Australasian Transport Research Forum 2019 Proceedings
30 September – 2 October, Canberra, Australia
Publication website: http://www.atrf.info

Plugging in Brisbane’s bus network: hitting the switch on electric buses

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Abstract

Global warming is leading to wider temperature fluctuations, rising sea levels, more frequent extreme weather events, and oceans that are warming and acidifying among other environmental impacts. The largest man-made cause of this warming is greenhouse gas emissions, stemming from activities such as energy production, transportation, and agriculture. In recent times, it has become commonplace for governments worldwide to encourage citizens to make choices to abate these emissions, and the Queensland Government is no exception – devoting millions of dollars in resources to the fight against climate change. With the use of electric vehicles becoming increasingly popular as a low emissions alternative to traditional combustion engine vehicles, this paper analyses the potential environmental impacts of transitioning the Brisbane City Council’s existing bus fleet from mostly diesel powered to fully electric. In doing so, the analysis will consider the lifecycle of both diesel vehicles and electric vehicles and subsequent environmental impact, including a high-level quantification of the upstream emissions from charging an electric vehicle from Queensland’s coal-based power grid. This paper analyses the difference in lifecycle emissions, reviewing existing literature to arrive at consolidated estimates of the incremental environmental impact in each emissions-generating phase of the vehicle’s life. The results of this analysis are intended to feed into further work, such as a full cost-benefit analysis or assessment of the economic impact of electric buses.

1 Introduction

In 2015, 152 million tones of carbon-dioxide-equivalent (CO2-e) greenhouse gases were emitted in Queensland (Queensland Government Statistician's Office, 2017). For perspective, if Queensland was its own country this figure would place it in the top 20% of countries worldwide, and is roughly equivalent to the total CO2-e absorbed by 3.9 billion mature trees in a year (United States Environmental Protection Agency, 2017). A major focus of the Queensland Government has been finding ways to reduce this figure (Queensland Government Department of Environment and Heritage Protection, 2017).

A large contributor to greenhouse gas emissions is the transport industry, contributing approximately 18% of total CO2-e emissions in Australia (Australian Government - Department of the Environment and Energy, 2015). It is well documented that burning fossil fuels for use in vehicles is carbon intensive. Forecasts of direct greenhouse gas emissions for Australian road transport estimate that buses alone could account for over 1,600 gigagrams (or 1.6 million metric tonnes) of CO_2 equivalent emissions by 2020 (Department of Infrastructure, Transport, Regional Development and Local Government, 2009). However, this figure pales in comparison to the emisions created in Queensland from electricity generation – otherwise known as stationary energy. Due to Queensland's high dependence on non-renewable sources for electricity generation (mainly coal), the stationary energy sector is the largest source of emissions in Queensland, historically being responsible for around 40-50% of total emissions (Queensland Government, 2017).

It is indisputable that electric vehicles are a promising option for reducing the tailpipe emissions that result from the transport sector. This paper is designed to summarise the relevant literature to establish indicative lifecycle emissions for the Brisbane bus network which will then create the foundation for an economic cost-benefit analysis. This paper will firstly review and provide a current consensus on greenhouse gases and carbon emissions in Australia and Queensland, before utilising the Brisbane bus network as a case study to examine the potential opportunities and impacts of transitioning a large scale carbon intensive public transport sector to a fully electric network. Importantly, this paper considers how the emissions from charging an electric bus compare to the tailpipe emissions from the existing bus fleet, covering the existing literature regarding the differences in life-cycle emissions between electric buses and the current fleet.

2 Background

2.1 Greenhouse gas emissions in Australia

The largest emitter of greenhouse gases in Australia is the energy industry, which comprises stationary energy, transport, and fugitive emissions. This trend is mirrored internationally where total emissions tend to increase with total electricity use. The average Australian's electricity use is approximately the same as that seen in other developed countries, yet greenhouse gas emissions per capita are almost triple.

Table 1: Energy use and CO2-e emissions per capita of the top 20 most developed countries worldwide by Human Development Index (HDI)

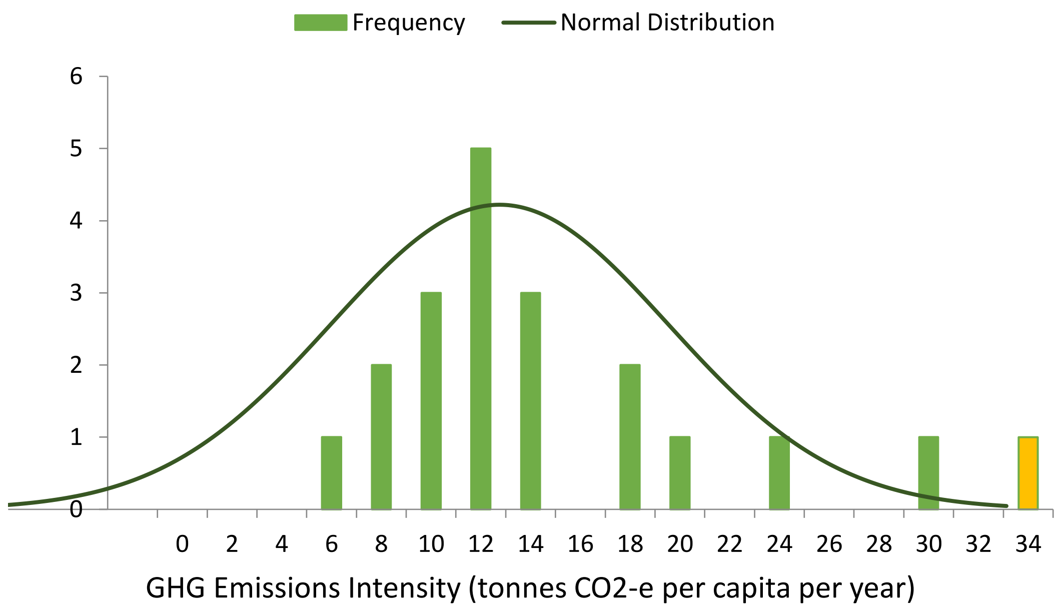
HDI	Country	Electricity Use (kWh / capita / year)	GHG Emissions (tonnes CO2 equivalent / capita / year)
1.	Norway	23,000	12.37
2.	**Australia**	**10,059**	**32.47**
3.	Switzerland	7,520	6.61
4.	Germany	7,035	11.75
5.	Denmark	5,859	9.52
6.	Singapore	8,845	10.22
7.	Netherlands	6,713	11.61
8.	Ireland	5,722	13.52
9.	Iceland	53,832	16.85
10.	Canada	15,546	28.89
11.	United States	12,987	19.91
12.	Hong Kong SAR, China	6,083	8.09

HDI	Country	Electricity Use (kWh / capita / year)	GHG Emissions (tonnes CO2 equivalent / capita / year)
13.	New Zealand	9,026	17.33
14.	Sweden	13,480	6.78
15.	Liechtenstein	10,292	5.37
16.	United Kingdom	5,129	9.07
17.	Japan	7,819	11.62
18.	Korea, Rep.	10,497	13.18
19.	Israel	6,601	10.23
20.	Luxembourg	13,915	22.67
	Average (ex-Australia)	**12,100**	**12.93**

SOURCE: UNITED NATIONS DEVELOPMENT PROGRAM; CIA WORLD FACTBOOK

Figure 1 depicts the GHG intensity data seen in Table 1 as a frequency distribution. The overlayed line approximates a normal distribution with the same mean and standard deviation as this sample[1]. Australia is represented by the yellow bar. Most values are centrally located around the mean. Australia is well above almost all the countries in the sample, and more than three standard deviations away from the mean.

Figure 1: Distribution of values for the GHG emissions intensity data



[1] The use of the normal distribution as a comparator here is purely for illustrative purposes. Visually, the data set displays some characteristics of the normal distribution, however skewness and kurtosis both appear to be present, and the distribution has a slightly heavier right-hand tail than would be expected if it were normal. This may indicate that the data may be approximated better with another distribution. However, the data set is too small to make any meaningful conclusions on the true nature of its probability distribution as this point, and this is not the focus of this paper.

The fuels which are burned to create electricity in Australia drive this seemingly disproportionately high figure. Australia has the highest per capita coal production in the world at 21 tonnes per capita, a function of the nation's stockpile of coal reserves (BP, 2017) (The World Bank, 2016). Coal has the largest carbon footprint of all electricity sources, with almost 250kg of CO_2 emitted per gigajoule of coal-powered energy consumed (Clean Energy Regulator, 2017). This is compared to renewable energies which can have up to 97% fewer emissions for the same electricity production (World Nuclear Association, 2011).

Converting the existing Brisbane bus fleet to electric power will increase the demand on the electricity grid significantly. As the infrastructure for coal already exists, this electricity is likely to be generated predominantly by coal, at least until more renewable energy infrastructure is built which can be relied upon to power a public transport system. This means that an electric bus fleet, under the current electricity generation pathways, should be viewed as a coal bus fleet. This brings into question whether electric buses would deliver a positive environmental impact when compared to traditional combustion engine vehicles.

2.2 Electricity generation mix in Australia and Queensland

The Australian Government's Renewable Energy Target sets a goal for 50% of total electricity generation in Australia in 2030 to be from large scale renewable sources. As an interim target, the government is aiming for 23.5% of Australia's energy to be generated from renewables by 2020 (Australian Government, 2017). The most recent government statistics estimate that currently 15% of electricity nationwide is generated using renewables; the remaining 85% is fossil fuel based (see Table 2: Australian electricity mix).

Table 2: Australian electricity mix

Source	% Total Electricity
Black Coal	46%
Brown Coal	17%
Gas	19%
Oil	2%
Total Fossil Fuels	**85%**[2]
Renewables	15%

SOURCE: (DEPARTMENT OF THE ENVIRONMENT AND ENERGY, 2018)

Over 60% of black coal in Australia is mined in Queensland and the electricity mix in Queensland has a high dependency on the coal that it mines, with a much higher proportion of the mix in Queensland coming from black coal. Unfortunately, the Queensland Government does not release up-to-date statistics on the current state of the electricity mix. As such, the NEM "Live Supply & Demand Widget" was used to estimate the mix[3]. This tool reports live statistics on electricity generation for each state, supplied by AEMO. To estimate the mix for this report, the data were extracted at various points in time over a 5-hour period and averaged. The data captures live supply statistics for black coal, brown coal, gas, oil, hydroelectric, wind, and both rooftop and large-scale solar.

[2] Inconsistencies due to rounding.
[3] The tool can be accessed via https://reneweconomy.com.au/nem-watch/.

On average, approximately 80% of the state's electricity generation at any point in time will be coal-based, specifically black coal. The remainder can be attributed to gas and oil (5%), and renewables where 15% is generated predominantly by solar, with a relatively small amount of hydroelectric and wind power.

A second dataset was analysed, provided by the Queensland Government, on the annual greenhouse gas emissions for all power generation facilities in Queensland (excluding rooftop solar), as well as their annual electricity generation (in kWh), which can then be used to calculate the average emissions intensity per kWh for energy produced in Queensland for each fuel type. This, together with the statistics extracted from the NEM Widget, forms the basis of the quantification of the lifecycle emissions from charging an electric vehicle (see Table 3).

Table 3: Queensland electricity mix and average emissions intensity

Source	% Total Electricity	Emissions Intensity (kg CO2-e per kwh)
Black Coal	79%	0.88
Gas	5%	0.48
Oil	1%	0.81
Large Scale Renewables	5%	0.01
Rooftop solar	10%	0.02

SOURCE: (CLEAN ENERGY REGULATOR, 2017) (GLOBAL-ROAM PTY LTD, 2017) (WADE, 2016)

Renewables and solar are not completely emissions free, as there are emissions associated with the supporting infrastructure required to run the plant. Black coal is by far the most carbon-intensive source in Queensland, with almost 900 grams of CO2-e emitted for every kWh of electricity it produces. As a result, running an electric bus fleet in Brisbane – where the generation mix is so dependent on coal – will almost certainly result in a significant amount of emissions. The central question of this paper is: how do these emissions compare to the emissions currently generated by conventional buses?

2.3 Brisbane bus fleet & bus technology

Bus transport is the most commonly used public transport mode in Brisbane, with approximately two-thirds of Brisbane's public transport users travelling on buses (Brisbane City Council, 2017). As of June 2018, there were 1,233 buses in the Brisbane fleet, approximately 65% of which are run on diesel fuel, with the remainder run on compressed natural gas (CNG)[4] (Brisbane Transport Buses, 2018).

The combustion of diesel in bus engines emits approximately 2.7 kilograms of carbon dioxide equivalents per litre (Australian Government - Department of the Environment and Energy, 2015). It takes approximately ten years and 1.2 million trees to absorb the amount of CO2-e that the entire Brisbane bus fleet contributes to the atmosphere

[4] In the interest of keeping this paper focused, CNG buses will not be discussed further. This paper focuses only on diesel buses so that the desired depth of analysis can be achieved within the given page limits.

in a single year (approximately 46,000 tonnes) (United States Environmental Protection Agency, 2017).

The below table summarises the alternative fuels and technologies that have been proposed in the literature as alternatives to traditional diesel internal combustion engines.

Table 4: Alternative fuels, drivetrains, and technologies that can be implemented in vehicles

Alternative Fuels	Alternative Drivetrains	Vehicle Technologies
Biofuels Natural gas Synthetic diesel Liquefied petroleum gas Hydrogen Others include electric, solar, compressed air	Fully electric (medium to long term) Hybrid electric (short term) Mechanical hybrid	Improved vehicle aerodynamics Ancillary equipment/ accessories Transmissions Improved tyre technology

SOURCE: (RARE CONSULTING, 2010)

The Victorian Department of Transport (Rare Consulting, 2010) assessed each of these technologies in terms of their fuel and emissions benefits, cost, suitability for a public transport fleet and commercial availability. They found that biofuels may deliver strong reductions in emissions, however significant breakthroughs in the production technology is required before these fuels become readily available for transport use. Further, the development of hydrogen and fuel cell vehicle technology is still in its infancy, and whilst it is a developing pathway for transport internationally (particularly in Japan and Korea) it is unlikely to be available in Australia for another decade until a consensus is achieved to allow the development of infrastructure and safety standards. The fully electric option is the most promising alternative technology in the short to medium term and as a result is the focus of this paper.

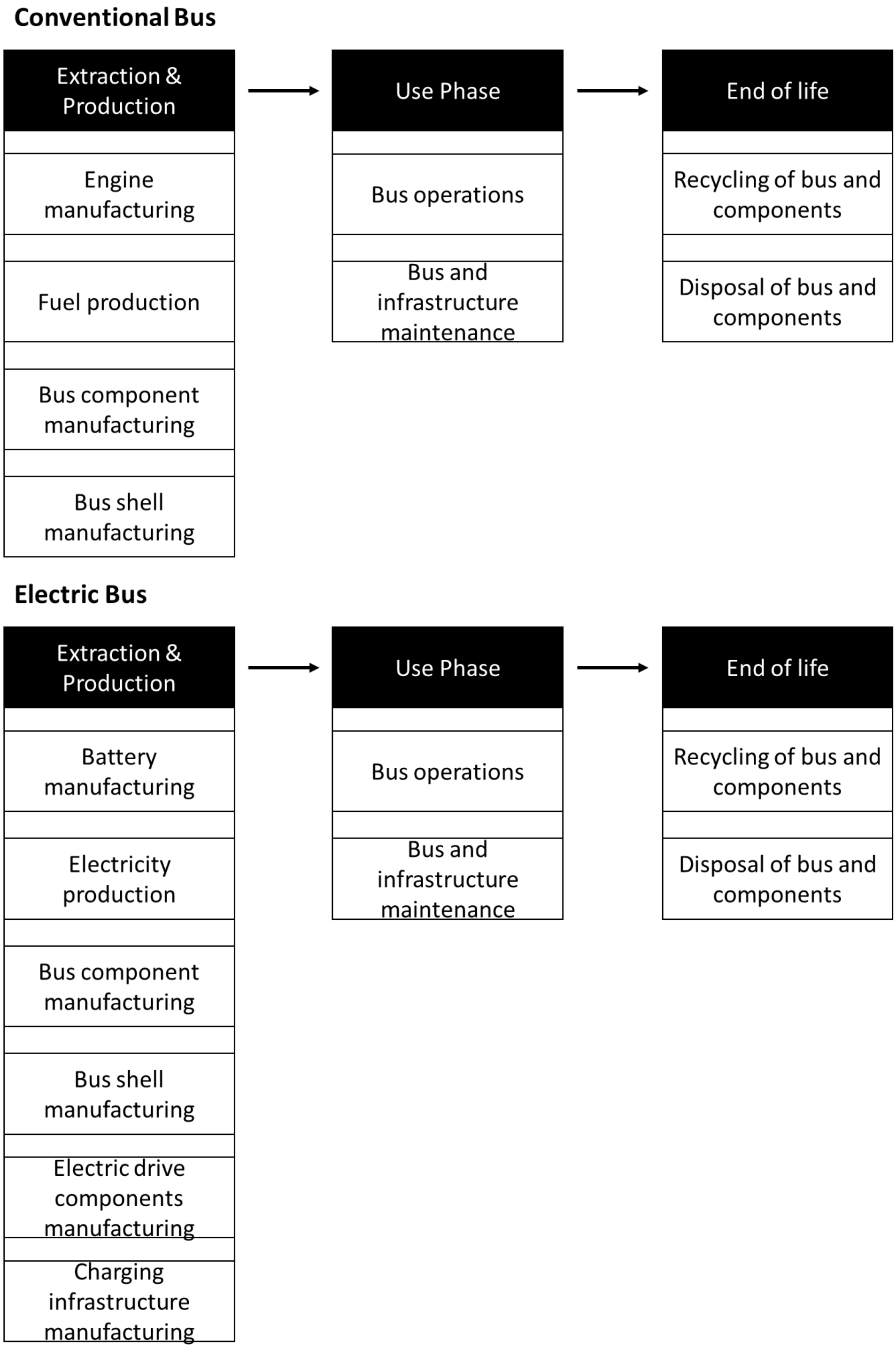
3 Lifecycle emissions of an electric vehicle

The analysis of electric buses requires more than just a comparison of tailpipe emissions and electricity production emissions. The whole-of-life emissions must be considered for both conventional buses and electric buses, including extraction and production of energy, use of vehicle and the end of life disposal processes.

Similar types of analysis have been undertaken in other markets. For example, Faria and colleagues (2013) quantified the difference in emissions between electric and traditional vehicles for three electricity mixes – Poland, Portugal, and France, with approximately 90%, 20%, and 5% coal use respectively. They found that when quantifying emissions on a life-cycle basis (i.e. including emissions attributable to battery and vehicle production, maintenance activities, operations and disposal), running either a hybrid electric or fully electric vehicle on a coal-dependent electricity mix (such as Poland) generates varying results, depending on the comparator vehicle. In the best case, one model of electric vehicle generated approximately 7% fewer emissions than a similar size gasoline vehicle (Faria, et al., 2013). However, in most cases, the electric vehicle generated more carbon emissions than the comparator diesel/gasoline vehicle. Running all-electric vehicles in Portugal or France, however, delivers a life-cycle reduction in carbon emissions in all cases, with up to a 70% reduction seen in France (Faria, et al., 2013).

This section compares the lifecycle emissions of an electric vehicle and conventional buses to allow a direct, whole-of-life comparison for buses in the Brisbane Bus Network. Figure 2 shows the main emissions generating phases in the lifecycle of a conventional bus versus an electric bus.

Figure 2: Emissions generating phases over the life of conventional and electric buses



SOURCE: (COONEY, ET AL., 2013)

The emissions from the manufacture of the bus shell and components, for both electric and conventional vehicles, have been excluded from the analysis to follow. This assumes that the materials used to create the shell and components (such as seats, steering wheel, etc.) are the same for both electric and conventional vehicles, and hence, there would be only a marginal, if any, incremental difference in emissions seen for this component.

3.1 Lead acid battery manufacture vs lithium-ion battery manufacture

There are several battery types used in vehicles, including lithium-ion, lead-acid, nickel-cadmium, nickel-metal-hydride and sodium-sulfur (Sullivan & Gaines, 2010). Traditional combustion engine vehicles rely on lead-acid batteries, largely due to their low cost. Lithium-ion batteries are viewed as the best option for use in electric vehicles, due to their comparatively high energy density, power and lifespan and hence these batteries are the focus of this section.

Seven studies were reviewed which attempt to place an estimate on the carbon emissions intensity of the production of lithium-ion batteries. The results are summarised in Table 5. The lowest value was seen in a study from Notter and colleagues (2010), which reported 6.0 kilograms of CO2 equivalents per kilogram of battery weight; the highest was seen in a study by Ellingsen and colleagues, whose 2013 study of a sample of vehicles found an average of 51 kilograms of CO2 equivalents per kilogram of battery weight. The average of these studies was 21.6 kilograms with a median of 21.7 kilograms.

The spread of values seen is a result of different study assumptions. For example, the country in which the lithium batteries are built impacts the carbon emissions produced, depending on the local energy sources. Note that none of the studies used the Australian electricity grid sources. However, the majority (more than 99.9%) of lithium-ion batteries and electric vehicles sold to the Australian market are manufactured overseas. As a result, it is likely that many of the batteries used in Australian electric vehicles will have originated overseas, making the below figures an appropriate indication of the range of values for global warming potential that could be realised in this phase of the vehicle’s life.

Table 5: Emissions intensity per kilogram of battery weight for li-ion batteries

Source	Notes	Estimate (kg CO_2-eq/ kg battery weight)
Cooney et al. (Cooney, et al., 2013)		17.1
Samaras and Meisterling, 2008 (Samaras & Meisterling, 2008)		9.6
Notter and colleagues, 2010 (Notter, et al., 2010)		6.0
Ellingsen at al., 2013 (Ellingsen, et al., 2013)	Lower bound value (most energy efficient)	18.0
	Asymptotic value	25.0
	Average value in sample	51
Majeau-Bettez et al., 2011 (Majeau-Bettez, et al., 2011)		22
Amarakoon et al., 2012 (Amarakoon, et al., 2012)[5]	$LiMnO_2$	12.7
	Li-NCM	24.2
	$LiFePO_4$	30.2
Hawkins et al., 2012 (Hawkins, et al., 2012)	Li-NCM	21.6
	LiFePO4	21.7
	Average	**21.6**
	Median	**21.7**

Traditional internal combustion engine vehicles (ICEVs) require a lead-acid battery, which research has demonstrated also have effects on the environment. Hawkins and colleagues (2012) estimated the carbon dioxide equivalent emissions from the production of a lead acid battery, using the Mercedes A-Class as a base, and calculated an estimate of approximately 4.33 kg CO2-eq/ kg battery weight. The mining and smelting of lead ores to produce the battery is the largest contributor to these emissions.

The Ganzizhou Rongda Lithium mine in Tibet, now closed, endured three separate incidents from 2009-2016 where lithium originating in the mine leaked into the local waterways, resulting in mass deaths of fish and livestock in the region (Katwala, 2018). Additionally, over 50% of the world's lithium supply is mined in the Lithium Triangle in South America, a region encompassing parts of Chile, Argentina, and Bolivia, lying within the Atacama Desert – the second driest place on earth (Katwala, 2018). Notably, lithium mining consumes up to 65% of the water in this region, a significant amount given the arid climate (Katwala, 2018). This has had large effects on the local economy, which is driven by agriculture and reliant on this water. The focus of this paper is on the global warming potential of electric vehicles, and as such, other environmental impacts such as these will not be analysed in further detail. However, it is important to note that the impacts of lithium-ion battery production extend beyond just carbon emissions and a full economic assessment of the battery technology should take such wider impacts into account. Using only global warming potential as

[5] Amarakoon and colleagues report emissions intensity in terms of kg/ kWh capacity, rather than kg/ kg battery weight. Here, the results are presented after converting using the convention of 0.2kWh capacity per kg. (Li, et al., n.d.) (CATL, 2017)

the measure, the above indicates that the lithium-ion battery for an electric vehicle has a greater effect on the environment than the traditional lead-acid battery.

3.1.1 Battery Weight & Specifications

To translate the above per kilogram emissions into a total for each bus, the weight of the battery is required, which changes depending on the size (capacity) of the battery. Key considerations regarding a suitable battery capacity is the range that the bus must be able to travel on a single charge, the time constraints for recharging and the operational demand of the fleet.

Each bus in the Brisbane transport network travels on average 54,700 kilometres each year, or 150km of travel each day (if all buses drive 365 days every year). Hence, the electric bus selected must have a listed driving range of at least 150km on a single charge. Evidence suggests that the range of the selected bus may have to exceed this minimum considerably. An electric bus tested during summer in Pheonix, Arizona, with typical summer temperatures of between 30 and 40 degrees Celsius, ran less than two thirds of its advertised range, largely due to the energy that is used up by air conditioning (Groom, 2017). Based on this, if in Brisbane a range of at least 150km is required, the bus may require an ‘advertised’ range 200km or more.

The BYD K9 is a commonly used electric bus, with approximately 17,000 in operation in Shenzhen, China alone. As a result, this paper will use the BYD K9 as the example vehicle, with its 500-kWh capacity battery, and driving range of 250km.

Based on a conversion rate of 0.2 kWh per kilogram (CATL, 2017) (Li, et al., n.d.), the 500kWh battery has a weight of 2.5 metric tonnes, leading to production phase emissions of approximately 54 tonnes of CO_2 equivalents. In contrast, the battery for a conventional bus typically weighs around 40kg (Century Batteries, 2019). Based on Hawkins and colleagues’ estimate of 4.33 kg CO_2e / kg, this corresponds to around 173.2kg of CO_2 equivalents from production. This difference – notably, quite extreme, of more than 53 tonnes – is driven by the weight of a lithium-ion battery being more than sixty times and the per kilogram emissions intensity being roughly five times that of a lead-acid battery.

Unless the emissions from other phases of the conventional bus’s life exceed those of an electric bus by more than 53 tonnes, then the emissions from the lithium-ion battery alone are significant enough to say that an electric bus will have a larger carbon footprint than a conventional bus. This highlights the importance of advances in battery technology and production processes, particularly those that allow for the size and weight of the battery to decrease while maintaining the same capacity and drive range.

3.1.2 Lead Acid Battery Replacement

A typical electric bus only requires one lithium-ion battery over its lifetime. On the other hand, a conventional bus may require many lead-acid batteries during its operations, due to the lower useful life of the lead-acid battery. Typically, over the course of ICEBs 15-year life, 2-4 battery changes may be required (MTA, n.d.) (Proterra, 2017). In analysing the potential lifecycle carbon emissions of the bus, the emissions for not just one battery must be accounted for, but up to four.

In this case, if the bus requires four battery changes over its life, then the total emissions attributable to the lead-acid battery is:

$$weight\ of\ each\ battery\ \times emissions\ per\ kg \times number\ of\ batteries$$
$$= 40kg\ \times 4.33kg\ \text{CO2eq/ kg battery weight}\ \times\ 4$$
$$= 692.8kg$$

As mentioned above, in the case of an electric vehicle, the total emissions attributable to the lithium-ion battery is:

$$capacity\ of\ battery\ in\ kWh \times kg\ weight\ per\ kWh\ \times emissions\ pe\ kg \times number\ of\ batteries$$
$$= 500\ kWh\ \times 5kg/kwh\ \times 21.6kg\ CO2\text{eq/ kg battery weight} \times 1$$
$$= 54{,}000\ kg$$

The difference between these results is notably very large, with the emissions from the lithium-ion battery exceeding the lead-acid by over 98%:

$$Percentage\ difference = 1 - \frac{692.8}{54000} = 98.7\%$$

Hence, even with more frequent battery replacement considered, the battery for a conventional bus still results in more than 98% fewer carbon emissions. Again, this is driven by the larger battery required for an electric bus in comparison to the battery in a conventional bus, as producing a bigger battery is more resource intensive, leading to greater emissions during production. This follows from the fact that the lead-acid battery is required mainly for ignition in the engine, whereas the lithium-ion battery must be large enough to power all actions of the bus for a full day.

3.2 Fuel production and use vs electricity production

To compare the expected CO_2-e emissions associated with ongoing use of different bus types, several assumptions were made about the specifications of the bus. The assumptions used to estimate use phase emissions in the Brisbane bus network are summarised in Table 6.

Table 6: Assumptions for the use phase emissions calculation

	ICEB	BEB	**Source/s**
Average annual distance travelled, km	54 700	54 700	Brisbane City Council, 2017 (Brisbane City Council, 2017)
Fuel economy, L/100km	42	-	Personal correspondence with industry
Battery efficiency, kWh/km	-	2.0	Zhou et al, 2016 (Zhou, et al., 2016)
Charging efficiency (%)	-	90%	
Loss from the distribution network (%)		10%	

The operating emissions from a conventional bus run on fuel type i, $M_{C,i}$, can be expressed as:

$$M_{C,i} = F_i \cdot d \cdot C_i \cdot \sum_j E_{i,j}$$

Where:
F_i is the per kilometre efficiency of fuel type i (kL/km);
d is the total distance travelled by the bus per period (kilometres);
C_i is the energy content factor of the fuel type i (GJ/kL);
$E_{i,j}$ is the emissions intensity of gas type j from burning fuel type i.

The unit values for C_i and $E_{i,j}$ were adapted from the recommendations of the Australian National Greenhouse Accounts Factors, the annual publication of the Australian Government which sets out a methodology for individuals and companies to estimate greenhouse gas emissions (see Table 7) (Department of the Environment and Energy, 2017).

Table 7: Diesel fuel – parameters used for the quantification of emissions

Parameter	Value
Fuel Efficiency (F), kL/km	0.00042
Energy content factor (C), GJ/kL	38.6
Carbon dioxide emissions intensity (kg CO_2-e/GJ)	69.9
Methane emissions intensity (kg CO_2-e/GJ)	0.01
Nitrous oxide emissions intensity (kg CO_2-e/GJ)	0.6

SOURCE: (DEPARTMENT OF THE ENVIRONMENT AND ENERGY, 2017)

Hence, for a diesel bus running in Brisbane, total operating emissions are:

$$M_{C,diesel} = F_{Diesel} \cdot d \cdot C_{Diesel} \cdot \sum_j E_{Diesel,j}$$
$$= 0.00042 \cdot 54700 \cdot 38.6 \cdot (69.9 + 0.01 + 0.6)$$
$$= 62{,}528 \; kg \; CO_2^{equiv}$$

In contrast, total operating emissions from an electric bus, M_E, can be expressed as:

$$M_E = \frac{U}{\varepsilon(1-L)} \cdot d \cdot \hat{I}^T \hat{p}$$

Where:
U is the per kilometre energy use (kWh/km) of the electric bus;
L is the electricity loss factor of the transmission and distribution network;
ε is the efficiency of the battery charging process;
d is the total distance travelled by the bus per period (kilometres);
$\hat{I}$ is the vector of emissions intensities, with each I_j denoting the emissions intensity of fuel type j (see Table 3, emissions intensity column);
$\hat{p}$ is a vector with each p_j denoting the proportion of electricity in the study area which is generated using fuel type j (see Table 3, % total electricity column).

According to AEMO, the transmission and distribution loss factor in the Australian electricity network is approximately 10%. This means that approximately 10% of the total energy that is transported between power stations and final use is lost to resistance and heat along the distribution network (Australian Energy Market Operator, 2018). Additionally, the charging efficiency of an electric bus is assumed to be 90% - as with the overall transmission loss factor, this indicates that a further 10% of the energy generated at the grid will be lost during the charging process (again to sources such as heat).

Based on the above, we have the following for an electric bus running in Brisbane:
U = 0.9,
L = 10%
ε = 90%;
d = 54 700km;

$$\hat{I} = \begin{bmatrix} 0.88 \\ 0.48 \\ 0.81 \\ 0.01 \\ 0.02 \end{bmatrix}, \hat{p} = \begin{bmatrix} 0.79 \\ 0.05 \\ 0.01 \\ 0.05 \\ 0.1 \end{bmatrix}$$

And the total annual operating emissions per bus is

$$M = \frac{U}{\varepsilon(1-L)} \cdot d \cdot \hat{I}^{\boldsymbol{T}} \hat{p}$$

$$M = \frac{2.0 \cdot 54700}{90\%(1-10\%)} [0.88 \quad 0.48 \quad 0.81 \quad 0.01 \quad 0.02] \begin{bmatrix} 0.79 \\ 0.05 \\ 0.01 \\ 0.05 \\ 0.1 \end{bmatrix}$$

$$= 98{,}568\ kg\ CO_2^{equiv}$$

Hence, based on these high-level calculations, running an electric bus in Queensland would result in over than 50% more emissions than a conventional bus travelling the same distance.

This result is highly sensitive to two factors:

1. The types of fuel which form part of the electricity mix; and
2. The amount of electricity required to power the vehicle – that is, the ‘electric fuel efficiency’ (kWh consumed per km).

The first factor will be explored in detail in section 3.2.1, in the form of a sensitivity analysis where the electricity mix will be varied. Regarding the second factor, improvements in battery technology have the potential to significantly reduce the emissions from the vehicle, without having to change the underlying electricity generating mix. The emissions from an electric vehicle on a per kWh basis are lower than the emissions per litre of fuel used in a conventional vehicle. The efficiency of the battery used in the model is 2.0 kWh per km travelled; however, if technology improves so that the electric bus can operate on 1.0 kWh per km, the electric bus outperforms the conventional bus from an environmental standpoint – even with the current carbon dependant electricity mix. Advances in electric drive technology may have an even larger effect on carbon emissions, and the above results, than the electricity mix and renewable technologies will.

3.2.1 Case Study – Electric Buses under the 2030 Renewable Energy Target

As mentioned earlier, the government has set a target for 50% of Australia's energy to be generated using large scale renewables by 2030. To demonstrate how the use of renewables heavily influences the preference between electric and conventional buses, this section will quantify the emissions from an electric bus in this scenario.

Firstly, note that the exact electricity mix in 2030 is unknown, apart from the overall goal of 50% large scale renewables. Hence, assume that the 2030 electricity mix is as follows, where black coal-based production has decreased to allow increases in large scale renewables. In order to arrive at this mix, the following was assumed:

1. Large scale renewables will form 50% of the electricity mix, as per the renewable energy target;
2. Natural gas consumption was grown at 3% per annum, reflective of the ten-year average annual growth rate for the sector (Enerdata, 2018);
3. The solar panel proportion was grown at 6.7% per annum, in accordance with the average annual growth rate over the last three years (Enerdata, 2018);
4. Oil has been held constant; and
5. Coal has been calculated to fill the remaining capacity after gas, oil, and renewables were calculated.

Table 8: Example electricity mix in a 50% renewable scenario

Fuel type number (j)	Fuel	Proportion ($\hat{p}$)
1	Black Coal	0.26
2	Gas	0.07
3	Oil	0.01
4	Large scale renewables (e.g. wind, hydroelectric)	0.50
5	Rooftop solar	0.16

In this scenario, the emissions would be:

$$M = \frac{2.0 \cdot 54700}{90\%(1-10\%)} \begin{bmatrix} 0.88 & 0.48 & 0.81 & 0.01 & 0.02 \end{bmatrix} \begin{bmatrix} 0.26 \\ 0.07 \\ 0.01 \\ 0.50 \\ 0.16 \end{bmatrix}$$

$$= 37{,}538\ kg\ CO_2^{equiv}$$

This indicates that, in a scenario where a greater proportion of electricity comes from renewable energy use, the electric bus results in almost 40% less carbon emissions than the conventional one during its use phase.

3.4 Charging infrastructure vs refuelling infrastructure

Manufacturing supporting infrastructure – such as charging stations for electric buses, and refuelling stations for conventional buses – also generate emissions, and as such, should be measured. Lucas and colleagues (2012) conducted a study in a Portuguese context and found that supporting infrastructure for diesel vehicles (refinery and pipeline, refuelling stations, refinery maintenance, and well) on average emit 0.676 kilograms of CO_2 equivalents per gigajoule of energy supplied. Likewise, supporting infrastructure for electric vehicles (including those from maintaining the grid, charging stations, and maintenance) emit approximately 0.029 kilograms of CO_2 equivalents per kWh of electricity supplied (Lucas, et al., 2012). At the time of writing, this is the only peer-reviewed study available which compares the supplying infrastructure required for diesel vehicles to that required for electric vehicles.

3.5 End of life activities – disposal, recycling

As mentioned above, it is assumed that the bus shell and components will be the same for conventional and electric buses. This may be an oversimplifying assumption; it is known for example that the safety standards for lithium batteries, due to their fire risk, require a greater degree of fire proofing than conventional vehicles. However, the research surrounding the emissions impact of this is lacking and hence has not been included in this paper. As a result, it is assumed that in the comparison of end of life activities for conventional and electric buses, the main incremental difference in emissions will come from the disposal or recycling of the battery.

The recycling of lead-acid batteries is widespread, in part due to legislation, but also due to the ease by which the recycling process is conducted. By mass, over 60% of a lead acid battery is made of lead metal and no other metal is present, greatly simplifying recycling as it eliminates the need to separate and refine metals (Gaines, 2014). In general, the more materials that are used to make a battery, the more challenging it will be to recycle at the end of its life. As seen in the below table, while lead-acid batteries are the easiest to recycle of the three most common batteries, lithium-ion batteries are the most complex, due to the very diverse materials and chemicals used in their construction.

Table 9: Materials used in the three most common car battery types (Gaines, 2014)

	Lead acid	Nickel-metal-hydride	Lithium ion
Cathode	Lead Oxide	Nickel hydroxide	$LiMO_2$
Cathode plate/ foil	Lead	Nickel foam	Aluminium
Anode	Lead	Metal hydride	Graphite
Anode plate/ foil	Lead	Nickel plated steel	Copper
Electrolyte	Sulfuric acid	Potassium hydroxide	Lithium hexafluorophosphate + organic solvent
Separator	Polyethylene or polyvinyl chloride with silica	Polyolefin	Polyethylene or polyvinyl chloride
Cell case	Polypropylene	Stainless steel	Metal or laminate

As a result, in Australia, around 85% of the lead-acid batteries used in conventional vehicles are recycled (Battery Rescue, n.d.). Comparatively, according to a 2018 investigation into lithium battery waste by the CSIRO, barely 2% of lithium-ion battery waste is recycled, with most of the waste disposed of in landfill (King, et al., 2018).

Recycled battery components have the power to reduce the emissions associated with future battery production. A study by Rydh and Karlstrom (2002) found that up to 75% less energy is required to recycle precious metals such as nickel than that which is required to extract and refine the virgin metal (Rydh & Karlstrom, 2001). This translates directly to lower emissions during the production phase, which as discussed in section 3.1, can be significant. Further, Unterreiner and colleagues (2016) found that using recycled materials in lead-acid batteries reduces the environmental impact by up to 49%, and for lithium-ion batteries, by 23% (Unterreiner, et al., 2016). This 23% reduction equates to an approximate 12.4 tonne saving in emissions (based on the battery emissions calculations seen in section 3.1.1). However, even considering this saving, with only 2% of batteries recycled and the emissions from producing batteries already so high, it is unlikely that this would make a material difference to the outcome.

3.6 Summary of findings

This section has compared the whole-of-life greenhouse gas emissions of conventional buses and electric buses. The comparison found that, under the existing electricity generation mix, electric vehicles generate: more carbon emissions in the extraction and production phase due to the larger battery requirement; more carbon emissions in the use phase due to the requirement for coal to generate electricity; and similar carbon production in the end-of-life process, with recycling more widespread for conventional bus batteries.

The below table summarises the unit values used and calculated throughout this paper. As seen in the table, the internal combustion engine bus (ICEB) outperforms the electric bus (EB) in all categories assuming the existing energy generation mix in Queensland, delivering lower carbon emissions. The two largest contributors to the carbon emissions of the vehicle are those from battery production and those from the use phase of the bus, indicating that improvements on these areas should be the focus if electric buses are to become a viable alternative to ICEBs.

Table 10: Summary of parameters

Factor	ICEB	EB
Emissions intensity – battery production (kg CO2-e per kg weight)	4.33	51.0 (High) 6.0 (Low)
Battery weight (kg)	40	2,500
Diesel tailpipe emissions (kg CO2-e)	62,528	
Electricity production – emissions (kg CO2-e)		99,703
Supporting infrastructure	0.676 kilograms of CO2 equivalents per gigajoule supplied	0.029 kilograms of CO2 equivalents per kWh supplied
Reduction in production emissions due to battery recycling	49%	23%

The use phase emissions of an electric bus – that is, the lifecycle emissions resulting from its electricity use –can be improved in one of two ways:

1. Changes in the electricity generation mix, specifically a significant reduction in the use of fossil fuels in the electricity generation process (akin to that which may be expected under the 2030 Renewable energy target);
2. Improvements in the electricity efficiency of the electric bus, so that an electric bus can travel further on a single charge (i.e. a lower kWh/km energy use).

Similarly, improvements in the carbon footprint of the electric battery production process should be expected if there are improvements in technology that allow for a reduction in the size and weight of the electric battery, while maintaining the same capacity in kWh.

Figure 3 compares the use phase emissions of an electric bus to that of a conventional bus as the proportion of electricity produced by renewables increases. The dark green line represents the ratio of emissions from an electric bus to a conventional bus, with a value of 1 indicating that the emissions are equal (the light green horizontal line indicates where 1 is). As seen in the figure, when the proportion of total renewables (i.e. large-scale renewables plus rooftop solar) is approximately 45% or more, electric buses result in less carbon emissions than conventional buses (during only the use phase).

Figure 4 displays the same information, however including the emissions from battery production in the comparison. The figure displays the emissions when the high estimate seen in Table 5 is used (of 51.0 kg of CO2-e per kg battery weight) and the low estimate is used (of 6.0 kg CO2-e per kg battery weight). As seen in the figure, under the high battery emissions scenario, the emissions of the electric bus and conventional bus are never equal. However, under the low estimate, when the renewable percentage is more than approximately 55%, the saving in emissions from the use phase of the bus is enough to cover the higher emissions from battery production.

Figure 3: Forecast of comparative emissions (use phase only, i.e. electricity production vs diesel use)

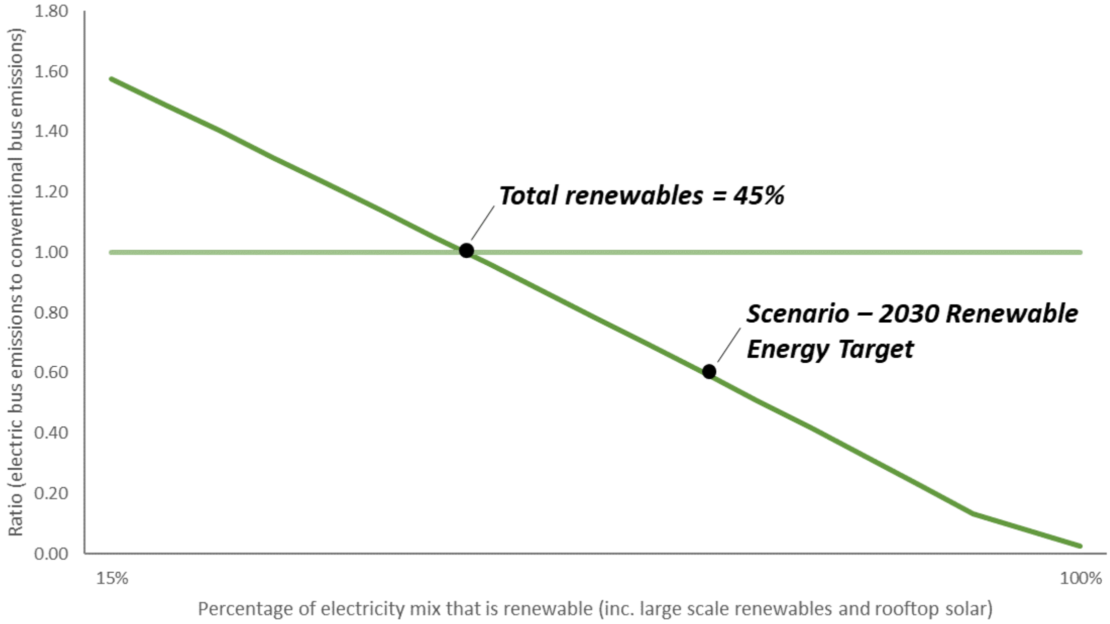
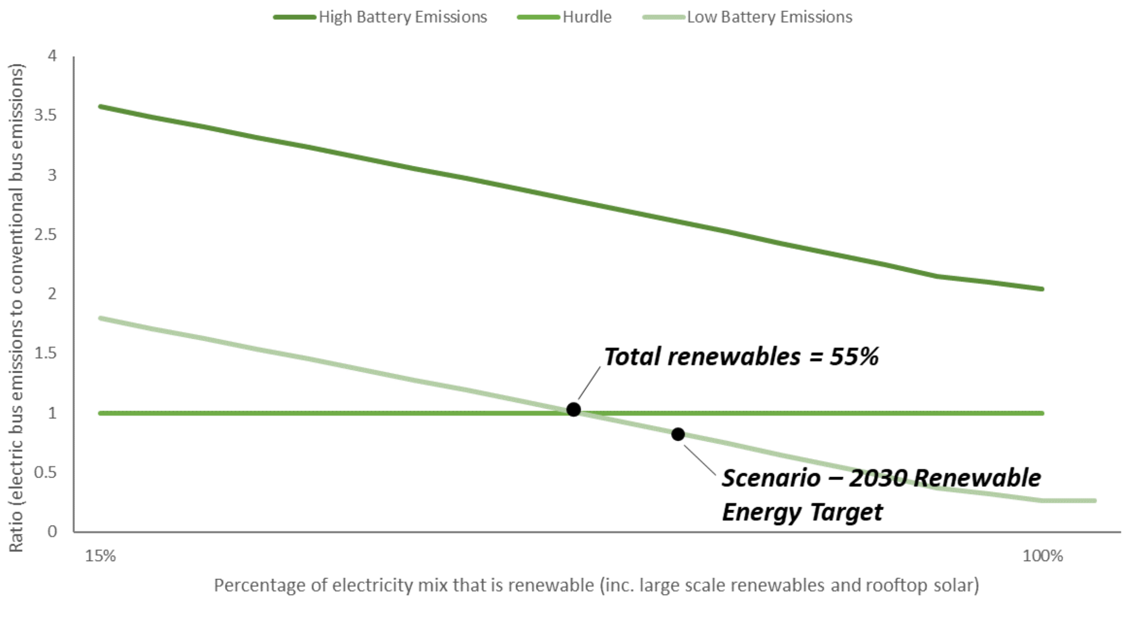


Figure 4: Forecast of comparative emissions (use phase plus battery production emissions)



4 Conclusions and future considerations

The transport sector is Australia's second largest greenhouse gas emitter responsible for 18% of total emissions and increasing every year. Recently, the potential for electric vehicles to be a low-emissions alternative to internal combustion engine vehicles has been the focus of much media attention, also stimulating much political debate.

Those in favour of electric vehicles argue that, as they do not emit exhaust out of their tailpipe, electric vehicles must be 'cleaner' environmentally than traditional internal combustion engine vehicles. However, this fails to consider the electricity that is required to run these vehicles, and how this electricity is produced. Given most of Australia's energy is powered by fossil fuels, the key question is: if an electric vehicle is charged using coal-powered energy, is its environmental impact materially different compared to that of a conventional vehicle?

This paper has found if electric buses were to be run in Brisbane today, they would emit more carbon emissions than conventional buses. This is driven largely by electricity production in Queensland being heavily reliant on coal which, when compared to fuels used in transportation, leads to more carbon in the atmosphere. If this remains unchanged, the future for electric buses is not bright, unless technologies change dramatically. Further, evidence shows that the 2030 emissions target makes electric buses significantly more attractive. Hence, a shift is required, driven by the Queensland Government and energy providers, in the electricity production landscape before the discussion of electric buses can be taken seriously. Not considered as part of this assessment, however, are the broader environmental impacts for lithium-ion batteries, differences in shell manufacturing and differences in maintenance schedules. Consideration of these factors may impact the conclusions identified in this paper.

The state's electric vehicle and renewable energy strategies need to be considered in parallel. While the Queensland Government's Electric Vehicle Strategy discusses the importance of renewable energy in making electric vehicles more attractive, it does not highlight how central the renewable energy strategy is to this technology advancing. Without investment in renewable energy, the initiatives under the electric vehicle strategy are wasted energy. This paper has demonstrated that the environmental benefits asserted in the strategy will not be achieved without investment in renewables. The recent government approval of the Adani coal mine is inconsistent with the Government's claims that "the future is electric" as coal-powered energy stifles the advancement of electric vehicles.

Of course, changes to the electricity grid, while essential from an environmental standpoint, are not the only important consideration if the Brisbane bus network was to transition to fully electric. Other steps must also be taken to prepare the network for the major shift in service delivery to answer questions such as "Where will buses re-energize?", "Are the existing routes still possible", and "How can we transition the fleet most effectively?" Through this, reasons may be uncovered, outside of carbon emissions, that drive a change to electric buses – such as efficiency or productivity gains. However, if transitioning purely for environmental reasons, Queensland has a long way to go before it should be entertaining such a discussion.

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