Where Are We Heading With Electric Vehicles?

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ABSTRACT

This paper concludes that compared to conventional fossil-fuelled vehicle technologies, electric vehicles (EVs) are the best and most robust option with regard to moving to a zero emission road transport system. They enable significant to very deep (98%) *reductions* in greenhouse gas emissions, where large reductions depend on the extent renewable energy generation. Fuel cell vehicles appear not to have the same benefits as battery electric vehicles. They perform only slightly better than conventional fossil-fuelled vehicles in terms of well-to-wheel energy use per km. In contrast, EVs use approximately a factor of 3-5 times less energy. In fact, fuel cell vehicles are expected to produce a large *increase* in greenhouse gas emission of about a factor of two, based on the emissions intensity of the existing electricity grid. Fuel cell vehicles have the potential to substantially reduce greenhouse gas emissions in the long term, but only on the strict condition of a significant increase in renewable energy.

EVs and fuel cell vehicles are both expected to significantly improve local air quality, particularly in urban areas where population and associated transport needs are concentrated. However, the extent to which renewable energy is used, is again an important factor in relation to level of improvement that will be achieved. The economic case for EVs is strong. The (hidden) economic costs of air pollution and associated public health impacts caused by fossil-fuelled vehicles will be substantially reduced. 'Total cost' parity (purchase plus operating) with conventional vehicles is expected to occur in the early to mid 2020s.

In contrast to other regions in the world, Australia has a relatively sluggish track record in EV promotion and uptake, mainly due to a lack of supportive policies. New Zealand and some jurisdictions in Australia have taken a significantly more active stance regarding EVs. It is prudent that Australia does the same nationally, given the current transformation towards connected and autonomous vehicles (AVs) where electric vehicles are considered to be the 'natural partner' of AVs. EVs can support the transition to a more renewable energy system, functioning as relatively cheap energy storage devices.

So where are we heading with electric vehicles? Although there are significant differences between countries and regions in the world, the available data suggest we are definitely heading away from fossil-fuelled road transport towards a fully transformed road transport system where electric vehicles will dominate, or at least play a key role. Electric vehicles are the obvious choice when considering environmental and economic benefits. Other fundamental shifts such as autonomous vehicles and renewable energy are mutually reinforcing developments. Co-development with a clean and climate-friendly electricity generation system will enable deep cuts in greenhouse and air pollution emissions.

Keywords: *Electric Vehicles, Energy Efficiency, Air Quality, Emissions, Hydrogen Fuel Cell Vehicles, Air pollution, Greenhouse.*

INTRODUCTION

Motorised road transport was borne as an electric vehicle (EV), built in the United States in 1834 by Thomas Davenport. It was over fifty years later that Benz and Daimler developed the first road vehicle with a fossil-fuelled internal combustion engine (ICEV) in Germany. Around 1900, electric vehicles had a significant share of all engine-driven cars. For instance, EVs became the top-selling road vehicles in the US in 1900, capturing 28% of the market. EVs and ICEVs were competing with each other until Henry Ford, in 1908, chose an ICEV for the first mass production car in history. As a consequence, ICEVs replaced EVs, which became all but extinct by 1935.

From air quality and climate change perspectives, whilst complicated by energy sourcing issues, cradle-to-grave considerations, sole source versus mobile source emissions management, and end of life environmental impacts, the market penetration of ICEVs has been a challenging, if not regrettable development. The need to rapidly decarbonise the transport system and achieve international emission reduction targets will require deep cuts in greenhouse gas emissions from the transport sector. With an increasing focus on the public health impacts of transport emissions, there is also a strong push to reduce the volume of pollutants generated by motor vehicles. For some time now, EVs have been heralded as the obvious mechanism to achieve both of these outcomes (e.g. Arar, 2010; IEA, 2013), notwithstanding the above mentioned complexities.

Despite EVs being a promising pathway forward, surveys suggest that there may be a high level of ignorance and/or misconceptions in the community regarding this vehicle technology (IEA, 2018). This may in fact be one of the principal barriers towards a rapid transition to a clean and low-carbon transport system. Education, with the aim of presenting accurate (unbiased) and factual information, is therefore paramount. In the light of this, this paper aims to provide an overview of the current state of play on EVs in a global context, and will make comments regarding the situation in Australia and New Zealand.

BACKGROUND

When discussing the relevance of electric vehicles regarding current and future road transport, it is useful to define the different types of drivetrain options on offer today, and potentially in the near future. Firstly, there are internal combustion engine vehicles (ICEVs); being the vast majority of vehicles driven today. These vehicles can be powered using various liquid or gaseous fossil fuels (petrol, diesel, LPG, CNG) and/or biofuels (bioethanol, biodiesel, etc.), and involve igniting the fuel to drive pistons and/or rotors to turn a driveshaft, and in turn, propel the vehicle forward. Through this process, most of the energy stored in the fuel is lost, as will be discussed later, which is why ICEVs are relatively energy inefficient, and produce significant amounts of greenhouse gases and air pollutant exhaust emissions.

In an effort to find alternatives to fossil fuels to improve fuel security and reduce carbon emissions, various efforts have been undertaken to run ICEVs utilising biofuels. Biofuels vary significantly in composition, cost and emissions profile. They have the potential to reduce greenhouse gas emissions, but still emit on-road air pollutant emissions. Importantly, many biofuels impact feedstock commodities currently used for food production; an issue that needs to be carefully managed.

More recently, electric vehicles have again emerged as a viable alternative to ICEVs, in particular due to the significant advances in battery energy density. In this paper, a distinction is made between the two main types of plug-in electric vehicles (EVs): battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

- BEVs are powered solely by an electric motor, which uses electricity stored in a battery and is plugged-in to charge. There are no greenhouse gas or air pollutant exhaust emissions.

• In comparison, PHEVs include an internal combustion engine that predominantly generates additional electricity to extend driving range once the on-board battery is depleted. In some cases, the combustion engine can also directly propel the vehicle, but generally only at higher speeds due to the higher gearing of these engines for maximum fuel efficiency. Greenhouse gas and air pollutant emissions are generated when the combustion engine is used. PHEVs can also be plugged-in to charge, and emit no exhaust emissions whilst running on electricity. This is the principal difference between PHEVs and standard hybrid vehicles, such as the Toyota Prius, which for the purposes of this paper we do not define as an EV.

Finally, fuel cell vehicles (FCVs) use hydrogen, stored in on-board tanks, in combination with a fuel cell stack to generate electricity, which in combination with a small battery, powers an electric motor. FCVs are not plugged-in to charge, and are refilled with hydrogen in a similar manner to existing ICEVs. FCVs emit no greenhouse gas emissions, however, they do emit water (vapour).

Further details regarding the relative pros and cons of EVs, compared to these other drivetrain technologies, are discussed in the following sections of this paper.

THE CASE FOR ELECTRIC VEHICLES

There are several potential advantages to encouraging a transition towards EVs, both in terms of BEVs and PHEVs. Here we describe these issues in greater detail, and provide the relative pros and cons of EVs compared to other vehicle drivetrain technologies, by taking into consideration:
- Energy and GHG emissions performance
- Air quality and public health impacts
- Costs, and
- Grid impacts.

Energy and GHG Emissions Performance
Road transport currently uses large amounts of fossil fuels and therefore makes a significant contribution to global greenhouse gas emissions. It is estimated that approximately 17% of global fossil fuel related emissions is caused by road transport (OECD, 2010). For the environmental evaluation of vehicle technologies, energy consumption and emissions are often divided into well-to-tank (WTT) and tank-to-wheel (TTW) components. WTT refers to the stage from the extraction of feedstock until the delivery of fuel to the vehicle tank, whereas TTW quantifies the performance of the drivetrain. The well-to-wheel (WTW) efficiency combines these two stages, and is the proper statistic to evaluate and compare technology options. Typical values and reported ranges for energy loss are presented in Table 1 and Figure 1.

Although there is a substantial range in reported values (see Arar, 2010; Helmers and Marx, 2012; Xu et al., 2015), the values in Figure 1 and Table 1 are considered to be generally representative. These values are used in this paper to provide a high level overview and consistent basis to illustrate

Vehicle Technology	Energy Loss			WTW Efficiency	Energy use kWh/km
	WTT	TTW	WTW		
ICEV petrol	20%	82%	86%	14%	1.36
ICEV diesel	20%	75%	80%	20%	0.95
ICE LPG	10%	82%	84%	16%	1.19
ICE CNG	25%	75%	81%	19%	1.00
PHEV	25%	40%	55%	45%	0.42
FCV	60%	45%	78%	22%	0.87
BEV	21%	15%	33%	67%	0.28

Table 1 - Representative WTT, TTW and WTW (combined) energy losses from different vehicle drivetrain technologies and associated normalised on-road energy use and energy efficiency
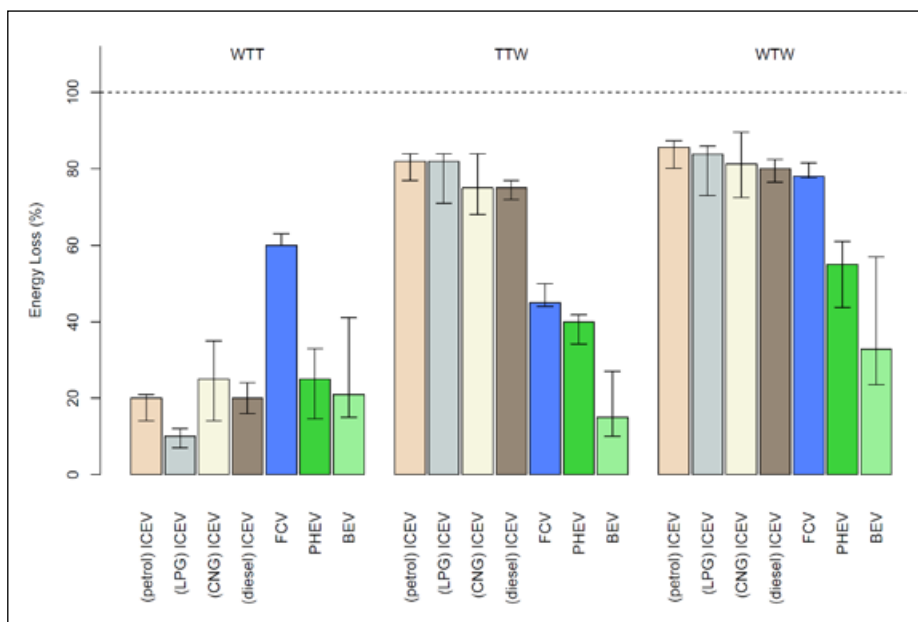

Figure 1 - WTT, TTW and WTW (combined) energy losses from different vehicle drivetrain technologies showing typical values in the bar plot, with reported ranges.

and discuss the main differences between different vehicle drivetrain technologies, in a general sense. It should be recognised however, that these figures can vary across specific vehicle models.

Figure 1 illustrates a number of important points. Firstly, in terms of overall (WTW) energy *loss*, the various ICEV options and the FCV have similar performance, i.e. typically losing 75-85% of (fuel) energy content in the process of production, transport and usage. In other words, for these vehicle drivetrain technologies only 15-25% of the 'initially available' energy contained in the fuel is actually used to drive the vehicle, and 75-85% of the energy is lost in the form of heat, leakage, pressurisation, transport and/or energy required for processing. Despite their inefficiency ICEVs have been successful due to the very high energy density of fossil fuels.

In contrast, BEVs may require (slightly) more energy in the WTT process than ICEVs, but waste only a small amount of energy (10-20%[1]) in the drivetrain as compared with ICEVs. PHEVs also perform better than ICEVs, but with higher energy losses than BEVs. It should be noted, however, that PHEV performance varies strongly with respect to individual use of these cars. In Figure 1 and Table 1 it has been assumed that the PHEV operates in electric mode for 60% of the

total travelled distance. When PHEVs operate exclusively using electricity, their performance will closely align with that of BEVs.

An advanced feature of BEVs and PHEVs that improves their energy efficiency is their ability to capture (electric motor) and store (battery) energy through the regenerative braking system. This modifies substantially the conventional relationship between emission rates (g/km) and average speed for ICEVs (i.e. substantially higher emission rates in both congested and high-speed conditions), into one with stable or lower (indirect) emission rates in low speed and congested conditions. As a consequence, BEVs and PHEVs use significantly less energy in urban city driving, with regular stop-go-stop traffic situations.

Nevertheless, both BEVs and PHEVs have room for improvement. The energy density of the best performing lithium-ion (Li-ion) batteries still sits at less than 0.2 kWh/kg, which means that EVs need heavy batteries to achieve an acceptable driving range. For instance, assuming an energy density of 0.15 kWh/kg and an average real-world electricity consumption of 0.19 kWh/km, a 30 and 75 kWh battery would have a weight of about 200 and 500 kg, respectively, and a corresponding driving range of about 150 and 400 km. PHEVs are also caught in a trade-off between acceptable electric driving

range, and a battery weight penalty beyond the efficiency gains of the hybrid-electric drivetrain. Vehicle mass is one of the main factors determining vehicle energy use (e.g. Smit, 2014a), and is the dominating factor regarding energy use in urban city driving. As a result, improvements in battery energy density, and in turn battery weight, will result in substantial further improvement of both BEV and PHEV energy efficiency. It is worth noting that the smaller the EV, the more energy-efficient it is. This is also the case for ICE vehicles, however, it is more pronounced with EVs due to the higher battery weight.

Energy loss by vehicle class presented in Table 1 can be used to compute normalised energy use expressed per kilometre of travel for the different ICEV technology classes on the road today. Average energy required to propel a car one kilometre along the road is computed, using the following equation:

$e = \eta \, (c \, \Sigma \, (f_i \, \theta_i) \,) / (T)$
e = real-world energy use for on-road car fleet (kWh/km)
c = conversion factor from MJ to kWh (0.278)
f_i = total real-world fuel consumption for vehicle technology class i (kg/annum)
θ_i = lower heating value for (fossil) fuel used by vehicle technology class i (MJ/kg)
T = total real-world travel for on-road car fleet (vehicle km/annum)
η = weighted energy efficiency of on-road car fleet (19%)

Australian fuel, emissions and travel data have been used for this purpose (Smit, 2014b; ABS, 2011). The Australian passenger car fleet consumed a total of approximately 13.6 million tonnes of fossil fuels in 2010. After consideration of the breakdown by fuel type (petrol, diesel, LPG, E10) and using corresponding lower heating values, this total fuel use corresponds to 600 PJ of energy per year. Eighty-two percent of this energy is used for petrol, ten percent is used for diesel cars and eight percent is used by LPG cars, which gives a weighted average (TTW) efficiency of about 19% for ICEVs. Total annual travel was 163.4 billion kilometres, which means that, on average, 1.0 kWh of fossil fuel energy was used per km of travel for Australian cars. Multiplying this with the 19% efficiency of ICEVs (η) gives e: an average required *on-road* energy figure of 0.19 kWh/km for Australian cars.

This value is similar to the 0.18 kWh/km figure that has been used in the US, reflecting a slightly lower (petrol) vehicle efficiency of 17%, used by Arar (2010). As the next step, the required normalised on-road energy (0.19 kWh/km) is used to estimate the total energy required per kilometre of travel for each vehicle type by dividing this value by vehicle-specific WTW efficiency, which is defined as 100% minus WTW energy loss. The results of this calculation are shown in Table 1 (last column). It is clear from Table 1 (and Figure 1) that BEVs are the only vehicle type that represents a technology jump of significance in terms of energy improvement in mobility. BEVs use approximately a factor of 3-5 times less energy as compared with conventional ICEVs.

Given the recent media attention in Australia, the results for FCVs may at first seem surprising given they have an energy use per km that is better when compared with diesel and LPG ICEVs, but still significantly higher when compared with EVs. As such, FCVs do not exhibit the significant improvement in energy efficiency that is possible with new technologies. This is primarily due to the high electricity consumption of zero-emission hydrogen generation (using water electrolysis) and significant energy losses during fuel cell operation. An FCV requires about three times the amount of energy per km as compared with a BEV.

Whilst some reductions are expected over the coming years, the universal laws of thermodynamics dictate that a minimum of 39 kWh of electricity is required to split 9 litres of water into 1 kg of hydrogen gas in a 100% efficient electrolyser[2]. In addition, clean water must be supplied and/or treated, requiring more energy (Lampert et al., 2015). The hydrogen gas must then be compressed (or liquefied) for use in transport, given its low energy density at standard atmospheric pressure, requiring up to another 15-20 kWh of electricity in total per kilogram of hydrogen gas, and then be distributed for use. One kilogram of hydrogen gas is expected to drive a FCV approximately 100 kilometres (under US EPA test conditions). This translates to an input of 80-100 kWh of electricity per 100 km travelled (after accounting for electrolyser inefficiencies and energy losses), compared to less than 30 kWh for BEVs (after accounting for electricity transmission losses).

The reason for using energy units (kWh/km) in Table 1 instead of greenhouse gas units[3] (CO_2-equivalent/km) is that the latter measure is highly variable and a function of the regional fuel mix and/or the processes used to produce and distribute the fuels/electricity, e.g. biofuels, solar/wind energy, hydrogen pathway, coal, etc. This is particularly the case for hydrogen production and electricity generation.

As stated earlier, we calculated that at the fleet level 1.0 kWh of fossil fuel energy was used per km of travel on average for Australian cars. This is a real-world *TTW* estimate for ICEVs, and it reflects the 75-80% energy loss shown in Table 1. Using the fuel type specific energy proportions mentioned before[4], a weighted average WTW estimate of 1.36 kWh fossil fuel energy per km of travel is computed. Using a weighted average lower heating value of 44.3 MJ/kg (12.3 kWh/kg), this energy use corresponds to about 110 grams of fossil fuel per km, and an emissions rate of 350 g CO_2 per km[5]. This number is multiplied with 101.5% to account for other greenhouse gas emissions such as methane and nitrous oxide and convert the WTW estimate to 355 g CO_2-e per km.

According to data presented in Woo *et al*. (2017), the current Australian (mainly fossil-fuel based) electricity generation system produces 748 g CO_2-e per kWh. However, if Australia transitioned to a decarbonised electricity system, like Norway (only 2% fossil fuels, 98% renewable energy, mainly hydro power), it would produce only 19 g CO_2-e

per kWh. An Australian system less reliant on coal, and with a greater proportion of sustainable energy in the energy mix[6], would produce about 300 g CO_2-e per kWh.

Combining these values with the required energy (kWh/km) in Table 1 for BEVs and FCVs provides the following:
- Current Australia: BEV 213 CO_2-e/km, FCV 647 CO_2-e/km.
- More sustainable Australia: BEV 85 CO_2-e/km, FCV 260 CO_2-e/km.
- Decarbonised Australia: BEV 6 CO_2-e/km, FCV 17 CO_2-e/km.

It is noted that PHEVs would have CO_2-e emission rates somewhere between BEVs and ICEVs depending on the proportion of driving in electric mode.

When compared with ICEVs, BEVs will achieve significant GHG emission reductions of about 40% ('Current Australia'), to deep cuts of about 75% ('More Sustainable Australia'), to very deep cuts of 98% ('Decarbonised Australia'). For FCVs, the picture is different. When compared with ICEVs, FCVs will produce a large *increase* in GHG emission of about 80% ('Current Australia'), which changes sign to a GHG emission reduction of about 25% ('More Sustainable Australia'), to very deep cuts of 95% ('Decarbonised Australia'). In particular the impacts of FCVs on total GHG emissions strongly depends on the sustainability of the electricity generation system, whereas this is less so for BEVs. In fact, significant reductions in greenhouse gas emissions with fuel cell vehicles appear *only* possible if Australia makes a fundamental shift towards almost an almost 100% renewable energy system, which is unlikely in the near to medium future. BEVs are therefore considered the safer and more robust option with regard to moving to a zero emission road transport system. Clearly, BEVs, PHEVs and FCVs should use electricity from non-fossil fuel and renewable energy sources to the maximum extent possible, in order to reduce the carbon footprint of road transport.

Although WTW energy and CO_2-e estimates are aiming to quantify a complex and location-specific system, the strong benefits of BEVs, as compared with ICEVs and FCVs, are consistently reported in international research. For instance, Xu *et al*. 2015 reported that CNG, diesel, conventional hybrid and hydrogen fuel cell buses all have similar WTW CO_2-e emission rates of about 2 kg/km, but battery-electric buses have about 1 kg/km, half of the other technologies. If electricity were generated with 100% sustainable energy, such as solar and wind power, the WTW CO_2-e emission rate for EVs would drop to essentially zero g/km (see Wang *et al*., 2015).

The argument that BEVs have little CO_2 benefits because of the carbon-intensive electricity generation infrastructure in Australia demonstrates a concerning lack of foresight. The world's energy generation system is increasingly decarbonised and penetration of renewable energy generation is rapidly increasing. Australia is expected to follow this trend, sooner or later. As illustrated before, in countries where electricity grids are already significantly decarbonised, such

as Norway and New Zealand, these vehicle technologies can lead to deep reductions in energy use and greenhouse gas emissions.

It is considered only a matter of time that the same will happen in Australia. As a result, the environmental performance of EVs will inevitably and substantially improve over time, whereas at best only marginal improvements can be expected for ICEVs. As a consequence, only EVs, and to a significantly lesser extent FCVs, are believed to have the potential to create, or relevantly move towards, a zero-emission transport system.

Air Quality and Public Health Impacts

Ambient air pollution is associated with a wide range of adverse health effects, ranging from minor respiratory tract irritation to increased mortality. The close proximity of motor vehicles to the general population makes this a particularly relevant source from an exposure and public health perspective. International studies have found that motor vehicles are the largest single contributor to human health effects (e.g. Caiazzo et al., 2013).

In fact, health effects due to air pollution are similar or larger in terms of a (premature) death toll as compared with traffic accidents (WHO, 2005). It is estimated that motor vehicle pollution contributes to 40% more premature deaths than vehicle fatalities in Australia each year (Schofield et al., 2017). Several studies show a causal link between motor vehicle pollution and respiratory disease and illness, particularly amongst young children and the elderly (e.g. Bai et al., 2018). As a consequence, there are significant economic costs related to these health effects, and it has been estimated that these costs to the Australian economy are in the order of 1 to 4 billion Australian dollars per year (BTRE, 2005).

The combination of increasingly strict air quality criteria around the world and the range of carcinogenic pollutants without safe thresholds emitted by ICEVs, warrants a push to minimise motor vehicle air pollutant emissions and minimise population exposure to the largest extent feasible.

EVs and FCVs are expected to significantly improve local air quality, particularly in urban areas where population and associated transport needs are concentrated. This is because BEVs (and PHEVs when using only electricity) are essentially 'zero-emission' vehicles and, compared to ICEVs do not produce 1) exhaust gas emissions or 2) evaporative emissions (fuel storage, fuel lines, leakage, etc.). The only local air pollutant emissions all vehicles produce are non-exhaust particulate matter emissions due to brake wear, tyre wear and road wear (including resuspended road dust) – noting that brake wear is lower in EVs due to use of regenerative braking.

The only major emission from FCVs is water. FCVs produce no carbon emissions if the hydrogen is produced using electrolysis, powered by renewable energy, and the hydrogen is also transported to the fuelling site using renewable energy and/or zero-emission transport. As a result of the electrolysis process, FCVs displace approximately 9 litres of water for every 100

kilometres travelled[7]. The broader impacts of water emissions from FCVs (as both a liquid and a vapour) are still under investigation.

Nevertheless, careful assessment of the urban air quality impacts of complete fleet electrification is required. For instance, Yu and Stuart (2017), simulated the impacts for 2050 in Florida (US) and found a 65-85% reduction in population weighted exposure to selected carcinogenic compounds, but a 60% increase for NO_x. The latter was due to increased electricity demands, i.e. increased operation of local (coal-fired) power stations. However, assuming the same fuel mix and no improvement in power station emission control over the next 30+ years appears unrealistic. Nevertheless the results suggest that a fleet of 100% EVs does not guarantee deep reductions in emissions and population exposure for all air pollutants, and that local air quality impacts will depend on how (fuel mix) and where (e.g. distance of power stations to urban areas) electricity is generated.

Costs

The technical structure of a BEV is simpler compared to an ICEV since there is no starting, exhaust or lubrication system, and generally no gearbox. This means that maintenance, repair and service costs are substantially reduced in comparison with conventional ICEVs, or PHEVs, which contain dual powertrains. In addition, 'fuel costs' are significantly lower. Based on an average electricity price of $0.20 per kWh (after discounts) and BEV energy consumption 0.19 kWh per km[8], this translates to an average cost of about $3.80 per 100 km for BEVs. In comparison, at an average petrol price of $1.60 per litre and an average new ICEV fuel consumption of 11.1 L per 100 km, this translates to a cost of $17.76 per 100 km. Therefore, the energy cost of new BEVs is about 20% of new ICEVs, on average.

The battery is the largest cost of a BEV, and has arguably been the largest cost barrier to mass-market EV deployment. The real-world driving range of BEVs varies substantially, and is closely related to the size of the battery and therefore purchase price. For instance, a Nissan LEAF with a 24 kWh battery is expected to achieve a range of about a 100 km, whereas the Tesla Model S with a 100 kWh battery has a much larger range of more than 500 km (IEA, 2018). Given that average daily trip distance is generally close to or below 10 km (e.g. Smit and Ntziachristos, 2013), the issue of driving range may be more of a perceived issue ('range anxiety') than an actual issue for most people living in urban areas.

With a price tag of about 1000 USD per kWh in 2008, battery costs have continued to come down quickly through economies-of-scale. Battery costs currently stand at approximately 200 USD per kWh, and the point of price parity with ICEVs, without incentives, is expected to be achieved at 100 USD per kWh, which should be reached in the early-to-mid 2020s (McKinsey, 2017).

Nevertheless, at this stage the up-front purchase costs for non-luxury BEVs and PHEVs are significantly higher than their

ICEV counterparts, even when combined with subsidies that may be locally available. It is noted that attractive and new vehicle financing options, such as 'battery leasing' or a 'guaranteed residual value' for the battery/vehicle at the end of its life, could potentially overcome this issue in the short-term.

In Table 2, an example comparison between similar BEV, PHEV, FCV, ICEV-Hybrid and ICEV models has been included, using figures from the US market, where all 5 of these vehicles are currently available. Firstly, whilst it could be argued that the Toyota Mirai (FCV) is a larger vehicle compared to the alternative models presented in Table 2, in terms of passenger and cargo volumes, it is equivalent to or less than the alternative models shown. The Toyota Mirai was also the closest comparable FCV model available at the time of this analysis. As shown in Table 2, despite higher upfront costs, both the ICEV-Hybrid and PHEV models end up being only marginally higher than the ICEV model after fuel savings are taken into account. These figures are also based on the relatively conservative split of 60% electric and 40% petrol driving for the PHEV model. For city commuters, the electric component of driving could be closer to 80% (when electric driving range is greater than 40 km), which in turn would bring the total cost down to almost on par with the ICEV model's total cost.

Comparing the BEV model to the ICEV model, the upfront cost is about 45% higher. After taking into account the significant fuel and maintenance savings achieved by switching to electric, this difference is reduced to 13%. Currently this price differential presents a challenge, and it is being addressed in some international jurisdictions through government incentives. Nevertheless, as battery costs continue to fall, so too will the upfront cost of BEVs. It is expected that in the early-to-mid 2020s BEVs will have reached price parity with ICEVs (IEA, 2018), and, importantly, be cheaper to own on a total cost basis. Based on the current figures, the payback period for a BEV is expected to range from 6-8 years.

The FCV model shown in Table 2 has a much higher upfront cost and operating cost compared to all other drivetrain technologies. As will be discussed further in the section following on State of the Market, the FCV market is still relatively immature, with a production rate similar to EVs in the late 2000s. Needless to say, we would expect that as manufacturing volumes increase, economies-of-scale will lead to reductions in the upfront cost; likely to a level similar to that of PHEVs, but not as low as BEVs, given FCVs have more components: hydrogen tanks, fuel cell stack, on-board battery and an electric motor.

However, the greater challenge for FCVs is believed to be in their high operating costs, given the high energy and water intensity requirements of producing hydrogen from water using electrolysis, as was discussed before. As such, whilst the cost of hydrogen may reduce further than the CSIRO's current expected cost of $15 per kg (Hamilton-Smith, 2018), FCV operating costs are expected to remain around 4 times as expensive as BEVs.

In the case of both the BEV and PHEV models shown in Table 2, the associated operating costs could also be further reduced through off-peak, solar and free public charging, due to the flexibility of being able to charge EVs at different sites. This compares to the relatively rigid model for ICEV, ICEV-Hybrid and FCV vehicles, where service stations control supply, and there is very little price variation from site to site.

It should be noted that the figures included in Table 2 are based on averages, and EPA drive cycle test figures for the US market, which may deviate, to some extent, in real-world conditions. Despite this, the expectation is that the relative differences in costs between vehicle drivetrain technologies will remain similar.

Finally, another issue that is not captured in the figures above is the relative uncertainty in resale values for BEVs, PHEVs and FCVs. This uncertainty has contributed to higher depreciation rates for these vehicles, which further increases the upfront cost and/or leasing rates. No doubt, in the near future, the opposite will be true, and in fact a higher depreciation rate will switch to being associated with ICEVs as the transition accelerates, and ICEVs become more difficult to sell. However, at least until second-hand markets are established for BEVs, PHEVs and FCVs, higher depreciation rates will remain a considerable barrier to mainstream adoption.

Grid Impacts

A transition away from fossil fuels to electricity for transport presents a number of potential challenges and opportunities – whether it be through the direct charging of electric vehicles (BEVs/PHEVs) or using electricity to split water into hydrogen for fuel cell vehicles (FCVs).

Some studies have suggested that existing electricity generation would be insufficient to facilitate a complete shift to EVs (e.g. Wong *et al.*, 2017), whereas others point out that the availability of electricity is a non-issue as long as vehicles are mainly charged at night when excess generating capacity is available (e.g. Wu *et al.*, 2015b).

Assuming vehicle utilisation rates remain constant, the aggregate electricity requirements of EVs are expected to be relatively minor compared to other alternative technologies, such as hydrogen fuel cell vehicles.

In the case of Australia, if the existing fleet of 14 million passenger and light commercial vehicles (ABS, 2018) was converted to 100% BEVs, continued travelling an average of approximately 14,000 kilometres per year (ABS, 2017), and using the previously estimated mean real-world electricity consumption of 0.19 kWh/km, this would result in a gross electricity requirement of 37 TWh per annum i.e. 15% of Australia's annual electricity generation (250 TWh/annum; Department of the Environment and Energy, 2017). Similarly, if New Zealand's existing fleet of almost 4 million passenger and light commercial vehicles was converted to 100% BEVs, and continued travelling an average of 10,000 kilometres per year (Ministry of Transport, 2018), this would result in a gross electricity requirement of 8 TWh per annum i.e. 18% of New Zealand's annual electricity generation (43 TWh/annum; Ministry of Business, Innovation and Employment, 2018). These figures are in line with similar modelling carried out for the US, which estimated that a 100% conversion of the US car fleet to BEVs would require a 20% increase in annual electricity generation (Arar, 2010).

In comparison to BEVs, the electricity

	ICEV	ICEV-Hybrid	FCV	PHEV	BEV
Make/Model	Toyota Corolla Sedan	Toyota Prius	Toyota Mirai	Hyundai Ioniq Plug-in	Hyundai Ioniq Electric
Length	4,651 mm	4,539 mm	4,890 mm	4,470 mm	4,470 mm
Width	1,775 mm	1,760 mm	1,815 mm	1,821 mm	1,821 mm
Wheelbase	2,700 mm	2,700 mm	2,780 mm	2,700 mm	2,700 mm
Kerb Weight	1,309 kg	1,395 kg	1,848 kg	1,505 kg	1,435 kg
Passenger Volume (m3)	2.7	2.6	2.4	2.7	2.7
Cargo Volume (m3)	0.4	0.7	0.4	0.7	0.7
Energy Source	Petrol	Petrol	Hydrogen	Petrol/Electricity	Electricity
Rated Equivalent Fuel Consumption according to US EPA Test Cycle	7.4 L/100 km	4.5 L/100 km	3.6 L/100 km (1 kg H_2 per 100km)	2.0 L/100 km (17.4 kWh/100 km; 4.5 L/100 km when battery depleted)	1.7 L/100 km (15.5 kWh/100 km)
Fuel / Energy Cost (based on Australia/ New Zealand)	$1.60 per L (petrol) = $11.80 per 100 km	$1.60 per L (petrol) = $7.20 per 100 km	$15 per kg ($H_2$) = $15 per 100 km	Electricity only: $0.20 per kWh = $3.5 per 100km 60% Electricity/ 40% Petrol = $5.0 per 100 km	$0.20 per kWh = $3.10 per 100 km
Estimated annual scheduled maintenance cost	$250	$250	$150* *(most FCVs are leased with maintenance included; have estimated cost similar to BEV)*	$250	$150
Total operating cost over 5 years @ 15,000 km p.a. (excluding tyres, unscheduled maintenance)	$10,130	$6,875	$12,000	$5,000	$3,075
Upfront cost (based on US pricing in $AUD)	$28,000 (Baseline for comparison)	$32,000 (14% higher than ICEV)	$80,000 (186% higher than ICEV)	$34,000 (21% higher than ICEV)	$40,000 (43% higher than ICEV)
Total Cost over 5 years (upfront + operating; excluding depreciation/ resale value)	$38,130 (Baseline for comparison)	$38,875 (2% higher than ICEV)	$92,000 (141% higher than ICEV)	$39,000 (2% higher than ICEV)	$43,075 (13% higher than ICEV)

Table 2 – Example comparison of BEV, PHEV, FCV, ICEV-Hybrid and ICEV models

Sources: Data compiled from Toyota Motor Sales USA and Hyundai Motor America, combined with local electricity and fuel prices.

requirements of FCVs are far greater due to the energy intensity of producing hydrogen from water using electrolysis. On the basis of FCVs using 80 kWh of electricity per 100 km travelled, (see previous section on Costs) if the existing passenger and light commercial fleet in Australia was converted to 100% FCVs this would result in a gross electricity requirement of 157 TWh per annum i.e. 63% of Australia's annual electricity generation. Similarly, in New Zealand, a 100% FCV passenger and light commercial fleet would result in a gross electricity requirement of 32 TWh per annum i.e. 74% of New Zealand's annual electricity generation.

Whilst both Australia and New Zealand, individually already produce enough renewable energy annually to power passenger and light vehicle fleets of 100% BEVs, a significant shift to hydrogen FCVs would require a substantial increase in electricity generation capacity in both countries.

In regards to specific grid demand issues, 'spiking' due to millions of EVs charging at higher rates at the same time, or significant volumes of hydrogen being produced simultaneously, can both largely be managed through time-of-use and demand electricity tariffs, that encourage electricity usage outside of peak demand periods. No doubt, without such control measures, EVs, and to a lesser extent FCVs, have the potential to have similar negative consequences as other major electrical appliances have had on grids in the past e.g. air-conditioners.

On the other hand, smart charging regimes, specifically for EVs, have the potential to deliver a range of significant benefits for the wider electricity grid. EVs are essentially mobile batteries, storing around 1-7 days of a household's normal electricity usage. Yet, the reality is that despite owners wanting the ability to drive 500 kilometres in a single charge, the average car in Australia and New Zealand is only driven 30 to 40 km per day (ABS, 2017; Ministry of Transport, 2018). This means that most EVs would have significant surplus battery capacity on an average day that could be used for other purposes.

In the first instance, EVs could be used to improve climate resilience by providing electricity to power homes, buildings, and emergency services during disasters and grid blackouts. Secondly, however, this surplus battery capacity could be used to capture grid renewables during peak renewable periods, and export this energy back to the grid during peak demand periods, effectively acting similar to stationary storage, but at a far lower cost compared to investing in dedicated battery storage.

What is clear is that based on the current uptake in renewables, particularly solar photovoltaics (PV), the load profiles of electricity grids around the world are dramatically changing already, not accounting the future uptake of EVs and FCVs. An increase in solar is expected to meet a significant proportion of electricity grid demand during daytime hours. As night time approaches a significant ramping of other generation assets is required in order to reach evening peak demand. Again, EVs

have the ability to absorb a proportion of solar-generated electricity during the day, and export this to the grid during the evening, in order to not only support the uptake of renewables, but reduce the ramping strains that intermittent renewables are introducing into grids without significant storage capabilities e.g. pumped hydro, stationary storage, etc. It should be noted that hydrogen has also been touted as a potential storage medium for this purpose, however, with its far lower efficiency, this only makes economic sense after all battery storage has been saturated, given the much higher efficiencies of these devices.

A recent California study modelled the potential of using electric vehicle-to-grid (V2G) technologies to support the uptake of renewables, whilst minimising the ramping strains caused by renewable intermittency, in order to reach the state's target of 50% renewable energy by 2030 (Coignard, 2018). By modelling the state's EV target of 1.5 million vehicles by 2025 (1 million PHEVs, 0.5 million BEVs), and assuming V2G services were available at 60% of EV homes, and 30% of EV workplaces, it was found that this EV fleet could provide services to the grid equivalent to $US12.8 - $US15.4 billion of stationary storage, meeting the State's 50% target, but at a fraction of the cost (Coignard, 2018).

Whilst further research into the precise costs of V2G services is still underway, this alternative potential benefit of EVs is significant and should be taken into account when considering the relative merits of this technology compared to alternative options.

STATE OF THE MARKET

Given the previously outlined business case for EVs, it is important to examine the current state of the market to understand where Australia, New Zealand and the rest of the world is tracking in regards to the uptake of this innovative and beneficial transport technology.

Market Penetration
Market penetration of EVs over the past decade was initially slow, but has increased

over the last few years. In 2017, more than 1 million EVs were sold around the world, with the global EV fleet reaching more than 3 million vehicles (IEA, 2018). In Norway, arguably the leading EV market globally, just under 40% of new vehicle sales in 2017 were EVs. The largest EV market, China, has also seen a rapid increase in EV sales in recent years, from a mere 0.4% in 2014 to 2.2% in 2017 (IEA, 2018; EV-Volumes, 2018). Whilst this proportion is still relatively low, given the size of the Chinese vehicle market, this equates to approximately 579,000 EV sales in 2017, more than any other country in the world (IEA, 2018).

It is clear from these sales figures that EVs are an emerging vehicle technology in many markets around the world. To put this into perspective, Figure 2, shows the trajectory of global sales for BEVs, PHEVs, and FCVs between 2012 and 2017. As shown, the zero emission vehicle market is dominated by BEVs, shortly followed by PHEVs. In comparison, FCVs are a minor component and hardly visible in Figure 2, with a sales rate similar to that of EVs more than 10 years ago.

To explore this aspect further, Figure 3 shows sales data for markets that have shown the most interest in FCV technology: Japan and South Korea. FCV sales again have been a minor component in comparison particularly to BEVs, but also PHEVs in the case of Japan.

Whilst the uptake of EVs globally has increased significantly in recent years, EVs are still not a major component of vehicles sales in either Australia or New Zealand at present. As of mid-2018, there were approximately 9,000 EVs in Australia (EV-volumes, 2018), out of a total fleet of 14 million passenger vehicles i.e. 0.06% (Australian Bureau of Statistics, 2017) and approximately 9,000 EVs in New Zealand out of a total fleet of almost 4 million passenger vehicles i.e. 0.23% (New Zealand Ministry of Transport, 2018). Despite a low proportion of sales being electric in both of these countries, the rate of EV sales in both Australia and New Zealand has increased significantly in recent years, as shown in Figure 4.

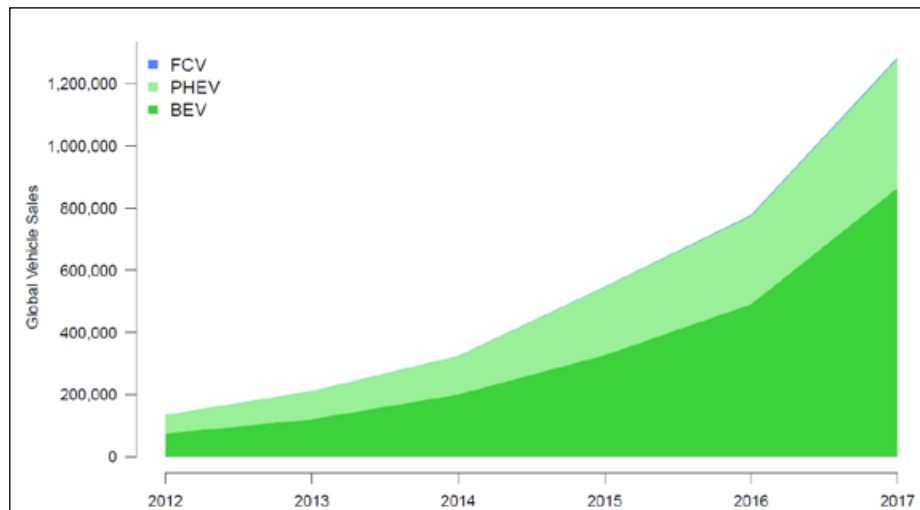It should also be noted that New Zealand consumers face minimal barriers in purchasing

Figure 2 - Sales of BEVs, PHEVs and FCVs globally between 2012 and 2017 (data taken from EV-Volumes, 2018).

EVs privately imported from other right-hand drive markets, such as the United Kingdom and Japan. The uptake of these grey imports has also increased significantly in recent years. In contrast, there are considerable restrictions on grey imports in Australia, and as such, it has not been a viable pathway for Australian consumers to acquire an EV.

Australia's relatively sluggish track record in EV uptake is, in large part, due to a general lack of federal government incentives for EVs, the absence of supportive policies for increasing fuel efficiency, and limited government support for reducing vehicle emissions. EV manufacturers have therefore not concentrated on the Australian market, providing consumers with a limited EV model choice and higher prices. An exception to this dearth of local policy has been the Queensland Government, which released its EV Strategy ("The Future is Electric"), in October 2017, with a particular focus of supporting the rollout of charging infrastructure (Department of Transport, 2018).

Until recently, the policy situation in New Zealand was relatively similar to Australia. However, in May 2016, the national government announced its Electric Vehicle

Programme, which included:

- a goal of reaching 64,000 EVs in New Zealand by the end of 2021,
- exemption from road user charges for light electric vehicle until the end of 2021,
- bulk government and commercial purchases of EVs,
- rollout of public charging infrastructure,
- a contestable fund to support innovative low emission vehicle projects, and
- establishment of an EV leadership group to pro-actively promote initiatives and share information across government and industry.

In line with the introduction of this programme, there has been a significant increase in the local uptake of EVs in New Zealand, with a tripling of EV registrations between the 2015/16 financial year (prior to policy introduction) and 2016/17 financial year (post policy introduction). The number of new EV registrations in New Zealand has doubled again between FY 16/17 and FY 17/18 (New Zealand Ministry of Transport, 2018).

Charging Infrastructure

The main advantage of an ICEV or FCV compared to a BEV, is an the relatively quick refilling of the tank. However, it is noted that for FCVs the necessary hydrogen filling station infrastructure is not yet available around the world, so hydrogen-powered fuel cell vehicles would have to return daily to the same filling station (Helmers and Marx, 2012).

In tandem with an increase in EV sales globally, over recent years there has also been a rapid increase in the rollout of EV charging infrastructure, both in the form of slow charging (SCh) and fast charging (FCh) infrastructure. Here we define SCh as charging infrastructure that delivers AC current to an EV for its on-board charger to convert into to DC current to charge the battery. SCh infrastructure charging rates vary from 2-43 kW, with the rate limited by an EV's on-board charging capabilities. SCh infrastructure can charge an average BEV battery in 2-12 hours, depending on the rate of charge and size of battery. FCh is defined here as charging infrastructure that delivers DC current directly to an EV's on-board battery, with a varying charging rate of 25-500 kW. Existing BEVs can fully charge using this infrastructure in 20-40 minutes, and in the near future will be able to take advantage of higher charging rates to reduce charging time down to less than 10 minutes.

SCh is the dominant form of charging infrastructure around the world. This corresponds with the majority of EV charging being carried out at home overnight or during the day at workplaces. FCh infrastructure has increased substantially over the past two years, in part due to a range of collaborations between vehicle manufacturers, as well as Tesla rolling out its own dedicated supercharger network. As of 2018, there were over 270,000 publicly-available EV chargers globally, of which over 85,000 were FCh units (IEA, 2018; EV-Volumes, 2018). In Australia there were approximately 100 FCh units and over 750 SCh units as of April, 2018 (EV-Volumes, 2018).

The optimum mix of SCh/FCh infrastructure, and the optimum EV-to-charger ratios, are a matter of debate, but largely depends on local travel needs and preferences. The EU has suggested a 2020 target of one publicly accessible charging points for every 10 EVs on the road. Looking at the status of charging infrastructure around the globe, coverage rates vary significantly across EV markets. For instance, Japan has the highest EV/FCh ratio of about 33 i.e. 1 public FCh unit for every 33 EVs, as compared to 100 in the Netherlands, 400 in the US, 80 in Australia, and 36 in New Zealand (IEA, 2018; EV-Volumes, 2018). In comparison, the Netherlands has the highest EV/SCh ratio of about 2, i.e. 1 pubic SCh unit for every 2 EVs, as compared with 5 in the US, 10 in Japan, 12 in Australia, and 16 in New Zealand (IEA, 2018; EV-Volumes, 2018). Looking forward, as the number of EVs increase in the global vehicle fleet, there will be an increasing need for publicly accessible SCh and FCh infrastructure to keep place with these developments.
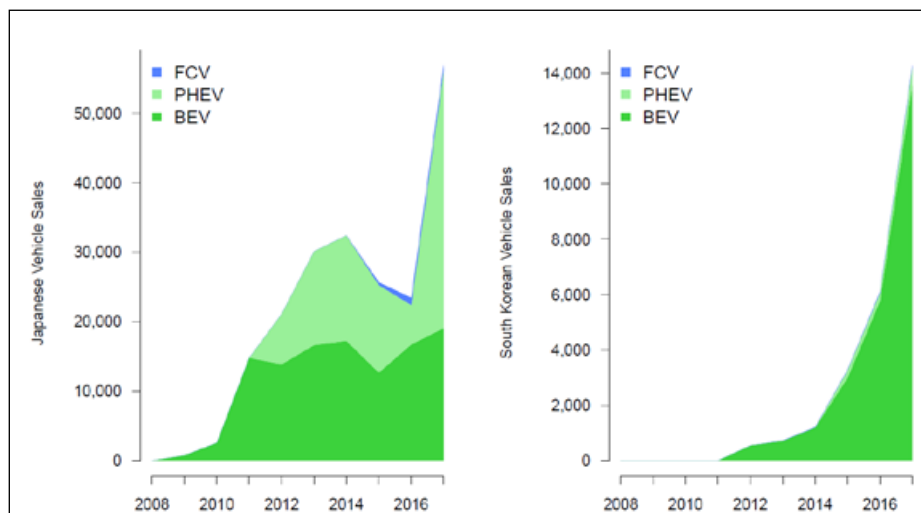

Figure 3 - Sales of BEVs, PHEVs and FCVs in Japan and South Korea 2008-2017 (data taken from EV-Volumes, 2018).
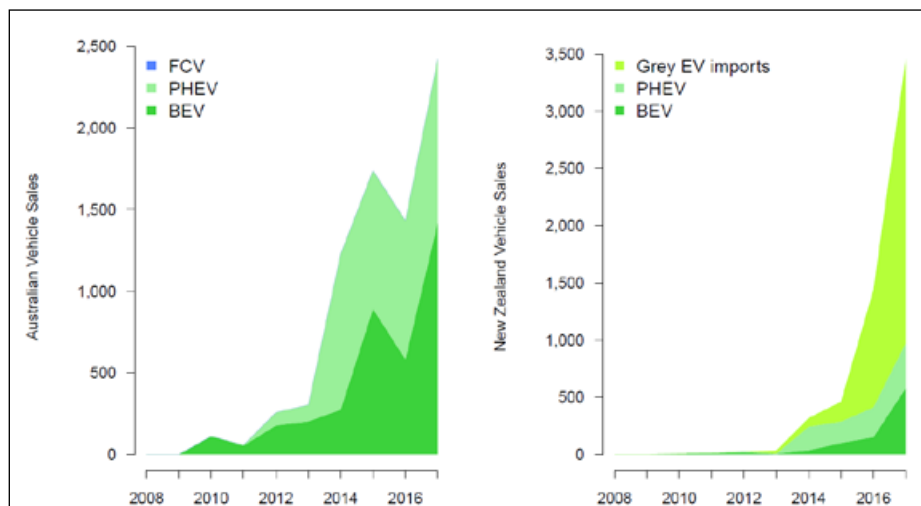

Figure 4 - Sales of BEVs, PHEVs and FCVs in Australia and New Zealand 2012-2017 (Australian data taken from EV-Volumes, 2018; New Zealand data taken from New Zealand Ministry of Transport, 2018).

FUTURE DEVELOPMENTS

The following section of this paper details EV targets and bans, future market projections, autonomous vehicles, and finally a brief section on community awareness and perceptions.

Future Projections
Looking forward there are various projections in regards to the uptake of electric vehicles. Bloomberg New Energy Finance is predicting that about a quarter of all new vehicle sales with be EVs by 2030, and this will increase to over 50% by 2040 (BNEF, 2017). These figures translate to 10% of the global vehicle fleet being electric by 2030, increasing to a third by 2040 (BNEF, 2017). The International Energy Agency also expects a global fleet of 13 million EVs by 2020 (increasing from 3.7 million in 2017) and up to almost 130 million EVs by 2030. These projects correspond to a 24% average, year-on-year sales growth over the projected period (IEA, 2018).

Turning specifically to the Australian market, a recent study commissioned by the Australian Renewable Energy Agency (ARENA) and Clean Energy Finance Corporation (CEFC) outlined that up to 60% of new local vehicle sales could be EVs by 2030, and that this would increase to up to 100% of sales by 2040. These projections translated to up to 25% of the national fleet being EVs by 2030, and up to 60% by 2040 (Energeia, 2018). Similarly, the New Zealand Government expects EVs to make up approximately 40% of the local fleet by 2040 (Ministry of Transport, 2017).

Clearly, as battery costs continue to fall and consumers become more familiar with EV technology, as well as aware of the environmental and economic benefits, the rate of EVs is expected to rapidly increase over the coming 5-10 years. In order to assist in facilitating this transition, governments around the world are setting targets and bans, as described further below, sending a clear signal to both the market and consumers.

Future Targets and Bans
In acknowledgment of the need to provide confidence to the market, a number of countries have publicly committed to EV targets. Whilst many countries have targets applying to a number of vehicle types/categories, Table 3 shows the specific targets relating to electric passenger vehicles. China in particular has an aggressive target of 5 million EVs in its vehicle fleet by 2020 (approx. 2% of the fleet), and 40-50% of new vehicles sales being 'new-energy vehicles' i.e. electric or fuel cell vehicles, by 2030. Some countries such as the Norway, the Netherlands and Ireland have even higher ambitions, targeting 100% EV sales by 2025-2030. As mentioned previously, New Zealand has set a target of 64,000 EVs by 2021, however, at present, no Australian government has set a state or national EV target (outside of government fleets).

As shown in Table 3, in addition to EV targets, a number of countries have also announced bans on ICEV sales and/or ICEVs

Country	Targets	ICEV Bans	Major ICEV Access Restrictions
Canada	N/A	N/A	Vancouver: 2030
China	5 million EVs by 2020; 40-50% NEV sales by 2030	Under consideration	N/A
EU	15% EV sales by 2025, 30% by 2030	N/A	Athens: Diesel by 2025 Copenhagen: 2030 Rome: 2030
France	N/A	2040	Paris: Diesel by 2024. All ICE by 2030
Finland	250,000 EVs by 2030	N/A	N/A
India	30% EV sales by 2030	N/A	N/A
Ireland	500,000 EVs / 100% EV sales by 2030	2030	N/A
Japan	20-30% EV sales by 2030	N/A	N/A
Netherlands	10% EV sales by 2020, 100% by 2030	2030	N/A
New Zealand	64,000 EVs by 2021	N/A	Auckland: 2030
Norway	100% EV sales by 2025	2025	N/A
South Korea	200,000 EVs by 2020	N/A	N/A
Slovenia	100% EV sales by 2030	2030	N/A
Sri Lanka	N/A	2040 (entire fleet without ICE vehicles)	N/A
Sweden	N/A	2045 (entire fleet without ICE vehicles)	Stockholm: 2030
Scotland	N/A	2032	N/A
UK	396,000 to 431,000 EVs by 2020	2040	London, Oxford: 2030
USA	3.3 million EVs in eight states combined by 2025 California: 1.5 million zero-emission vehicles and 15% of sales by 2025, 5 million zero-emission vehicles by 2030.	N/A	Los Angeles, Seattle: 2030

Table 3 - Global EV targets, ICEV bans and major ICEV access restrictions (adapted from IEA, 2018).

in their local fleets. Whilst Norway has the most ambitious aim of banning ICE sales by 2025, the majority of other bans – including those of major economies such as France and the UK – are set to come in place relatively soon, between 2030 and 2040. No Australian or New Zealand government has publicly announced plans to introduce a similar ban.

Finally, a number of local jurisdictions have also committed to introducing major access restrictions for diesel and other ICEVs in the near future. This move is principally in response to the air quality and health impacts of ICEVs in urban areas, with access restrictions providing an important signal to the market that ICEVs will be no longer supported in the future (Table 3). No Australian or New Zealand government has publicly announced plans to introduce similar access restrictions.

Autonomous Vehicles
Many researchers believe that the transport system is currently undergoing a disruptive transformation towards full use of connected and autonomous vehicles (AVs), where the transport system becomes significantly safer, cheaper, cleaner and more energy-efficient. AVs may catalyse a large behavioural shift from the classical individually-owned vehicle model towards an 'on-demand' shared-mobility service in a fully autonomous transport system, with associated infrastructure effects such as reshaped cities (increasing urban density, reduction in available parking spaces, dynamic and adaptive lane availability, etc.). AVs can even be instrumented with low-cost air quality sensors, to become real-time air quality monitoring devices (e.g. Carpentiero *et al.*, 2017). One could imagine this system to direct AV driving routes to minimise greenhouse gas emissions as well as local exposure to air pollutants.

From a technical perspective, AVs have a large potential to reduce energy use, and provide the needed deep cuts in GHG and air pollutant emissions. Reported reductions in energy use and GHG emissions by switching to AVs range from 40-90%, without sacrificing personal mobility (e.g. Simon *et al.*, 2015; Igliński and Babiak, 2017). This includes light-weighting vehicles (enabled by AVs being significantly safer), and the use of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity for communication and information exchange. The latter can be used to optimise system-wide on-road AV operation with vehicles following each other closely, leading to reduced congestion and 'platooning' (Barth *et al.*, 2013).

On the other hand, there are various mechanisms that could lead to increased total travel, expressed as vehicle kilometres travelled (VKT), and therefore emissions. For instance, additional VKT may be added by unoccupied AVs moving around without passengers. Reduced congestion levels may cause more (induced) travel. Similarly, a different valuation of travel time could increase the acceptable commuting radius and therefore VKT (Miller and Heard, 2016). These adverse effects can at least to some

extent be managed with additional policies such as road pricing.

BEVs are the 'natural partner' of AVs as the high level of electrification of AV systems naturally extends to the powertrain, and shared mobility and automated recharging can make BEVs attractive (Simon *et al.*, 2015). As such the transformation towards an AV transport system may mutually re-inforce the use of BEVs.

Awareness/Perception
Perceptions regarding the safety and reliability of EVs remain an issue throughout the market. Fire-related incidents in China (ChinaAutoWeb, 2011) and the United States (Green *et al.*, 2011) in 2011, for instance, attracted high-profile media attention. While extensive testing and evaluation have demonstrated that EVs do not pose a greater risk of fire than petrol-powered vehicles, these incidents have brought extra scrutiny of EV safety. By comparison, there is usually little media reporting on the more than 250,000 ICE vehicle fires per year recorded in the United States (Ahrens, 2010). Other reports of battery failures, recalls, and climate-related battery degradation have further raised doubts about EV technology. Thus, the bar appears to be set quite high in the public mind in terms of EV safety and reliability, and remains an issue that needs to be addressed.

CONCLUSIONS

This paper compares conventional fossil-fuelled vehicle technologies with electric and fuel cell technology vehicles. It is found that electric vehicles (EVs) are the only vehicle type that represents a technology jump of significance in terms of energy improvement in mobility. They provide an immediate and substantial reduction in energy use by road transport, i.e. EVs use approximately a factor of 3-5 times less energy, as compared with the conventional vehicles. Fuel cell vehicles only perform slightly better than conventional vehicles.

When compared with conventional vehicles, EVs are computed to achieve significant greenhouse gas emission reductions in Australia, varying from about 40% (current situation) to very deep cuts of 98%, depending on what extent the Australian electricity generation uses renewable energy. In contrast, fuel cell vehicles are expected to produce a large *increase* in greenhouse gas emission of about 80% (current situation), but have the potential to substantially reduce greenhouse gas emissions provided that Australia significantly increases its use of renewable energy. In fact, significant reductions in greenhouse gas emissions with fuel cell vehicles appear *only* possible if Australia makes a fundamental shift towards almost an almost 100% renewable energy system, which is unlikely in the near to medium future. EVs are therefore considered the safer and more robust option with regard to moving to a zero emission road transport system. Only EVs, and to a significantly lesser extent fuel cell vehicles, are shown to have the potential to create, or relevantly move

towards, a zero-GHG emission transport system.

EVs and fuel cell vehicles are both expected to significantly improve local air quality, particularly in urban areas where population and associated transport needs are concentrated. However, the extent to which electricity generation uses renewable energy is again an important factor in relation to level of improvement that will be achieved.

The economic case for EVs is strong. At society level it will substantially reduce the significant (hidden) economic costs of air pollution and associated public health impacts caused by fossil-fuelled vehicles. For EV users, up-front purchase costs are currently significantly higher as compared with conventional vehicles, but they are falling. In contrast, operating costs (maintenance, repair, fuel/energy) are 20% or less of these costs for fossil-fuelled vehicles. 'Total cost' parity (purchase plus operating) is expected to occur in the early to mid-2020s.

Whilst both Australia and New Zealand already produce enough renewable energy annually to power passenger and light vehicle fleets of 100% EVs, a significant shift to fuel cell vehicles would require a substantial increase in electricity generation capacity in both countries. EVs can play a positive role as relatively cheap energy storage devices that would help a transition to a more renewable energy system.

Whereas several regions/countries in the world have set specific EV targets, and in some cases even future bans for fossil-fuelled vehicles, Australia has a relatively sluggish track record in EV promotion and uptake. This is largely due to a general lack of federal government incentives for EVs, the absence of supportive policies for increasing fuel efficiency, and limited government support for reducing vehicle emissions. Local initiatives such as Queensland's EV strategy may herald a change for Australia. New Zealand has now taken a significantly more active stance regarding EVs with its Electric Vehicle Program, which is already reflected in an accelerated uptake of EVs.

Many researchers believe that the transport system is currently undergoing a disruptive transformation towards full use of connected and autonomous vehicles (AVs), where the transport system becomes significantly safer, cheaper, cleaner and more energy-efficient. Electric vehicles are the 'natural partner' of AVs as the high level of electrification of AV systems naturally extends to the powertrain, and shared mobility and automated recharging can make BEVs attractive. As such the transformation towards an AV transport system may mutually re-inforce the use of BEVs.

So where are we heading with electric vehicles? Although there are significant differences between countries and regions in the world, the available data suggest we are definitely heading away from fossil-fuelled road transport towards a fully transformed road transport system where electric vehicles will dominate, or at least play a key role. Electric vehicles are the obvious choice when considering environmental and economic benefits and other fundamental shifts such as

autonomous vehicles and renewable energy are mutually reinforcing developments. Co-development with a clean and climate-friendly electricity generation system will enable deep cuts in greenhouse and air pollution emissions.

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FOOTNOTES

1. With reported values typically varying between 10-20% (see Helmers and Marx, 2012; Wong, 2017), a value of 20% is probably too conservative. BEV energy efficiency has been shown to be improving in line with improvements in battery performance, e.g. a 10% improvement for the same BEV for model years 2012 to 2015 (Wong et al., 2017).

2. 100% efficiency is unlikely to be achieved due to losses.

3. Carbon dioxide equivalent or CO_2-e quantifies the amount of CO_2 emissions, which would have the equivalent global warming impact as a given mixture of greenhouse gas emissions (e.g. carbon dioxide, methane, perfluorocarbons, and nitrous oxide) over a specified timescale (generally, 100 years).

4. Petrol 82%, Diesel 10%, LPG 8%.

5. Conversion of the 0.26 kWh/km WTT to CO_2-e emissions is inherently complex and requires a thorough understanding of the energy use and processes required to produce a litre of fossil fuel for on-road consumption in the country or region of interest. In the computation it has been assumed that the CO_2-e emission rate per kWh of fossil fuel energy is approximately the same for WTT and TTW.

6. Assumptions are 15% coal, 24% natural gas, 1% oil, 10% hydro, 10% wind, 4% biomass and 36% solar.

7. Production of hydrogen using electrolysis: $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$; 1 mol H_2O produces 1 mol H_2; 18 grams H_2O produces 2 grams H_2, so 9 kg H_2O (i.e. 9 litres) produces 1 kg H_2. 1 kg H_2 propels an FCV approximately 100km, therefore FCVs displace 9 litres of water per 100 km.

8. This figure should be considered as conservative, given many battery electric vehicles have lower energy consumption rates.

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