strengthen transmission networks.

The paper is structured as follows. The following section is a review of BEBs and FCEBs in the ZEB market, together with the energy consumption and emissions of BEBs and FCEBs, and other factors influencing energy consumptions and the economy of ZEBs. We then provide an overview of progress and commitment to ZEBs in Australia, followed by an explanation of the sources of emissions and the state of renewables in electricity generation compared to coal-fire powered stations. We then present the emission intensity rates associated with the production of the various energy sources. A number of scenarios are then presented using a new decision-support system we have developed to identify the change in CO_2 emissions, capital and operating costs under various transition plans away from diesel to mixtures of BEBs and FCEBs. A number of conclusions highlight the contributions of the paper.

Past Research on Battery Electric and Fuel Cell Technology

A crucial consideration associated with proceeding to ZEBs is to select the technology, or more precisely, the proportions of BEBs and FCEBs in future ZEB bus fleets. This is a challenging task to avoid stranded assets as BEBs are compared to the appeal of FCEBs in terms of current and future technology, operational contrasts, and economics. For BEBs, the main technology and operational considerations are charging strategies and methods. For FCEBs, the main obstacle is the low demand which is driven by the higher cost in bus making and infrastructure and the higher cost in production, compression and transportation of hydrogen. Future fleet sizes for BEBs and FCEBs are quite different, with BEBs dominating. In a recent IEA report on EVs, the BEB fleet is forecast to increase from 600,000 in 2020 to 1.6 million in 2025 and 3.6 million in 2030 (IEA 2021). On the other hand, FCEBs and hydrogen trucks are only predicted to reach 45,000 in the EU, with 1,200 FCEBs in Japan, and 11,600 FCEBs and hydrogen coaches in China (Deloitte-Ballard 2020).

The trend across the globe to shift away from diesel buses is currently dominated by transitioning to BEBs powered by Li-ion batteries, followed by FCEBs, and various forms of hybrid buses using both new and conventional fuels (e.g., Li 2016; Li et al. 2018; Pagliaro & Meneguzzo 2019). Li et al. (2018) examined trends for BEB adoption in 22 countries across the Americas, Asia-Pacific and Europe. They reveal that in most of these countries, the procurement of BEBs is supported by public grants. In countries such as China, Singapore, South Korea, and Sweden, private grants are also given by large organisations. These grants come from local, national or international sources, in cash, in-kind or tax incentives. The same level of support does not yet exist for other ZEBs.

There are generally two charging strategies and three charging methods. On charging strategy, bus operators can choose depot charging or opportunity charging. The latter is also referred to as on-route charging. There are three leading charging technologies including lower power charging through cable and plug-in (alternate or direct charging) which are common methods for depot charging, higher power charging through conductive charging using fast charging equipment like a pantograph, and fast charging through inductive/wireless charging using a magnetic field (UITP 2019). The fast charging methods using a pantograph and a magnetic field are primarily used for opportunity charging but may also be used in depot charging if charging infrastructure is installed. Conductive or inductive charging technology may be chosen depending on the facilities. With the differences in technology, the depot and opportunity charging can be used in combination for most BEBs if the infrastructure is available. In addition to these three methods, BEBs and FCEBs also include an on-board regenerative braking process that may recharge up to 40% of the electricity back to the battery during operation, especially in a metropolitan bus with many stops and starts. For depot charging, energy consumption and CO_2 emissions may differ depending on the charging time. It is expected that the speed of charging and hourly variation during the day in the electricity grid can cause slight but significant variations in both energy and CO_2 emissions (Miller et al. 2020; National Renewable Energy Laboratory 2016).

BEB Battery Types

BEBs designed for fast conductive/inductive charging may be more suitable for smaller batteries using high energy density materials like lithium nickel manganese cobalt oxide (NMC), allowing a high proportion of the battery to charge within a short time (Li et al. 2020), or Lithium Titanate (LTO) used particularly for bi-articulated electric buses using flash (super-fast) charging. On the other hand, overnight depot charging often uses larger or heavier batteries built in more conventional materials with lower energy density but higher safety such as lithium iron phosphate (LFP). Table 1 summarises the key differences between the two types of leading battery technologies.

Table 1 Key differences between the main battery types

	LFP Battery	**NMC Battery**
Configuration	Lithium, iron and phosphorous	Lithium, nickel, manganese and cobalt
Countries batteries mostly made in	Almost all bus batteries made and used in China are LFP	Japan, Korea, the US
Manufacturers	BYD, Yutong and other Chinese BEBs	Proterra
Market Share in 2018	88%	1.35%
Market Share predicted for 2028	58%	42%
Energy density	100 to 110 Wh/kg, or at most 60 to 70% of NMC	200 Wh/kg
Space occupation	bigger battery	smaller battery (40 to 50% smaller)
Mostly used in	Buses/Trucks	Cars (e.g., Tesla)
Safety	Safe against fire; less chance to have flames in a crash; high-temperature resistant	Less safe; overheating; fire incidence
Temperature	Better performance for high temperature	Better performance for low temperature (e.g., at -20 degree still can release 70% of capacity vs 55% from LFP batteries)
Charging efficiency	Slow due to low energy density	Fast due to high energy density
Cycle life	Longer. It can remain at 80% capacity after 3000 cycles of charge/discharge	Shorter. The theoretical life of NMC is 2000 cycles. Capacity fades to 60% after 1000 cycles.
Price difference	20% to 40% cheaper than NMC, can be as low as US$80/kWh after 2021	20% to 40% more than LFP battery
EU Bus Choice	Most	Less often

Hydrogen Mix

Hydrogen is an excellent energy carrier in terms of its weight. One kilogram of hydrogen can generate about 33 kWh of usable energy, whereas petrol and diesel only hold 12 kWh/kg. One kilogram of hydrogen, used in a fuel cell to power an electric vehicle, contains approximately the same energy as a gallon of diesel. On the other hand, the volumetric energy density for hydrogen is low because hydrogen is very light and weighs 0.082 kilograms per cubic metre (0.082 kg/m^3) at 22°C and normal atmospheric pressure. It is a challenge when hydrogen must be transported from its generation to a refuelling station, suggesting that hydrogen needs to be compressed or liquefied for storage, distribution and use.

Once the compressing and storage challenges are met, hydrogen can be stored in tanks. A fuel cell then combines hydrogen and oxygen to produce electricity, heat and water. A chemical reaction to usable electricity produces energy. FCEBs have two main advantages over BEBs charged from the electricity grid. First, the refuelling time required for FCEBs is much quicker (i.e., similar to fueling up a diesel bus). Second, FCEBs can operate over a more extended range, given the high density of hydrogen.

In comparing the fuel/energy efficiency with diesel and electric buses, emissions from hydrogen can differ significantly due to different production methods, as shown in Table 2. To produce 1 kg of hydrogen, CO_2 emissions can vary considerably from a low of 0 kg CO_2-e using 100% renewable electricity for electrolysis to 40.5 kg CO_2-e using Australian grid electricity for electrolysis. The Decision Support System (DSS) in a later section allows an operator to choose the proportions for the three most common types of hydrogen, namely grey, blue and green hydrogen.

Table 2 Emissions intensity of hydrogen production

Production Technology	Emissions (kg CO_{2-e}/kg hydrogen)
Electrolysis – Australian grid electricity	40.5
Electrolysis – 100% renewable electricity	0
Coal gasification, no Carbon Capture and Storage (CCS)	12.7 – 16.8
Coal gasification + CCS – best case	0.71
Steam methane reforming (SMR), no CCS	8.5
Steam methane reforming (SMR) + CCS, best case	0.76

Source: Council of Australia Government Energy Council (2019)

Deliali et al. (2021) recently compared several technologies for ZEBs covering BEBs, FCEBs and a hybrid of the two (e.g., Ford HySeries Drive System, which can be powered by both battery and fuel cell) in the US. They find that a BEB has the highest energy efficiency and lowest procurement price with lower operation and maintenance costs. BEBs are currently chosen by most bus operators. The hybrid version for the two technologies is not attractive because of the high procurement and maintenance costs (i.e., maintaining both types). In the passenger vehicle market, van de Kaa et al. (2017) compared the two technologies and concluded that the battery is a better choice than the fuel cell due to technology superiority, compatibility, brand reputation and credibility.

On the other hand, a claimed strength of hydrogen driven heavy vehicles is its reliability in intensive use over a long distance and high load capacity, which makes it ideal as the future alternative for heavy and long-range buses (or coaches) and trucks currently run on diesel (Bethoux 2020; Deloitte & Ballard 2020). Fuel cell durability targets are, however, consistently missed, and it is suggested by the US DOE that it is unlikely that hydrogen semi will have equivalent reliability to diesel semi-trailers until closer to 2050. Trencher and Edianto (2021) gathered expert opinion in Germany and found that the main obstacles for fuel cell vehicles relate to the fuel cell passenger car market, with the most significant obstacle being lack of demand and supply of both fuel cell passenger cars and refuelling stations. It is unlikely that the volume of car sales will use hydrogen and will stay with battery electricity. The situation for the transit bus market is much more favourable because demand is driven by government support. The reason at present that FCEBs are not being chosen over BEBs is the higher bus purchase price. A priority to provide a competitive alternative is to reduce the production cost of an FCEB. Bethoux (2020) indicates that technology development in FCEBs should focus on a versatile design to decouple fuel cell modules and hydrogen tanks so that manufacturers can have the flexibility to reduce production costs in dealing with different specifications. These developments which are occurring at a fast pace, raise concerns about whether decisions taken today on particular technology risks stranded assets. Australia is in ann excellent position to be a world leader in the production, distribution and export of hydrogen, which in itself means that FCEBs cannot be discounted as the preferred energy source in the future for buses.

Energy Consumption and Emissions of diesel buses, BEBs and FCEBs

The fuel consumption of a bus depends on many factors such as the size and age of the bus, kilometres driven, road condition, patronage loading, and speed. Fuel consumption figures for a diesel bus can vary from a typical low of 28 L/100 km up to 65 L/100km (e.g., Ally & Pryor 2016; BudgetDirect 2020; Hydrogen Europe 2020, Bus Industry Confederation 2021). The average fuel consumption for a metro bus fleet in the major Australian capital cities is typically around 40 to 45 L/100 km (Balbontin et al. 2020). A regional bus fleet could be higher. According to Ecoscore (2020), 1 litre of diesel generates 2.64 kg of CO_2 tailpipe emission. If, for example, a bus uses 41 litres of diesel per 100km., then for each kilometre, a diesel bus would produce about 1.08 kg of CO_2.

In passenger per kilometre units, diesel buses in Australia emit 14 to 22 gCO_2-e per passenger kilometre (Climate Council 2017). The Australian Department of the Environment and Energy (2017) has provided detailed equations and factors for calculating transport fuel emission levels. If a bus fleet consumes 10,000 kL of diesel, the relevant emissions are 26,981 tons of CO_2. Car passengers switching to bus travel can deliver noticeable environmental benefits. According to the Institute for Sensible Transport (2018), buses produce 17.7 gCO_2-e per passenger kilometre on-road emissions in Melbourne, far better than 243.8 gCO_2-e per passenger kilometre for a car.

Energy sources such as electricity and hydrogen, when consumed on the road, do not generate on-road tailpipe emissions or generate a negligible emissions level (Climate Council 2017). However, the manufacturing, production, and disposal processes impose non-zero emission outcomes, resulting in positive overall life cycle emissions. In comparing the total lifecycle emissions associated with alternative fuels to operate buses, these other upstream emissions should not be ignored. A comparison of life cycle environmental impacts of alternative energy types is summarised by Sharma and Strezov (2017). Interestingly they find that electricity-linked sources create some of the greatest negative environmental impacts compared to some other energy sources when the full life cycle is accounted for.

Chang et al. (2019) compared CO_2 emission levels associated with buses operating in the city of Tainan, Taiwan. They conclude that emission levels are 63.14 gCO_2-e/pkm (grams of carbon dioxide equivalent per passenger kilometre) for CNG buses, 54.6 gCO_2-e/pkm for diesel buses, 47.4 gCO_2-e/pkm for LPG buses, 37.82 gCO_2-e/pkm for plug-in BEBs, and 29.17 gCO_2-e/pkm for FCEBs. These results suggest that reducing emission levels by moving from a diesel bus fleet to a fully electric bus fleet significantly reduces overall emissions. However, when we consider the whole life cycle and not just end-use, we cannot claim zero emissions, and in general the debate on ZEBs is misleading. Logan et al. (2020) recently compared the emission levels of conventionally fuelled diesel buses with BEBs and FCEBs in the UK. They found that conventionally fuelled diesel bus emissions were 36 times higher than BEBs and nine times higher than FCEBs, considering the various electricity and hydrogen generation process profiles in the UK.

From tests run by electric bus makers such as Solaris and VDL, the types of BEBs and how much BEBs consume in energy also depend on conditions associated with on-road operations such as temperature, air conditioning, heating, driving behaviour and other factors. According to the manufacturer's data, BEBs with a 300kWh battery charge may operate at 375 kms in the best case but may also only run as few as 130 kms in harsh weather. This result also implies that the total emissions can vary significantly depending on electricity consumed for the same distance travelled. Some hybrid BEBs with fossil fuel used to run the air conditioning and heating may save electricity but will generate more on-road emissions due to fossil fuel consumption (Sustainable Bus 2020).

Without considering production, emissions from FCEBs are negligible in fuel consumption. In a small hydrogen vehicle such as the Hyundai Nexo, for example, 1 kg of hydrogen can support travel up to 100 kms. In heavy vehicles such as the transit bus, the fuel consumption level can be as low as 9 kg per 100 km in a new FCEB. FCEBs can operate for 300 to 450 kms without refuelling, offering a similar level of capacity as the diesel bus in operation (Hydrogen Europe 2020). Table 3 provides a summary of fuel and energy consumption and related emissions of CO_2 for a diesel bus, a BEB and a FCEB.

Table 3 Energy Consumption and Emission of BEBs and FCEBs

	Diesel	**Battery Electric**			**Fuel Cell Electric (Hydrogen)****		
		Plug-in charging	**Conductive charging**	**WPT/IPT* (Inductive charging)**	**Grey Hydrogen (best case)**	**Blue Hydrogen (best case)**	**Green Hydrogen**
Life cycle emission (g CO_2/km)	1350 (0.5 ltr/km)	656 (1 kWh/km)	682 (1 kWh/km)	650 (1 kWh/km)	850 (0.1kg/km)	71 (0.1kg/km)	0 (0.1kg/km)
Emission percentage relative to diesel (per km)	100.00%	48.59%	50.50%	48.15%	62.70%	5.26%	0.00%
Fuel efficiency per 100 kms	40 to 60 litres		90 to 150 kWh		9 to 10 kgs	9 to 10 kgs	9 to 10 kgs
Unit cost	$AUD1.50/ litre		$AUD0.25 /kWh		$AUD6.60 /kg	$AUD9.06 /kg	$AUD11.64 /kg
Energy/Fuel cost per 100 kms (low end) $AUD2021	$AUD60.00		$AUD22.50		$AUD59.40	$AUD81.54	$AUD104.76
Energy/Fuel cost per 100 kms (high end) $AUD2021	$AUD90.00		$AUD37.50		$AUD66.00	$AUD90.60	$AUD116.40
Cost saving relative to diesel (best case) (high end)	100.00%		75.00%		26.67%	-0.67%	-29.33%
Cost saving relative to diesel (low end) (per km)	100.00%		37.50%		1.00%	-35.90%	-74.60%

*Wireless Power Consortium (WPT) provides information on the principles, technology options, and advantages of this technology. Wireless charging adopts the Inductive Power Transfer (IPT) method that exploits basic laws in electromagnetics. That is, a wire carrying an electric current produces a magnetic field around the wire (Ampere's Law). A coil intersecting a magnetic field produces a voltage in that coil (Faraday's Law). Electromagnetic power transfer between electrical circuits across an air gap can be achieved using magnetic field coupling at resonance (Tesla).
** The Clean Energy Finance Corporation (2021, p.22), provides the following definitions: Grey Hydrogen formed through the processing of hydrocarbons, such as via SMR, where there is an unmanaged by-product of carbon dioxide; Blue Hydrogen is formed through the same processes as grey, black and brown hydrogen but where the carbon dioxide by-product is captured and secured via an appropriate Carbon Capture Utilisation and Storage (CCS) technology; Green Hydrogen is formed via electrolysis of water using renewable electricity source(s) with no process-related carbon emissions.

Ally and Pryor (2016) show that distance, operating time, stops per distance, percent idle time, average operating time per day and average speed are closely related to energy consumption. This coincides with findings by Balbontin et al. (2020). Some other factors have also been identified as closely related to the energy consumptions of BEBs. For example, route characteristics and the number of turns contribute to the energy consumed in electric buses (Beckers et al. 2020). Other factors that may impact energy consumption include tyres, air conditioning, length and weight of the vehicle and fuel systems. For example, a 15% reduction in rolling resistance of tyres is equivalent to a 3% reduction in energy consumption, and the best tyre technology can reduce rolling resistance by as much as 30% (National Academies of Sciences, Engineering, and Medicine 2020). Ritari et al. (2020) investigated the relationship of multispeed gearboxes of BEBs and energy efficiency to energy consumption and costs and found that a two-speed gearbox can save about 3% of energy while continuous variable transmission can consume 4% more in BEBs

Higher energy consumption on the road will also result in higher costs in operation to offset the benefits of BEBs in using electricity compared to diesel. Mohamed et al. (2018) point out that cost is one of the top reasons that hinder Canadian bus service providers from adopting BEBs. Besides capital costs for purchasing BEBs and operating costs for human resources and infrastructure, fuel savings and electricity rates are the primary cost consideration. Lajunen (2018) simulated different operational conditions and scenarios of BEBs for factors influencing energy efficiency, consumption and costs such as bus configuration, charging method and operating routes. They concluded that the battery's energy capacity is crucial, while battery size has an insignificant impact on energy consumption and costs. The results also show that depot charges are more cost-effective than fast opportunity charging in terms of life cycle costs.

On FCEBs, Lee et al. (2019) suggest that the energy consumption of hydrogen buses is related to multilayer factors, and results can vary significantly, with examples of these factors related to each other such as geographic factors and regional electric grids. The US government considered energy efficiency for FCEBs very important, so a benchmark was established to achieve 8 miles per gallon diesel equivalent (MPDGE). The fuel economy is also largely influenced by the temperature at which the bus fleet operates. Average MPDGE data for BEBs indicate a considerable loss in efficiency when temperatures drop from 18°C (18.8 MPDGE) to 0°C (14.8 MPDGE). The FCEB data indicate a loss from 6.0 to 4.7 MPDGE for the same temperature drop. Both show a reduction of approximately 21% in the energy economy. The loss in efficiency for BEBs leads to a smaller increase in fuel consumption than it would for FCEBs (Henning et al. 2019).

This overview of the alternative evolving technologies provides the latest evidence on the two main technologies of interest in transitioning to ZEBs. This gives us the necessary inputs required to calculate the emissions and various costs associated with each technology, which will be used in constructing a decision support system (implemented in the Australian context but having relevant in many geographical jurisdictions) to obtain predictions of the relevant costs in transitioning from diesel to clean energy buses.

Moving to ZEBs in Australia

In Australia, all state governments have committed to commence the process of introducing ZEBs. Their actions include trials of ZEBs with an increasing number beginning or active in several states. For example, the timetable for achieving 100% ZEBs has been announced in NSW by the Minister for Transport, with the goal to convert the entire NSW bus fleet of over 8,000 buses to BEBs by 2030 (Cotter 2021, Transport for NSW (TfNSW) 2021). In February 2021, the first 10 BEBs began operating in NSW, and 50 more BEBs were rolled out during 2021.

Both BEBs and FCEBs have been tested in Australia (Li 2016); however, the general trend is to shift to BEBs due to the relative maturity of the technology and current lower costs. According to a most recent strategic report by Transport for NSW (TfNSW), BEBs may eventually account for 80 to 90 percent of ZEBs in metropolitan locations, while FCEBs may become the preferred choice for rural and regional areas (TfNSW 2021). State transport authorities are cautious in estimating the cost involved, with ongoing research to establish the feasibility of the switch plan to 100% ZEBs. For example, in Western Australia, the transit authority has tested buses using alternative energy sources, including diesel-electric hybrid and hydrogen. The results show the cost of running a diesel-electric hybrid was 10% higher than running on diesel and much higher if running on hydrogen when hydrogen was at $AUD 22/kg in 2016 (Ally & Pryor 2016). A lot of development has occurred since then, and the farmgate/production cost of hydrogen has dropped significantly to below $AUD10/kg even for green hydrogen produced from renewable sources (CEFC 2021). A report for the Victorian Department of Transport (Rare Consulting 2010) suggests that in achieving the stated targets for emission reduction, four evaluation criteria must be considered, including fleet suitability, fuel and emission benefits, cost implications, and the timeframe of assessment of the merits of alternative fuels (e.g., electric and hydrogen), alternative drivetrains (e.g., fully electric and hybrid), and vehicle technologies (e.g., vehicle aerodynamics and tyre technologies).

A report by the International Association of Public Transport (UITP 2021) provides a summary of the current state of ZEBs in the Australian states and territories:

- New South Wales: The government has committed to the electrification of all bus fleets by 2030, with more than 50 new BEBs on the road in 2021.
- Australian Capital Territory: The first 90 BEBs are expected to commence operating in 2021 to 2022, with the remaining delivered no later than 2024.
- Queensland: The Department of Transport and Main Roads has announced that all buses purchased by 2030 will be ZEBs. New ZEB trials are being operated in South-East Queensland in 2021.

- Victoria: The government has committed a $AUD20 million investment in the 2021 to 2022 budget for a three-year trial of ZEBs.
- South Australia: The government has announced the action plan for 2021 to 2025 to start the transition to ZEBs.
- Western Australia: The government has announced that from 2022, BEBs will start operating on certain roads.

Emission Reduction and ZEBs

The primary objective in adopting ZEBs is to reduce CO_2 emissions and achieve the net-zero (at tailpipe) emission target for the public transport sector. Although tailpipe emissions from ZEBs are zero, the life cycle emissions are not zero, with low emissions often used as the preferred representation. Three definitions relating to emissions have been noted in the "Low Emission Bus Guide" by LowCVP (2016, p11): "Well-to-Wheel' (WTW) includes all the emissions involved in the process of extraction/creation, processing and use of fuel in a vehicle to gauge the total carbon impact of that vehicle in operation. 'Well-to-Tank' (WTT) only includes all the emissions associated with fuel up to the point that it enters a vehicle's fuel tank or energy storage device. 'Tank to Wheel' (TTW) covers the emissions associated with fuel combustion in the vehicle, i.e., from the tailpipe."

The tailpipe emissions for ZEBs are equivalent to TTW. The other emissions occur in electricity generation and distribution for BEBs and production, compressing, transport and distribution for FCEBs, or WTW and WTT emissions. Figure 1 illustrates the life cycle emissions from WTT to TTW for three types of buses: diesel, BEB and FCEB. At the WTT stage, all three types of buses have emissions. At the TTW stage, only the diesel bus produces CO_2 emissions, hence the "ZEB" term.

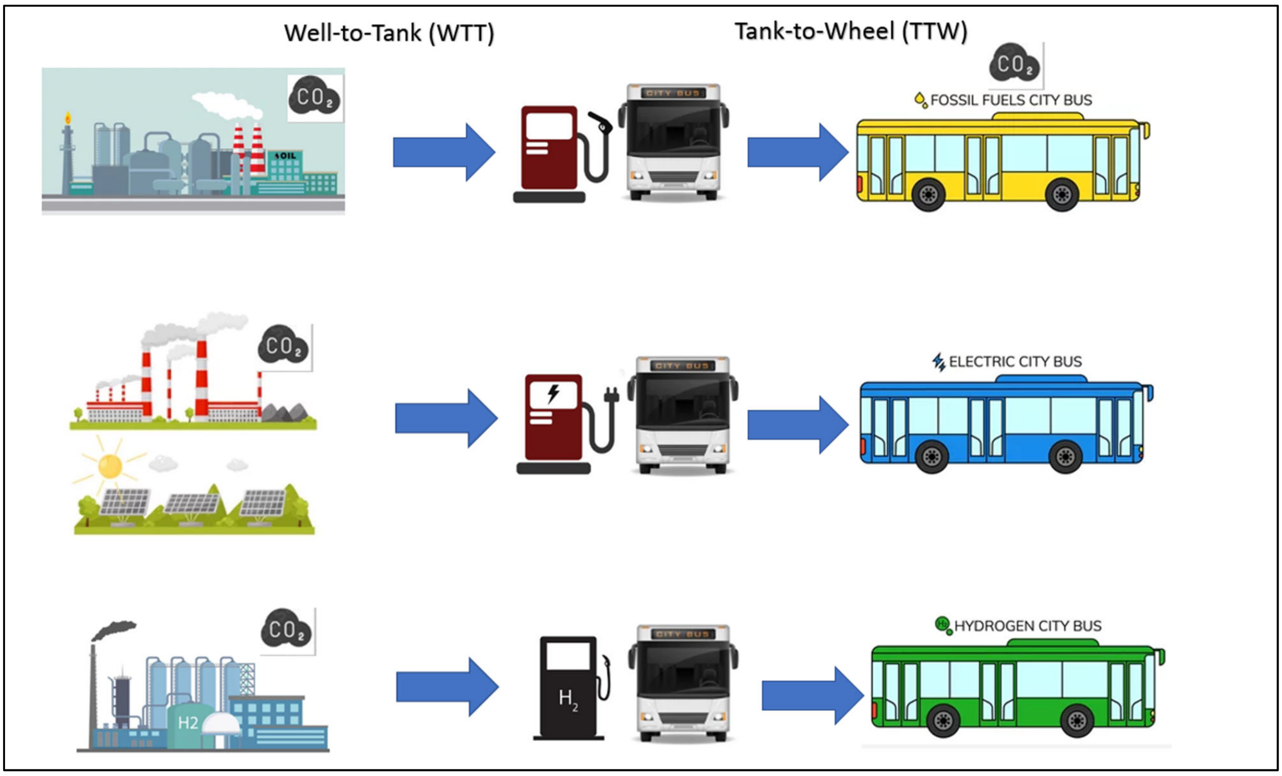


Figure 1 Conceptual illustration of emissions for diesel, BEB and FCEB.

Australia's electricity production has high fossil-fuel intensity with 62% coming from coal, 9.9% from natural gas, 27.7% from renewable energy, and 0.5% from other waste and mine gas or other liquids (Clean Energy Finance Corporation 2021). The emission factors average 1kg CO2-e/kWh for coal and 0.5 kg CO_2-e/kWh for gas, and close to zero-emissions from renewable energy. This matches the emission factors reported in the USA (National Renewable Energy Laboratory 2016). The emission intensity varies by state in Australia with Table 4 providing a summary of the configuration of energy sources used for electricity generation in each Australian state and territory.

Table 4 Renewable energy penetration by state (Source: Clean Energy Council 2021). GWH = gigawatt hours

State	Total Generation (GWH)	Fossil Fuel Generation (GWH)	Total Renewable Generation (GWH)	Renewable Proportion of Generation	Renewables as Proportion of Consumption
Tasmania	10,956	90	10,866	99.2%	100.0%
South Australia	14,285	5,763	8,523	59.7%	60.1%
Victoria	49,390	35,705	13,685	27.7%	28.4%
Western Australia	19,171	14,528	4,643	24.2%	24.2%
New South Wales	68,158	53,846	14,312	21.0%	19.1%
Queensland	65,426	54,537	10,888	16.6%	18.0%
National	227,386	164,469	62,917	27.7%	27.7%

A diesel bus will generate 1.35 kg/km of CO_2 emissions. An electric bus requires 1 to 1.4 kWh of electricity from the grid to run 1km. Let us make it simple: assuming 1km requires 1kWh, the actual level of CO_2 emissions from an electric bus running 1km is about 1kg CO_2 if charged from a coal-powered station, and 0.5kg CO_2 from a gas-powered station. Hence, the actual life cycle emission reduction can be as low as 26% if electricity is produced from coal and 63% if electricity is produced from gas, compared to diesel. In addition, if hydrogen is produced with carbon capture and storage (CCS), the emission rate is 0.28 kg/kWh, plus some additional emissions for compressing and transport; hence, the emission reduction will be more than coal or gas generated electricity charged electric buses, calculated as a 75% reduction in the life cycle emissions relative to diesel. If electricity or hydrogen are produced from renewables (e.g., solar, wind) and then used to power BEBs, the life cycle CO_2 emissions will be close to zero or very low. For example, in the above case, if BEBs are adopted in Tasmania, where electricity has a very low carbon density ((Table 1), BEBs can truly be called ZEBs.

For FCEBs, several main hydrogen production processes include steam methane forming (SMR), electrolysis, solar, wind or biological driven processes (Energy.gov 2020; Rapier 2020). Clean Energy Finance Corporation (2021) suggest that around 95% of the world's hydrogen production comes from the reforming of natural gas or other hydrocarbons, gasified coal or gasified heavy oil residuals. The technology used is steam methane reforming. The alternative technology is auto-thermal reforming[2]. The CO_2 emission equivalent from steam methane reforming using natural gas feed is about 8.5 to 10 CO_2-e kg/kg of hydrogen, called "grey hydrogen". Applying carbon capture and storage technology to reduce carbon intensity will produce "blue hydrogen". The Council of Australian Governments Energy Council (2019) statistics are very similar to the above and shown in Table 5.

Table 5 The emission intensity of production (from COAG Energy Council 2019)

Production technology of hydrogen	Emissions (kg CO_2-e/kg hydrogen)
Electrolysis – using Australian grid electricity	40.5
Electrolysis – 100% renewables	0
Coal gasification, no carbon capture and storage (CCS)	12.7 – 16.8
Coal gasification + CCS – best case	0.71
Steam methane reforming (SMR), no CCS	8.5
SMR + CCS – best case	0.76

In the foreseeable future, the planned hydrogen production and usage are grey, blue and green hydrogen. As shown in Table 2, the best-case levels of CO_2 emissions are 8.5 kg $CO_{2\text{-e}}$/kg for grey hydrogen and

[2] Auto-thermal reforming is a process for producing syngas which is composed of hydrogen and carbon monoxide, and entails partially oxidizing a hydrocarbon feed with oxygen and steam and subsequent catalytic reforming.

0.71 to 0.76 kg $CO_{2\text{-}e}$/kg for blue hydrogen. The zero-emission hydrogen is green hydrogen only. Australia has vast resources to support hydrogen production using both CCS and renewable methods in order to avoid high emission levels (Geoscience Australia 2020). Having clean production pathways is considered critical in determining whether FCEBs can help achieve emission reduction targets from the diesel bus fleet (Liu et al. 2018).

Using a Decision Support System to Compare ZEB Transition Scenarios

The review of the literature has provided us with a context for investigating the environmental and financial costs associated with a transition to ZEBs. We have developed a Decision Support System (DSS) that includes assumptions based on the evidence from the extant literature for all of the factors that are known to influence the levels of emissions and financial outlays associated with the transition away from a diesel-based bus fleet to one with varying numbers of BEBs and FCEBs. Defining 2020 as the starting base year with a chosen number of diesel buses in a bus fleet, the DSS allows users to explore selected electrification plans to identify the financial and emissions implications over ten years from 2021 to 2030. Users can assign different numbers of BEBs and FCEBs for each year to determine the pace of the ZEB transition using the DSS screen in Figure 2.

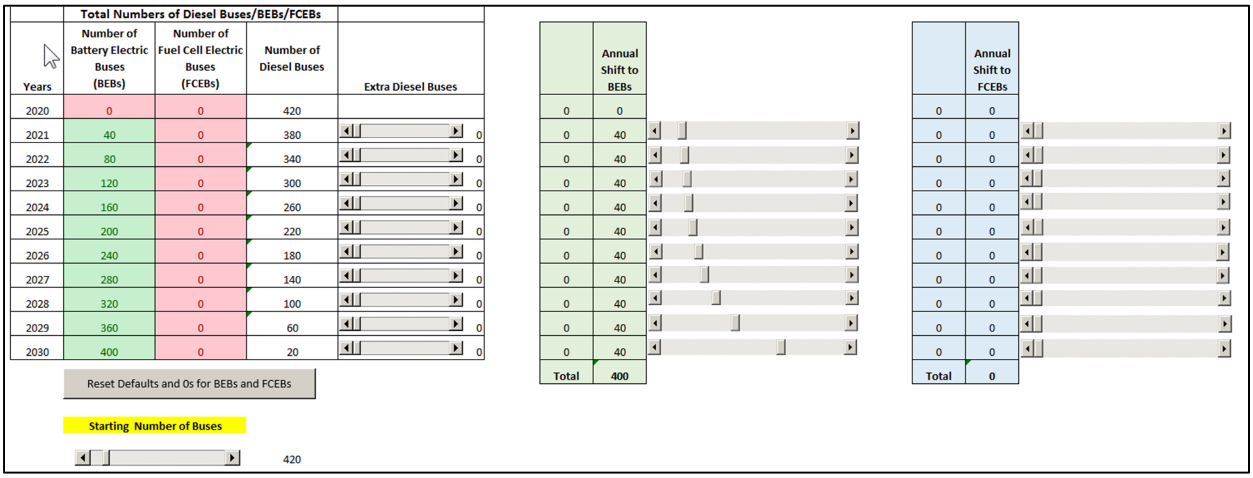


Figure 2 The DSS component for setting the annual plan for ZEB transition.

For each year, users can select the fuel consumption, a charging strategy and method, battery type, and other choices relating to BEBs and FCEBs. The DSS also allows users to change some variables in the DSS such as the price of diesel, electricity and hydrogen to reflect market prices, by using the sliders (i.e., the variables that do not have any sliders cannot be directly changed as they are a calculation of the other variables). Other charges may influence bus operators such as a distance-based charge proposed for electric cars in some states. These selections are shown in Figure 3 with the full set of assumptions given in the Appendix.

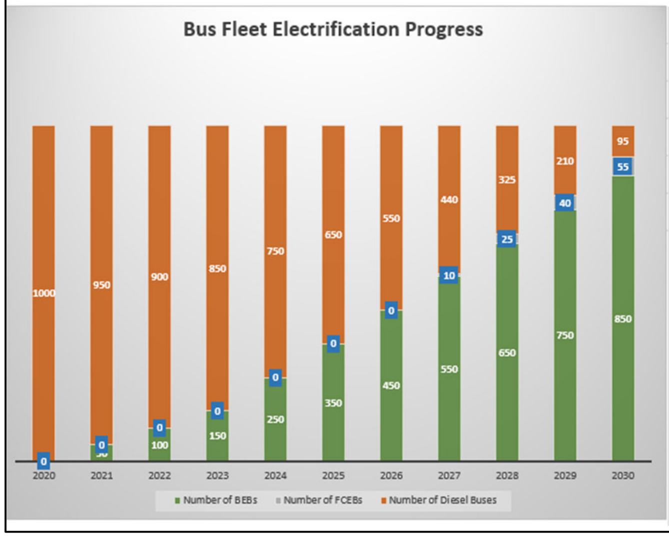
Reset to Base Defaults	BEBs	FCEBs	Diesel
Number of Buses	550	10	440
Annual Kms Per Bus	66,400	66,400	66,400
Annual average occupancy rate per bus (%)	50%	50%	50%
Fuel Consumption (100 kms)			
Diesel (litre/100kms)			42
BEB (kWh/100kms)	97		
FCEB (kg/100kms)		10	
Annual Consumption (diesel in litre)			12,270,720
Annual Consumption (kWh of electricity)	24,797,080		
Annual Consumption (kg in hydrogen)		46,480	
Charging (BEB only)			
Depot charging %	100%		
Opportunity charging (Fast) %	0%		
Braking charge energy saved			
Braking charging save energy up to %	30%	30%	
Charging Time (BEB only)			
Off-peak hour charging (e.g., 11pm to 4am)	50%		
Battery Type and Price (BEB only)			
LFP Battery (e.g., in BYD, Yutong BEBs) %	88%		
NMC (e.g., in Proterra BEBs) %	12%		
LFP Battery Size (kWh per bus)	345		
NMC Battery Size (kWh per bus)	425		
Price per kWh for LFP battery	$200		
Price of NMC battery over LFP battery (higher in %)	40%		
Electricity mix (BEB only)			
% renewables & others	17%		
% of Coal	60%		
% of CNG	23%		
Hydrogen Type			
Grey Hydrogen %		40%	
Blue Hydrogen %		30%	
Green Hydrogen %		30%	
Cost for fuel/energy			
$/litre (diesel)			$1.33
$/kWh (electricity)	$0.124		
$/kg (hydrogen base price)		$8.85	
Price for New Diesel and Hydrogen Bus		$1,000,000	$450,000
Distance-Based Charge (cents/km)	0	0	0
Total Emissions (CO_2 in tonne)	16,843	168	33,131
Total Energy/Fuel Costs	$3,062,439	$411,348	$16,320,058
Total Battery Costs for BEB	$41,250,000		
Total Capital Costs to Purchase New Buses	$330,000,000	$10,000,000	-$2,800,000
The numbers of diesel and ZEBs changes for 2021	550	10	-560
Resale Value of Diesel Bus (per bus)			$5,000
BEB Bus Value / BEB Battery Pack Value (Times)	8		
Distance-Based Charge ($)	$0	$0	$0
Maintenance Costs Per Bus	$36,000	$46,000	$50,000
Average depot infrastructure cost per ZEB	$100,000		

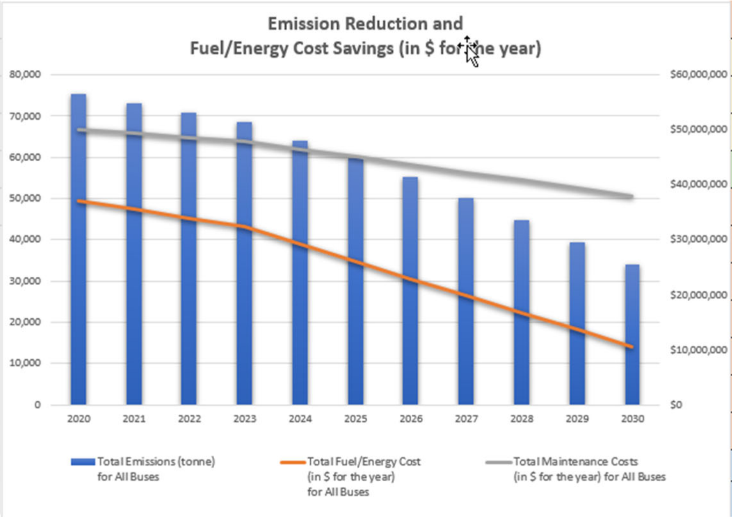
Total Emissions (CO_2 in tonne of Three Types)	50,142
Total Energy/Fuel Costs of Three Types	$19,793,845
Total Capital Investment for 2021	$392,200,000
Total Distance Based Charge	$0
Total Maintenance Costs	$42,260,000
Total Depot Infrastructure Costs	$55,000,000

Figure 3 The DSS component for setting annual bus fleet variables.

The summary worksheet provides the overall yearly and accumulated total CO_2 emission reduction, fuel/energy cost-saving, capital investment and maintenance costs associated with a ZEB procurement plan, as shown in Figure 4. Infrastructure refits in the depot are included in the capital cost. In using the DSS, users can either apply the default levels set up based on previous research and market level or specify levels of variables based on the actual figures of their bus fleets.

	Number of Diesel Buses	Number of BEBs	Number of FCEBs	Annual Increased New ZEBs	Total Emissions (tonne) for All Buses	Total Fuel/Energy Cost (in $ for the year) for All Buses	Capital Investment ZEBs (in $ for the year)	Distance-Based Charge (in $ for the year)	Total Maintenance Costs (in $ for the year) for All Buses	Total Fuel/Energy Cost (in PV$2021)	Capital Investment ZEBs (in PV$2021)	Distance-Based Charge (in PV$2021)	Maintenance Costs (in PV$2021)	Emission Reduction Over Base %	Fuel Cost Saving Over Base % (in $ for the year)	Maintenance Cost Saving Over Base % (in $ for the year)
2020	1000	0	0	0	75,298	$37,091,040	--	--	$50,000,000	$37,832,861	--	--	$51,000,000	--	--	--
2021	950	50	0	50	73,064	$35,514,892	$34,750,000	$0	$49,300,000	$35,514,892	$34,750,000	$0	$49,300,000	2.97%	4.25%	1.40%
2022	900	100	0	50	70,830	$33,938,743	$34,750,000	$0	$48,600,000	$33,273,278	$34,068,627	$0	$47,647,059	5.93%	8.50%	2.80%
2023	850	150	0	50	68,597	$32,362,595	$34,750,000	$0	$47,900,000	$31,105,916	$33,400,615	$0	$46,039,985	8.90%	12.75%	4.20%
2024	750	250	0	100	64,129	$29,210,298	$69,500,000	$0	$46,500,000	$27,525,516	$65,491,402	$0	$43,817,989	14.83%	21.25%	7.00%
2025	650	350	0	100	59,662	$26,058,001	$69,500,000	$0	$45,100,000	$24,073,565	$64,207,257	$0	$41,665,429	20.77%	29.75%	9.80%
2026	550	450	0	100	55,195	$22,905,704	$69,500,000	$0	$43,700,000	$20,746,402	$62,948,291	$0	$39,580,436	26.70%	38.24%	12.60%
2027	440	550	10	110	50,142	$19,793,845	$79,450,000	$0	$42,260,000	$17,576,368	$70,549,326	$0	$37,525,671	33.41%	46.63%	15.48%
2028	325	650	25	115	44,797	$16,702,205	$84,425,000	$0	$40,800,000	$14,540,274	$73,497,043	$0	$35,518,855	40.51%	54.97%	18.40%
2029	210	750	40	115	39,452	$13,610,564	$84,425,000	$0	$39,340,000	$11,616,485	$72,055,925	$0	$33,576,311	47.61%	63.30%	21.32%
2030	95	850	55	115	34,107	$10,518,924	$84,425,000	$0	$37,880,000	$8,801,765	$70,643,063	$0	$31,696,289	54.70%	71.64%	24.24%





Summary	
Average Annual Emission Reduction %	25.63%
Average Annual Fuel/Energy Cost Saving %	35.13%
Average Annual Maintenance Cost Saving %	12.87%
Total Emission Reduction (in tonne)	193,001
Total Fuel/Energy Cost Saving from 2020 to 2030 ($ for the year)	$130,294,630
Total Capital Investmentfor Purchasing ZEBs ($ for the year)	$645,475,000
Total Fuel/Energy Cost Saving from 2021 to 2030 (PV$2021)	$115,062,428
Total Capital Investmentfor Purchasing ZEBs (PV$2021)	$581,611,551
Total Distance-Based Charge (PV$2021)	$0
Total Maintenance Costs Saving from 2021 to 2030 ($ for the year)	$58,620,000
Total Maintenance Costs Saving from 2021 to 2030 (PV$2021)	$51,743,812
Total Costs Savings Including Fuel and Maintenance 2021 to 2030 ($ for the year)	$188,914,630
Total Costs Savings Including Fuel and Maintenance 2021 to 2030 (PV$2021)	$166,806,239

Figure 4 The DSS summary of emissions and cost outlays for 2020 to 2030.

We have established some default starting values based on understanding BEBs and FCEBs in operation, such as charging strategies and methods, battery types, hydrogen types and costs, and other aspects.

Cost Factors in the DSS

With the continuing development of battery technology, the kWh cost of the battery is also changing. The average cost has decreased from US$400/kWh in 2010 to US$200/kWh in 2018. The price is expected to continue to fall to US$100/kWh in 2025 (Borén 2020). The price for a Lithium-ion battery has been forecast to fall by over 50% from 2018 to 2030 (Sustainable Bus 2018). The price for a 250kWh battery pack may cost as little as US$38,000, compared to its cost in 2016 at US$150,000.

In Australia, using average fuel consumption for a 12-metre bus to run of 100 kms, the average fuel cost of a diesel bus is between $AUD63 (42 litres) and $AUD68 (45 litres) at $AUD1.50/litre for 42 to 45 litres. For BEB, electricity usage rates vary from state to state and even within different parts of the same state. The average price of electricity per kWh in New South Wales as of May 2021 is 34.24 cents per kWh. The average cost for BEBs is $AUD29 (97 kWh) to $AUD45 (150 kWh) for 97 to 150 kWh of electricity and $AUD0.3025 per kWh. The cost of running a BEB is about 43% to 67% of the cost of running a comparable diesel bus. Recent BEB trials in Australia have shown that the daily cost savings per BEB can be as much as $AUD70 per bus compared to a diesel bus, and hence the annual cost saving per bus can be as much as $AUD20,000, depending on the days the bus fleet operates.

In addition, the maintenance cost is much lower, typically as much as 50% to 60% of the diesel bus per km. The maintenance cost for BEBs still under warranty can be as low as 20% of a currently operating diesel bus (National Renewable Energy Laboratory 2020). For FCEBs, the price is not so clear because hydrogen production technology and costs keep evolving. Using the Clean Energy Finance Corporation's (CEFC) estimation, if a hydrogen bus uses 10 kilograms of hydrogen to run 100 km, the parity price for hydrogen should be about $AUD6.75/kg to match diesel (45 litres/100kms at $AUD1.50/litre) and about $AUD3.30/kg to compare with an electric bus (97 kWh/100kms at $AUD0.34/kWh). Green hydrogen can be produced for between $AUD6 and $AUD9 per kilogram. To achieve the $AUD2/kg target, electrolyser costs will need to fall from $AUD2 and $AUD3 million per megawatt to $AUD500,000 per megawatt, and the cost of electricity from solar and wind will need to halve from today's levels[3]. Key hydrogen production cost metrics can also be found in the CEFC report (Clean Energy Finance Corporation 2021). In 2020, the green hydrogen retail cost is about $3.88/kg. Blue and grey hydrogen cost even less to produce at $AUD3.02/kg and $AUD2.20/kg. Considering the environmental impact, the green and blue hydrogen costs need to reduce to $AUD2/kg, which may be achievable if technology advances.

In South Australia and Victoria, a 2.5 cents per kilometre distance-based charge is proposed to be implemented on electric cars to offset the loss of fuel excise tax. The same policy will apply in New South Wales once electric vehicles account for 30% or more new car sales. There has not been any debate on whether the same will be applied to ZEBs. This option is provided for users to choose.

For the procurement price of a BEB, a slider is provided to allow users to choose a BEB price as a multiplier of the battery cost since the battery is considered a key part of the BEB price and is a fixed proportion in general. For an FCEB, the price is set to at $AUD1 million as a starting value. In reality, the FCEB often cost a lot higher, but the price will decline over the next decade once the FCEB production cost comes down.

---

[3] From https://arena.gov.au/blog/australias-pathway-to-2-per-kg-hydrogen

The cost of infrastructure has been introduced over a range based on the advice we have from a number of operators. This cost is based on the number of buses housed at a depot, and it is assumed that all charging will occur at the depot (the preferred model in Australia), be it battery re-charge or hydrogen refuelling and that the depot is large enough to accommodate the changes required. Specifically the capital cost per bus for depot restructuring, using data from Transit Systems, varies depending on whether the refit relates to electric or hydrogen fuels. In Australia, any medium to large-scale transformation of a diesel bus depot into an electric bus depot with equipment such as chargers, solar generation and the electric grid is in the early planning and testing stage. The only large plan released in the media in October 2021 is the plan for a $AUD 40 million outlay to purchase 40 BEBs and install five 120 kW chargers, thirty-one 80 kW chargers, and one 388 kW on rooftop solar PV. This depot transform at the Leichhardt bus depot in Sydney will be managed by Transgrid and the UK energy company Zenobē[4] Early infrastructure costs at the same depot in 2019 by Transit Systems were over AUD$2.3 million for four BEBs[5]. With the new 40 BEBs, the average depot infrastructure cost per bus is predicted to be as high as $AUD200,000, given the depth of the concrete slabs that will have to be resolved. Jefferies and Göhlick (2020) provide TCO parameters for a standard electric bus in Europe. The installation cost for a charging station is as high as 100,000 € per slot for a normal charger and 200,000 € for a fast charger. However, recent tenders for BEB infrastructure for depots, obtained from industry sources in Australia, are showing lower costs such as AUD$60,000 for a charging station. The infrastructure cost should become clearer with more trials in Australia. Land use and storage is an important issue. Operators we have discussed this with, are confident that they can accommodate the changes within the existing depots, but if not then we would have to recognise relocation costs including purchase of another location and the sale of the exiting location (or keeping both sites). We are not able to offer any advice of this matter at this stage as we watch plans evolve.

On FCEB refuelling stations for depots in Australia, we cannot find related research or actual industry figures given that FCEBs are in a very early stage of development in Australia. Industry sources have indicated[6] that hydrogen refuelling will most likely be handled by independent hydrogen distributors. They will invest in building refuelling facilities that are not within a bus depot. These refuelling stations may even have the capacity to produce green hydrogen on the spot to top up hydrogen supply. We expect that the FCEB refuelling process would be similar to the existing diesel bus fleet refuelling process. Hydrogen distributors will recover their investment in any infrastructure investment through the hydrogen retail price. Industry experts have suggested that a hydrogen bus will consume around 25 kg of hydrogen per day and be priced appropriately. Each of the refuelling stations may cost over $AUD3 million to build in order to provide a daily hydrogen volume to support 25 to 30 hydrogen buses. In this paper, we do not consider the costs associated with building these refuelling facilities as a part of the costs to bus operators, with distributors recovering their investment from charging higher hydrogen prices to bus operators. If this circumstance changes, we can adjust the decision support system (see below) to account for this cost).

ZEB Transition Scenarios

We have applied the DSS to generate outcomes for different scenarios, providing valuable insights for a typical bus operator. We chose a bus fleet with 400 diesel buses in 2020 to start with and want to identify the emission reduction, fuel and maintenance cost savings, and capital required for bus fleet electrification. For each scenario group, we compare the emission reduction, fuel and energy cost saving, capital investment cost and the total cost saving including both energy and maintenance costs.

Three simulated scenarios are analysed:

---

[4] From http://www.lumea.com.au/news/transgrid-and-zenobe-drive-next-generation-electric-bus-depot-in-australia

[5] From https://www.parliament.nsw.gov.au/ladocs/submissions/66975/Submission%20-%2011.pdf

[6] Personal communications in confidence.

1. First, we tested a scenario where all ZEBs are 100% BEBs; with 40 BEBs replacing diesel buses per annum from 2021 to 2030, to reach 100% ZEBs by 2030. This scenario group has a direct implication for NSW bus operators. The current ZEB target in NSW is to achieve 100% of BEBs by 2030. We tested the different electricity prices per kWh, at the current level of $AUD0.34 per kWh and a highly discounted level at $AUD0.124 per kWh, given that some bus operators would use depot off-peaking charging for BEBs or can reach an agreement with electricity providers for a much less price (i.e., we understand some bus operators are operating with discounted price agreements).
2. Second, we tested the scenario that all ZEBs are FCEBs, with 40 FCEBs purchased per annum from 2021 to 2030, which will reach 100% ZEBs by 2030. This scenario group is not likely to happen because FCEBs are under development and not a mainstream ZEB. Nonetheless, it is helpful to provide a comparison. Under this scenario group, we tested the hydrogen prices at $AUD6.98/kg with 90% as grey hydrogen and nearly $AUD11.26/kg with 90% as green hydrogen at the current price levels. Lastly, we test the widely suggested ideal price of $AUD2.00/kg with 90% green hydrogen for the future.
3. Third, we tested a mixed ZEB scenario group with 50% BEBs and 50% FCEBs in the 400 ZEBs fleet, incrementing equally over ten years. For this scenario group, we set the current BEB electricity price at $AUD0.34 per kWh and $AUD6.98/kg with 90% of grey hydrogen, and the best scenario with BEB electricity price at $AUD0.124 per kWh and $AUD2.00/kg with 90% of green hydrogen.

Scenario Results and Discussion

Scenario Group One – Converting Diesel Bus Fleet to BEB Bus Fleet

In Scenarios 1a and 1b, we replaced a bus fleet with 400 diesel buses in 2020 with 400 BEBs by 2030, with 40 BEBs replaced each year from 2021 to 2030. This scenario group has a direct implication for NSW bus operators with BEBs set as the target ZEB. We compared the outcomes when the electricity price is $AUD0.34/kWh as standard, with a much cheaper electricity price of $AUD0.124/kWh with both off-peak and discount included. Other aspects of BEBs and diesel buses have been set at the default levels such as 100% depot charging with 30% recharging through the bus braking system, and the current levels of the electricity generation mix, with 17% from renewable sources, 60% from coal and 23% from compressed natural gas. As shown in Table 6, Scenario 1b (with the lower electricity price) will result in 14.6% more cost savings in fuel and energy costs, with an extra $AUD10.6 million total cost-saving than Scenario 1a.

Table 6 Emission reduction and cost savings for two BEB scenarios

	Scenario 1a Electricity Price at $AUD0.34/kWh	**Scenario 1b Electricity Price at $AUD0.124/kWh**
Average Annual Emission Reduction %	32.63%	32.63%
Average Annual Fuel/Energy Cost Saving %	32.14%	46.74%
Average Annual Maintenance Cost Saving %	16.80%	16.80%
Total Emission Reduction (in tonne)	98,281	98,281
Total Fuel/Energy Cost Saving from 2020 to 2030 ($AUD for the year)	$AUD47,677,883	$AUD69,350,530
Total Capital Investment for Purchasing ZEBs and Changing Depot ($AUD for the year)	$AUD278,000,000	$AUD278,000,000
Total Maintenance Costs Saving from 2021 to 2030 ($AUD for the year)	$AUD30,800,000	$AUD30,800,000
Total Costs Savings including Fuel and Maintenance 2021 to 2030 ($AUD for the year)	$AUD78,477,883	$AUD89,036,442

The outcomes also reveal the significant benefits of replacing a diesel bus fleet with a BEB fleet. The total CO_2 emission reduction is 98,281 tonnes or a 32.6% reduction. Further improving electricity production from renewable sources will reduce the overall emission, but it may result in a higher electricity price. For capital investment, the default purchase price for a BEB, mainly using the LFP battery, is set at close to $AUD590,000. In reality, the price may be lower or higher. With the global trend of lower battery prices, the BEB price should further decline. The default maintenance costs for

BEB and diesel buses in the DSS are $AUD36,000 and $AUD50,000 per bus per annum, respectively, based on a report prepared for Transport for NSW, including parts and labour costs (Whitehead 2019). The actual maintenance costs for BEBs, especially in the first few years under warranty, can be much lower, further increasing the total cost saving.

In summary, the transition to the BEB bus fleet will generate a significant cost saving for bus operators and an effective emission reduction for the environment above 30% based on the current electricity production mix.

Scenario Group Two – Converting Diesel Bus Fleet to FCEB Bus Fleet

For comparison, we tested three scenarios (2a, 2b and 2c) if the diesel bus fleet is replaced with an entire FCEB fleet; with 40 FCEBs replaced each year from 2021 to 2030. The default scenario (2a) has 90% grey hydrogen and 5% blue and green hydrogen. The hydrogen price is set at $AUD6.98/kg based on the current production plus estimated transportation and distribution prices for the three types of hydrogen. Emissions during production are much higher than if blue or green hydrogen has a higher level in the mix. We then compared two scenarios with 90% of hydrogen as renewable sourced green hydrogen. One scenario (2b) at the current estimated retail price at $AUD11.26/kg, and the other scenario (2c) with the widely suggested $AUD2/kg price to make hydrogen competitive. Both scenarios are unlikely to happen soon because both FCEB and green hydrogen production are evolving technologies. Nevertheless, it is helpful to test these as alternatives to the current dominant strategy of shifting to BEBs.

As shown in Table 7, with 90% of grey hydrogen, we can only expect an emission reduction of 28.9%. In contrast, a 90% green hydrogen supply will ensure a 53.4% emission reduction, much higher than the 32.6% for BEBs that is charged by electricity generated with the current energy mix. At the $AUD2/kg for hydrogen, the cost-saving for an FCEB fleet on fuel/energy is higher than a BEB fleet at the current electricity price of $AUD0.34/kWh, with $AUD61.1 million for the FCEB fleet and $AUD47.6 million for the BEB fleet. However, with the default maintenance cost included ($AUD46,000 per FCEB per annum), the best scenario for FCEBs (Scenario 2c) will still be $AUD19 million short on total cost saving compared to the best scenario for BEBs (Scenario 1b). A green hydrogen-powered FCEB fleet will need to improve on the cost-saving regardless of the high emission reduction level. It is doubtful whether $AUD2/kg for hydrogen price is adequate for FCEBs to be competitive if the electricity price is low for BEBs, notwithstanding that FCEBs have a much higher procurement cost. Green hydrogen at existing prices will not be competitive and will result in no cost savings but extra costs of $AUD 24 million including both fuel and maintenance costs (Scenario 2b). The grey hydrogen scenario (Scenario 2a) has less cost saving and less emission reduction compared to BEB scenarios.

Table 7 Emission reduction and cost savings for three FCEB scenarios

	Scenario 2a Grey hydrogen 90% & $AUD6.98/kg	**Scenario 2b Green hydrogen 90% & $AUD11.26/kg**	**Scenario 2c Green hydrogen 90% & $AUD2.00/kg**
Average Annual Emission Reduction %	28.91%	53.44%	53.44%
Average Annual Fuel/Energy Cost Saving %	6.93%	-22.60%	41.19%
Average Annual Maintenance Cost Saving %	4.80%	4.80%	4.80%
Total Emission Reduction (in tonne)	87,071	160,951	160,951
Total Fuel/Energy Cost Saving from 2020 to 2030 ($AUD for the year)	$AUD10,276,728	-$AUD33,529,742	$AUD61,107,143
Total Capital Investment for Purchasing ZEBs and Changing Depot ($AUD for the year)	$AUD398,000,000	$AUD398,000,000	$AUD398,000,000
Total Maintenance Costs Saving from 2021 to 2030 ($AUD for the year)	$AUD8,800,000	$AUD8,800,000	$AUD8,800,000
Total Costs Savings including Fuel and Maintenance 2021 to 2030 ($AUD for the year)	$AUD19,076,728	-$AUD24,729,742	$AUD69,907,143

Scenario Group Three – Converting Diesel Bus Fleet to BEB/FCEB Bus Fleet

We tested a mixture of 50% for each of BEB and FCEB, with 20 new buses for each type purchased from 2021 to 2030. First, we assume all current conditions for BEBs and FCEBs, including setting the electricity price at $AUD0.34 per kWh and $AUD6.98/kg with 90% of grey hydrogen (Scenario 3a). Next, we set the best conditions for both fuel types, with the electricity price at $AUD0.124 per kWh for BEBs and $AUD2.00/kg with 90% green hydrogen for FCEBs (Scenario 3b). These two scenarios can address the current and best cases for a mixed ZEB fleet. The results are shown in Table 8.

Table 8 Emission reduction and cost savings for mixed ZEB scenarios

	Scenario 3a BEB and FCEB current status	**Scenario 3b BEB and FCEB best scenario**
Average Annual Emission Reduction %	30.77%	43.03%
Average Annual Fuel/Energy Cost Saving %	19.53%	43.97%
Average Annual Maintenance Cost Saving %	10.80%	10.80%
Total Emission Reduction (in tonne)	92,676	129,616
Total Fuel/Energy Cost Saving from 2020 to 2030 ($AUD for the year)	$AUD28,977,305	$AUD65,258,837
Total Capital Investment for Purchasing ZEBs and Changing Depot ($AUD for the year)	$AUD338,000,000	$AUD338,000,000
Total Maintenance Costs Saving from 2021 to 2030 ($AUD for the year)	$AUD19,800,000	$AUD19,800,000
Total Costs Savings including Fuel and Maintenance 2021 to 2030 ($AUD for the year)	$AUD48,777,305	$AUD85,028,837

The current case of a mixed ZEB fleet (3a) will deliver higher emission reductions and cost-savings compared to the current scenario of the FCEB fleet (2a) but still perform worse than the present case of a BEB fleet (1a). On the other hand, the best scenario of a mixed ZEB fleet (3b) can perform better on emission reductions than the BEB fleet (1b), although it cannot match the green hydrogen-powered FCEB fleet (2c). The cost-saving of the best scenario for a mixed ZEB fleet (3b) can outperform the FCEB scenario (2c) by nearly $AUD20 million but is short of $AUD4 million compared to the BEB fleet (1b), including fuel and maintenance costs.

Summary

As shown in Table 9, with three current scenarios, 1a, 2a and 3a, the 100% BEB transition (1a) is the best ZEB transition strategy overall. It ensures a high level of emission reduction at 32.63% and a total cost saving of approximately $AUD78.5 million from 2021 to 2030 for a bus fleet of 400 buses. If the hydrogen mix does not improve and we retain a high proportion of grey hydrogen, the FCEB option (2a) does not have any extra benefits over the BEB option. A mixed ZEB scenario (3a) can generate a similar level of emission reductions, but it has higher overall costs, including procurement and maintenance costs than the current BEB scenario.

Table 9 The comparison of three current status scenarios for BEB, FCEB and BEB/FCEB.

	Scenario 1a Electricity Price at $AUD0.34/kWh	**Scenario 2a Grey hydrogen 90% & $AUD6.98/kg**	**Scenario 3a BEB and FCEB current status**
Average Annual Emission Reduction %	32.63%	28.91%	30.77%
Average Annual Fuel/Energy Cost Saving %	32.14%	6.93%	19.53%
Average Annual Maintenance Cost Saving %	16.80%	4.80%	10.80%
Total Emission Reduction (in tonne)	98,281	87,071	92,676
Total Fuel/Energy Cost Saving from 2020 to 2030 ($AUD for the year)	$AUD47,677,883	$AUD10,276,728	$AUD28,977,305
Total Capital Investment for Purchasing ZEBs and Changing Depot ($AUD for the year)	$AUD278,000,000	$AUD398,000,000	$AUD338,000,000
Total Maintenance Costs Saving from 2021 to 2030 ($AUD for the year)	$AUD30,800,000	$AUD8,800,000	$AUD19,800,000
Total Costs Savings including Fuel and Maintenance 2021 to 2030 ($AUD for the year)	$AUD78,477,883	$AUD19,076,728	$AUD48,777,305

Table 10 shows the three best scenarios for BEB, FCEB and mixed ZEB scenarios (Scenarios 1b, 2c and 3b). The complete BEB scenario (1b) still produces the highest cost savings, but it has the lowest level of emission reduction, at 32.63%. However, if electricity generation sources can be improved (outside what bus operators can control), the BEB fleet may achieve a higher emission reduction.

Table 10 The comparison of the three best scenarios for BEB, FCEB and BEB/FCEB.

	Scenario 1b Electricity Price at $AUD0.124/kWh	**Scenario 2c Green hydrogen 90% & $AUD2.00/kg**	**Scenario 3b BEB and FCEB best scenario**
Average Annual Emission Reduction %	32.63%	53.44%	43.03%
Average Annual Fuel/Energy Cost Saving %	46.74%	41.19%	43.97%
Average Annual Maintenance Cost Saving %	16.80%	4.80%	10.80%
Total Emission Reduction (in tonne)	98,281	160,951	129,616
Total Fuel/Energy Cost Saving from 2020 to 2030 ($AUD for the year)	$AUD69,350,530	$AUD61,107,143	$AUD65,258,837
Total Capital Investment for Purchasing ZEBs ($AUD for the year)	$AUD278,000,000	$AUD398,000,000	$AUD338,000,000
Total Maintenance Costs Saving from 2021 to 2030 ($AUD for the year)	$AUD30,800,000	$AUD8,800,000	$AUD19,800,000
Total Costs Savings Including Fuel and Maintenance 2021 to 2030 ($AUD for the year)	$AUD89,036,442	$AUD69,907,143	$AUD85,028,837

With the best case for each BEB, FCEB and mixed ZEB scenario, the FCEB and mixed ZEB scenarios have greater emission reduction levels, with about 21% and 10% more reduction than the BEB scenario. While the FCEB scenario is several million dollars less in fuel and energy cost savings and higher on maintenance costs, the mixed ZEB scenario seems a better option than the BEB scenario with a 10% extra emission reduction and a close level of cost-saving. The difference is a higher upfront investment due to the high price of FCEBs. The price for FCEBs may reduce in the future, reducing the upfront investment for the mixed ZEB scenario.

A mix of BEB and FCEB at unequal proportions may provide an optimal combination depending on electricity and green hydrogen costs. If the hydrogen mix improves to include 90% of green hydrogen with $AUD2/kg for hydrogen price, the FCEB scenario will generate the highest level of emission reduction at 53.4% and a good level of energy cost saving. As mentioned above, it is doubtful whether $AUD2/kg hydrogen is adequate to compete with a low electricity price like $AUD0.124/kWh but will undoubtedly be competitive if the cost of electricity is around $AUD0.20 to $AUD0.35 per kWh. If a high proportion of renewable energy is used in electricity generation and the electricity price can remain low for bus operators, then BEBs will maintain a competitive advantage in the ZEB transition. Importantly, revisions can be included in the DSS applications as new evidence evolves on the improvements in emissions and costs as new technology comes on stream.

Conclusions

The focus of the paper is on the environmental and financial implications of various technological and transitional timing choices for ZEBs. Recognising that the various costs and indeed emissions levels may change with changing technology and scalability of sold volumes of buses, our key findings to date, based on a number of plausible scenarios are:

1. Given the current market prices for electricity and hydrogen in Australia, BEBs offer the best prospects for emission reductions and cost savings.
2. For a scenario where electricity has a low discounted price, and hydrogen has a $AUD2/kg parity price with 90% green hydrogen, we should consider a FCEB fleet due to its high emission reduction level; however, the FCEB price and maintenance costs will still need to come down to be competitive with BEBs.

3. The electricity generation mix needs to be much greener in Australia which currently has a high carbon footprint (Tasmania as an exception), in order to obtain a higher level of emission reduction for BEBs. This is outside the control of bus operators and in the hands of electricity companies and government policy on energy, such as how much fossil fuel like coal should be used in electricity generation.

In the process of achieving a smooth transition of the bus fleet, regardless of whether it involves BEBs or FCEBS or a combination, the question of who will pay for these transitional costs remains (Bakker and Konings 2018, Hensher 2021). Many approaches have been proposed with the dominant plan being the transfer of most of the risk to the government through capital grants, or the government taking control in purchasing and paying for buses, the redesign of the depots and labour training. As a consequence of risk redistribution, in large measure linked to the great uncertainty faced by bus operators in costing their future services either through negotiation or competitive tendering, the idea that the current contracting model between government and the operator is sustainable is open for review. With an increased role for energy suppliers in particular, a paradigm shift from traditional contracting (i.e., contracts between government and operator), to contracts or management agreements between government and consortiums that account for the entire supply chain (i.e., energy, OEM, asset owners, and operators), might be more appropriate as it will give the government more certainty of service continuance in a ZEB era (Hensher 2021).

Specifically, regardless of whether the contract between the bus operator and the regulator (government) is tendered or negotiated, there might be a competitive process involved at another agent interaction level to obtain a partnership between the bus operator and crucial contributors to the ZEB task. This approach focuses on risk allocation in order to de-risk the arrangement between the bus operator and government (or reduce the risk) to, in part, minimise offloading all the risk to the government as is often discussed in the transition to ZEBs. Bus operators will probably have a positive view on this, since it gives them a direct link to these supporting services rather than having this controlled by an external process. The supporting services process is competitive, having various suppliers offering prices and service levels to the bus operator in order to participate in a specific role in their transition process. Through the bus operator, or a broker on their behalf, we can obtain the best competitive deal from a selected retail energy provider, bus manufacturer and associated businesses, battery or fuel cell supplier and any other advisory group such as service and planning advisers. We then arrive at an offer to government as a supply chain partnership, either through tendered bids or by negotiation with the incumbent who can share the competitive process with others to arrive at the offer price.

Future research will require close monitoring of the fast pace developments in battery electric and fuel cell technologies as applicable to buses, together with the changing costs associated with the full supply chain of inputs into a bus operation. What this will do is change the relative contribution of each technology roadmap to reductions in emissions under varying cost regimes. The decision-support system presented and implemented in this paper is sufficiently flexible to be able to accommodate any such change.

References

Ally, J., & Pryor, T. (2016). Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. *Energy Policy*, 94, 285-294.

Bakker, S and Konings, R. (2018) The transition to zero-emission buses in public transport – The need for institutional innovation, *Transportation Research Part D*, 64, 204-215.

Balbontin, C., Hensher, D.A., Ho., L. and Wei, E. (2020) Identifying the relationship between tyre performance, fuel consumption and maintenance costs in operating urban bus services: A case study in Sydney, Australia, using telematics and fitted sensors, Institute of Transport and Logistics Studies, The University of Sydney.

Beckers, C. J. J., Besselink, I. J. M., & Nijmeijer, H. (2020). Assessing the impact of cornering losses on the energy consumption of electric city buses. *Transportation Research Part D*, 86(102360).

Bethoux, O. (2020). Hydrogen Fuel Cell Road Vehicles: State of the Art and Perspectives. *Energies,* 13(5843), 1 to 28.

Bi, Z., Song, L., De Kleine, R., Mi, C.C., & Keoleian, G.A. (2015). Plug-in vs. wireless charging: Life cycle energy and greenhouse gas emissions for an electric bus system. *Applied Energy*, 146, 11-15.

Borén, S. (2020). Electric Buses' sustainability effects, noise, energy use and costs. *International Journal of Sustainable Transportation,* 14 (12), 956-971.

Budget Direct. (2020). Average fuel consumption in Australia 2020. Retrieved from https://www.budgetdirect.com.au/car-insurance/research/average-fuel-consumption-australia.html

Bus Industry Confederation (2021) *Moving People - Australian Bus and Coach Industry: A Snapshot,* Report prepared by the Institute of Transport and Logistics Studies, The University of Sydney, and BIC, September. Available at *https://movingpeople.com.au/industry-stats/*

Chang, C.-C., Liao, Y.-T., & Chang, Y.-W. (2019). Life cycle assessment of alternative energy types e including hydrogen e for public city buses in Taiwan. *International Journal of Hydrogen Energy*, 44, 18472-18482.

Clean Energy Finance Corporation (CEFC) (2021). Australia hydrogen market study – Sector analysis summary.

Climate Council. (2017). Transport Emissions: Driving Down Car Pollution in Cities.

Committee on Transport and Infrastructure (CTI), Legislative Assembly of New South Wales (2020). Electric buses in regional and metropolitan public transport network in NSW.

Council of Australian Governments Energy Council. (2019). Australia's National Hydrogen Strategy. Council of Australian Governments (COAG), Canberra.

Cotter, F. (2021). NSW Bus Operator Interline Starts 10 E-Bus Roll-Out. , February. Retrieved from https://www.busnews.com.au/industry-news/2102/nsw-bus-operator-interline-starts-10-e-bus-roll-out.

Deliali, A., Chhan, D., Oliver, J., Sayess, R., Pollitt, K. J. G., & Christofa, E. (2021). Transitioning to zero-emission bus fleets: state of practice of implementations in the United States. Transport Reviews, 41(2), 164-191.

Deloitte-Ballard. (2020) Fueling the Future of Mobility – Hydrogen and fuel cell solutions for transportation.

Department of the Environment and Energy. (2017). National Greenhouse Accounts Factors - Australian National Greenhouse Accounts, Canberra.

Ecoscore. (2020). How to calculate the CO2 emission from the fuel consumption? Retrieved from https://ecoscore.be/en/info/ecoscore/co2

Energy.Gov. (2020) Hydrogen Fuel Basics. Retrieved from https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics

Geoscience Australia. (2020). Hydrogen. Retrieved from https://www.ga.gov.au/scientific-topics/energy/resources/hydrogen

Henning, M., Thomas, A.R., & Smyth, A. (2019). An Analysis of the Association between Changes in Ambient Temperature, Fuel Economy, and Vehicle Range for Battery Electric and Fuel Cell Electric Buses. Report prepared for The Midwest Hydrogen Center of Excellence.

Retrieved from https://www.sustainable-bus.com/wp-content/uploads/2019/12/An-Analysis-of-the-Association-between-Changes-in-Ambient-Tempera.pdf.

Hensher, D.A. (2021) The compelling case for returning to or continuing with negotiated contracts under the transition to a green fleet, *Transportation Research Part A*, 154, 255-269.

Hydrogen Europe. (2020). Hydrogen Buses. Retrieved from https://hydrogeneurope.eu/hydrogen-buses

Jefferies, D. & Göhlick, D. (2020). A comprehensive TCO evaluation method for electric bus systems based on discrete-event simulation including bus scheduling and charging infrastructure optimisation. World Electric Vehicle Journal, 11(56), 1-43.

IEA (2021). Global EV outlook 2021 – prospects for electric vehicle deployment. Retrieved from https://www.iea.org/reports/global-ev-outlook-2021/prospects-for-electric-vehicle-deployment.

Lajunen, A. (2018). Lifecycle costs and charging requirements of electric buses with different charging methods. Journal of Cleaner Production, 172, 56-67.

Lee, D.-Y., Elgowainy, A., & Vijayagopal, R. (2019). Well-to-wheel environmental implications of fuel economy targets for hydrogen fuel cell electric buses in the United States. *Energy Policy*, 128, 565-583.

Li, J.-Q. (2016). Battery-electric transit bus developments and operations: A review. *International Journal of Sustainable Transportation,* 10(3), 157-169.

Li, X., Castellanos, S., & Maassen, A. (2018). Emerging trends and innovations for electric bus adoption—a comparative case study of contracting and financing of 22 cities in the Americas, Asia-Pacific, and Europe. *Research in Transportation Economics*, 69, 470-481.

Li, M., Feng, M., Luo, D., & Chen, Z. (2020). Fast Charging Li-Ion Batteries for a New Era of Electric Vehicles. *Cell Reports Physical Science*, 1, 10, 2-16.

Liu, F., Zhao, F., Liu, Z., & Hao, H. (2018). The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: The China case. *International Journal of Hydrogen Energy*, 43, 22604-22621.

Logan K. G., Nelson, J. D., & Hastings, A. (2020). Electric and hydrogen buses: Shifting from conventionally fuelled cars in the UK. *Transportation Research Part D*, 85(102350).

LowCVP (2016). The Low Emission Bus Guide.

MarketWatch (2021). China Electric Bus Market Report 2019: By Key Players, End-User, Type, Market Share, Forecast to 2025. Retrieved from https://www.marketwatch.com/press-release/china-electric-bus-market-report-2019-by-key-players-end-user-type-market-share-forecast-to-2025-2021-02-12.

Miller, I., Arbabzadeh, M. & Gencer (2020). Hourly Power Grid Variations, Electric Vehicle Charging Patterns, and Operating Emissions. *Environmental Science & Technology*, 54, 16071-16085.

Mohamed, M., Ferguson, M., & Kanaroglou, P. (2018). What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers. *Transportation Research Part D*, 64, 134-149.

National Academies of Sciences, E., and Medicine. (2020). Reducing Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report.

National Renewable Energy Laboratory (NREL) (2016). Emissions Associated with Electric Vehicle Charging: Impact of Electricity Generation Mix, Charging Infrastructure Availability, and Vehicle Type.

OzeBus. (2020). Climate Change and Public Transport. Retrieved from http://bic.asn.au/information-for-moving-people/climate-change-and-public-transport

Pagliaro, M., & Meneguzzo, F. (2019). Electric Bus: A Critical Overview on the Dawn of Its Widespread Uptake. *Advanced Sustainable Systems*, 3(1800151).

Quarles, N., Kockelman, K. M., & Mohamed, M. (2020). Costs and Benefits of Electrifying and Automating Bus Transit Fleets. *Sustainability*, 12.

Rapier, R. (Producer). (2020). Estimating the Carbon Footprint of Hydrogen Production. Retrieved from https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/?sh=3feec8b824bd

Rare Consulting. (2010). Bus technologies in Australia to 2020 and beyond - A discussion of the opportunity for new technology adoption for the Australian bus industry, Sydney.

Ritari, A., Vepsäläinen, J., Kivekäs, K., Tammi, K., & Laitinen, H. (2020). Energy Consumption and Lifecycle Cost Analysis of Electric City Buses with Multispeed Gearboxes. *Energies*, 13(2117).

Sharma, A., & Strezov, V. (2017). Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. Energy, 2017, 1132-1141.
Sustainable Bus (2018). Lithium-ion battery price will go down by 52 between 2018 and 2030, according to BNEF. Retrieved from https://www.sustainable-bus.com/news/battery-price-going-down-according-bloomberg-new-energy-finance.
Sustainable Bus (2020). Electric bus range, focus on electricity consumption. A sum-up. Retrieved from https://www.sustainable-bus.com/news/electric-bus-range-focus-on-electricity-consumption-a-sum-up/.
Sustainable Bus (2021). Zero emission buses in the USA: +24% in 2020. 2,800 delivered or ordered. Retrieved from https://www.sustainable-bus.com/news/zero-emission-buses-north-america-2020/.
Transport for NSW (2021). Zero Emission Bus Transition Strategy.
Trencher, G., & Edianto, A. (2021). Drivers and Barriers to the Adoption of Fuel Cell Passenger Vehicles and Buses in Germany. *Energies*, 14(833), 1-26.
UITP (2019). The Impact of Electric Buses on Urban Life, UITP, Paris.
UITP (2021). 2020 Zero Emissions Bus Forum – Report and Key Findings, UITP, Melbourne.
Van de Kaa, G., Scholten, D., Rezaei, J., & Milchram, C. (2017). The Battle between Battery and Fuel Cell Powered Electric Vehicles: A BWM Approach. *Energies*, 10(1707), 1-13.
Whitehead, J. (2019). Electric Buses in Regional and Metropolitan Public Transport Networks in NSW.

Appendix

In the decision support system, there are different default values and formulas for calculating emission, fuel/energy costs and capital investment.

Diesel bus

1. The average annual kms per bus (including dead running time) is set to be 66,400 kms, based on figures from a large bus fleet. Users can change this using a slider.
2. The annual average occupancy rate per bus is set to be 50%, but this can be higher (during peak hours) or lower (during off-peak hours). Users can change this using a slider.
3. The average diesel consumption is 42 litres per 100kms, at 50% occupancy. Users can change this using a slider.
4. The cost of diesel is set as $AUD1.33/litre by default but can be changed using a slider.
5. The total annual fuel consumption in litre can be calculated as: the number of buses * fuel per km*(1+ (occupancy % above 50%) *10%) (* Fully occupied bus can have 10% extra fuel consumption than empty bus)
6. The annual total emissions is 2.7 kg CO_2 per litre diesel multiplied by total annual diesel consumption, convert to tonnes.
7. The annual total energy/fuel cost is equal to the $AUD per litre of diesel multiplied by the annual fuel consumption in litres.

FCEB (fuel cell electric bus or hydrogen bus)

1. The average annual kms per bus (including dead running time) is set to be 66,400 kms, based on figures from a large bus fleet. Users can change this using a slider.
2. The annual average occupancy rate per bus is set to be 50%, but this can be higher (during peak hours) or lower (during off-peak hours). Users can change this using a slider.
3. The average hydrogen consumption for FCEB is 10kg of hydrogen per 100kms, at 50% occupancy. Users can change this using a slider. A hydrogen promotor and industry expert has suggested to us that the consumption may be as low as 6kg per 100kms. We will revisit this when we have future trial information in Australia.
4. For both BEBs and FCEBs, regenerative braking systems can recharge a battery during driving/start/stop. Depending on the condition of driving and driving behaviour, up to 40% of the battery power can be recharged. We have set 30% as the default level but this can be changed using a slider.

5. Hydrogen types have a direct impact on the well to wheel (WTW) emissions as well as the cost of hydrogen. According to the current hydrogen production scenario, we have set the default levels as 90% of grey hydrogen, 5% of blue hydrogen and 5% of green hydrogen. In general, the base hydrogen price and emissions will be influenced by these three levels. There are three sliders to choose this percentage mix.
6. The hydrogen base price is set at $AUD8.85 conditioned on the existing hydrogen profile and prices. This base price can be adjusted up and down using a slider.
7. The total annual energy consumption in kg can be calculated as: (hydrogen per km * number of FCEBs * total kms per bus) *(1+0.1*(occupancy % above 50%) *(1-proportion of recharge from regenerative braking)
8. The annual total emissions is equal to (0.85kg * proportion of grey hydrogen+0.07*proportion of blue hydrogen) * total kgs of hydrogen, convert to tonne.
9. The annual total energy cost can be calculated by dollar per kg of hydrogen multiplied by annual energy consumption in kg.

BEB (Battery driven electric bus)

1. The average annual kms per bus (including dead running time) is set to be 66,400 kms, based on figures from a large bus fleet. Users can change this using a slider.
2. The annual average occupancy rate per bus is set to be 50%, which can be higher (during peak hours) or lower (during off-peak hours). Users can change this using a slider.
3. The average electricity consumption for a BEB is 97 kWh of electricity per 100kms (based on trial data for BEBs in major Australian cities), at 50% occupancy. Users can change this using a slider.
4. There are two charging strategies: depot charging and opportunity charging. By default, we set deport charging as 100%, matching the existing trials in NSW and other states. From past research, fast opportunity charging may save energy by only 0.3%.
5. For both BEBs and FCEBs, a regenerative braking system can recharge the battery during driving/start/stop. Depending on driving and driving behaviour, up to 40% of the battery power can be recharged. We have set 30% as the default level, but this can be changed using a slider.
6. Charging time is related to both depot charging and opportunity charging. For example, overnight depot charging can be scheduled for off-peak times, contributing to both lower cost and lower emissions for power generation. By default, we have set the off-peak time at 50%.
7. There are two leading battery technologies for BEBs. For example, LFP is the main battery technology with a larger/heavier battery pack and relatively lower energy intensity for all buses produced in China. However, it is a mature and stable technology that offers flexibility and lower requirements for operations. Newer technology is the NMC battery which is the technology chosen in the US and other countries. The NMC battery is lighter and has a higher level of energy intensity. With its benefits in energy efficiency, the disadvantage is that it is more expensive and has higher requirements for operations. By default, we have set 88% for LFP and 12% for NMC. If BEBs are imported from China (e.g., Yutong), the battery technology can be set as 100% for LFP.
8. The default levels set up for the LFP and NMC battery packages are respectively 345 kWh and 425 kWh, matching our understanding of existing models made with the two types of technology.
9. The price per kWh for an LFP battery is set at $AUD200/kWh by default, and the price for an NMC is set at 40% more expensive than the LFP battery, by default.
10. In Australia, electricity from the grid has a mix of 60% from coal, 23% from CNG and 17% from renewable sources. These figures can be varied based on the electricity mix for the state or regions. Different electricity mixes have an impact on the emission levels.
11. The electricity price with the default setting (e.g., 50% off-peak, the default electricity mix) is set at $AUD0.12/kWh. Users can change this using a slider based on the actual price received.
10. The price for a BEB, including all accessories, is generally within the range of 4 to 10 times the cost of the battery, depending on whether an expensive recharge facility is included as a

part of the package. By default, the level is set at seven times the battery pack price (i.e., Price of BEB = 7 * Battery Pack Price).

11. The total annual electricity consumption in kWh can be calculated using the following formula with factors influencing energy usage all included:
    Electricity consumption per km *Annual per bus kms *Number of BEBs *(1+0.1*(occupancy % above 50%)*(1-proportion of recharge from regenerative braking)*(Opportunity Charging proportion * 0.997 + Deport charging proportion*1)/2
12. The annual total emissions is equal to (1*Coal proportion+0.5*CNG proportion + 0*Renewables proportion)*Annual consumption in kWh/1000*(1-Offpeak time charging proportion*0.1)
13. The annual total energy cost can be calculated as electricity price $AUD/kWh*Annual consumption in kWh for all BEBs
14. The total battery cost for new BEBs can be calculated as: (the number of new BEBs for the year) *(Price for LFP Battery $AUD/kWh *LFP Battery Pack Size*LFP Battery Proportion)+ (Price for NMC battery $AUD/kWh*NMC Battery Pack Size*NMC Battery Proportion)
15. The total capital cost to purchase a new BEB can be calculated as the total battery cost for all new BEBs*(BEB value / BEB Battery value). Note: the default is 7 times.
16. Depot infrastructure is set at $100,000 per BEB based on the latest information.