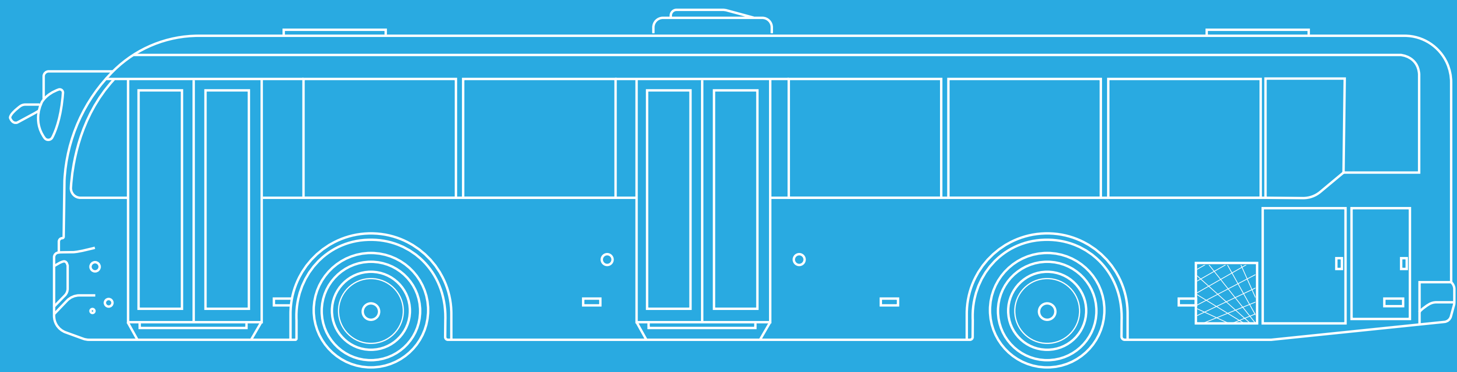
ELECTRIC BUS TECHNOLOGY

TRANSPORT RESEARCH REPORT

June 2017



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DOCUMENT INFORMATION

Acknowledgements

This research was undertaken with partial funding from Callaghan Innovation.

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ACRONYMS AND ABBREVIATIONS

Acronym	Meaning	Acronym	Meaning
AFCB	American Fuel Cell Bus	**KBRC**	kilometres between road calls
BEB	battery electric bus	**kW**	kilo Watt
BEV	battery electric vehicle	**kWh**	kilo Watt hour
CNG	compressed natural gas	**L**	litre
CO2 eq	carbon dioxide equivalent	**LCA**	life cycle assessment (or life cycle analysis)
DB	diesel bus	**MBRC**	miles between road calls
DGE	diesel gallon equivalent	**mi**	mile(s)
DOE	(U.S.) Department of Energy	**MJ**	mega joule(s)
EM	electric motor	**MJ/MJf**	Mega joules per mega joule transported
EV	electric vehicle	**NG**	Natural gas
FCEB	fuel cell electric bus	**NGSR**	natural gas steam reforming (for H2 production)
GGE	gasoline gallon equivalent	**NOx**	nitrogen oxides
GHG	greenhouse gas	**NREL**	(U.S.) National Renewable Energy Laboratory
g	grams	**PEMFCs**	polymer electrolyte membrane fuel cells (or proton exchange membrane fuel cells)
H2	hydrogen	**PMx**	particulate matter (also called particle pollution) with a diameter of micrometres or smaller
HEB	hybrid electric bus	**powertrain**	the vehicle components that generate power and deliver it to the wheels
HEV	hybrid electric vehicle	**TCO**	total cost of ownership
HFCV	hydrogen fuel cell vehicle	**TTW**	tank-to-wheel
hp	horse power	**WTT**	well-to-tank
ICE	internal combustion engine	**WTW**	well-to-wheel

Table 1: *Acronyms and abbreviations*

1. INTRODUCTION

The purpose of this report is to summarise the current status of electric bus technology for a New Zealand audience. The motivation for compiling this report reflects growing interest in electric vehicle technologies in general, as well as increasing support for electric public transport in particular.

1.1 *Buses in Public Transport*

Buses are the dominant form of public transport in New Zealand. In 2015, 112 million passengers were recorded boarding buses around New Zealand (Ministry of Transport, 2016), which represented 78% of total public transport boarding's nationally[1]. Moreover, bus patronage is growing fast; between 2001 and 2015 bus patronage increased by 60%, or 3.4% per annum (Ministry of Transport, 2016). These numbers exemplify the important contribution of buses to public transport in New Zealand's cities and towns.

Bus technology continues to develop as other technologies improve; buses are constantly improving in energy efficiency, passenger comfort, and reducing air pollution. Some of these improvements in New Zealand have been driven by regulatory standards for urban passenger buses (NZ Transport Agency, 2014). More broadly, however, there seems to be heightened community awareness of the benefits of clean, comfortable buses.

Given the important role of buses in New Zealand's public transport networks, as well as changing technology and community expectations, this report seeks to provide an overview of current electric bus technology.

In doing so, we consider three main types of electric buses: the hybrid electric bus (HEB), the fuel cell electric bus (FCEB), and the battery electric bus (BEB). This discussion focuses on aspects of the technologies, and their potential market share, operational performance, and environmental performance.

1.2 *Why Electric Buses, Not Improved Diesel Buses?*

All well-utilized buses, regardless of which type of powertrain (mechanisms for generating bus propulsion) is used, offer an efficient public transportation method when compared to car usage; buses are space, energy and emissions efficient (UITP - Union Internationale des Transports Publics, 2011). A diesel bus[2] at 20% capacity, for example, produces approximately one-third of the CO2 emissions per passenger kilometre compared to the equivalent number of private vehicles[3] required to transport the same number of people. When the bus is at full capacity, the reduction in CO2 emissions increases to more than 90% (UITP - Union Internationale des Transports Publics, 2011).

The first reason for considering electric buses rather than diesel is that while diesel buses are more efficient than private vehicles, they still make a significant contribution to GHG emissions, which could largely be reduced by utilising electric buses. Many national and regional governments around the world are thus investigating measures to reduce GHG emissions from their public transport fleets by investing in alternative powertrains.

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[1] *The remainder was made up of 26 million train passenger boardings (18%) and nearly 6 million ferry passenger boardings (4%).*

[2] *12 metre standard bus with 80 passenger capacity.*

[3] *Here passenger cars have an assumed efficiency of 8 litres/100km and an average occupancy of 1.2 passengers. As a reference: passenger vehicles (cars) in Australia, in 2014, had an average fuel consumption of 10.7 litres/km (Australian Bureau of Statistics, 2015); new vehicles in the EU require an average emissions level of 130 grams of CO2 per kilometre (g CO2/km) – equivalent to a fuel efficiency of about 5.6 litres/100km (Directorate-General for Climate Action, 2016).*

1. INTRODUCTION

Electric buses are also attractive because they support efforts to reduce local air pollution ("Doctors call for ban on diesel engines in London," 2016). Urban air quality is attracting increasing attention globally, and several international cities are moving to ban diesel vehicles from inner city roads over the next decade (Harvey, 2016). Even new, efficient diesel engines emit dangerous substances such as nitrogen oxides (NOx) and particulate matter (PM10). These pollutants are of particular concern in dense urban areas with high numbers of pedestrians and cyclists, which are typical of the conditions in which buses operate. Alternative bus powertrains that reduce or remove the need for a diesel engine, while retaining the advantages of buses, are of growing interest, especially in dense urban environments.

A third incentive to adopt electric buses in New Zealand is that they provide energy security and increase transport fuel diversity (Ally & Pryor, 2016). New Zealand's transport industry uses oil to satisfy 98% of its energy demands (Ministry of Business, Innovation & Employment, 2016), while approximately 70% of New Zealand's oil is imported (Bartos, López-Bassols, Nishida, & Robertson, 2014). High dependence on imported fossil fuel makes New Zealand's transport system more vulnerable to oil price changes and shortages.

The advantages of electric buses have been recognised in the policies being implemented in several major cities around the world. London has recently announced that no new diesel buses will be purchased for its inner-city routes from 2018 (London Assembly, 2016). Currently, London has three fully electric bus routes, seventy-one zero emission buses in service, and has purchased (in a joint EU-funded project) twenty hydrogen fuel cell buses, built by UK bus manufacturing company Wrightbus (London Assembly, 2016). Cape Town, Copenhagen, Hamburg, Los Angeles, New York, Oslo, Rugao (China), Amsterdam, and San Francisco have also committed to zero emission bus fleets. Collectively, these cities have agreed to adopt one-thousand "zero emission" buses in their public transport fleets over the next five-years (London Assembly, 2016).

1.3 Report Outline

This report includes the findings on the research into electric bus technology. In particular, this report comments on:

- ***Electric bus technologies*** which are currently available, and their recent developments.
- ***Economic***, operational, and environmental performance of electric buses.
- ***Life cycle analysis*** and energy efficiency analysis of electric buses.
- ***Current*** and predicted market share of electric buses.
- ***A selection*** of electric bus trials around the world.

2. OVERVIEW OF TECHNOLOGIES

Hybrid electric, fuel cell electric and full battery electric buses are currently being used in a number of public transport networks around the world. Different types of electric bus technology vary in terms of whether electrical energy is generated or stored onboard, specifically:

- ***Hybrid electric buses*** (HEBs) generate electricity on-board during operation using a diesel engine.
- ***Fuel cell electric buse*s** (FCEBs) use hydrogen fuel cells to generate electricity on-board during operation.

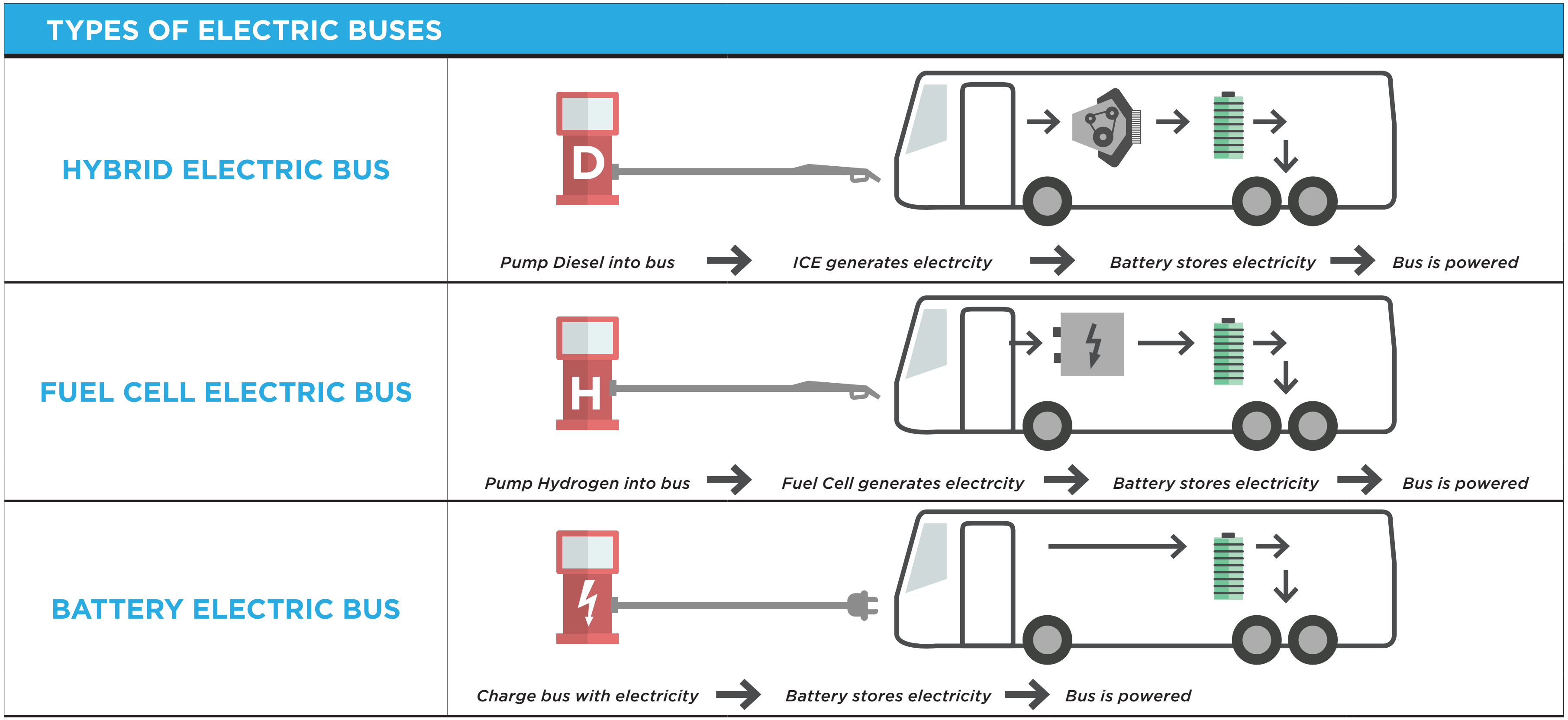

Figure 1: *The defining components of different types of electric buses*

[4]*Information source unless otherwise specified: (Varga, Iclodean, & Mariasiu, 2016).*

2. OVERVIEW OF TECHNOLOGIES

- ***Battery electric buses*** (BEBs) store electricity on-board, and are charged either overnight, or intermittently throughout the route (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016).

Figure 1 outlines the main components involved in each electric bus technology option. Specific advantages and disadvantages to each type of powertrain will be discussed in their respective sections below, while a set of common advantages and disadvantages across all types of electric buses are outlined here[4].

ADVANTAGES

- ***Emissions***, less GHG and local pollutant emissions.
- ***Reduced vibration***, increasing passenger comfort and reducing damage to surrounding infrastructure.
- ***Noise***, electric motors produce less noise than ICEs and do not keep running when a bus is stationary.
- ***Fuel efficiency***, all types of electric buses usually demonstrate increased energy efficiency.

DISADVANTAGES

- ***Cost***, electric bus options are currently more expensive to purchase than their diesel alternatives.
- ***Infrastructure***, electric bus options require different types of additional infrastructure.

2.1 Hybrid Electric Buses

HEBs use both an internal combustion engine (ICE), which is usually diesel powered, and an electric motor (EM) to power the vehicle. They are the most common type of electric bus in operation globally, and continue to be the most purchased type of new electric bus (Mahmoud et al., 2016).

The advantages and disadvantages of HEBs specifically are outlined here. Note the generic advantages and disadvantages of all electric bus types mentioned at the start of Section 4.

ADVANTAGES

- ***Smaller technology changes,*** HEBs are a comfortable transition for many, as they rely on much of the same technology as traditional DBs.

DISADVANTAGES

- ***Heavy,*** powertrain components increase vehicle weight, potentially limiting what roads these buses can operate on.
- ***Capacity***, increased weight means that vehicle capacity is often reduced due to maximum axle weight limits.
- ***Infrastructure***, may require additional infrastructure, such as charging stations.
- ***Reliability***, battery capacity and useful life may be reduced by extreme temperatures (Buchmann, 2016).

2.1.1 Hybrid Configurations

As well as an ICE and an EM, hybrid electric vehicle powertrains include an energy storage system (batteries or ultracapacitors), a generator, a power management system, and coupling elements to pair the mechanical and electric systems. The configuration of these components takes three main forms: series (serial), parallel, and series-parallel (mixed). In general, a series configuration is more efficient for low speed operation and a parallel configuration is more energy efficient for higher speed operation (Cobb, 2014; Lajunen, 2014). **Figure 2** shows the configuration of the components in a standard diesel bus.

Acronym	Meaning
AUX	Auxiliary devices
EM	Electric motor
FD	Final drive (differential)
GEN	Generator
ICE	Internal combustion engine
TC	Torque coupler
TX	Transmission

Table 2: *Key for vehicle configuration figures*

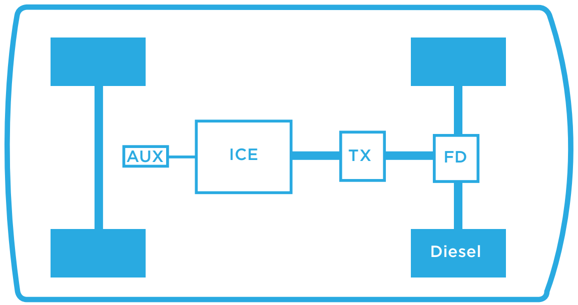

Figure 2: *Conventional diesel bus configuration*

SERIES ARCHITECTURE

In a series configuration **(Figure 3** and **Figure 4)**, the ICE never mechanically propels the vehicle; instead it runs a generator to produce electrical energy, which is then either delivered directly to the EM or sent to the energy storage system for later use (Lajunen, 2014; Mahmoud et al., 2016).

The main advantages of the series configuration include the freedom to place powertrain components almost anywhere within the chassis due to the absence of a physical mechanical link between the ICE and the wheels (Lajunen, 2014); and a more simplified energy management system, whereby the generator simply generates energy to replenish the electricity storage system, regardless of when that energy will be consumed by the vehicle

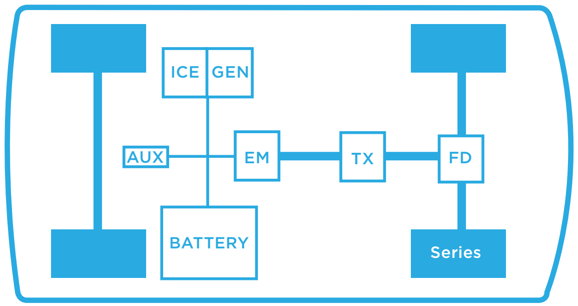

Figure 3: *Conventional series hybrid electric configuration*

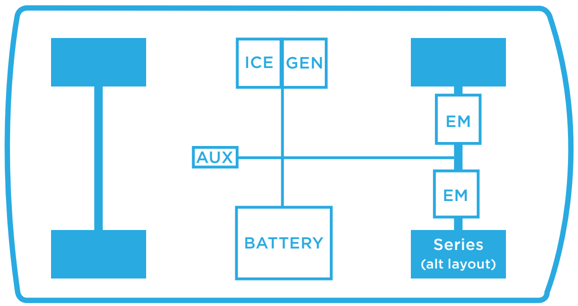

Figure 4: *Alternative series hybrid electric configuration*

2. OVERVIEW OF TECHNOLOGIES

(Lajunen, 2014). Varga et al. (2016) also notes the advantage of being able to position separate electric motors at each wheel delivering propulsion individually and removing the need for the final drive and transmission, as shown in **Figure 4**.

The series configuration has two inherent disadvantages. Firstly, the electric motor(s), must be capable of delivering enough power to run the bus under all operational conditions, as the ICE can never directly propel the bus (Varga et al., 2016). Secondly, the two instances of energy conversion in the series hybrid powertrain reduce overall energy efficiency (Varga et al., 2016); kinetic energy produced by the ICE is converted into electrical energy by the generator, which is then converted back into kinetic energy by the electric motor(s). The parallel configuration does not experience this energy inefficiency.

PARALLEL ARCHITECTURE

In the parallel hybrid drivetrain configuration, traction at the wheels can be delivered by either the EM, the ICE, or a combination of both, shown in **Figure 5**. Unlike the series configuration discussed above, the ICE cannot directly recharge the energy storage system. Instead, during deceleration and braking, the electric motor is run in reverse and the electric energy generated is stored in the on-board batteries. In other words, unless the vehicle is capable of plug-in charging, which would allow it to be charged from an external source, the only energy available for use by the electric motor, is that which is stored during regenerative braking.

There are several advantages to the parallel architecture compared to the series configuration. Most importantly, independent propulsion systems allow the use of a propulsion source appropriate to the surroundings (Lowry & Larminie, 2012). For example, a HEB with this configuration can use only the EM within the inner-city zones where reduced noise and air pollution are important, and can switch to using the ICE once outside of the inner city where faster acceleration and higher speeds might be important. The parallel system also allows for a smaller electric motor, because if the conditions require additional power beyond the capabilities of the EM, the ICE can support it by directly supplying power to the wheels. Limitations of the parallel configuration include the need to retain the mechanical connection between the ICE and the wheels and the inability to directly charge the battery from the ICE.

SERIES-PARALLEL ARCHITECTURE

The series-parallel hybrid, or mixed hybrid, combines the configurations of both the series and parallel architectures. As shown in **Figure 6,** the addition of a generator and electrical pathway linking the ICE and on-board battery allows for direct generation and storage of electricity, as occurs in the series hybrid architecture. Furthermore, a mechanical link from both the EM and ICE to the wheels allows vehicle propulsion to be supplied independently, as performed in the parallel configuration.

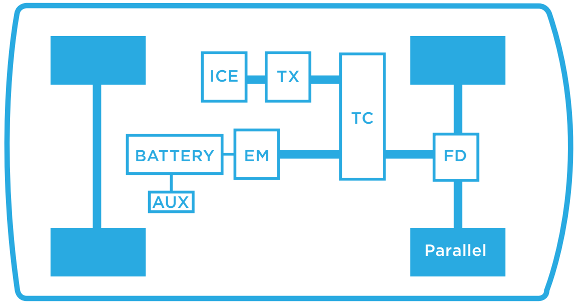

***Figure 5**: Parallel hybrid configuration*

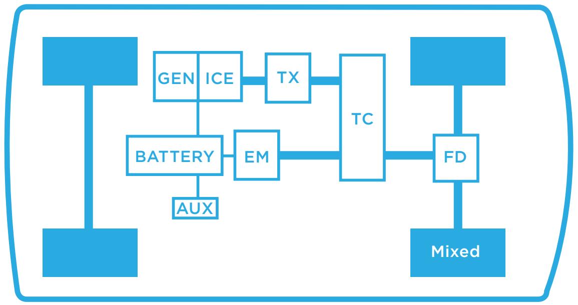

***Figure 6:** Mixed (series-parallel) hybrid configuration*

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2.1.2 *Degree of Hybridisation*

'Degree of hybridisation' is a term commonly used in discourse on hybrid electric vehicles, so it is useful to be aware of. Degree of hybridisation is used in literature to describe both the proportion of maximum vehicle power delivered by the EM (Lowry & Larminie, 2012), and the amount of hybrid technology (e.g. stop-start technology[5], regenerative braking, EM propulsion) incorporated in a vehicle (Cobb, 2014). These two definitions are essentially the same, as the more relative power produced by the EM, the more operational tasks it can perform. For example, hybrids with larger batteries and more powerful EMs that allow plug-in charging can rely more heavily on EM propulsion than other hybrids without these features. Alternatively, some modern hybrid electric vehicles with "micro" hybridisation may only use the EM to enable stop-start technology or to support the powering of on-board auxiliary devices and therefore provide no propulsion assistance (Cobb, 2014).

2.1.3 *Mechanisms for Improved Efficiency*

Hybrid electric vehicles improve energy efficiency in several ways. The presence of an on board battery and electric motor gives access to both regenerative braking and start stop technologies[5]. Using an ICE to drive a generator, instead of directly driving the vehicle, means that the ICE can be smaller and can be run at the optimal speed and load more often to improve efficiency. An on-board battery also gives the potential to incorporate plug-in charging technology to further increase the relative contribution of the electric motor (Cobb, 2014).

2.1.4 *Recent Developments in Hybrid Technology: Turbine Engines*

Wrightspeed, a US based company started by Tesla, co-founder Ian Wright, is producing serial hybrid electric motors that use an internal combustion turbine engine instead of the usual internal combustion reciprocating (piston) engine. Details from the Wrightspeed website claim their hybrids reduce fuel consumption by approximately 70% and reduce criteria pollutants by up to 90% ("Wrightspeed Powertrains Official Website," 2016). However, the validity of this data is unclear, as it has been released by the manufacturers and has not been independently verified.

Wrightspeed hybrid electric powertrains are designed for use in medium to heavy weight vehicles that perform frequent stop-starts and often operate at slow speeds. The technology has been applied to delivery trucks, garbage trucks, and buses; vehicles that often have poor fuel efficiency due to their slow speeds and stop-start operating conditions, while still being required to travel very large distances per day (Abuelsamid, 2016b). Wrightspeed claims that full battery electric technology is not a solution for this vehicle type due their high daily energy demand and inherent need to maximise vehicle carrying capacity; the large weight and volume of the required battery capacity for full electric propulsion would significantly reduce the performance and functionality of the vehicle (Abuelsamid, 2016b).

Their technology has been trialled by international companies such as FedEx and Mack (Abuelsamid, 2016b). NZ Bus signed a US$30m deal with Wrightspeed in early 2016. NZ Bus will be supplied with Wrightspeed hybrid systems to both refit their suspended electric trolley buses and convert existing conventional diesel bus systems (Abuelsamid, 2016a; Green, 2016). It will be interesting to observe the performance of this technology in a demanding New Zealand public transport context.

[5] *Stop-start technology refers to the ICE being automatically shut down when a vehicle is idle for a period of time.*

2.2 Fuel Cell Electric Buses

Fuel cells use a chemical reaction between stored hydrogen and ambient oxygen to create electricity. In the case of a hydrogen fuel cell, the general reaction is $2H_2 + O_2 \rightarrow 2H_2O$. There are a number of different types of fuel cells, but the following section will only discuss polymer electrolyte membrane fuel cells (PEMFCs), also referred to in some literature as proton exchange membrane fuel cells, as they are considered most appropriate for use in vehicle propulsion (Brandon, 2004; Lowry & Larminie, 2012).

Potential advantages and disadvantages of using polymer electrolyte membrane fuel cells (PEMFCs) for vehicle propulsion are outlined below.

ADVANTAGES

- ***Low tailpipe emissions***, at low operating temperatures[6], almost no criteria pollutants are created during vehicle operation (Lowry & Larminie, 2012).
- ***Increased availability***, theoretically, less maintenance should be required due to the absence of internal moving parts (Brandon, 2004; Mekhilef, Saidur, & Safari, 2012).
- ***Customisable power output,*** fuel cells can be coupled to easily customise the power output (Brandon, 2004).
- ***Long range***, hydrogen fuel cell vehicles do not suffer from the same range issues that currently restrict battery electric vehicles (Lowry & Larminie, 2012).

DISADVANTAGES

- ***Infrastructure***, extensive hydrogen storage and refueling infrastructure will be required to successfully incorporate FCEBs.
- ***High cost***, FCEBs are currently around seven-times more expensive than both DBs and electric buses (Mahmoud et al., 2016), and the cost of constructing a hydrogen refuelling station is approximately US$5 million (Eudy & Post, 2014b).
- ***System management,*** fuel cell components are very sensitive to heat changes, water concentration levels, and impurities within the hydrogen fuel. Poor management of these conditions can cause permanent fuel cell damage (Lowry & Larminie, 2012).
- ***Hydrogen density,*** hydrogen is less energy-dense than diesel, so more storage space is required to match the range of diesel buses.

[6] *If hydrogen is used as a fuel source at higher operating temperatures, the chemical reaction also produces criteria pollutants.*

2.2.1 Fuel Cell Configurations

Early FCEBs were configured with the fuel cell directly connected to the electric motor, shown in **Figure 7**. More recent FCEBs use a hybrid electric powertrain (Ammermann, Ruf, Lange, Fundulea, & Martin, 2015), which is similar to the series hybrid configuration discussed in Section 4.1.1, replacing the ICE with a fuel cell. **Figure 8** shows the hybridised fuel cell configuration. Advantages of the fuel cell hybridisation include a reduction in the required size of the fuel cell stack (which reduces the cost), and access to regenerative braking technology to increase fuel efficiency (Ammermann et al., 2015; T. Hua et al., 2014).

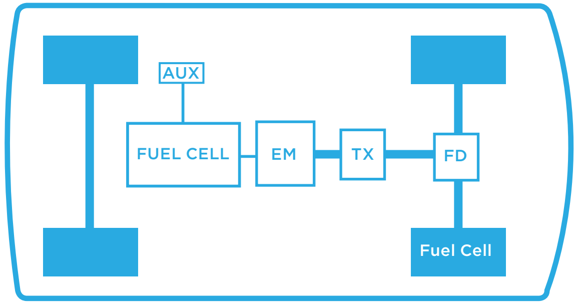

***Figure 7**: Early fuel cell electric bus configuration*

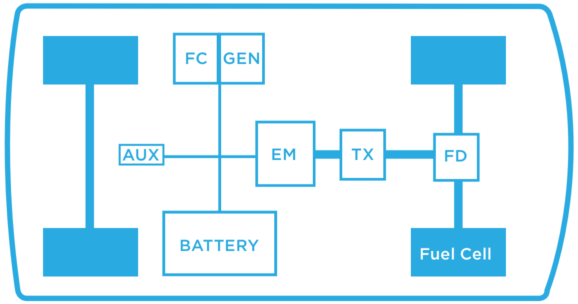

***Figure 8:** Hybridised fuel cell electric bus configuration*

2.2.2 Competing Technology: Hydrogen as a Fuel Source for Internal Combustion Engines

Hydrogen fuel can be combusted in an ICE, instead of petrol or diesel, to directly create kinetic energy. Due to the higher operating temperature of ICE's, the emissions of this process are slightly different to hydrogen fuel cells; the tailpipe pollutants will include small amounts of NOx (Lowry & Larminie, 2012). Direct combustion of hydrogen is relatively clean, and the ICEs are much cheaper and lighter than fuel cells. Hydrogen combustion in ICEs can also use impure hydrogen fuel (Pearson, Leary, Subic, & Wellnitz, 2011).

Despite the aforementioned advantages of hydrogen combustion engines, fuel cells generally continue to be preferred due to their potential to achieve much higher energy efficiencies (Lowry & Larminie, 2012). Fuel cells are able to achieve higher efficiencies because of their lower operating temperatures (Pearson et al., 2011). It is also expected that over time, the durability, weight, and cost of fuel cells will continue to improve.

While the hydrogen combustion engine concept is a feasible one, it is unlikely to become a commercial reality for two main reasons. Firstly, the low maximum efficiency of the ICE would require a very large on-board hydrogen storage space to achieve the normal daily distances travelled by current public transport buses. Secondly, hydrogen fuel is very expensive; without the increased fuel efficiency offered by fuel cells (or a significant reduction in the cost of hydrogen,) hydrogen ICEs would have very high operating costs.

2.3 Battery Electric Buses

Full battery electric buses (BEBs) store all required energy in an on-board battery. Energy is transferred to the vehicle via electric charging systems, while regenerative braking is used to recover kinetic energy during operation.

2. OVERVIEW OF TECHNOLOGIES

Outlined below are some advantages and disadvantages specific to BEBs, beyond the general advantages and disadvantages of all types of electric buses, which were mentioned at the start of Section 4.

ADVANTAGES

- ***No tailpipe emissions,*** and very low overall emissions if renewable energy sources are used.
- ***Efficient***, very high vehicle energy efficiency of the electric motor.
- ***Reduced operating cost,*** based on current electricity prices, the cost of operating BEBs would be much cheaper than DBs. This is true even if the current fuel tax was added to the electricity price.

DISADVANTAGES

- ***Low distance range,*** current BEBs are limited to a reasonably small distance range. The effects of this can be reduced by rapid-charging on-route.
- ***Heavy***, current batteries are heavy, adding to the weight of the bus, potentially limiting what roads they would be able to operate on.
- ***Capacity***, the increased weight means the vehicle capacity is reduced to stay below maximum axle weight limits.
- ***Infrastructure***, BEBs require charging infrastructure (either at depots, bus stops, or both).

2.3.1 Battery Configurations

The energy for a BEB is stored in a battery (or ultracapacitor) to be supplied to the electric motor, as shown in **Figure 9**. The potential to replace the final drive and transmission with separate EMs at either wheel was discussed in Section 4.1.1, and is applicable for BEBs as well. There are three types of batteries commonly used in BEBs: lithium iron phosphate, lithium-titanate, and nickel cobalt manganese lithium-ion (commonly shortened to NCM Li-ion). Volvo and BYD use lithium iron phosphate batteries in their BEBs; Proterra uses lithium-titanate; VDL Bus and Coach use NCM Li-ion (Thorpe, 2016).

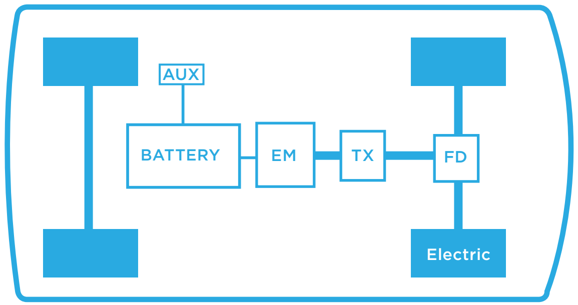

Figure 9: *BEB configuration*

2.3.2 *Battery Electric Bus Categories*

BEBs can be divided into two categories based on their range and charging routine. The first category is the opportunity BEB, which has a shorter range and can be rapidly charged throughout the day, at convenient 'opportunities'. The second category is the overnight BEB, which has a longer range to complete a day's service, and is slowly charged overnight.

Opportunity BEBs have a shorter range than overnight BEBs, usually 30-70 km, and can often recharge 80-100% in five to ten minutes (Mahmoud et al., 2016).

Overnight BEBs are charged slowly overnight, and might also make use of some opportunity charging throughout the day. Proterra[7], a U.S. BEB manufacturer, claims that its longest range BEB, the E2 max, has a nominal range of 560km and a charge time of five hours. This Proterra BEB range is not independently verified and BEB ranges can vary greatly under different operating conditions; air conditioning load, average passenger volume, stopping frequency, driver behaviour, and route gradient are just a few examples of factors that can greatly affect a bus's energy consumption and potentially significantly reduce its overall range.

In practice, the range of a BEB is governed by the design choices of the manufacturer. A BEB can be designed to have any reasonable range by installing different batteries. The two main consequences of increased range (by increasing battery size) are increased vehicle purchase price and increased vehicle mass. The latter is of particular concern as it reduces both vehicle passenger capacity and vehicle energy efficiency. This will be discussed in more detail in Section 5.

2.4 *Ultracapacitor Electric Buses*

This section will give a brief description of ultracapacitor (also known as super-capacitor) use in electric buses. Relative to other advanced electric bus technology such as BEBs and FCEBs, there is little published material about ultracapacitor buses. For this reason, the technology will not be discussed elsewhere in this report.

Ultracapacitors can be used in hybrid systems as the energy storage system alongside an ICE or a fuel cell, and they are often desirable for this purpose as they charge quickly (Bubna, Advani, & Prasad, 2012). However, they can also be used as the sole source of on-board energy, and can be recharged at charging stations, similar to opportunity BEBs (Hamilton, 2009).

Ultracapacitors have similar features to batteries in general, however the different technology requires it to be considered separately. The advantages and disadvantages of ultracapacitors are noted here, alongside the general advantages and disadvantages of all electric buses that were mentioned at the start of Section 4.

ADVANTAGES

- ***No tailpipe emissions,*** and low overall emissions if original energy sources are renewable.
- ***Fast charging***, ultracapacitors can be rapidly charged without decreasing their overall capacity (Benz, 2015).
- ***Long life time,*** ultracapacitors can be discharged and recharged many times without degrading their capacity (Chandramowli, 2014).

[7] *Founded in 2004 in Colorado, USA, Proterra produce both short and long range BEBs. Their current models are either 35-foot (10.7m) or 40-foot (12.2m) buses. Proterra uses carbon-fibre-reinforced composite materials to produce the bus body as opposed to steel framing, which is used by other bus manufacturers. This reduces vehicle weight and increases the lifetime of the vehicle body ("Proterra official website," 2016).*

DISADVANTAGES

- ***Short range,*** ultracapacitors discharge quickly, so have a small range, however this feature of them also enables them to be recharged very quickly (Benz, 2015).
- ***Infrastructure,*** because ultracapacitors have a short range, they need to be recharged often, so significant infrastructure is required before they can be deployed on any route.
- ***Not flexible,*** as ultracapacitors need to be recharged often, the locations of the charging infrastructure limit what routes the buses can follow.

Operational buses that use ultracapacitors as their sole energy-source recharge regularly throughout a route. The common charging mechanism involves a boom (pantograph) on the roof of the bus which connects with fixed catenary wires positioned above bus stops (Chandramowli, 2014). Despite the ultracapacitors not being capable of storing a large amount of energy, their charge times are relatively very fast (Hamilton, 2009). A charge time of 30-90 seconds can give a bus enough charge to travel a further 5-10 km (Chandramowli, 2014), although some bus manufacturers claim even faster charge times than this (Howe, 2015).

3. PERFORMANCE OF ALTERNATIVE BUS TECHNOLOGIES

3.1 Economic Performance

This section will discuss the economic performance of different types of electric buses, using DBs as a comparison. Economic performance will be assessed across five categories: purchase price, maintenance costs, operating costs, infrastructure costs, and total cost of ownership (TCO). Costs considered in bus TCO include the aforementioned costs, as-well-as other costs such as insurance, emission penalties, vehicle taxation, and end-of-life (vehicle resale value) (Mahmoud et al., 2016).

Much literature on electric buses suggests that over the vehicle lifetime, electric buses are more expensive to operate than diesel buses (Ally & Pryor, 2016; Mahmoud et al., 2016; Williamson, 2012). However, these findings are sensitive to factors such as advances in electric bus technology, changes to fuel prices, perceived value of energy security, and emission taxes. It seems widely accepted that given current trends, electric buses will hold a cost advantage over DBs in the future (Ally & Pryor, 2016). Increased investment in electric buses globally, such as the US$30m NZ Bus deal with Wrightspeed hybrid technology, and documented examples of well-designed electric bus demonstration projects, such as the Milton Keynes electric bus project (see Section B.1), suggests that electric bus solutions are becoming commercially viable options for public transport companies.

Much of the costing data discussed in this section comes from a journal article authored by Mahmoud and colleagues (2016). The article presents average costing data on electric buses, collected from a range of published sources. While this costing data helps to give an indication of the relative economic performance of different electric buses, specific information about the original sources and how the costing data was created is hidden from readers of this report. This includes any assumptions, data generation methodologies, author bias, and operational contexts. For this reason, care should be taken when interpreting the generalised economic findings below.

3.1.1 Hybrid Electric Bus Costs

HEBs are the cheapest of all types of electric buses, and are around 50% more expensive than DBs (Mahmoud et al., 2016). They usually have increased fuel efficiency and therefore reduced running costs (Mahmoud et al., 2016). The amount of increased fuel efficiency varies across different publications and is likely the result of HEB experimental data being collected from different operational contexts; different bus service routes, stages of technology development, degrees of hybridisation, different comparison DBs, or different hybrid configurations can all cause variations in fuel efficiency. Mahmoud and colleagues (2016) wrote that HEBs achieve an average well-to-wheel (WTW) energy loss of 22-26%. However, there have also been instances where comparative trials found HEBs had higher energy consumption; a 2011-2012 Sydney trial found the tested HEB to have a 4% increase in fuel consumption when compared with an advanced diesel technology control vehicle (Williamson, 2012).

Mahmoud and colleagues (2016) also state that the maintenance costs of HEBs are slightly lower than DBs, but more expensive than BEBs and FCEBs. However, Ally and Pryor (2016) claim that HEBs will have higher maintenance costs (almost double that of DBs) due to the high cost of replacement parts and the addition of battery servicing costs.

HEBs have the same infrastructure costs as DBs because there are no additional infrastructure requirements, assuming plug-in technology is not used (Mahmoud et al., 2016). As shown in **Table 3**, the average TCO of HEBs is slightly higher than DBs, at 2.85 US$/km and 2.98 US$/km for parallel and series HEBs respectively (Mahmoud et al., 2016).

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Powertrain	Configuration	Unit price $	Maintenance cost $/km	Running cost $/km	Infrastructure cost $/km	TCO $/km
ICE	Diesel	280,000	0.38	0.8	0.04	2.61
HEB	Series	410,000	0.24	0.68	0.04	2.98
HEB	Parallel	445,000	0.26	0.76	0.04	2.85

Table 3: *Average costs of electric buses in published articles[8]*

Ally and Pryor (2016) give a more in-depth analysis of HEB TCO in an Australian context. Their study[9] used operational data from a HEB in Perth. The study found the TCO of HEBs to be almost AU$90,000 higher than DBs; an increase of 11%. It was stated that the TCO of DBs and HEBs converged when the fuel efficiency of HEBs increased by 43%, or when diesel prices reached 3.20 AU$/L[10], a value 2.5 times higher than current retail diesel prices in Australia[11] (Ally & Pryor, 2016). These results were echoed in another Australian study[12] which took operational data from a HEB used in the Sydney public transport network. The Sydney study (Williamson, 2012) found the TCO of the HEB to be $114,000 greater than that of the control DB despite the HEB having 15% better fuel efficiency.

3.1.2 Battery Electric Bus Costs

Published data suggests BEBs have nearly twice the purchase price of DBs with the overnight BEB being more expensive than the opportunity BEB due to its much larger battery capacity (Mahmoud et al., 2016). Mahmoud and colleagues (2016) suggested that BEBs have the lowest maintenance and running costs as there are fewer complexities in the system than in ICEs for DBs. However, caution should be taken when interpreting this statement.

Firstly, the running costs will be highly dependent on context, particularly the relative diesel and electricity prices. For example, a comprehensive U.S. assessment of Foothill Transit's BEBs found the per kilometre energy costs of the BEBs to be 70% higher than the CNG fuelled control buses, despite the BEBs having an operational energy efficiency four times greater than the CNG buses (Eudy, Prohaska, Kelly, & Post, 2016). Secondly, the lower maintenance costs of BEB demonstration projects may be distorted by significant amounts of servicing and replacement parts that is unaccounted for, as they are covered under warranty (Eudy, Prohaska, et al., 2016).

BEBs have very large infrastructure costs due to requiring overnight and/or opportunity charging stations. For opportunity BEBs, the number of on-route charging stations depends on the vehicle's battery capacity and the route used (Mahmoud et al., 2016). For example, charging infrastructure for the Milton Keynes BEB project (discussed in Section B.1) consisted of two road-surface inductive charging platforms, placed 25 km apart and an overnight charging system at the depot (Miles & Potter, 2014). Over the vehicle lifetime, Mahmoud and colleagues (2016) suggest that BEBs are 1.5 times (opportunity BEBs) or 2.6 times (overnight BEBs) more expensive to operate than DBs.

[8] Values are documented averages, compiled by Mahmoud and colleagues (2016) from a variety of sources. $ = USD.

[9] The Perth CAT study assumed an operational lifetime of fifteen years and a yearly bus travelling distance of 30,000 km.

[10] Ally and Pryor's (2016) study found HEBs to have significantly higher maintenance costs. If HEB maintenance costs were set to be equal to DBs, the TCOs for HEBs and DBs converged at a diesel price of 1.95 AU$/L.

[11] The average weekly retail price for diesel fuel in Australia, during the week ending January 8th, 2017, was 1.28 AU$/L.

[12] The Sydney study assumed an operational lifetime of twenty-five years and a yearly bus travelling distance of 70,000 km.

3.1.3 Fuel Cell Electric Bus Costs

FCEBs have high costs across all economic performance categories and over the vehicle lifetime are one of the most expensive electric buses to operate (Mahmoud et al., 2016). Average published maintenance costs were higher for FCEBs than all other vehicle types. Similarly, infrastructure costs were higher than all vehicle types except opportunity BEBs (Mahmoud et al., 2016). These high costs are likely due to the need for hydrogen servicing and refuelling facilities[13], the high cost of fuel cell parts, and the early stage of development of fuel cell technology. While Mahmoud and colleagues (2016) suggested that the running costs of FCEBs were slightly lower than that of DBs and HEBs, the findings from two U.S. FCEB case studies did not agree with this result; one of these case studies found the per kilometre fuel costs for FCEBs to be more than three-times greater than that of DBs, which reflected the much greater cost of hydrogen over conventional fossil fuels (Eudy, Post, & Matthew, 2016).

FCEBs have very high initial purchase prices. North American case studies from the last five years quoted purchase prices of US$2,400,000 and US$2,100,000 (Eudy & Chandler, 2013; Eudy & Post, 2014b). Ally and Pryor (2016) gave a more conservative FCEB unit price of AUS$1,315,789 (approximately US$980,000 at current exchange rates). In Europe, FCEBs produced in 2010 had purchase prices ranging from US$1,433,000 to US$2,150,000[14] (T. Hua et al., 2014). While historical purchase prices have been very high, a 75% decrease in FCEB purchase price was observed between 1990 and 2015 (Ammermann et al., 2015). If current target prices are achieved, the next generation of FCEBs in the U.S. and Europe would have purchase prices of US$1,000,000 (T. Hua et al., 2014) and US$700,000 (Pocard & Reid, 2016) respectively, which would have significant impacts on the TCO of FCEBs.

Findings from the Perth study found the TCO of a FCEB to be AU$1.3m or 2.6 times greater than that of a diesel bus (Ally & Pryor, 2016). If the 2020 performance and cost targets set by the U.S. Department of Energy for hydrogen fuel cell technology are achieved, this difference would be significantly reduced. Under the Department of Energy targets, a FCEB would have a TCO AU$420,000 higher (only 1.5 times greater) than the current DB TCO.

Despite the current high cost of FCEBs, there is an increasing global investment in the development and deployment of FCEBs (T. Hua et al., 2014). As of 2014, 100 FCEBs were in operation in demonstration projects around the world (T. Hua et al., 2014). The persistent interest in fuel cell systems, undeterred by its relatively high cost, is likely because of inherent advantages of fuel cells over other electric bus systems; FCEBs have long range potential, reasonably short refuelling times, near zero local emissions and do not require on-route infrastructure (Ammermann et al., 2015). Furthermore, clean hydrogen production via water electrolysis can integrate well with renewable electricity generation.

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[13] *Around US$5 million for just one hydrogen storage and refuelling facility (Eudy & Post, 2014b).*
[14] *Converted from prices given in EUR using a January 1st, 2010 exchange rate of 1.433 USD/EUR.*

3.1.4 Economic Performance Sensitivity

A number of studies (Mahmoud et al., 2016; Nurhadi, Borén, & Ny, 2014) have noted the high sensitivity of electric bus TCO to changes in the predicted values used for the different parameters. Nurhadi and colleagues (2014) found that distance travelled per year, retirement age, purchase price, and maintenance costs were the four most influential factors (listed from most to least influential) affecting electric bus TCO. To demonstrate the different degrees in sensitivity, consider the following changes to the TCO for an overnight BEB: a decrease in BEB yearly mileage of 10-30% leads to an increase in BEB TCO of 13-30%; whereas an increase in electricity costs of 10-30% results in an increase in BEB TCO of only 2-4% (Nurhadi et al., 2014). Other TCO sensitivities are presented in **Table 4**.

Factor	% Change in factor cost	TCO of overnight BEB
Bus purchase cost	+ (10 to 30%)	+ (5 to 14%)
Yearly distance travelled	- (10 to 30%)	+ (13 to 30%)
Years in service	+ (10 to 30%)	- (8 to 34%)
Electricity cost	+ (10 to 30%)	+ (2 to 4%)
Maintenance costs	- (10 to 30%)	- (2 to 5%)

Table 4: *Overnight BEB TCO sensitivity to parameter adjustments (Nurhadi, Borén, & Ny, 2014)*

3.2 Operational Assessment

3.2.1 Hybrid Electric Buses

HEBs can achieve a similar range to DBs if they have a similar sized fuel tank. They also require no additional infrastructure, unless plug-in hybrid systems are used, in which case charging infrastructure gives valuable benefits. The similar range capacity and lack of required additional infrastructure make the transition from DBs to HEBs an easy transition within existing networks. One operational disadvantage of using HEBs instead of conventional DBs is the increased vehicle kerb weight which may decrease bus passenger capacity (Varga et al., 2016).

3.2.2 Battery Electric Buses

One of the main barriers to BEB usage in existing DB public transport networks, is the trade-off between vehicle range and weight (Mahmoud et al., 2016; Miles & Potter, 2014). BEB range is mainly determined by on-board battery capacity. Increasing the battery capacity results in an increased range, however this also increases the vehicle cost, increases kerb weight, and decreases passenger capacity (due to the maximum axle weight limits on roads). On the other hand, BEBs with a reduced battery capacity will generally require more charging infrastructure, which causes additional costs and barriers.

If a BEB has sufficient range for their daily service, they only require overnight charging stations, whereas an opportunity BEB needs charging stations throughout its route as well as possibly requiring overnight charging capacity at the depot. Opportunity charging can restrict operational capabilities (Benz, 2015); opportunity BEBs are restricted to routes where charging systems are installed, and in service charging times must be factored into bus schedules and may lead to additional service disruptions.

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There are several different charging systems available for BEBs including overhead systems, direct plug-in systems, and inductive energy transfer (Mahmoud et al., 2016). Plug-in systems are relatively low cost and are common for overnight charging, but are cumbersome for regular opportunity charging scenarios. Inductive energy transfer is more effective for opportunity charging; it is easy to use, requires low driver responsibility, and is aesthetically unobtrusive when installed at bus stops. However, there are energy losses incurred through induction that reduce the overall well-to-wheel energy efficiency of the vehicle (Benz, 2015). Burst charging at bus stops, with longer charging at bus depots and layover points has been employed using overhead wires and pantographs by ABB and in a joint venture between Siemens and Rampini (Benz, 2015), and is a common system for ultracapacitor buses. The disadvantage of this type of system is that it requires a lot of infrastructure (Benz, 2015). Another type of overhead system lowers a charger head to meet a contact point on the bus's roof. This type of system is used by Proterra's opportunity BEBs (Ruoff, 2016).

Battery swapping technology is also mentioned in discourse whereby depleted on-board batteries would be removed from the vehicle and replaced by fully-charged batteries during daily operation (Mahmoud et al., 2016). If this system were optimised for speed, it could allow an in-service bus to operate over large daily distances, without the need to either regularly charge the batteries during service, or carry sufficient battery capacity for an entire day's service. However, BEB batteries are large, very heavy, and often stored in several different places throughout the bus. Therefore, comprehensive infrastructure would be required to quickly replace the batteries in an in-service bus, and it is generally agreed that this solution may be infeasible.

Overloading of the local electricity grid is another infrastructure challenge that arises through BEB implementation, especially if large numbers of opportunity BEBs are used in one area (Mahmoud et al., 2016). Energy delivery speeds will also require ongoing development to see BEBs become more appealing. While charger power ratings continue to increase with time, the charge times of most BEBs are still much slower than the diesel refuelling times of conventional buses.

3.2.3 *Fuel Cell Electric Buses*

To achieve large ranges, FCEBs require a very large fuel storage space to account for the much smaller energy density of hydrogen, despite it having around three times the specific energy (energy per unit mass) of diesel (Elert, 2017). The FCEBs operating in Whistler, Canada, carried 56kg of hydrogen and had an average range of 360km[15] (Eudy & Post, 2014b). FCEBs from a Portland trial (the Zero Emission Bay project) had greater average fuel efficiency[16] than the Whistler buses, travelling approximately 350km[17] on just 40kg of hydrogen (Eudy, Post, & Matthew, 2016). 40kg of hydrogen at 5000 psi requires a storage capacity of approximately 1400 litres[18] (1.4m3), not including the tank wall thickness, valves, or any other components[19]. On-board storage of hydrogen in liquid form would reduce the hydrogen volume by more than half to 565 litres (U.S. Department of Energy, 2015), but liquid hydrogen still falls well short of the energy density of diesel.

Based on the Portland trial, a FCEB requires at least 565 litres of tank space to be capable of travelling 350km, while the control diesel buses in the same study required a tank size of just under 200 litres to achieve the same range[20].

[15] *Range calculated using the Whistler FCEB fleet's average energy efficiency of 15.48 kg / 100 km and total on-board hydrogen capacity of 56 kg (Eudy & Post, 2014b).*
[16] *Reduced average fuel efficiency of the Whistler fleet (compared to the Portland fleet) is possibly due to more demanding operating conditions. Suggested factors include, colder winter temperatures, greater cumulative elevation gain, higher average ridership.*
[17] *Range calculated using the Portland FCEB fleet's average energy efficiency of 11.36 kg / 100 km and total on-board hydrogen capacity of 40kg.*
[18] *Calculated using volumetric data on hydrogen gas at room temperature from the U.S. Department of Energy website (U.S. Department of Energy, 2015) and the ideal gas law (PV = nRT).*
[19] *Hau and colleagues (2010) state that 24% of the volume of a type III, 6kg hydrogen storage tank, is made up by tanks materials other than the gas itself.*
[20] *The control Gillig diesel buses had an average fuel economy of 55.3 L/100km. The FCEBs have an average range of 352km.*

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Some early generation FCEBs stored on-board hydrogen in liquid state[21], but due to the extreme low temperatures required to store liquid hydrogen, recent models have preferred gaseous hydrogen (Rose, Gangi, & Curtin, 2013). On-board storage pressures for gaseous hydrogen range from 200 to 450 bar (2900 to 6527psi respectively) (Rose et al., 2013). Hydrogen storage at greater pressures or in liquid form would reduce the amount of on-board storage space required for fuel, however the expected improvements to fuel cell efficiency could avoid such changes being necessary. The FCEBs in the Portland trial had an average fuel consumption of 11.36 kg/ 100 km, while the next generation of FCEBs are expected to be capable of achieving an average fuel consumption of just 8 kg/100 km (T. Hua et al., 2014). If the Portland FCEBs were capable of this fuel consumption, their level of hydrogen storage would give them a range of about 500 km.

Large vehicle weights are another operational disadvantage for FCEBs. As discussed for both HEBs and BEBs, increased bus kerb weight reduces passenger carrying capacity due to the maximum axle weight limits on roads. The kerb weights of FCEBs can exceed that of DBs by 2.5 tonnes or more (T. Hua et al., 2014). Assuming the kerb weight of a 12 metre DB to be approximately 12 tonnes[22], the Portland and Whistler FCEBs were 2.2 tonnes and 3.5 tonnes heavier than this (Eudy & Post, 2014b; Eudy, Post, et al., 2016). Hua and colleagues (2014) suggest that FCEB kerb weights will eventually match that of conventional buses as fuel economy increases (reducing the weight of the fuel and its storage tanks) and design improvements reduce the weight of the vehicle powertrain.

Hydrogen distribution, storage, and refuelling infrastructure is an additional operational requirement for FCEBs. Some FCEB studies also discuss local or on-site hydrogen production from either water electrolysis (Ally & Pryor, 2016; Eudy, Post, et al., 2016) or through natural gas using steam reforming (Eudy & Chandler, 2013). The fuelling stations in the U.S. and Canadian FCEB studies we have explored have purchased liquid hydrogen from external producers (Eudy & Post, 2014b; Eudy, Post, et al., 2016). The supplied fuel remained in liquid form on-site, with conversion to intermediate, low capacity gaseous storage taking place prior to delivery to the buses.

Figure 10: *Image showing rooftop gaseous hydrogen storage (Pocard & Reid, 2016)*

[21] *Trials using liquid on-board hydrogen storage included: Lisbon, Portugal, 2002-2003; Copenhagen, Denmark, 2002-2003; Berlin, Germany, 2002-2003; Berlin, Germany, 2006-present (Rose, Gangi, & Curtin, 2013).*
[22] *Public transport DB kerb weights for a set of bus models ranged from 11.45 to 12.82 tonnes (Varga et al., 2016).*

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FCEB fuelling times can be slow. The fuelling station for the SunLine FCEBs had a hydrogen delivery rate of just under 1 kg per minute (Eudy & Chandler, 2013). At this fuelling rate, refuelling a FCEB with a range of 400km would take 39 minutes[23], while refuelling a DB to achieve the same range takes less than two minutes[24]. The U.S. Department of Energy's FCEB targets includes an ultimate hydrogen delivery target of less than 10 minutes (Spendelow & Papageorgopoulos, 2012). A delivery rate close to this target has been achieved in at least one operation; the Whistler (Canada) FCEBs achieved an average hydrogen delivery rate of 5kg/min (T. Hua et al., 2014). While the hydrogen delivery times in both the Whistler and SunLine projects are still much faster than the recharging times of current BEBs, they are much slower than is achievable with DBs, so staffing and infrastructure requirements for refuelling would increase if transitioning to FCEBs.

3.2.4 *Impact of Increased Vehicle Mass*

To illustrate the importance of keeping the mass of a bus as low as possible, consider the following comments:

- Proterra's shortest range (40-foot) BEB has a manufacturer's specified nominal range of almost 80 km and a kerb weight of almost 12,000 kg (Proterra, 2016).
- Proterra's longest range (40-foot) BEB has a manufacturer's specified range of 560km and a kerb weight of 15,000 kg.
- New Zealand heavy rigid-vehicle mass limits specify a single, large-tyred axle limit of 7,200kg and twin-tyred axle limit of 8,200kg (Land Transport NZ, Ministry of Transport, & NZ Transport Agency, 2002). This axle set gives a combined limit of 15,400 kg.
- Given these axle limits[25], the long range Proterra BEB mentioned above would only be able to carry six adults on New Zealand roads. The shortest range Proterra BEB would have a maximum passenger loading of 52 adults[26], which is still low compared to the passenger limits of DBs in New Zealand.

Australia has a considerably higher axle limit of 17,500kg for two axle buses (National Heavy Vehicle Regulator, 2016). Under Australian legislation, the two Proterra buses would have maximum passenger capacities of 38 and 84 passengers.

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[23] *Fuel consumption and refuel time calculation for the American Fuel Cell Bus (AFCB) Project's FCEB with a range of 400km uses the following parameters: fuel consumption of 0.095 kg/km, refuelling time of 1.031 min/kg.*

[24] *Ou and colleagues (2010) stated the average fuel economy of a DB is 45 litres/100km. U.K. law allows heavy vehicle, diesel pump flow rates of up to 130 litres/min (Department for Business Innovation and Skills, 2011). We have assumed a lower pump flow rate of 90 litres/min to estimate the DB refuelling time.*

[25] *Under New Zealand legislation, a single large-tyred axle (SL axle) has tyre dimensions of at least 330mm width by 24-inch diameter (NZ Transport Agency, 2013). The bus tyre dimensions specified on the Proterra website (2016) have a width of 305mm and diameter of 30.9 inches. To meet the SL axle minimum tyre width parameter, it is assumed that marginally wider tyres would be fitted to the Proterra buses.*

[26] *In the appropriate calculations in this section, the assumed mass of each passenger is 65 kg. This matches the 1989 Australian Design Rules (ADR) specification used to calculate Australian bus passenger capacities (National Transport Commission, 2014).*

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In 2015, a law was passed to increase the Californian axle weight limits for buses. Among other reasons, this was done to allow electric buses with increased kerb weight to operate at full capacity, encouraging investment in electric bus technology and driving further electric bus development (Shaw, 2015). The normal dual tyre axle limit in California is 20,500lb (9,300kg) per axle. An increased limit of 25,000lb (11,340kg) per dual tyred axle was provided for zero-emission buses purchased between January 1, 2016 and December 31, 2017. This increased limit will be reduced in stages, to reach a limit of 22,000lb (9,979kg) per dual tyred axle for zero-emission buses procured after January 1, 2022.

Figure 11 shows the kerb weights and ranges for a variety of electric and diesel buses. Notice that the BEBs, FCEBs, and HEBs are all significantly heavier than the DBs, with the exception of the shortest range BEB. It must be stressed that the values presented here came from a variety of sources and contexts; comparisons between models of buses may not be entirely appropriate, however a general understanding of the differences can be gained from this chart.

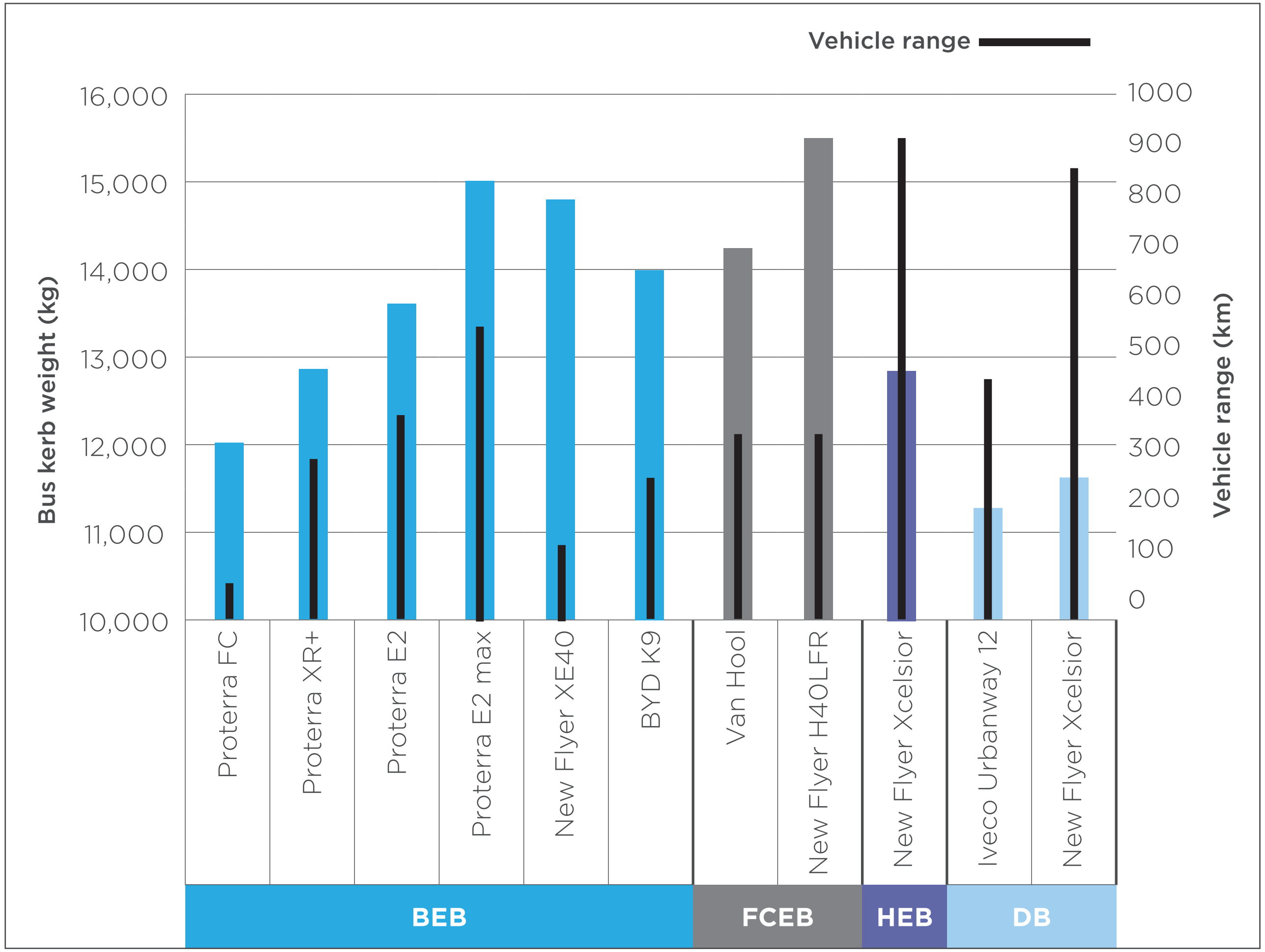

Figure 11: *Bus kerb weight and range*[27]

[27] The data for the New Flyer XE40 was obtained from a comprehensive, independent, vehicle test and is for a vehicle produced in November 2013 (Bus Testing and Research Center, 2015). The Proterra and BYD BEB bus data is from the manufacturers' websites and is for their 2016 model vehicles (BYD, 2016; Proterra, 2016).

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Figure 12 shows bus passenger capacity[28] for the same buses presented in **Figure 11** under New Zealand, Australian, and Californian bus axle limits. The capacities were calculated using bus kerb weights and an assumed average adult weight of 65kg (National Transport Commission, 2014).

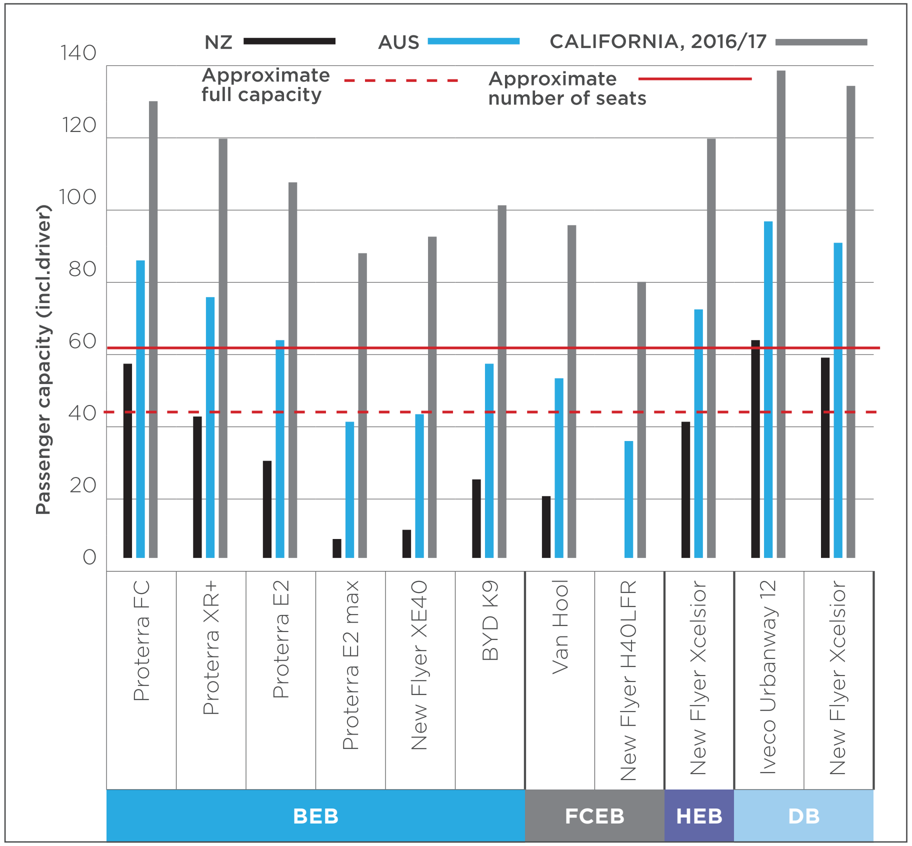

Figure 12: Adult passenger capacity under various axle limits, including benchmark of approximate capacity [29]

Figure 13 presents the required increase in axle limits for the same electric buses and DBs to operate at full capacity in Australia and New Zealand. **Figure 13** demonstrates that axle weight limits on New Zealand and Australian roads need to be relaxed before most current generation electric buses can operate alongside conventional bus technology.

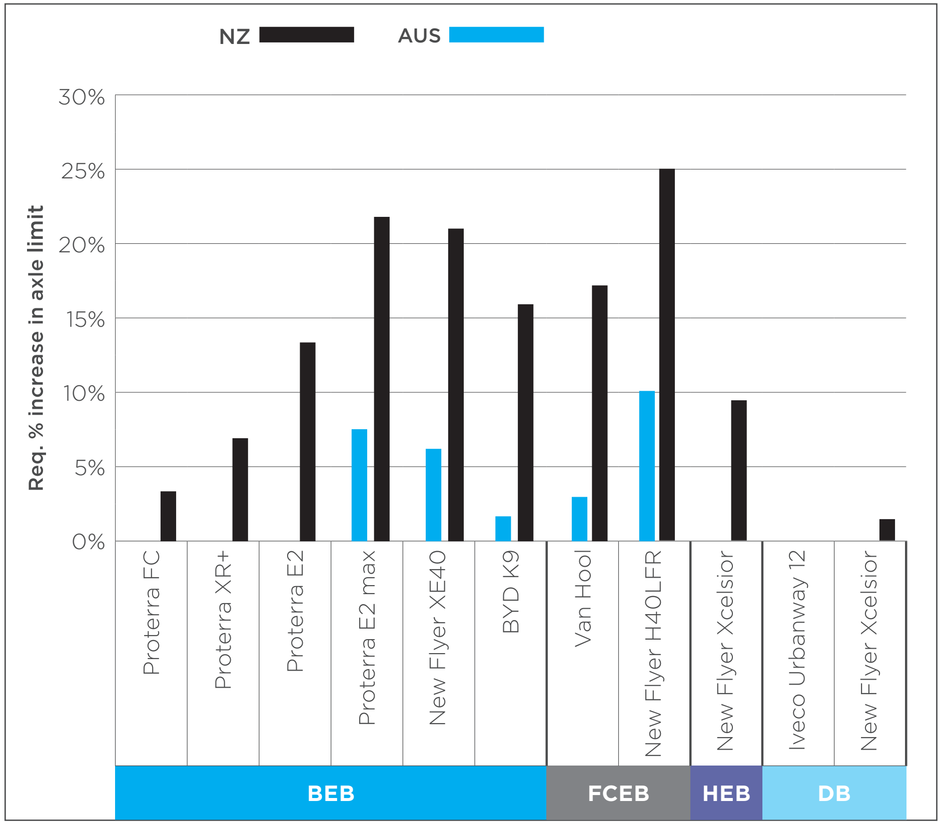

Figure 13: Required increase in axle limits for buses to operate at full capacity in Australia and New Zealand[29]

[28] *Assuming full capacity of a 12 metre or 40 foot bus to be 58 adults, including the driver.*

[29] *Assuming all 40-foot or 12 metre buses presented have a single tyre steering axle, a dual tyre rear axle, and a capacity of 58 passengers including the driver (approximately 40 seated and 18 standing).*

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Figure 14 combines much of the data presented in the previous vehicle range and weight graphs. Here it can be seen that only the DBs and Proterra FC could legally operate at near-full capacity on NZ roads. With the higher Australian axle limits, the DBs, HEBs, and short range BEBs can legally operate at full or near-full capacity. Only in California, with the significantly relaxed axle weight limits for zero-emission buses, can the longer range BEBs and FCEBs operate at full capacity.

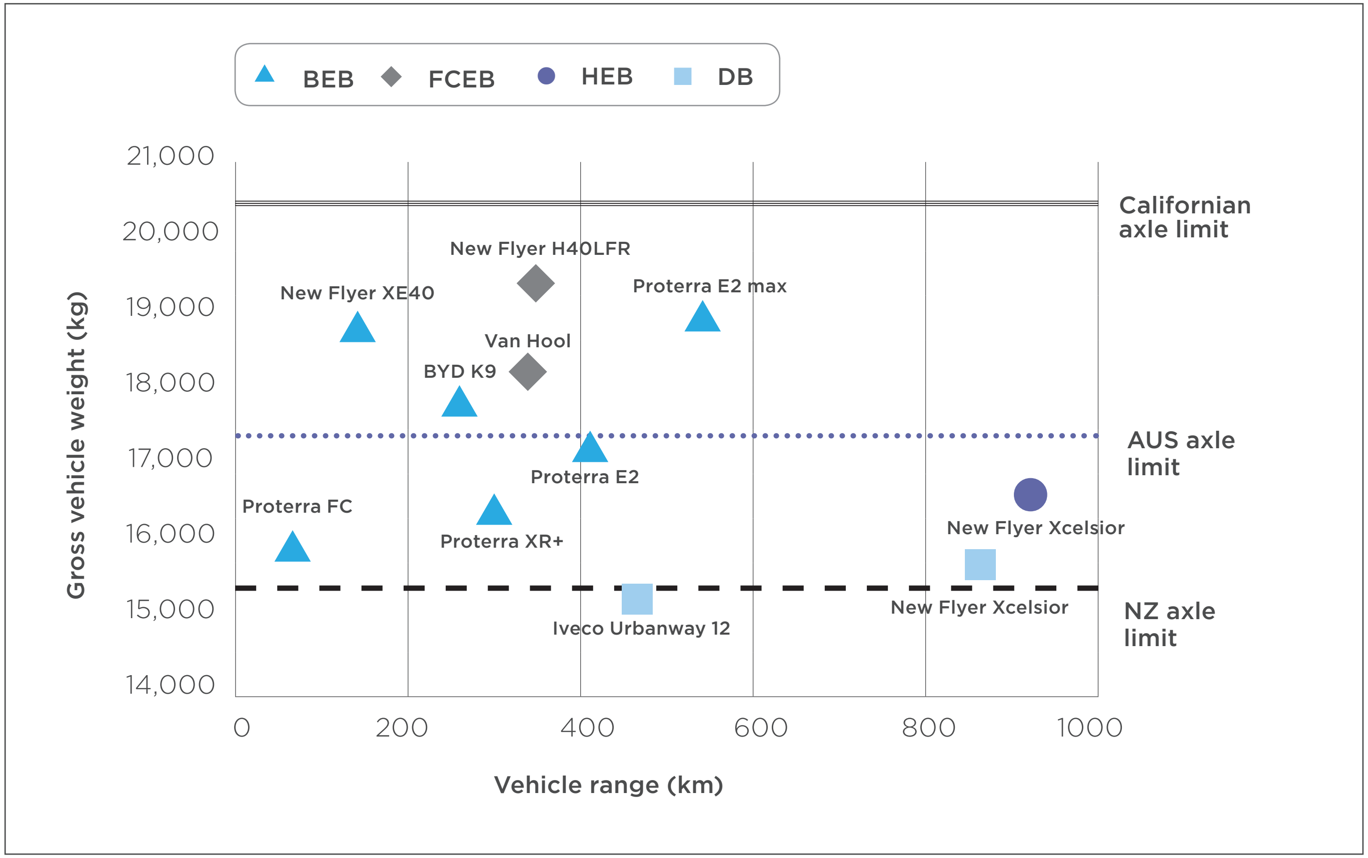

Figure 14: Relationship between fully loaded vehicle weight and range

3.3 Environmental Assessment of Electric Buses and Energy Pathways

Environment impact analysis of a vehicle and its energy source can be performed over a number of categories such as climate change, particulate matter, photochemical oxidation, resource depletion, human toxicity, eco-toxicity, and air acidification (Energy Efficiency and Conservation Authority, 2015). This section will firstly discuss literature around the climate change effects of electric bus usage, followed by a discussion on the findings of in-depth environmental impact studies of electric buses.

3.3.1 Environmental Assessment Details

The green houses gas (GHG) emissions performance of a vehicle energy source is often analysed over three stages[30]: well-to-tank (WTT), tank-to-wheel (TTW), and well-to-wheel (WTW) (Mahmoud et al., 2016). WTT considers all GHG emissions resulting from any extraction, transportation, production, refinement, distribution, and storage of the energy source. TTW considers all GHG emissions from the energy source when the bus is in operation. WTW combines the WTT and TTW effects (Mahmoud et al., 2016; Ou, Zhang, & Chang, 2010).

Separating GHG emissions into the discrete stages described above allows for a more complete comparison of different energy sources in different regional contexts. It also highlights the need to be careful when interpreting emissions data, as it may not consider the full process of generating/collecting and consuming the energy source. For example, BEBs are often described as "zero emission vehicles", which is true when considering only their tailpipe (TTW) emissions. However, it neglects to consider the energy source pathway from WTT, which often produces some emissions.

Common units for quantifying GHG emissions are grams of carbon dioxide equivalent per mega-joule[31] or per kilometre. It should be noted that carbon dioxide equivalent refers to both CO2 and other GHGs. The quantities of gases other than CO2 are scaled in accordance to their known warming affect (global warming potential, GWP) relative to that of CO2 over a specified time scale (Energy Efficiency and Conservation Authority, 2015). This allows for the construction of a single, time-sensitive value that represents all emissions, grams CO2 equivalent (g CO2 eq), and considers the varying degrees of warming that different compounds can incur, and the different lengths of time it takes for compounds to breakdown in the atmosphere. For example, methane has a GWP of 34 over a one-hundred-year timescale. Thus, one gram of methane is equivalent to 34 g CO2 eq.

[30] In some literature well-to-tank and tank-to-wheel are labelled as well-to-pump (WTP) and pump-to-wheel (PTW) respectively (Ou et al., 2010).

[31] For WTT, g CO2 eq/MJ refers to mega-Joules of energy delivered to the vehicle. For TTW, g CO2 eq/MJ refers to mega-Joules of energy consumed by the operational vehicle.

3.3.2 Environmental Impact from Operation of Electric Buses

Well-to-tank emissions vary greatly for different fuel sources and different regions. **Figure 15** shows some processes that may be involved in supplying the energy used in these electric bus technologies. Emissions at every intermediate process should be considered when comparing the total emissions of each powertrain option. For fossil fuels, varying methods of extraction, refinement, transportation, and distribution will all lead to variation in the final quantity of GHG emissions. As outlined in **Table 5**, WTT emissions from diesel production is around 12-22 g CO2 eq/MJ (Mahmoud et al., 2016).

	WELL-TO-TANK				TANK TO WHEEL	WELL-TO-WHEEL (g CO_2 eq)
	EXTRACTION		TRANSPORTATION	DISTRIBUTION		
DIESEL	Extract	Refine	Drive	Pump	Engine	1222
HYDROGEN	Electrolysis		Drive	Pump	Reverse Electrolysis	320
ELECTRICITY	Hydro Power	Wind Power	Power Grid	Charge	Battery	173

Figure 15: *Different energy sources undergo different processes, leading to different well-to-wheel emissions*

WTT GHG emissions from electricity production are highly dependent on the original fuel source and the method of generation. Countries with a high proportion of electricity generation from fossil fuels such as coal will have relatively high emissions per unit of electricity generated. Approximately two-thirds of US electricity generation in 2015 came from fossil fuels with 33% of total generation from coal (U.S. Energy Information Administration, 2016). Whereas in New Zealand in 2016, over 80% of electricity production came from renewable sources, with less than 5% from coal (MBIE, 2016). This is reflected in the WTT GHG emission values presented in **Table 5**. Electricity production in the US and China produces more than 200 g CO2 eq/MJ while electricity production in Canada and NZ, both with high proportions of electricity generation from renewable energy sources, produce less than 60 g CO2 eq/MJ.

The results in **Table 5** suggest that the emissions from using diesel as an energy source are much lower than the emissions from using hydrogen or electricity, even when the electricity generation comes from mostly renewable sources. However, this does not account for the different vehicle powertrain energy efficiency; vehicles powered by ICEs typically have an efficiency of around 20%, fuel cell vehicles have an efficiency of around 90%, and battery electric vehicles have an efficiency of around 50% (Lowry & Larminie, 2012). This means, for example, that a BEB will travel much further on one MJ of electricity than a DB will travel on one MJ of diesel. Specifically, using values given by Ou and colleagues (2010) for operational city buses of equivalent size[33], a diesel bus will travel an average of 62 metres per MJ, and a BEB will travel an average of 185 metres per MJ. This proves to illustrate that when considering the WTT GHG emissions of an energy source, one must also consider the energy efficiency of the vehicle it will be used in, as well as the TTW emissions. **Table 6** shows the breakdown of WTT, TTW, and WTW emissions for different types of vehicles, and refers to the g CO2 eq per kilometre, to include the effect of the different efficiencies of different types of buses.

The operational TTW GHG emissions are measured as the average tail pipe emissions that are produced during bus operation, shown in **Table 6** for different types of buses. BEBs and FCEBs produce no tailpipe GHG emissions during operation. HEBs produce less GHG emissions than DBs; on average, 21% less for series HEBs and 13% less for parallel HEBs (Mahmoud et al., 2016). It should be noted that for buses that incorporate an ICE (DBs and HEBs), the volume of TTW emissions will be dependent on factors such as engine condition, engine standard, degree of hybridisation, fuel quality, and the environment in which the vehicle is operating (Mahmoud et al., 2016). **Figure 22** in Section 5.5.1 compares the WTW energy efficiencies of the alternative bus technologies in a bar chart.

Country	Diesel (g CO2 eq/MJ)	Hydrogen from NGSR (g CO2 eq/MJ)	Hydrogen from WE (g CO2 eq/MJ)	Electricity (g CO2 eq/MJ)
China	12.4			289.6
US	19	265	256	223
EU	13.8	306		150
Canada	21.7			60
NZ (2012)				46
NZ (2013)				36

Table 5: *WTT GHG emissions (Mahmoud et al., 2016). NZ emissions calculated separately*[32]

[32] *NZ 2013 electricity consumption: 38,998 GWh (Ministry of Business, Innovation & Employment, 2014a); NZ 2013 electricity GHG emissions: 5,043 (kt CO2 eq) (Ministry of Business, Innovation & Employment, 2014b).*

[33] *Values from actual in-operation bus data. Bus specifications: 12 metre length, 70 passenger capacity.*

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Powertrain	Energy source	WTT GHG (gCO2 eq/km)	TTW GHG (gCO2 eq/km)	WTW GHG (gCO2 eq/km)	Average % reduction of GHG compared to DB
DB	Diesel	218	1004	1222	N/A
HEB - parallel	Diesel	188	870	1058	13.42%
HEB - serial	Diesel	172	796	968	20.79%
FCEB	H2 – Central NGSR	320	0	320	73.81%
FCEB	H2 - WE	305	0	305	74.96%
BEB	Electricity – US mix[34]	1070.4	0	1070.4	12.41%
BEB	Electricity – EU mix	720	0	720	41.08%
BEB	Electricity – NZ mix[35]	172.8	0	172.8	85.86%
BEB	Electricity – 100% renewable	20	0	20	98.36%

Table 6: *GHG emissions from DBs and electric buses (Mahmoud et al., 2016)*

[34] *Calculated separately using a BEB fuel efficiency of 4.8 MJ/km (to match other BEB fuel efficiency calculations in the table) and NZ electricity GHG emissions data from Table 3.*
[35] *Calculated separately using a BEB fuel efficiency of 4.8 MJ/km (to match other BEB fuel efficiency calculations in the table) and US electricity GHG emissions data from Table 3.*

3.3.3 Environmental Impact from Non-Operational Processes

Section 5.2.1 does not offer a complete comparison of all emissions attributable to a bus. Missing from the above discussion is the GHG emissions released from phases outside of the day-to-day operation of buses. These include emissions from bus component manufacturing and assembly, vehicle maintenance, vehicle importing, end-of-service recycling and disposal, and emissions from infrastructure-related manufacturing, installation, and maintenance. For a complete analysis of the environmental impact of electric bus technology, these other phases must also be considered. In some contexts, where electric bus technology only marginally improves on the WTW GHG emissions from conventional bus technology, a more complete analysis may find conventional bus technology to have a lesser environmental impact.

To quantify the significance of non-operational GHG emissions, consider the following findings by the Energy Efficiency and Conservation Authority (2015): the operational WTW GHG emissions from an electric vehicle accounted for less than half the total lifetime GHG emissions of that vehicle, and over the lifetime of a battery electric car, approximately 25% of all GHG emissions were attributable to the construction of the original and one replacement Li-ion battery.

3.4 Life Cycle Assessment of Electric Bus Technology

Cooney and colleagues (2013) present a life cycle assessment (LCA) on DBs and BEBs in a US context. The study specifically focuses on the performance of the two bus types across eleven environmental impact categories: global warming, ozone layer depletion, respiratory inorganics and organics, carcinogens and non-carcinogens, terrestrial ecotoxicity and acidification, and aquatic ecotoxicity, acidification and eutrophication. For each category, the impacts from DBs and BEBs were analysed over five stages: bus shell manufacturing, maintenance, battery manufacturing, charging infrastructure, and use. The environmental impacts that result from all resource inputs and outputs required for bus construction, maintenance, and daily operation within these five stages were considered.

The study excludes end-of-life costs for both bus types and assumes an operational bus life of twelve years. It was assumed that the operational performance of both bus types was comparable; that the BEB had sufficient range, capacity, power, and other operational requirements to match the performance of the DB. The BEB was assumed to require 5.5 replacement Li-ion batteries over its twelve-year service life.

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Overall, the study concludes that DBs are preferable to BEBs in a US context. DBs had a lower lifetime environmental impact across eight out of the eleven impact categories, shown **Figure 16**. BEBs only obtained lower environmental impact scores in the non-carcinogens, terrestrial acidification, and aquatic eutrophication categories. In the ecotoxicity, ozone depletion, and carcinogen categories, the battery production stage is the predominant contributor to BEBs poor results. Cooney and colleagues (2013) state that often this poor performance is primarily due to one or two by-products of the battery manufacturing process. Cobalt releases during the positive electrode production are the main cause of poor ecotoxicity results. Hydrofluorocarbon (HCFC) and chlorofluorocarbon (CFC) releases during the positive and negative electrode production are the main cause of poor results in the ozone layer depletion category.

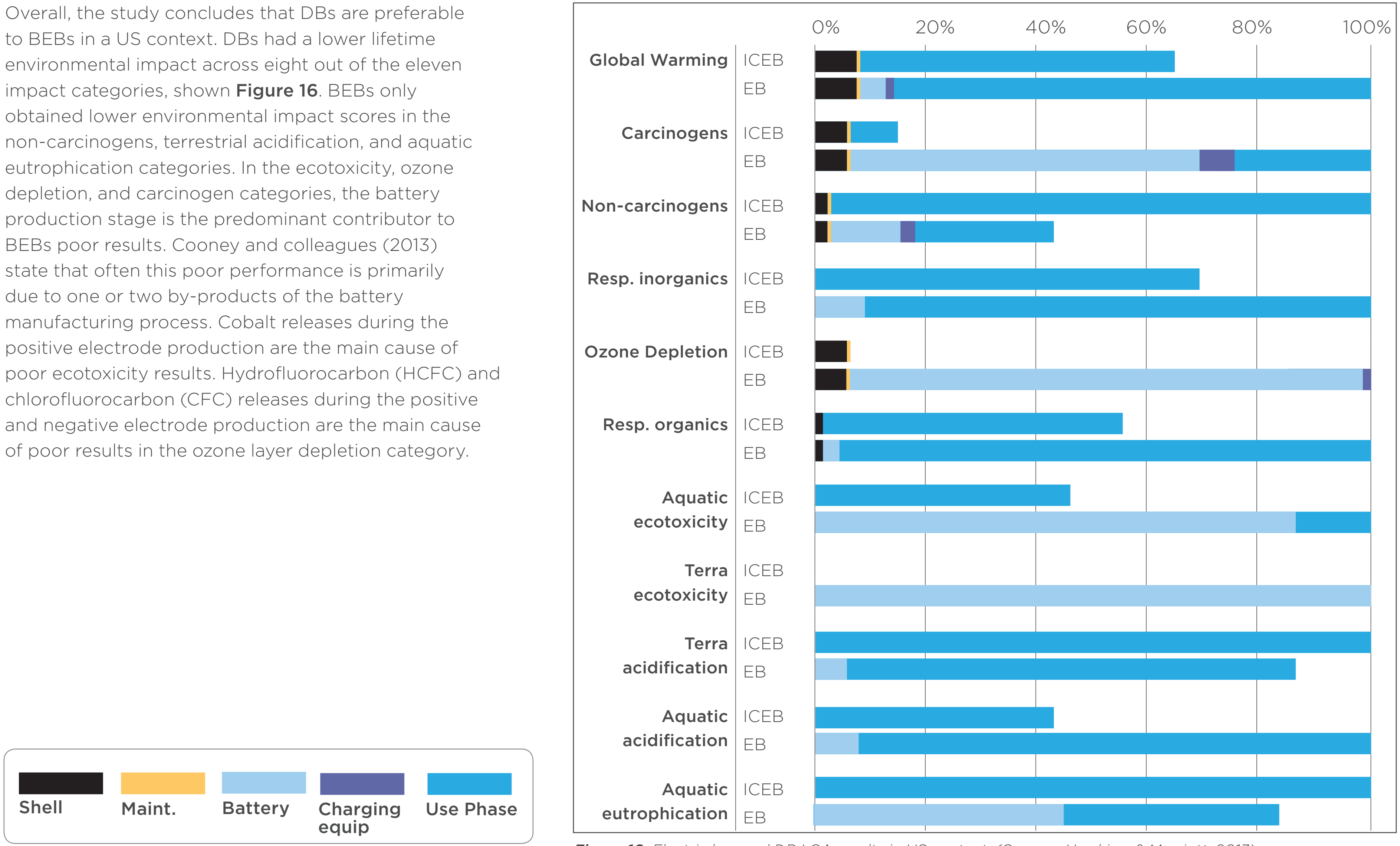
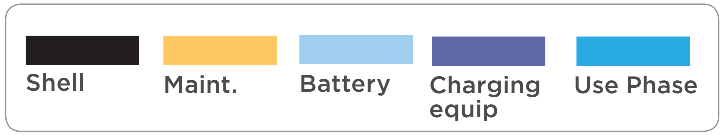


Figure 16: *Electric bus and DB LCA results in US context, (Cooney, Hawkins, & Marriott, 2013)*

3. PERFORMANCE OF ALTERNATIVE BUS TECHNOLOGIES

Cooney and colleagues (2013), suggest that development of recycling techniques, increased battery cycle life, increased energy density, enhanced battery manufacturing techniques, and battery production from safer and more abundant materials, will significantly reduce the poor environmental results from current battery production methods. Some examples from the study include: a 25% increase in Li-ion battery energy density would result in a 16% decrease in ozone depletion; a two-fold increase in battery cycle life would reduce ozone depletion by 39% (Cooney et al., 2013).

The US electricity generation mix has a strong influence on the results. The 2009 US electricity generation mix was dominated by non-renewables (51% coal, 19% nuclear, 16% natural gas, 8% fuel oil, 7% hydropower and 4% other) (Cooney et al., 2013) and thus electricity in the US has a relatively high emission faction. The 2011 US emissions factor from electricity consumption was 749 g CO2 eq per kWh (Cooney et al., 2013). In New Zealand, the emissions factor from electricity consumption for the same year was 79% lower at 152 g CO2 eq per kWh (MBIE, 2014). Due to the significant influence of the use phase in many of the impact categories, this difference in electricity generation mix in a NZ context would significantly change the LCA results. If the 79% reduction in use phase GHG emissions was reflected as similar use phase reductions in the other categories, BEBs would have a lower environmental impact in seven of the eleven categories and appear to hold a significant advantage over DB technology, as shown in **Figure 17**.



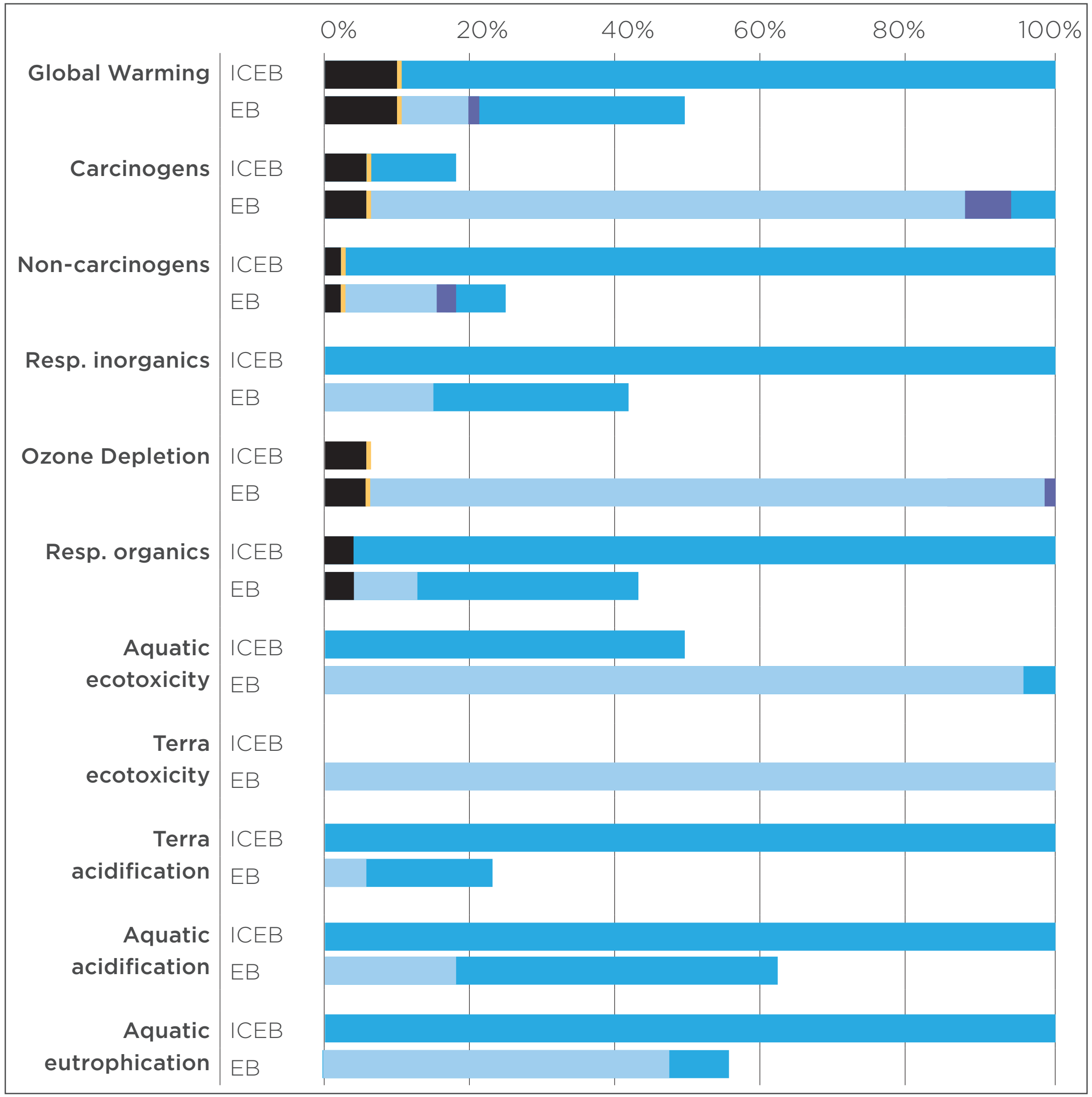


Figure 17: *Electric bus and DB LCA results with use phase EB results reduced by 79%, to represent NZ electricity sources, (Cooney, Hawkins, & Marriott, 2013)*

3.5 Energy Efficiency

The energy efficiency of a system describes the ratio of the energy output from the system to energy input into the system. Vehicles powered by ICEs, batteries, and fuel cells have efficiencies of around 20%, 90%, and 50% respectively (Lowry & Larminie, 2012). This means that for every unit of supplied energy, either in the form of electricity or diesel, an electric motor will produce more output energy (in the form of kinetic energy) than a diesel engine. It is important to understand however, that this comparison only considers the efficiency of transforming electric-potential energy into kinetic energy by the electric motor, and the efficiency of transforming chemical energy into kinetic energy by the ICE. The increased efficiency of the electric motor over the ICE does not imply that the total amount of primary energy[36] required to move a BEB and DB an equivalent distance is greater for the DB than the BEB, due to different efficiencies in the energy pathways and fuel source generation. The above comparison does not consider the amount of energy required to produce and deliver the refined energy sources to the buses. Also, it does not consider the efficiency of the BEB charger or the on-board battery. It does not consider the relative masses of the vehicles, the additional required energy for on-board auxiliary systems such compartment heating, or any mechanisms for regenerating energy. The entire system must be analysed to objectively assess the complete energy efficiency of each type of electric bus.

As with the analysis of electric bus GHG emissions, energy efficiency analysis is also commonly made over the same three stages: WTT, TTW, and WTW. This section will discuss the standard methods for analysing and quantifying the energy efficiency of DBs and BEBs over these three stages. However, other than for explanatory purposes, specific energy efficiency results will not be presented here as they are dependent on the context and vary across different published studies.

WTT energy efficiency of a bus assesses the energy efficiency of producing and delivering the required fuel to the vehicle. This includes the extraction and transportation of the feedstock (raw energy sources), fuel refinement or production (and compression if applicable), fuel transportation, fuel distribution, and fuel storage (Mahmoud et al., 2016; Ou et al., 2010; Torchio & Santarelli, 2010). WTT energy efficiency describes the amount of primary energy required to create and deliver a processed fuel to the vehicle. In the context of this report, processed fuels (also commonly referred to as energy carriers, secondary energies or finished fuels) will include diesel, electricity, and hydrogen.

There are two common methods for describing WTT energy efficiency. One method is the total amount of primary energy used during all WTT processes, for each unit of processed fuel delivered (**Table 7**, Equation 1); this allows for quantification of the energy efficiency of a fuel type regardless of how it will be used. The second method is the total primary energy consumed per unit distance travelled by a specific type of bus (**Table 7**, Equation 2) (Mahmoud et al., 2016; Ou et al., 2010; Torchio & Santarelli, 2010); this method is only valid when the fuel will be used in a vehicle. The second method can be derived from the first by applying the fuel efficiency of the appropriate electric bus to the fuel type under consideration (**Table 7** , Equation 4).

TTW energy efficiency describes the operational fuel efficiency of the bus type and fuel type combination during actual service. To retain continuity in the units of measurement and allow easy calculation of WTW energy efficiency, TTW energy efficiency is also defined in terms of MJ delivered fuel energy per km travelled (**Table 7** , Equation 3).

WTW energy efficiency (of a bus and fuel type combination) describes the total amount of primary energy used per unit distance travelled. It is the sum of both WTT and TTW energy efficiencies (**Table 7** , Equation 5).

[36] *Primary energy is energy in its raw, unconverted form. This includes oil, coal, solar energy and wind, to name a few examples.*

$$WTT_e = \frac{PE_x}{SE} \left[\frac{MJ_x}{MJ_f}\right] \quad (1)$$

$$WTT_e^* = \frac{PE_x}{D} \left[\frac{MJ_x}{km}\right] \quad (2)$$

$$TTW_e = \frac{SE}{D} \left[\frac{MJ_f}{km}\right] \quad (3)$$

$$WTT_e^* \left[\frac{MJ_x}{km}\right] = WTT_e \left[\frac{MJ_x}{MJ_f}\right] * TTW_e \left[\frac{MJ_f}{km}\right] \quad (4)$$

$$WTW_e \left[\frac{MJ_t}{km}\right] = WTT_e^* \left[\frac{MJ_x}{km}\right] + TTW_e \left[\frac{MJ_f}{km}\right] \quad (5)$$

$$WTT_e' = \frac{PE_t}{SE} \left[\frac{MJ_t}{MJ_f}\right] \quad (6)$$

$$WTT_e' \left[\frac{MJ_t}{MJ_f}\right] = 1 + WTT_e \left[\frac{MJ_x}{MJ_f}\right] \quad (7)$$

$$WTW_e \left[\frac{MJ_t}{km}\right] = WTT_e' \left[\frac{MJ_t}{MJ_f}\right] * TTW_e \left[\frac{MJ_f}{km}\right] \quad (8)$$

Table 7: *Methods for quantification of bus energy efficiency*

Symbol	Meaning
PE	primary energy
SE	secondary energy
e	energy efficiency
f	processed fuel (secondary energy)
x	expended (lost or consumed – see note 2 below) during fuel conversions and other processes
*	WTT quantification accounts from bus powertrain and associated operational energy efficiency
‘	WTT quantification includes all primary energy, including the energy contained in the delivered fuel

Table 8: *Subscript and superscripts used in energy efficiency equations*

It is important to note that:

- WTT energy efficiency values given in discourse, may or may not include the actual energy contained in the delivered fuel itself. Therefore, care must be taken when interpreting WTT energy efficiency data. For example, Torchio and Santarelli (2010) give the WTT energy values for diesel, in a European context, as both 0.16 and 1.16 (MJx/ MJf). The first quantity excludes the actual energy contained within the processed diesel; 0.16 MJ of primary energy is lost in associated conversions and processes, for every 1 MJ of diesel delivered to the pump in Europe. The second quantity includes the energy contained in the delivered diesel; 1.16 MJ of primary energy is required to create and deliver 1 MJ of processed diesel to the pump in Europe. **Table 7**, Equations 6, 7, and 8, define WTT energy efficiency and WTW energy efficiency when the total amount of primary energy is considered (i.e. the energy within the fuel is included in the WTT energy efficiency quantification).

- In some discourse, the energy efficiency of electricity generated from renewable fuels is assumed 100% energy efficiency. When this is the case, authors will instead refer to 'fossil fuel based' primary energy (instead of simply primary energy).

3.5.1 Bus WTW Energy Efficiency Data for China

The following section presents detailed energy efficiency data for public transport buses in China[37], fuelled by either diesel or hydrogen. The findings are from a comprehensive study by Ou, Zhang and Chang (2010). Selected results from the study are given here to assist the reader's understanding of WTW energy efficiency in the context of transportation fuels and alternative bus powertrains. It should be noted that this data is not a complete record of all fuel type and electric bus combinations, and may not accurately represent WTW energy efficiency findings outside of China.

Figure 18 and **Figure 19** present a breakdown of the quantity and distribution of secondary energies (refined fuels), expended during the upstream WTT processes for both diesel and hydrogen[38] in China. The WTT stage is broken into four sequential sub stages:

1. Feedstock (raw material) extraction
2. Feedstock transportation
3. Fuel production (including gas compression in the case of hydrogen)
4. Fuel transportation, storage, and distribution

The quantities given in these figures describe the amount of secondary energy consumed[39], during each of the WTT sub stages, for every MJ of refined hydrogen or diesel produced. Included in these figures, is the (secondary) energy efficiency of each sub stage; the ratio of secondary energy output to secondary energy input[40]. These figures clearly show the poorer performance of hydrogen WTT energy efficiency when compared to diesel. Hydrogen production is particularly inefficient, with very high crude natural gas and electricity usage. A hydrogen production efficiency of 71.5% and a compression efficiency of 92.5%, give an overall production sub-stage energy efficiency of only 66.1%. As a comparison, the diesel fuel refinement efficiency is 89.7%.

[37] Where appropriate, findings are specific to 12 m standard public transport buses operating in Chinese cities (Ou et al., 2010).
[38] Ou and colleagues (Ou et al., 2010) assumed hydrogen production to be via natural gas steam reforming.
[39] Excluding the energy contained within the MJ of produced fuel.
[40] Here, secondary energy input includes the energy contained within the MJ of produced fuel.

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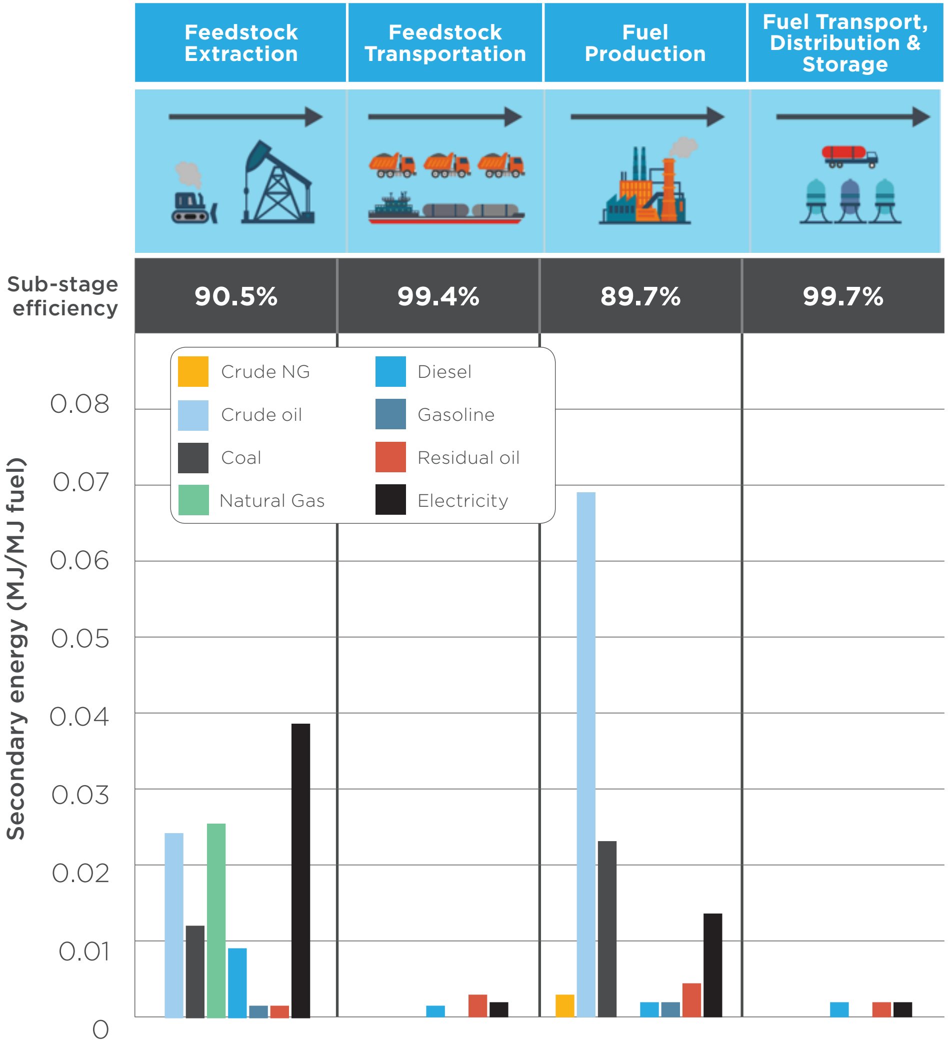

Figure 18: Secondary energy usage (and sub-stage efficiency) over the diesel WTT energy pathway in China[41]

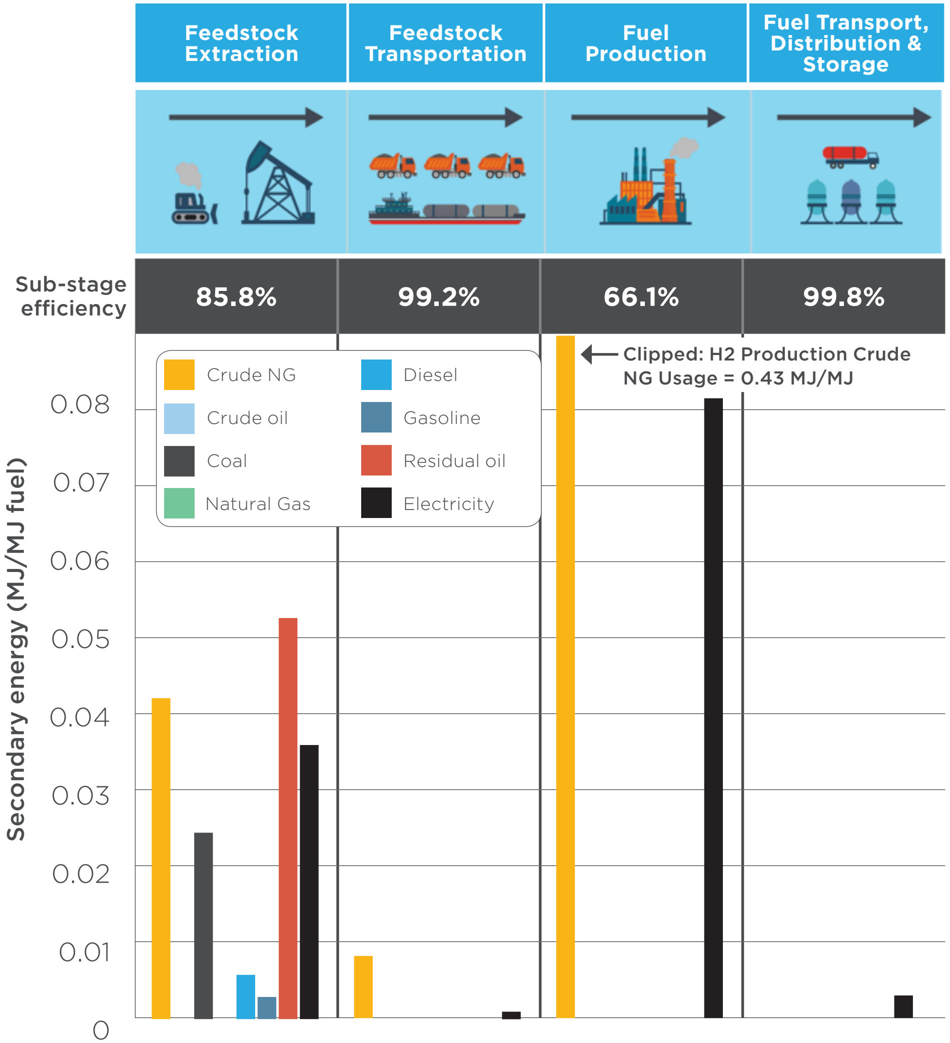

Figure 19: Secondary energy usage (and sub-stage efficiency) over the hydrogen WTT energy pathway in China[41]

[41] *Icons in the figures are appropriated from designs by freepik and macrovector at http://www.freepik.com/free-vector/.*

Figure 18 and **Figure 19** present the quantities of secondary energy expended. To allow for a more objective comparison of the energy pathways of different fuel types, a quantification of the amount of primary energy expended should instead be made. Because Ou and colleagues (2010) were only concerned with fossil fuel based primary energy efficiency, the relevant constituents of secondary energy sources are coal, natural gas, and oil. **Figure 20** presents the total amount of primary (fossil based) energy needed to produce one MJ of (processed) secondary energy in China. This is also referred to as the: "life-cycle primary fossil energy use factor for [each] processed fuel" (Ou et al., 2010, p. 407). In this figure data is presented for processed natural gas (NG), diesel, and electricity, however, Ou and colleagues also give the primary energy makeup of crude coal, crude natural gas, crude oil, coal, gasoline, and residual oil. As shown in **Figure 20**, producing one MJ of electricity requires 3.5 MJ of primary energy, with the majority of this energy coming from coal. Diesel and natural gas require much less primary energy to produce: 1.33 MJ/MJf for diesel and 1.2 MJ/MJf for natural gas.

By combining the data presented in the previous three graphs , the total amount of primary energy expended during each WTT sub-stage can be calculated (**Table 7**, Equation 1), shown **Figure 21**. Again, the low energy efficiency of the hydrogen WTT pathway is evident; for every MJ of hydrogen produced, an almost equivalent amount of primary energy (1.04 MJ) is lost during the WTT processes. The diesel WTT pathway has more than twice the efficiency, incurring only 0.39 MJ of primary energy losses for each MJ of diesel produced.

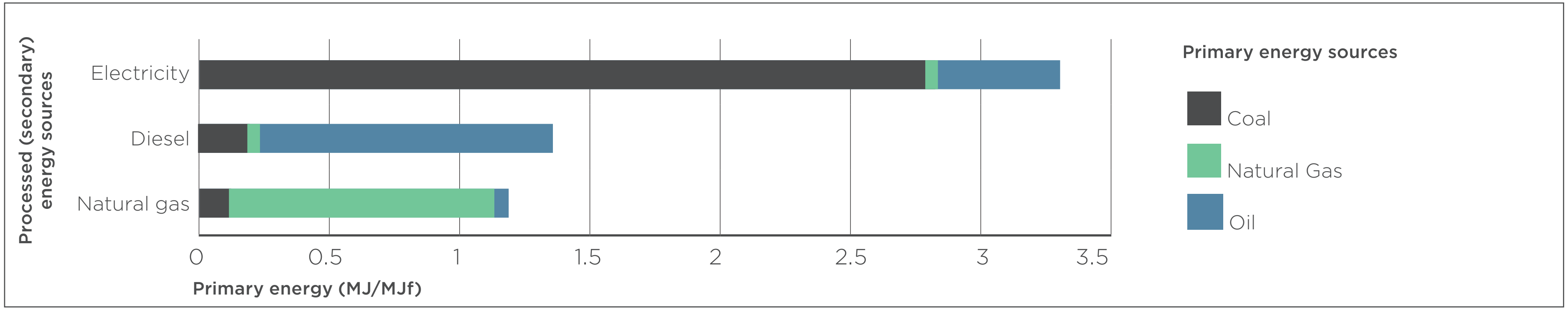

Figure 20: *Primary (fossil based) energy use for three secondary energy sources (over the entire energy pathway)*

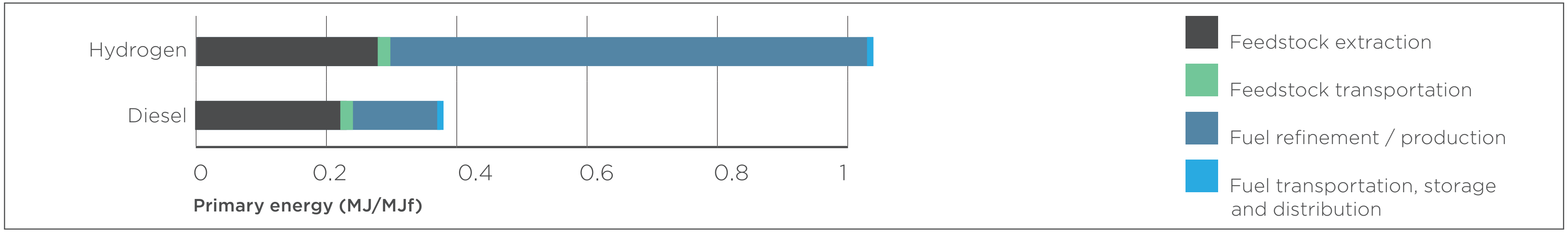

Figure 21: *Hydrogen and diesel WTT energy efficiency: primary energy expenditure during each WTT sub-stage*

Figure 22 shows the TTW, WTT, and WTW energy consumed per kilometre travelled for 12-metre FCEBs, HEBs, and DBs, in operation in Chinese cities. The TTW energy required is slightly smaller for FCEBs and HEBs than for DBs, meaning they require less on-board energy to travel an equivalent distance. However, this does not consider the energy density of the on-board power source. The TTW energy efficiency can be used to calculate the WTT and WTW energy efficiencies. The WTT (primary fossil) energy efficiency discussed above, and presented in **Figure 21** can be extended to include appropriate vehicle powertrains; this is derived using Equation 4 from **Table 7**, and is also presented in Figure 20. FCEBs consume a lot more energy in the WTT processes than HEBs and DBs, which results in them being less efficient overall (WTW) than HEBs and DBs.

The total WTW energy efficiencies can be calculated by summing the WTT and TTW findings (**Table 7**, Equation 5), shown in **Figure 22**. Overall, these findings show that significant improvements in the efficiencies of the hydrogen energy pathway and/or the fuel cell systems would be required to see hydrogen FCEBs match the WTT energy efficiency of DBs.

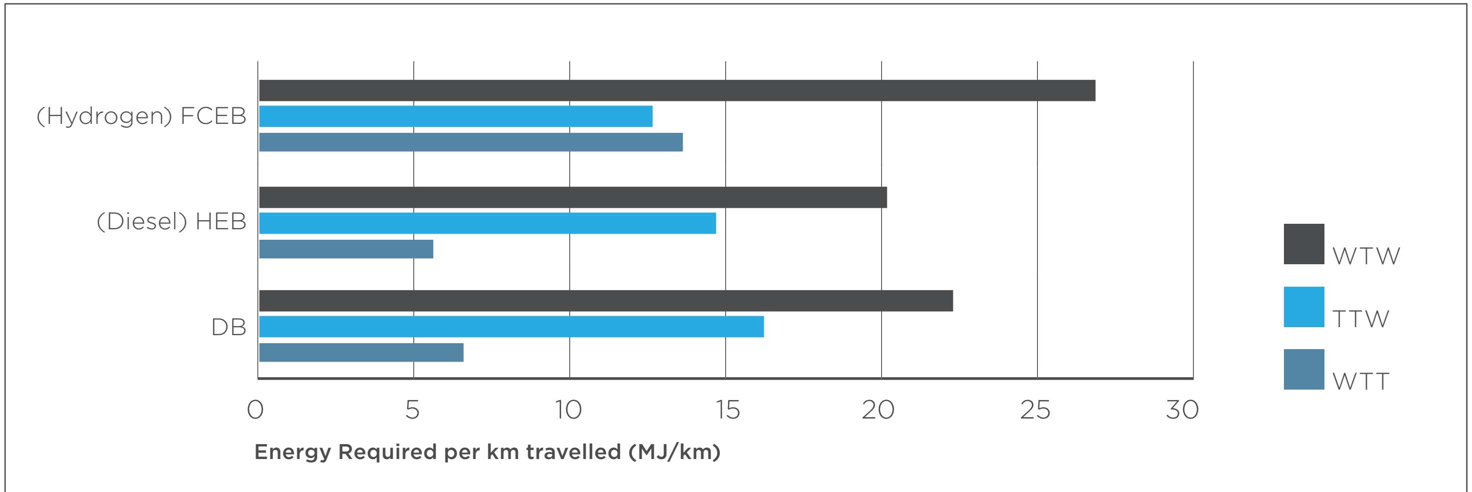

Figure 22: *WTT, TTW, and WTW energy consumption for in-operation buses in China*

3.6 Summary of Performance of Electric Bus Technologies

Figure 23 displays the performance of the alternative powertrain options compared to DBs, indicating whether their performance is better or worse than DBs. **Table 9** then provides a summary of the information discussed through Section 5. It generally gives an indication of the difference of each performance metric between the bus technology concerned and DBs, as the quantity of differences depend on various circumstances such as operating conditions and energy sources of electricity generation.

	HEB	FCEB	BEB
Purchase price	+50%	+200%	+100%
Maintenance costs	More	Much more	Less
Operating costs	Less	Much more	Much less
Infrastructure	More	More	More
Range	Less	Less	Much less
Weight	More	More	More
Refuel time	Less	More	More
Emissions (CO_2)	-20%	-75%	-85%

***Figure 23**: Performance of alternative powertrain buses compared to diesel buses*

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		HEB	BEB	FCEB
Economic	Purchase Price	50% more expensive than DBs	100% more expensive than DBs	Much more than all other buses
	Maintenance Cost	Slightly lower than DBs	Lower than DBs	Higher than all other buses
	Operating Costs	Slightly lower than DBs	Much lower than DBs	Higher than DBs
	Infrastructure Costs	Same or higher than DBs	Much higher than DBs	Higher than all other buses
	Total Cost of Ownership (TCO)	Slightly higher than DBs	Much more than DBs	Much higher than all other buses
Operational Performance	Range	Similar to DBs	Can be very small or reasonable	Less than DBs, but still reasonable range
	Refuelling Capability	Easy and cheap	Easy and expensive	Difficult and expensive
	Kerb Weight	A bit heavier than DBs	Often much heavier than DBs	A lot heavier than DBs
Environmental Performance	WTT Emissions[44]	Slightly less than DBs	In NZ, less than DBs	More than DBs
	TTW Emissions	Less than DBs	None	None
	WTW Emissions	Less than DBs	In NZ, about 85% less than DBs	About 75% less than DBs
Energy Efficiency	TTW Efficiency	Better than DBs	Much better than DBs (around 450% better)	Better than DBs (around 150% better)
	WTW Efficiency[44]	Unclear for NZ	Unclear for NZ	Much worse than DBs

Table 9: *Summary of performance indicators based on information supplied throughout Section 5*

[44] *When electricity is used, depends on mix of energy sources for electricity generation.*

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4. CURRENT AND PROJECTED MARKET SHARE

Over recent years, the uptake of electric buses into public transport networks has been slow but increasing (Mahmoud et al., 2016). Electric buses made up 6% of new heavy-duty global bus purchases in 2012, with 5% CNG and LNG purchases, and 89% DBs and other buses (Chandramowli, 2014). Of the electric bus procurements, 90% were hybrid electric, 6% full electric, and 4% fuel cell (Mahmoud et al., 2016). Frost & Sullivan (2014) predict that by 2020, the global share of new electric bus purchases will have increased to 15%. These new electric bus purchases are expected to consist of 73% hybrid electric, 8% full electric, and 19% fuel cell. Their estimations are presented in **Figure 24**.

Predictions are also available about the future market share of HEB powertrain configurations. HEBs produced in 2012 predominantly utilised the parallel configuration (56.4%), with 17.9% using series and 25.7% using series parallel configurations (Chandramowli, 2014). 2020 production estimates see an increase in the relative production volume of parallel configurations, with 67% parallel, 12% series and 21% series-parallel (Chandramowli, 2014). Frost and Sullivan (2014) suggest that this increase in demand for parallel hybrid buses over the other configurations is due to the lower total cost of the parallel hybrid vehicle components; parallel hybrid vehicles do not require a generator and can have a smaller electric motor and batteries due to being able to deliver power simultaneously from both the ICE and the electric motor (see Section 4.1.1 for more details of the configurations). Chandramowli (2014) gave no indication of whether or not they expect these new HEBs would incorporate plugin technology. However, a 3iBS (Intelligent, Innovative Integrated Bus Systems) survey launched in 2013 (Union Internationale des Transports Publics, 2013) gives some indication of the demand for the different technology types. Of the surveyed stakeholders representing European bus industries, over 40% indicated that their future plans were to purchase more electric buses. Of those respondents who indicated an increased preference for electric buses, 69.7% said they planned to purchase more HEBs and 33.3% intended to purchase more plug-in HEBs (Corazza, Guida, Musso, & Tozzi, 2016; Union Internationale des Transports Publics, 2013).

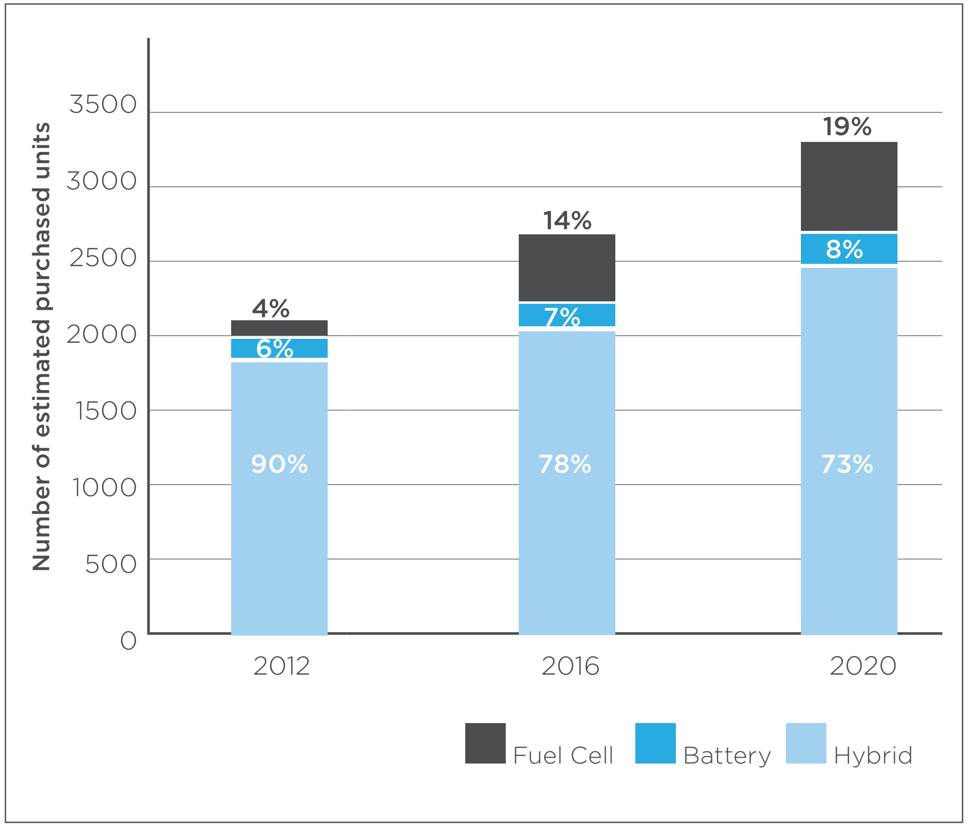

***Figure 24:** Volume and break-down of US electric bus market. Source: (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016)*

5. CONCLUSION

Today, electric buses hold a clear advantage over DBs in several performance categories, particularly the reduction (or elimination) of tailpipe and GHG emissions. Electric buses may also deliver benefits in terms of energy efficiency, environmental impact, passenger comfort, and integration with renewable energy sources. Electric buses are already becoming the bus of choice for a number of cities and public transport providers worldwide.

While EBs still suffer from increased vehicle kerb weight and higher total costs of ownership, ongoing technology development and increased production volumes should reduce these obstacles in coming years. Recent investments in electric buses around New Zealand, including the independent BEB trials taking place in Auckland and Wellington this year, and the large investment in hybrid bus systems by NZ Bus, are signs of a shift in the types of buses that will operate in our future cities.

Given the high proportion of New Zealand patronage delivered by bus, developments in electric bus technology provide an exciting opportunity to significantly improve the environmental performance of New Zealand's public transport systems, and contribute to the clean, green vision for New Zealand.

APPENDIX A: COMMON TERMS USED IN BUS ASSESSMENTS

Below is a list of commonly used terms in bus assessment reports.

Term	Meaning
Availability	Availability is a measure of the percentage of scheduled operation days that a bus is available to operate. The target availability for a public transport bus fleet is usually around 85% which allows for routine and unscheduled maintenance.
KBRC (or MCRC)	A measure of bus reliability is kilometres (or miles) between roadcalls (breakdowns) - see the definition of roadcalls below. KBRC (or MCRC) is also known as mean distance between failures. KBRC can be calculated by dividing total distance travelled by number of breakdowns. KBRC can be calculated for all breakdowns or those due to failures of specific components of the bus. Common KCRC categories are energy storage system related breakdowns and propulsion system related breakdowns.
Breakdown (or roadcall)	An instance where a fault with an in-service bus requires it be replaced (during operation), or causes significant disruption to its schedule.

APPENDIX B: INTERNATIONAL CASE STUDIES

There has been a steady increase in electric bus use in public transport routes around the world. Many of these are demonstration projects where the performance of the electric buses is closely monitored and compared against the performance of conventional buses. Demonstration projects assess the readiness of electric bus technology for commercial deployment and stimulate technology development. The following section introduces some of these trials and gives links to online reports and articles.

B.1 Battery Electric Bus Case Studies

B.1.1 The Milton Keynes Demonstration Project

The Milton Keynes trial programme is a 5-year study that began in 2014. It is led by MASP (MBK Arup Sustainable Projects Limited), a joint venture between Mitsui Group (a trading, investment, and services company), and UK engineering firm Arup (Bowdler, 2014).

Eight opportunity buses (fully electric) replaced seven existing DBs on a now fully electric, 25-km route, between the Milton Keynes suburbs of Wolverton and Bletchley (Alibhai, 2014).

DESIGN CRITERIA

Miles and Potter (2014) state four design criteria that were fundamental requirements for the project:

1. Design and produce a BEB with lower battery capacity (the electric component of greatest cost) so that the BEB lifetime costs are similar to, or less than, that of an equivalent sized diesel bus.
2. A charging system that does not impede daily running time, to avoid the need for a BEB fleet that is larger than was required when the route was serviced by diesel buses.
3. An opportunity charging system that minimises additional responsibility and inconvenience for those involved in daily operation and gives the same degree of reliability as was offered during diesel powered operation.
4. A business model that supports multiple organisations with diverse areas of expertise, serves their commercial interests, and fairly manages the commercial risks for all involved.

DESIGN SOLUTION

Opportunity charging stations were installed at the route end points for this project, and bus schedules allowed for 5 to 10-minute layover periods at either end of the route. If running on time, a bus could charge its on-board batteries during these layovers. Alternatively, if running behind schedule, buses would carry enough battery capacity to skip some of these charging opportunities (Miles & Potter, 2014).

MASP created an ‘enabling company’ called electric Fleet Integrated Services Ltd (eFIS). This company purchased the buses and funded the installation of the charging infrastructure. It leases the buses to the local public transport operator at an agreed price and, throughout the project, maintains the vehicles and infrastructure. eFIS has directly enabled the adoption of innovative public transport technology in Milton Keynes. It has removed any risk or additional cost faced by the local council and bus operator, connected a range of infrastructure and manufacturing companies, and created a business model that could profit from a successful project (Miles & Potter, 2014).

RELEVANT ONLINE ARTICLES:

1. **Developing a viable electric bus service: the Milton Keynes demonstration project.**
   Miles, J. and Potter, S. (2014)
   Retrieve article from: **http://oro.open.ac.uk/41076/**

2. **Electric Buses: Lessons to be Learnt from the Milton Keynes Demonstration Project**
   Kontou, A., & Miles, J. (2015)
   Retrieve article from: **http://www.sciencedirect.com/science/article/pii/S1877705815021104**

B.1.2 Foothill Transit In-Service BEB Fleet Assessment

In 2013, Foothill Transit purchased twelve 35-foot Proterra BEBs through a US$10.2 million grant from Transit Investments for Greenhouse Gas and Energy Reduction (TIGGER) Program. These new buses were put into revenue service and replaced existing compressed natural gas (CNG) buses from Foothill Transit's fleet that were due to be retired (Eudy, Prohaska, Kelly, & Post, 2016).

The performance of the twelve new BEBs was assessed by the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) and the California Air Resources Board (CARB[45]) over a sixteen-month period from April 2014 to July 2015 (Eudy, Prohaska, et al., 2016).

Acquisition and demonstration of electric buses (particularly BEBs and FCEBs) in California is being driven by the CARB Fleet Rule for Transit Agencies. One of the requirements of this rule necessitates urban bus public transport agencies, with fleet sizes greater than 200 buses, make 15% of all new bus purchases zero-emission buses (Eudy, Prohaska, et al., 2016).

PROTERRA

Founded in 2004 in Colorado, USA, Proterra produce both short and long range BEBs. Their current models are either 35-foot (10.7m) or 40-foot (12.2m) buses. Proterra uses carbon-fibre-reinforced composite materials to produce the bus body as opposed to steel framing, which is used by other bus manufacturers. This reduces vehicle weight and increases the lifetime of the vehicle body (Proterra, 2016).

CHARGING INFRASTRUCTURE AND OPERATION

A semi-automated, overhead, fast charging station was built on-route at Pomona Transit Centre station. This station is a transfer stop for eight bus routes. For this reason, the charging station could also be used for the electrification of multiple services in the future.

The charging station has two 500 kW chargers which can charge two buses simultaneously. A bus parks under one of the elevated housings and the charging head connects to a contact point on the bus's roof. Docking, system checks, charging, and undocking is performed semi autonomously with communication between the bus and charging station taking place via Wi-Fi. The only responsibility on the driver is to steer the bus as they would when approaching a normal bus stop. Transit Centre layover periods were integrated into the service timetable to account for this 5-10 minute charging process (Eudy, Prohaska, et al., 2016).

[45] *Also known as ARB.*

APPENDIX B: INTERNATIONAL CASE STUDIES

BUS PERFORMANCE

The following results are sourced from published reports (Eudy, Prohaska, et al., 2016; Prohaska, Eudy, & Kelly, 2016).

The Foothill BEB buses were scheduled to operate every day. The overall average bus availability for the Foothill BEB fleet was 90%[46]. This was considered very high given the industry target of 85%, and the fact that the BEBs were not yet considered a fully commercial product at the time of the study.

The BEBs had an overall average operational TTW energy efficiency of 2.15 kWh per mile. This was nearly four times greater than that of the CNG control buses used in the study.

The electricity cost averaged 0.18 US$/kWh. This led to an operating energy cost of 0.39 US$/mile for each of the BEBs. The CNG fuel cost averaged 0.93 US$/GGE which equated to 0.23 US$/mile for each of the CNG buses.

Overall, the BEB maintenance cost equated to 0.16 US$/mile. The total CNG bus maintenance cost was 0.18 US$/mile.

OTHER PROJECT OUTCOMES

The project report highlights electricity costs and electricity demand charges as a cost related challenge for the public transport company. These challenges arise because the BEBs require intermittent opportunity charging throughout the day.

Demand charges[47] are an issue because, when charging during service, buses draw a large amount of power for a relatively short period of time. For 2014 and 2015, Foothills obtained exemption from demand charges. However, the energy supplier will apply demand charges from 2016 onwards due to the increase in the number of in-service BEBs.

Electricity costs are an issue because in-service buses are charging throughout all times of the day. This includes peak-charge times, when electricity is the most expensive. If the electricity supplier is charging at a tiered rate, as is the case for Foothill Transit, then busy day time periods coincide with the most expensive electricity costs.

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[46] *BEB availability used service reports from Proterra and daily activity sheets from the Pomona Depot. These sources only gave information on availability to operate at the beginning of the day, and thus may not accurately represent all-day data. Not all service reports and daily activity sheets were supplied to the researchers.*

[47] *Peak demand is a measure of the highest rate of energy consumption recorded, over discrete intervals (often 15-minute intervals), during a billing period. If demand charges apply, a consumer will be charged by the energy supplier in the following manner:*
*(demand charge rate) * (peak demand recorded). Energy suppliers use demand charges as an incentive for consumers to use power at a constant rate. (http://www.energysmart.enernoc.com/understanding-peak-demand-charges/).*

FUTURE GOALS

It appears that Foothill Transit is pleased with the performance of the BEBs as following the purchase of the twelve buses assessed in this study, Foothill Transit purchased two more fast-charge opportunity BEBs and thirteen extended-range BEBs. Also, on May 12, 2016, Foothill Transit announced a goal to fully electrify its fleet of over 300 vehicles by 2030 (Foothill Transit, 2016).

RELEVANT ONLINE REPORTS

1. Fast charge battery electric transit bus in-use fleet evaluation
Eudy, L., Prohaska, R., Kelly, K., & Post, M. (2016).
Retrieve report from: **http://www.nrel.gov/docs/fy16osti/65274.pdf**

2.Fast charge battery electric transit bus in-use fleet evaluation
Prohaska, R., Eudy, L., & Kelly, K. (2016)
Retrieve report from: **http://www.nrel.gov/docs/fy16osti/66098.pdf**

B.2 Fuel Cell Electric Bus Case Studies

The NREL website has a large database of public transport FCEB evaluation reports, on North American projects, conducted over the last fifteen years. While an overview of some of the main projects (evaluated by NREL) are given in the following section, the full database of reports can be accessed here: **http://www.nrel.gov/hydrogen/proj_fc_bus_eval.html.**

B.2.1 Zero Emission Bay Area (ZEBA) Demonstration Project in Oakland, California

A large FCEB demonstration project is currently running in Oakland, California. Alameda-Contra Costa Transit (AC Transit) is operating a fleet of thirteen FCEBs, which have collectively completed over two-million kilometres of service.

Performance results from the project include (Eudy, Post, et al., 2016):

- An average FCEB fuel economy which is 43% higher than that of the diesel control buses.
- FCEB availability of 74%.
- Per kilometre maintenance and fuel costs at least four times greater than that achieved by the diesel control buses (when including the FCEB maintenance costs covered by warranty).
- An overall FCEB reliability that exceeds the DOE/Federal Transit Administration's (FTA) ultimate FCEB target of 4,000 MCRC.

RELEVANT ONLINE REPORTS

1. Zero Emission Bay Area (ZEBA) fuel cell bus demonstration results: fifth report
Eudy, L., Post, M., & Matthew, J. (2016).
Retrieve report from: **http://www.nrel.gov/docs/fy16osti/66039.pdf**

B.2.2 American Fuel Cell Bus Project in Coachella, California

The American Fuel Cell Bus (AFCB) project includes four FCEBs with series configuration hybrid electric powertrains. The first of these buses entered service in November, 2011. The project is being run in Coachella, California and is jointly funded by both industry and the FTA's National Fuel Cell Bus Program (NFCBP). CALSTART and SunLine Transit Agency are leading the project. As with all other FCEB assessments in this section, evaluation of in revenue service was performed by the National Renewable Energy Laboratory (NREL) (Eudy & Post, 2015).

APPENDIX B: INTERNATIONAL CASE STUDIES

RELEVANT ONLINE REPORTS

1. **American fuel cell bus project: first analysis report**
   Eudy, L., & Chandler, K. (2013).
   Retrieve report from: **http://www.nrel.gov/hydrogen/pdfs/fta_report_no_0047.pdf**

2. **American fuel cell bus project: second report**
   Eudy, L., & Post, M. (2015).
   Retrieve report from: **http://www.nrel.gov/docs/fy15osti/64344.pdf**

B.2.3 BC Transit Fuel Cell Bus Project in Whistler, Canada

From 2009 until 2014, British Columbia Transit (BC Transit) ran a FCEB demonstration project in Whistler, Canada. The project included twenty FCEBs. At the time it was the largest FCEB fleet operating in one location. The fuel cell hybrid electric buses were built by New Flyer, with Ballard Power Systems supplying the fuel cell systems (Eudy & Post, 2014b).

The aim of the project was to investigate the capability of FCEBs at delivering daily public transport service in a demanding environment. The twenty FCEBs were supported by between three and six diesel buses throughout the year (Eudy & Post, 2014b).

A hydrogen fuelling station was built in Whistler by Air Liquide. Liquid hydrogen, produced through water electrolysis, using 98% renewable energy, was transported from the production facility in Becancour, Quebec, to Whistler by truck. As with the other North American projects, hydrogen was delivered to the FCEBs in gaseous form (Eudy & Post, 2014b).

This was a valuable demonstration project given the large fleet size and demanding operating conditions; over four-million kilometres were travelled by the FCEBs collectively and recorded outside air temperatures during the project ranged from -20ºC to 35ºC (Eudy & Post, 2014b).

RELEVANT ONLINE REPORTS

1. **BC Transit Fuel Cell Bus Project: evaluation results report**
   Eudy, L., & Post, M. (2014a).
   Retrieve report from: **http://www.nrel.gov/docs/fy14osti/60603.pdf**

2. **BC Transit Fuel Cell Bus Project evaluation results: second report**
   Eudy, L., & Post, M. (2014b).
   Retrieve report from: **http://www.nrel.gov/docs/fy14osti/62317.pdf**

B.3 Hybrid Electric Bus Case Studies

A number of older NREL reports (published between 2006 and 2008) on HEB trials in the U.S. can all be accessed from the following link: **https://www.nrel.gov/transportation/fleettest-evbus.html.**

A report on a more recent HEB trial (Williamson, 2012), conducted in Sydney, Australia, can be accessed here: **http://www.transport.nsw.gov.au/sites/default/files/b2b/publications/hybrid-bus-trial-final-report.pdf.**

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