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The role of hydrogen in Australia’s transport energy mix

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Abstract

In this study we review the trends and trajectories of energy use and emissions in Australia’s road transport sector. We find that energy use and emissions in heavy-duty vehicles are growing at a greater rate than light-duty vehicles, and that heavy-duty vehicle energy consumption will surpass that of light-duty vehicles by 2032. We explore whether popular light-duty alternative energy concepts, such as battery electric technology, are also competitive for heavy-duty vehicles. We observe that finding a sustainable energy technology that competes with the high energy density of diesel is a formidable challenge. Alternatives such as natural gas, propane and biofuels have managed to establish a beachhead. However, none have constituted a disruptive threat to diesel oil. The lack of any silver bullet technology indicates that further research into technology options is warranted. Hydrogen fuel cell systems have many characteristics which are attractive for the heavy-duty transport task, including complementarity with electric vehicles and a cross-benefit from developments in batteries and electric drivetrains. We conclude that for Australia, fuel cells may find their niche in the electrification of heavy-duty drivetrains, in markets where zero emissions are desirable, and where range, duty cycle or payload requirements exceed the capabilities of battery-only vehicles.

Keywords: hydrogen, fuel cells, transport energy, biofuels, electric vehicles, life cycle cost

1. Introduction

In January 2014, a workshop was held by the Australian Renewable Energy Agency (ARENA) in Canberra, bringing together national experts to discuss the future of renewable transport fuels in Australia. Amongst the objectives of the workshop, ARENA was seeking an update on the status of the technologies that were being developed for renewable transportation, and to identify how ARENA might be able to assist with the Research & Development (R & D) of viable renewable transport fuels.

There was little discussion of Electric Vehicles (EVs) during the workshop. The discussion instead focused on the production of renewable liquid and gaseous fuels. While
the development of electric vehicles is an extremely important and disruptive technology, the application of EV technology is currently limited to the light duty and short range segments of the transport sector.

The concept of renewable transport fuels is often conflated with the development of electric vehicles. EVs are regarded by many as a likely enabler of a more sustainable future for cars and other light-duty vehicles. However, a disaggregation of transport energy use reveals that there is a large and growing segment of the transport sector for which EVs are not suitable, and which holds significant opportunity for other alternative energy technologies.

Several aspects of the Australian context are unique. The country has vast resources of both renewable and non-renewable energy, which could be drawn upon for hydrogen production and a transition to de-carbonise the economy. In addition, Australia has experienced a decline in oil production and has become a net importer of transport fuel. As this oil trade deficit widens, so does the energy security risk and drive to develop indigenous transportation energy resources. In terms of vehicle choice, the population is sparsely settled which compels people to use vehicles that are capable of long distance driving, reducing the market for battery-only vehicles while expanding the market for hybrid vehicles. These characteristics make the Australian market particularly attractive for the development and deployment of innovative renewable fuels and sustainable transportation technologies.

1.1. Policy context

The approach of the Australian government on greenhouse gas emissions reduction has been extremely volatile, with each successive government working towards a different policy approach. The most recent change is the Government’s repeal of the Carbon Tax and associated Clean Energy Legislation [1]. Despite the vast difference in Party policies, Australia still has an enduring bipartisan and unconditional emissions reduction target of 5% from 2000 levels by 2020. While the preferred greenhouse gas reduction mechanism of the government of the day continues to be highly uncertain, the R & D effort must continue to bring new technologies to market that have the potential to deliver carbon emissions reduction.

1.2. Australia’s growing oil trade deficit

Recent data shows that peak oil for Australia has already passed. The trend of decline in Australian oil production is well established. The BP Statistical Review of World Energy published in 2012 [2] was particularly important for Australia because it showed that by 2011 Australia’s oil production had dropped to 41% from its peak in 2000, while oil consumption had increased to just over 1 million barrels per day, resulting in record oil imports which made up more than half of Australia’s total oil demand.

As recently as 2002/03, Australia had a trade surplus in oil and liquid fuels, but by 2013 the gap between supply and demand had increased, with Australia producing only 44.9% of its consumption [3]. The gap continues to widen at an alarming pace, as illustrated in the historical data presented in Figure 1. The Australian economy is increasingly dependent on imported petroleum products, and is exposed to the price volatility of global oil markets.

As a member of the International Energy Agency (IEA) Australia is required to hold oil stocks equivalent to 90 days of imports to contribute to any global oil emergency
that might be declared by the IEA. Australia is the only IEA member state that does not meet this commitment, and as indigenous production continues to fall and demand continues to rise, the shortfall will continue to increase.

The Australian Government’s 2013 Energy White Paper (Issues Paper) indicates that Australia may average only 60 days stock in 2014, and only 45 days stock by 2024 [4]. In a 2012 publication the IEA was unequivocal in its strong recommendation that Australia take action to become “fully and systematically compliant” with its stockholding commitment [5]. The Energy White Paper estimates that a build program to rectify this issue would require a $6.8 billion investment in domestic storage infrastructure. This magnitude of investment merits further investigation of the alternatives to Australia’s growing dependence on imported crude oil and refined oil products.

1.3. Transport energy and the greenhouse gas abatement task

Australia’s greenhouse gas emissions inventories have exhibited some remarkable changes in recent years. Most notably, total emissions from the electricity sector have fallen significantly for the past 5 years after peaking in 2008, reversing a trend of strong growth that had persisted for the previous 20 years\(^1\). However, emissions from the second-largest sector of the economy – the transport sector – have continued their steady year-on-year climb at a nearly linear rate of growth. The stark contrast between the trajectories of these two sectors is presented in Figure 2. The emissions of the transport

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\(^1\)This striking reversal is attributed to a moderation in electricity demand, driven by a combination of factors including consumer response to higher electricity prices, mandated energy efficiency standards, increasing availability of energy efficient appliances, greater awareness of energy saving opportunities, uptake of renewable energy sources, and structural changes in the economy [6],[7].
sector are linked to economic activity, population growth and oil prices, and are expected to grow unless the demand for transport starts to suddenly decline, a significant modal shift is made, or a technological change is made to reduce the emissions associated with transport activity [8].

The energy and emissions associated with Australia’s transportation energy sector are comprised of Civil Aviation (17%), Road Transportation (75%), Railways (3%), Navigation and shipping (5%), and Other Uses such as off-road vehicles (<1%). Of these sectors, Road Transport is clearly the largest energy user and therefore can be considered the greatest potential source of improvement from any disruptive innovation that improves the sustainability of the sector.

The Road Transport sector can be disaggregated into Cars, Trucks and Buses, and Motorcycles. The breakdown of energy use in each sub-sector is presented in Figure 3.

Energy use in cars is the dominant end use of road transport energy at 57%, with trucks and buses consuming most of the remaining 43% of total energy demand. However, the historical trends in these two sectors reveal a more sophisticated story. Figure 4 presents energy consumption data for 22 years from 1990 to 2012, and an extrapolated growth trend for the next 20 years to 2032. The extrapolation shows that Truck & Bus energy consumption is projected to exceed that of Cars beyond 2032. While this is only a simple extrapolation, the growth rates for Car energy consumption and Truck and Bus energy consumption are both relatively consistent, at 1.1% and 2.7%, respectively. More analysis is required to substantiate the robustness of these trends and their implications for transport energy in Australia.

The Car sector is clearly the dominant sub-sector, and much R & D attention should rightly be focused on improving the sustainability of car transportation. Electric Vehicles are considered by many to be an enabling technology that can improve the energetic and environmental performance of car transportation. The Trucks and Buses sector, while smaller than the car sector, is clearly also a major energy user and also merits
Figure 3: Breakdown of energy use for Road Transportation in Australia. Created using data from [10].

Figure 4: Historical trend and extrapolation of energy use for Cars and Trucks & Buses. Created using data from [10].
significant attention. This data reinforces the need to focus significant R & D investment on alternative energy sources for Australia’s heavy-duty fleet, to diversify primary energy supplies from imported diesel, and to reduce emissions from this important and growing sector.

2. Methods and Results

Gasoline- and diesel-fuelled hybrid electric vehicles can deliver an incremental efficiency improvement and may serve as a transition technology on the path to a more sustainable transport sector [11],[12]. However, these technologies still inherently link energy security and emissions to fossil energy sources.

The Western Australian Government has recognised that the only way to reduce reliance on imported oil and exposure to global oil price volatility is through diversity of fuel sources and competition [13]. Additional research is required to determine if other technologies can reduce emissions and de-couple transport energy from fossil fuels.

A fundamental challenge that faces engineers and innovators attempting to improve Australia’s transport emissions is that alternative energy technologies must compete with the very high energy density of oil based fuels. To be sure, gaseous technologies such as natural gas and liquid propane gas have managed to establish a beachhead in the sector. However, the uptake of these technologies has also been subdued and certainly has not been a disruptive threat to oil-based transportation.

In the pursuit of renewable transport fuels, one quickly arrives at two broad alternative paths:

1. Renewable liquids which are likely to be derived from biomass that may be able to be grown, harvested, processed and refined using 100% renewable energy.
2. Renewable gases which are likely to be derived from renewable biomass or the electrolysis of water.

The ARENA Renewable Fuels Workshop had a very strong focus on option (1), which is not surprising given the relatively large amount of activity in Australia’s biofuels sector and the relatively small amount of activity in the development of renewable gases such as hydrogen.

The question of whether hydrogen merits inclusion in Australia’s attempts to address the need for heavy-duty transport energy technologies, despite the lack of domestic R & D activity in this space, is worth further exploration.

2.1. Biofuels – valuable but not a silver bullet

The Garnaut Climate Review, which was updated in 2011, noted that biofuels using traditional agricultural land as a source of biological inputs are problematic, largely because they displace food crops. But the new (second-generation) biofuel production systems, which use advanced technologies and non-food plant materials, do not have these problems [14].

Professor Garnaut goes on to acknowledge that biofuels derived from algae are particularly relevant for Australia because they fit well with resources that are in abundance in Australia, such as world-class solar resources, vast areas of land and access to saline water. Large-scale production of biofuels is not yet cost competitive, but R & D in second generation biofuels in Australia is ongoing at a modest pace [14].
The Organisation for Economic Co-operation and Development (OECD) has stated that the potential for biofuels to replace fossil energy is relatively small and the scope to improve energy security in this way is limited [15]. Further R & D on second-generation biofuels is warranted, and Australia has the opportunity to be a significant contributor to the development of economical and environmentally beneficial biofuels.

Of the second-generation biofuel production methods, the conversion of biomass into a syngas - essentially a mixture of hydrogen and carbon oxides - is likely to be a significant source of renewable hydrogen that can complement hydrogen produced from other energy sources, ultimately improving the diversification of energy supplies available to Australia and the transition to low-carbon energy sources.

The IEA World Energy Outlook found that biofuels could contribute up to 8% of road transport fuel demand by 2035 [16]. The data shows that biofuels are not a silver-bullet, and more transport fuel alternatives will be required, elevating the importance of a common energy carrier such as hydrogen which can be produced from a diverse range of sources.

In Australia, one can already use the decisions of major diesel consumers as an indicator of where industry is heading. Fortescue Metals Group, with an annual spend of over $800 million AUD on energy and an annual consumption of diesel that is estimated to be over 1 billion litres, has started diversifying their stationary energy assets to natural gas, and has announced their intention to begin using natural gas to fuel their mine fleet [17].

Internal combustion engines fuelled by diesel are structurally different from natural gas internal combustion engines – the former uses compression ignition and the latter uses spark ignition. A retrofit from one to the other is prohibitively expensive which means each technology choice is locked in for the life of the asset.

If Fortescue proceeds down the path of introducing natural gas vehicles to their fleet, they will be making a structural transition throughout their energy chain, including supply, storage, fleet refuelling, and the fleet itself. The transition would be a massive capitalisation of gaseous fuel infrastructure, and equally significant divestment of liquid fuel infrastructure.

The strategic direction of Fortescue and other major mining companies to sink the massive amount of capital required for a transition to gaseous fuels is a strong indication that biofuels are not viewed by industrial leaders as a short- or medium-term replacement for diesel.

2.2. The electrification of drivetrains

A question that is often asked with regard to electric vehicles is which technology – hydrogen fuel cell or battery electric vehicles – will prevail. This is not a valid question, because hydrogen fuel cell vehicles inherently require an electric drive train to operate. Indeed, most contemporary fuel cell vehicles are hybrids which include batteries for energy storage, and are now referred to as either battery-dominant or fuel cell-dominant depending on the relative sizes of the battery and fuel cell systems on board the vehicle.

Hydrogen fuel cell and battery electric vehicle technologies are entirely complementary. The question, then, is not which one, but rather what combination of these technologies results in the optimal solution.

The answer, of course, depends on the application. For a private vehicle that travels tens of kilometres each day and is stored in a private carport overnight, a battery storage
Figure 5: Useful Specific Energy (energy per unit of mass) for battery and hydrogen fuel cell systems. Reproduced under STM Permission Guidelines from Thomas [19].

system may be sufficient. However, if the vehicle is required to travel hundreds of kilometres, or carry heavy payloads, then battery energy storage may not be sufficient to fulfil the daily duty cycle. Hybridisation is required, which could be achieved with conventional combustion engines, but if zero emissions is the objective then hydrogen fuel cells may be the most competitive fit. Thus, hydrogen fuel cell vehicles may find their niche in markets where zero emissions are desirable, and where range, operating time or payload requirements exceed the capabilities of battery-only vehicles. An analysis by Andrews and Shabani examined the gravimetric and volumetric energy densities of hydrogen and battery electric systems in relation to energy storage requirements for various modes of transport, and found that a combination of these technologies would need to be employed to service the full range of end-use road transport applications [18].

Several characteristics of EV technologies and hydrogen fuel cell technologies were compared by Thomas [19], in which the specific capabilities of each technology are quantified and illustrated. A comparison of the energy storage per unit of mass, termed the Useful Specific Energy, for different battery and hydrogen energy storage technologies is presented in Figure 5. The data indicates that hydrogen systems find their strength in applications where high useful specific energy is required, for example transporting heavy loads or travelling long distances.

Another way of illustrating the effect of this difference between the energy storage characteristics of EV and hydrogen technologies is to look at the total vehicle mass for each energy storage technology as a function of vehicle range, normalised for the same vehicle using a constant acceleration rate. The data presented in Figure 6 shows that the fuel cell electric vehicle does not suffer from a dramatic increase in weight to achieve long range capability. Extending the range of a battery electric vehicle requires a increase in the battery size, which triggers a dramatic increase in vehicle mass because the larger battery requires more energy to transport. In comparison, the range of a hydrogen vehicle
can be extended by increasing the size of the tanks with a negligible increase in weight, which is a significant advantage considering that vehicle mass has a direct influence on energy efficiency.

Another basis for comparison is the time required to refuel a vehicle, in which another stark contrast emerges. Hydrogen vehicles can be refuelled in a matter of minutes, usually well below 10 minutes even for heavy duty vehicles, whereas re-charging a battery of equivalent energy content ranges from several hours to an entire day, depending on the infrastructure and the specific type of battery. Quick charging mechanisms have been developed which may be able to reduce re-charging times down to 30 minutes, but would require a substantial infrastructure investment [20].

The infrastructure to supply energy to any vehicle technology must also be considered in planning the transportation systems of the future, and in this regard electric vehicles, like hydrogen technologies, will require a major infrastructure investment before they can make an appreciable impact. The Vehicle-to-grid (V2G) technology concept has been proposed as a way of improving grid efficiency. However, a study of electric vehicle penetration in Western Australia [21] found that the grid would only achieve better utilisation for the first two years of widespread Electric Vehicle (EV) uptake due to overnight charging of EVs, but after two years of fleet growth the very large electricity demand of EVs caused the grid to become less efficient and overall peak demand increased, requiring new peak load generation and transmission systems to be built to accommodate the growth in EVs.

Another way of describing this effect is a decreased impact on baseload and a greater impact on peak demand. This data shows that while EVs can certainly yield positive benefits as they progress towards commercialisation, and while the technologies to imple-
ment the V2G concept are readily available, the widespread adoption of EVs will yield marginal improvements in system utilisation but also will require new infrastructure to be built at substantial cost and resulting in an increase in the unit price of electricity which may outweigh the benefits [22].

Thus, the use of EVs as a central means of transportation to displace liquid fuelled vehicles is not a silver bullet either, and will require major infrastructure investment in both vehicles and electricity grid expansion before an appreciable market share can be taken up by battery electric technologies. To be sure, the deployment of hydrogen vehicles on a large scale would also require the implementation of an expansive and costly hydrogen infrastructure, and unlike EV charging infrastructure which can be built upon the existing electricity network, much of the hydrogen infrastructure must be built from scratch.

2.3. Buses as a platform for technology development and net transport efficiency improvement

In addition to the conversion from fossil fuel vehicles to electric drivetrains, tremendous efficiency gains are also available through the conversion from individual cars to mass transport. Buses are the most energy efficient form of passenger transportation, as illustrated in Figure 7, which compares full fuel cycle energy per passenger-kilometre for common modes of transportation.

Australian cities suffer from suburban sprawl which has created a dependence on long-distance car transport and is increasingly creating issues associated with transport-related urban air pollution.

Looking at the need for passenger transport as one subset of the transport task, a trend that has recently emerged is the decline in car use per capita [24]. This is

Figure 7: Energy efficiency comparison for different modes of passenger transportation. Data from [23].
particularly notable in cities which are experiencing very high population growth such as the major population centres of the developing countries. This trend is leading to more energy efficient public transportation.

The decrease in passenger car transport per capita is attributed to a combination of rising use of public transport and other personal mobility options such as bicycles. A strategy to actively reinforce this trend will lead to further favourable outcomes of net societal benefit, including the ongoing improvement in the efficiency of delivering the personal transport task, the increased use of cycling and walking with the consequent health benefits, as well as the overall environmental life cycle improvement that result from a decrease in the embodied emissions of car manufacturing and disposal.

Some might consider buses to be a relatively unexciting sector of the transport industry, but buses provide an ideal platform for the R & D and demonstration new technologies for the heavy-duty transport sector. They operate from a central depot where refueling and maintenance can be tightly managed, they operate on similar routes every day allowing performance to be measured, their duty cycle is rigorous with heavy loads and many start/stop sequences for durability testing, and they can serve as a prominent public display of innovation.

3. Discussion

Hydrogen has not yet made a strong entry into the transportation sector, and still faces a number of barriers. High costs and the lack of hydrogen refuelling infrastructure are two of the primary barriers to significant uptake of hydrogen vehicle technologies. However, the technology is progressing towards commercialisation on several fronts. When hydrogen fuel cell buses were introduced into Australia in 2004, they were part of the largest global fleet of hydrogen buses that had ever been assembled, which consisted of 36 buses operating in 12 capital cities around the world [25].

3.1. Hydrogen buses - continuous improvement and steady growth

By 2012 activity in the hydrogen fuel cell bus sector had expanded to 121 fuel cell buses and 40 active projects. Furthermore, 129 demonstration hydrogen fuel cell buses had already completed their demonstration role and had been retired from service [26].

The growth in North America from 2005 to 2014, reported in the Fuel Cell Buses in U.S. Transit Fleets: Current Status 2013 report [27], is presented in Figure 8.

The recent demonstration of 20 hydrogen fuel cell buses in Whistler, Canada, which is included in National Renewable Energy Laboratory (NREL) statistics, has been heralded as a great success.

“The demonstration of this zero-emission bus fleet at Whistler has enabled industry to improve their knowledge of hydrogen fuel-cell buses, generating international business opportunities for this made-in-B.C. technology,” said a British Columbia ministry spokesperson. “As a result, the next generation of buses are being deployed around the world.” [28]

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2 Hydrogen fuel cell buses have typically had a short service life of 2 to 5 years, as the rapid pace of technology quickly makes them obsolete.
The first dedicated Hydrogen fuel cell bus workshop was held in Hamburg in October 2013, where First Mayor of Hamburg Olaf Scholz reaffirmed his government’s stated commitment “to purchase only emission-free buses from 2020” [29]. The market for hydrogen fuel cell buses has continued to expand, driven by a growing global demand for zero-emission public transportation solutions, and a history of continuous technological improvements in vehicle and infrastructure technologies.

In May 2014 the City of Aberdeen, Scotland, opened the All-Energy 2014 conference by launching Europe’s largest hydrogen bus fleet, comprised of 10 hydrogen buses powered by Ballard fuel cells. The buses will be fueled by an on-site 1 MW electrolysis plant, which will be used to explore how on-site electrolysis can play a role in handling intermittent renewable generation and grid balancing [30].

In the United States, as of August 2014, the Department of Transport’s Federal Transit Administration had awarded over $90 million in grants through their National Fuel Cell Bus Program, with new projects announced in several US cities [31].

The growth in the hydrogen fuel cell bus market has helped to reduce the costs. The buses which were introduced to Perth had a cost of $2.1 million in 2004. Van Hool, a European bus manufacturer, is planning to deliver 27 fuel cell buses in Europe this year with Ballard fuel cells at a cost of $1.5 million, and Ballard Power Systems’ next generation fuel cell bus technology is expected to drop the price to below $1 million. “That will open the market substantially, we believe”, says Paul Cass, VP of Operations for Ballard Power Systems [28].
3.1.1. Hybrid drivetrains

Recent generations of advanced buses use hybrid architecture to improve energy efficiency and capture the benefits of regenerative braking. A hybrid powertrain can also improve the lifetime of the primary power source on board the vehicle by allowing a Fuel Cell (FC) or Internal Combustion Engine (ICE) to spend more time running at their optimal operating point. The power variation of the primary power source is one of the most important parameters in evaluating different hybrid concepts [32], with a parallel-hybrid placing more of the load and associated dynamics directly on the primary source while a series-hybrid buffers the primary source from transient power demands.

Hybrid technology will always carry a higher capital cost than conventional drivetrains due to the addition of an energy storage device. Hallmark et al. [33] evaluated the in-use fuel economy of 12 hybrid diesel-electric buses against a control fleet of 7 conventional diesel buses and found an average improvement of 11.8% over a 12-month trial period. The range of fuel economies reported for hybrid buses is quite large, with in-use studies reporting fuel economy improvements of between 5% and 18%, while lab tests have reported improvements of 30% to 74%. The difference between lab and on-road performance is that lab tests compare buses in a controlled test environment typically using a chassis dynomometer, whereas on-road results include a range of other factors. The data indicates that differences in duty cycle, driver handling, and chassis characteristics on the road, all have a significant influence on results. However, Hallmark et al. acknowledged that data for factors which can significantly affect fuel economy, such as duty cycle and number of passengers, was outside their control.

A trend that can be observed amongst these studies is that battery electric vehicles and hydrogen fuel cell vehicles are increasingly regarded as complementary technologies, and that both may have a role to play in a future electrified transportation system. A strong insight which is sometimes stated, and other times implicit in the data, is that lifecycle costs can be reduced through hybridisation, and by using FC or ICE primary power sources as range extenders which primarily exist to charge on-board battery systems in a series hybrid configuration.

The range extender arrangement reduces the size of the primary power source and allows the FC or ICE to operate at peak energy efficiency, leaving the electrical energy storage system to cope with the constantly-changing accelerator position and consequent load transients that a vehicle powertrain must endure. Energy and power management for hydrogen hybrid vehicles presents a multivariable problem with great complexity, and has become a very interesting area of research. Recent studies include the modelling and validation of real-time control algorithms [34], and the development of maximum efficiency tracking for range extenders [35]. It has been proposed that hydrogen consumption may be further improved through the use of dual energy storage devices, such as the combination of batteries and ultra-capacitors, in a fuel cell hybrid vehicle [36].

3.2. Hydrogen production and storage

Regarding the absolute availability of energy resources for hydrogen production, one of the best references is NREL’s 2013 Resource assessment for hydrogen production [37]. Fossil, nuclear and renewable energy resources are projected out to 2040, and compared...
with current demand, to develop a model which estimates the potential for hydrogen production. The hydrogen production potential is then compared with current and projected transport fuel demand. The analysis is based on the United States only, but the findings and the methodology are transparent and could be applied in other regions.

NREL concludes that ample low-carbon resources are available in the United States for hydrogen production. Spatial distribution of energy production resources and transport fuel demand centres were taken into account, to determine the extent to which hydrogen would need to be transported. In the United States the proximity between supply and demand is relatively close.

In other continents like Australia the distance can be quite large. The transition to widespread hydrogen use may require greater use of hydrogen gathering and transmission systems, such as hydrogen transmission pipelines and large-scale geologic storage. The combination of gigawatt-scale wind farms powering high-pressure electrolyzers, located near cavernous geologic formations which could be used for energy storage, and long distance hydrogen pipelines for transmission to load centers, was modeled by Leighty [38]. Using rough capital cost figures, and taking into account the seasonal advantages that are offered by large-scale storage in geologic formations to maximise the annual energy extraction from renewables, Leighty finds that the incremental cost of geologic storage to the generation-transmission system is 5-10%. However, the cost of transmission is significant, in one case increasing from $2.19 per kilogram hydrogen for a 320 km transmission distance to $3.38 per kilogram at a 1,600 km distance, an increase of 54%4. This study was conducted for Great Plains, USA, and a similar methodology deployed in the Australian context would likely yield a different result, due to the different topography, the distance between renewable resources, and the geological formations that could be used for hydrogen storage. Australia has vast renewable resources, the majority of which are located a great distance from the end users. The development of a hydrogen infrastructure in Australia may enable the use of long distance generation-transmission technologies and geologic formations for storage, potentially adding value to otherwise stranded renewable resources.

3.2.1. Hydrogen refuelling facilities

Hydrogen station construction and operations costs can be derived primarily from references that are specific to hydrogen bus demonstration projects. Analyses of hydrogen refueling station costs by Weinert et al. [39], Joffe [40], and the NREL studies cited in other sections, provide a basis for hydrogen production and refueling station Life Cycle Assessment (LCA) and costing.

The definitive analysis on hydrogen infrastructure in Australia is the Technology Roadmap for Australia’s Hydrogen Delivery Infrastructure, authored by Pigneri and Nolan, and commissioned by the CSIRO Energy Transformed Flagship [41]. This comprehensive study of hydrogen production and delivery pathways condenses data from a wide range of sources covering the costs and performances of an extensive range of hydrogen delivery and transmission technologies. The scope of the study addresses the barriers and opportunities for development and deployment of a hydrogen delivery infrastructure for the road transport sector. A transparent modeling approach presents

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4Costs are started in 2005 US Dollars. The values presented show the relative impact of transmission distance on the cost of delivered hydrogen.
a complex technical and economic assessment of wide-ranging alternatives for hydrogen delivery, based on the calculated energy demand of Australia’s national road transport fleet.

The great strength of the analysis conducted by Pigneri and Nolan is the quality of the economic analysis, which led to an understanding of the tradeoffs and breakeven points where different hydrogen production and transmission technologies should be applied. For example, the graph presented in Figure 9 presents the least cost hydrogen delivery pathways as a function of transmission distance and throughput. Similar results were produced for hydrogen generation technologies including fossil-fuel reformation, water electrolysis and biomass reformation. Many useful conclusions are drawn from the dataset and analysis, providing a very useful foundation for further life cycle costing analysis. One of the recommended future directions stated by Pigneri and Nolan is the integration of the modeling framework they have developed with broader system level modelling, and the incorporation of greenhouse gas accounting for each of the hydrogen delivery options that were examined.

![Figure 9: Hydrogen transmission least-cost delivery as a function of throughput and distance (reproduced with permission [41], Figure 38, p.146.). The nomenclature used in the graph is: LH2-T = Liquid Hydrogen (Trucked); CGH2-P = Compressed Gaseous Hydrogen (Pipeline); CGH2-T = Compressed Gaseous Hydrogen (Trucked)](image)

A key input to the study of hydrogen bus transportation in Australia is the research completed by PE International, on the LCA and Life Cycle Costing (LCC) of Hydrogen Production Pathways for Western Australia [42]. This project was commissioned by

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CREST\textsuperscript{5} and builds upon the work of Ilg \cite{43} on hydrogen production pathways. The CREST Hydrogen Pathways and the analysis of Pigneri and Nolan are extremely complementary. The data and findings of Pigneri and Nolan can be used as inputs to the CREST models in GaBi, creating a platform of hydrogen production and delivery technologies which the hydrogen fuel cell bus vehicle LCA and LCC can be built upon, resulting in a model set that can be used for comprehensive Life Cycle Engineering.

### 3.3. Hydrogen fuel cell bus performance

One of the primary performance parameters in the evaluation of any vehicle technology is the fuel economy, defined as fuel consumption per unit of distance travelled, as this parameter is a key factor in both the cost of operating the vehicles, and the well-to-wheel or life cycle environmental performance over the life of the asset. The results of several hydrogen fuel cell bus programs are summarised in Table 1\textsuperscript{6}, presenting a general trend of fuel economy improvement over time.

The early hydrogen buses were designed to demonstrate reliability, and design trade-offs were made to improve the reliability at the expense of energy efficiency. One of the objectives of these trials was to prove that fuel cell buses are sufficiently reliable to be competitive with conventional buses, and once this had been established the technology then advanced by maintaining that reliability standard while optimising energy efficiency. The projected fuel economy targets of industry and government bodies indicate that the technology is now reaching its full performance potential, however incremental improvements are still expected in the future.

<table>
<thead>
<tr>
<th>Year</th>
<th>Fuel economy (kg $H_2$/100km)</th>
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<tr>
<td>2009</td>
<td>15.5</td>
<td>BC Transit [44]</td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>9.8</td>
<td>CT Nutmeg [27]</td>
<td></td>
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<tr>
<td>2010</td>
<td>9.5</td>
<td>AC Transit [27]</td>
<td></td>
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<tr>
<td>2012</td>
<td>9.7</td>
<td>SunLine AFCB [27]</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>10.8</td>
<td>US DOE [45]</td>
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<td>FCH JU [46]</td>
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<td>2030</td>
<td>8.2</td>
<td>FCH JU [46]</td>
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Table 1: Fuel economy of hydrogen fuel cell buses. Future targets shown in italics.

\textsuperscript{5}CREST was a WA state-funded national centre of excellence for transportation research, consisting of a partnership between Murdoch University and Curtin University of Technology, and based at Murdoch University in Perth, WA.

\textsuperscript{6}Nomenclature used in the Table: HyFLEET:CUTE is a program established by the European Union which includes the operation of 33 fuel cell buses in 10 cities, on 3 continents including Australia; BC Transit operated 20 fuel cell buses in the Canadian Province of British Columbia; CT Nutmeg operates 4 fuel cell buses in the U.S. State of Connecticut; AC Transit operates 12 fuel cell buses in the San Francisco Bay Area; SunLine AFCB refers to Sunline Transit’s American Fuel Cell Bus Project, a single fuel cell bus which meets ‘Buy America’ requirements; US DOE refers to the United States Department of Energy; FCH JU refers to the European Union’s Fuel Cells and Hydrogen Joint Undertaking.
The operating conditions of the vehicle can have a significant effect on fuel economy, as demonstrated during the HyFLEET:CUTE program. The Clean Urban Transport for Europe (CUTE) trial, of which Perth was a member city, evolved into a program entitled HyFLEET:CUTE, which incorporated the CUTE program in an expanded and extended scope that included 33 hydrogen fuel cell buses and 14 H\textsubscript{2}ICE\textsuperscript{7} buses operating in 10 different cities. The final report of the HyFLEET:CUTE project\textsuperscript{25} is a valuable reference providing summary statistics on the operation of the buses, operated over 2 million kilometres, 140 thousand hours, and transporting over 8.5 million passengers in revenue service. The HyFLEET:CUTE project also reports on 10 different hydrogen refuelling stations and hydrogen supply chains including in-station water electrolysis, in-station steam reforming, and external hydrogen supplies.

The LCA of the HyFLEET:CUTE program included several very useful conclusions:

- Fuel economy is highly dependent on traffic conditions, stops per kilometere and topography\textsuperscript{8}.
- Hybridisation of the drivetrain results in an improvement in primary energy demand of between 25\%\textsuperscript{9} and 44\%\textsuperscript{10}.
- The manufacturing of next generation fuel cell hybrid buses create 10\% less global warming potential than previous non-hybrid generations, mainly due to weight reduction.

Data collected in regular revenue service showed a rough correlation between average speed and fuel economy. To illustrate this correlation, the data from nine of the cities that participated in the HyFLEET:CUTE trial is presented in Figure 10. The correlation between fuel economy and average speed is apparent. However, the correlation is not sufficiently strong to be considered statistically significant.

The performance data for the only Australian fuel cell bus trial, conducted in Perth, was documented by Cockroft\textsuperscript{47}. The economics of hydrogen bus transportation were analysed by Cockroft and Owen\textsuperscript{48} using a multi-criteria approach, which estimated the societal costs and benefits of the technology using data and statistics derived from the trial. An LCA on the trial was published by Ally and Pryor\textsuperscript{49},\textsuperscript{50}, and the potential for cost reduction of Australian fuel cell buses by leveraging the larger bus chassis market was explored in\textsuperscript{51}.

The HyFleet:CUTE trial evolved into the CHIC\textsuperscript{11} program, which is still underway as of the time of this writing. The CHIC website states that, “CHIC, the Clean Hydrogen in European Cities project, is the essential next step leading to full market commercialization of Fuel Cell Hydrogen powered buses”. The project involves integrating 26 Fuel Cell Hybrid (FCH) buses in daily public transport operations and bus routes in five

\textsuperscript{7}Hydrogen-fuelled internal combustion engine.

\textsuperscript{8}Summary statistics for the entire duration of the program shows that buses in Madrid achieved a fuel consumption of 29.1 kg/100km, while the same bus make and model in Perth achieved a fuel economy of 19.0 kg/100km, a 34\% difference.

\textsuperscript{9}Calculated for electrolysis hydrogen production systems using electrolysis from renewable energy sources.

\textsuperscript{10}For on-site natural gas steam reformers producing hydrogen from natural gas

\textsuperscript{11}Clean Hydrogen in European Cities (CHIC), www.chic-project.eu.
Figure 10: Data from the HyFLEET:CUTE trial, illustrating the correlation between fuel economy and average speed.

locations across Europe - Aargau (Switzerland), Blozano/Bolzen (Italy), London (UK), Milan (Italy), and Oslo (Norway) [29].

3.3.1. Fuel economy comparison with conventional buses

Using a fuel economy (FE) ratio, as opposed to absolute fuel economy figures, allows technologies to be compared to their diesel and Compressed Natural Gas (CNG) counterparts more easily by normalising for the local bus routes and topographic conditions.

\[
FE_{Ratio} = \frac{FE_{Diesel}}{FE_{FC}}
\]

To determine the \( FE_{Ratio} \) the fuel consumption data is first normalised from fuel economy units, such as \( kgH_2/100km \) or \( L_{diesel}/100km \), to a common energy SI unit, such as \( GJ/km \). An \( FE_{Ratio} \) above unity indicates that the fuel cell bus is more energy efficient than its conventional diesel counterpart. For clarity, this ratio evaluates the vehicle efficiency only, and does not account for primary energy consumption to produce and deliver the fuel to the vehicle.

In February 2014 the Canadian BC Transit Fuel Cell Bus project released its final evaluation results [44]. The fleet of 20 buses running typical transit routes in Whistler, BC, recorded a fuel economy that ranged from 13 \( kgH_2/100km \) to 17.8 \( kgH_2/100km \) with an average of 15.48 \( kgH_2/100km \) (equivalent, on an energetic basis, to 52.86 \( L_{diesel}/100km \)). The fuel economy of the diesel buses in the Whistler fleet is 55 \( L_{diesel}/100km \), which is a fuel economy ratio of 1.04 – an improvement over the diesel bus fleet, and a marked increase.
improvement over the fuel economy achieved by the CUTE buses several years prior, but still well below the efficiency that fuel cell vehicles are theoretically capable of achieving.

Other recent NREL publications cover fleets operated by the Sunline Transit Agency, the Santa Clara Valley Transit Authority, the American Fuel Cell Bus Project, the Connecticut Transit Fuel Cell Bus Trial, and others, summarised in an annual status report covering all the bus projects that are monitored by NREL [27]. In this latest report NREL’s data shows that the fuel economy of modern FCH vehicles measured in 2012 and 2013 recorded a fuel economy ratio of 1.8 to 2.3 over their diesel or CNG counterparts. Fuel economy is of critical importance, and this dramatic improvement flows through to all aspects of bus operation and hydrogen infrastructure costs and environmental performance.

The field of study has grown and research has been published by other organisations, such as McKenzie et al. [52] which developed an Input-Output LCA and LCC model of transit buses with alternative fuel technologies, and found that the additional capital costs to convert from diesel to CNG or Hydrogen buses, including the cost of fuel infrastructure, could be recovered in 5 years\(^{12}\). Importantly, McKenzie et al. also conducted a sensitivity analysis which concluded that hydrogen fuel cell buses were by far the least sensitive to changes in fuel price or passenger loading, which translates to greater certainty of year-to-year operating costs, and which would be particularly true in the Australian context where the lack of indigenous oil sources results in acute energy insecurity.

To be sure, there are studies which rank hydrogen fuel cell technology as a low R & D priority. An analysis by Nylund and Koponen for VTT Technology [53] in 2012 describes hydrogen’s current stage of development as pre-commercial, or research and development. This statement can be used as a reason to discount hydrogen as a realistic fuel option, and Nylund and Koponen’s finding is that the best way to reduce greenhouse gas emissions is a switch from fossil fuels to biofuels. In another study, an LCA of six alternative fuel bus technologies in China [54]\(^{13}\) concluded that only half of the technologies could realise an energy and Greenhouse Gas (GHG) savings in relation to conventional technologies, and hydrogen fuel cells was not one of these due to its low market penetration and the embodied emissions of hydrogen derived from natural gas in China. Other studies that discount hydrogen based on its current stage of development, such as the multi-criteria analysis of fuel cell buses conducted by Tzeng et al. [12] and the scenario analysis conducted by Wayne and Clark [55], find that retirement of old diesel buses for replacement by hybrid diesel buses is the most effective way to improve emissions within a reasonable cost.

The studies which do not rank hydrogen as a competitive technology for buses commonly do not include a zero-emissions objective amongst their critical success criteria, and particularly a zero tailpipe emissions objective to reduce local pollutants. In contrast, the programs where hydrogen fuel cell buses are being actively developed and demonstrated feature a zero-emissions objective as a key success factor. A zero-emissions goal

\(^{12}\)The life cycle cost analysis in this study assumed an emissions price of $100/tCO\(_2\)

\(^{13}\)Ou et al. published useful input data for well-to-pump and pump-to-wheels LCA calculations, and bus performance data based on actual operational results in China. This data can be referenced for scenario and sensitivity analysis. The six technologies studied by Ou et al. were Liquid Propane Gas ICE, Compressed Natural Gas ICE, Natural Gas Hydrogen Fuel Cell, Methanol Spark Ignition ICE, Direct Methanol Compression Ignition ICE and Electric Buses.
could arguably be too lofty of an objective, however these studies show that even without this target there is still no one clear technology *silver bullet* that is emerging as the clear choice.

The most recent data on hydrogen fuel cell bus performance, which could be used to estimate the performance of a future hydrogen fuel cell bus fleet in Australia, can be found in European and North American demonstration programs.

### 3.4. Future Hydrogen Bus Life Cycle Costs

The US Department of Energy (DOE) conducted a *request for information* to gather data from stakeholders and researchers on current performance and performance targets for fuel cell bus technologies. Submissions were received and a collaborative approach was used to arrive at a consensus. The DOE targets are not technology forecasts, rather they are market-driven goals which identify the specific performance, cost and durability values required to enable commercialisation of fuel cell bus technology.

The DOE Fuel Cell Bus Targets [45] which are relevant to the Life Cycle Engineering of a future hydrogen bus fleet in Australia are reproduced in Table 2. The 2012 status of the technology, based largely on US fuel cell bus trial data, is presented alongside the DOE targets which are expected to be achieved by 2016. In accordance with US Department of Energy definitions, the costs are separated into bus cost and power plant cost, and hydrogen storage system costs, and are projected based on a production volume of 400 units per year. The fuel economy values used by DOE are expressed in miles per gallon diesel equivalent\(^{14}\), for ease of comparison with diesel technology on an energetic equivalence basis.

<table>
<thead>
<tr>
<th>Item</th>
<th>Units</th>
<th>2012 Status</th>
<th>2016 Target</th>
<th>Ultimate Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Lifetime</td>
<td>years/miles</td>
<td>5/100,000</td>
<td>12/500,000</td>
<td>12/500,000</td>
</tr>
<tr>
<td>Bus cost</td>
<td>$</td>
<td>2,000,000</td>
<td>1,000,000</td>
<td>600,000</td>
</tr>
<tr>
<td>Power plant cost</td>
<td>$</td>
<td>700,000</td>
<td>450,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Hydrogen storage cost</td>
<td>$</td>
<td>100,000</td>
<td>75,000</td>
<td>50,000</td>
</tr>
<tr>
<td>Fuel economy, mpgde</td>
<td></td>
<td>7</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2: DOE current and projected costs for fuel cell electric buses in US dollars [45].

#### 3.4.1. Availability and reliability

Looking ahead, the NREL results have been used by Langford and Cherry to project a transition to hydrogen fuel for the Knoxville Area Transit system [56]. With a pure extrapolation of current technology, and a focus on fleet size and the bus depot infrastructure required, Langford and Cherry find that based on current technology the fleet would need to be expanded by 42% to achieve the same availability standard as the

\(^{14}\)The fuel economy unit that is used in this paper for comparing the energy content of hydrogen to diesel buses is litres per 100 km diesel equivalent \((L_{\text{diesel}}/100km)\). The 2012 status of 7 mpgde is equivalent to 33.6 \(L_{\text{diesel}}/100km\). The 2016 and Ultimate Target of 8 mpgde is equivalent to 29.4 \(L_{\text{diesel}}/100km\)
current fleet due to the current availability data measured by NREL. Interestingly, this figure is derived from a calculation that includes fleet expansion over the duration of the transition, calculated as:

\[ N = C \left(1 + \frac{Z}{A}\right) (1 + X) \]

In this equation, \( C \) is the current size of the transit agency’s bus fleet, \( Z \) is the availability standard, \( A \) is the availability of the hydrogen bus technology, \( X \) is the fleet expansion that is expected over the duration of the transition in percentage terms, and \( N \) is the required total number of hydrogen buses. Langford and Cherry acknowledge that their calculation of the number of buses is based on actual NREL demonstrations data and will come down as the technology improves.

Indeed, the Perth buses demonstrated a higher availability than the hydrogen bus fleets which were referenced by Langford and Cherry. Bus availability is clearly a key factor in determining the cost of transitioning a fleet to hydrogen. The availability data for many fuel cell bus demonstration programs and references, including the Perth buses\(^{15}\), is presented in Table 3. Besides these fleet size estimates, and calculations of fueling station size, Langford and Cherry do not examine the total cost to make the transition to hydrogen fuel.

3.4.2. Comparison of heavy-duty energy technologies

The NREL studies evaluate projects undertaken in the United States and Canada. A leading reference for hydrogen bus costs for future European projects is the Hydrogen Fuel Cell Bus Technology State of the Art Review [60]. The study examines the proposition that there are only two viable zero emission bus options for the urban transit market; hybrid fuel cell buses or electric trolley buses. The study does not attempt to evaluate battery-electric buses, although these have gained popularity since the release of that report. The findings are broadly consistent with that of NREL, in that on a Total Cost of Ownership (TCO) basis hydrogen fuel cell buses are not yet competitive with conventional diesel buses without subsidy or significant costs placed on diesel bus emissions. However, fuel cell buses are competitive with trolley buses on a TCO basis, with the added benefit of route flexibility whereas trolley buses are bound by an infrastructure of overhead cables. The TCO for hydrogen fuel cell buses is expected to converge with diesel buses in the 2025 to 2030 timeframe, depending on the relative difference between hydrogen and diesel fuel costs.

Electric Bus (EB)s have seen very limited deployment, largely due to the range limitations of the on-board battery storage device. The economics of EBs are dependent on location–specific variables such as the specific competing diesel fuel price and electricity price, and LCAs of EBs have found that they struggle to compete with conventional diesel buses in most jurisdictions due to the embodied emissions in grid electricity [61]. A 2014 cost-benefit analysis by Lajunen [62] provides a recent reference for current electric bus technology, and rather predictably found that the capital and energy storage system costs are the driving factors in the economics, but also found that the operating profile

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\(^{15}\)The first author was a lead engineer on the Perth fuel cell bus trial, and is particularly proud of the bus availability achieved in Perth.
<table>
<thead>
<tr>
<th>Site</th>
<th>Year published</th>
<th>Number of buses</th>
<th>FCB</th>
<th>Availability (%)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oakland, USA</td>
<td>2008</td>
<td>3</td>
<td>55</td>
<td>[57]</td>
<td></td>
</tr>
<tr>
<td>Thousand Palms, USA</td>
<td>2008</td>
<td>1</td>
<td>66</td>
<td>[58]</td>
<td></td>
</tr>
<tr>
<td>San Jose, USA</td>
<td>2006</td>
<td>3</td>
<td>58</td>
<td>[59]</td>
<td></td>
</tr>
<tr>
<td>Amsterdam, Netherlands</td>
<td>2009</td>
<td>3</td>
<td>94</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Barcelona, Spain</td>
<td>2009</td>
<td>3</td>
<td>87</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Beijing, China</td>
<td>2009</td>
<td>3</td>
<td>92</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Hamburg, Germany</td>
<td>2009</td>
<td>3</td>
<td>93</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>London, UK</td>
<td>2009</td>
<td>3</td>
<td>92</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Luxembourg</td>
<td>2009</td>
<td>3</td>
<td>96</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Perth, Australia</td>
<td>2009</td>
<td>3</td>
<td>95</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>Reykjavik, Iceland</td>
<td>2009</td>
<td>3</td>
<td>79</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>HyFLEET:CUTE average</td>
<td>2009</td>
<td>3</td>
<td>92</td>
<td>[25]</td>
<td></td>
</tr>
<tr>
<td>US DOE 2012 Status</td>
<td>2012</td>
<td>N/A</td>
<td>60</td>
<td>[45]</td>
<td></td>
</tr>
<tr>
<td>US DOE 2016 Target</td>
<td>2012</td>
<td>N/A</td>
<td>85</td>
<td>[45]</td>
<td></td>
</tr>
<tr>
<td>US DOE Ultimate Target</td>
<td>2012</td>
<td>N/A</td>
<td>90</td>
<td>[45]</td>
<td></td>
</tr>
<tr>
<td>Oakland, USA</td>
<td>2013</td>
<td>12</td>
<td>81</td>
<td>[27]</td>
<td></td>
</tr>
<tr>
<td>Connecticut, USA</td>
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<td>51</td>
<td>[27]</td>
<td></td>
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<tr>
<td>Thousand Palms, USA</td>
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<td>[27]</td>
<td></td>
</tr>
<tr>
<td>Thousand Palms, USA</td>
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<td>75</td>
<td>[27]</td>
<td></td>
</tr>
<tr>
<td>Austin, USA</td>
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<td>[27]</td>
<td></td>
</tr>
<tr>
<td>Whistler, Canada</td>
<td>2014</td>
<td>20</td>
<td>69</td>
<td>[44]</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Hydrogen bus fleet availability data

set by the transit authority was also a key variable in evaluating life cycle costs for EB technologies. Simulations of different bus routes were undertaken to explore the impact of duty cycle on the energy efficiency and cost efficiency of EBs. Lajunen concludes that more work needs to be done to better understand how operator scheduling and battery system sizing can be optimised on a location-specific basis.

For comparison with recent international studies, the European Fuel Cell and Hydrogen Joint Undertaking (FCH JU) published a more recent analysis of TCO for different urban bus technologies, which included battery electric buses [46]. The conclusions are approximately the same as the NREL study, in that fuel cell buses are expected to reach commercial competitiveness around 2025-2030, and that a combination of battery-electric buses and fuel cell buses are the most effective way to transition to a zero-emission urban bus transportation system. The TCO results of the FCH JU, presented in Figure 11, show that hydrogen, while competitive with diesel and CNG, is still slightly more expensive. The assumption is that there will be a mandate for zero-emission urban transport buses in the years approaching 2030 in order to achieve a significant reduction in transport-sector greenhouse gas emissions by 205016, and that diesel or CNG buses will therefore no longer be an option. In such a scenario the only remaining alternatives are buses that have an electric drivetrain and zero harmful tailpipe emissions. Four types of

16The European Union is committed to reducing emissions by 80% by 2050, which may require transport sector emissions to be cut by 95% [46].
electric buses are included in the analysis:

- Trolley buses which are powered by overhead cables.
- Hydrogen fuel cell buses.
- Opportunity e-bus (an electric bus that charges opportunistically at fast-charge bus stops along its route).
- Overnight e-bus (an electric bus that only charges overnight and has limited range).

The hydrogen fuel cell bus is competitive with the zero emissions options, and would be considered the most versatile of the options by transit authorities because it requires no fixed infrastructure such as overhead cables or charging stations distributed along the bus routes. On this basis, the study concludes that hydrogen fuel cell buses are the most viable technology for urban bus transport, and that the European Union should accelerate the development program.

![Figure 11: Total Cost of Ownership for urban bus powertrain technologies in 2012, 2020 and 2030. Created using data from [46]](image)

The FCH JU is a public-private partnership which is comprised of bus manufacturers, bus operators, infrastructure providers, technology providers, organisations and associations. The published aim of the FCH JU is “to accelerate the market introduction of [fuel cell and hydrogen energy] technologies in order to realise their significant potential within a low-carbon energy system”. Its analysis is based on well-referenced facts derived from industry and government sources, and its methodology is transparently detailed in
its report, however, its findings and conclusions represent the collective view of its member companies and organisations. The FCH JU analysis is a very thorough analysis, but it is not peer-reviewed and cannot be considered to be entirely independent.

The Hydrogen Joint Undertaking study included a description of the methodology and assumptions used to calculate TCO, which are similar in scope to the projections prepared by Zaetta and Madden for NextHyLights [60].

The studies commonly predict that after 2025 the TCO of all bus technologies begins to converge. If that is the case, and if transit agencies are willing to implement low emissions technology so long as the TCO is competitive, then 2025 is the approximate timeframe when we can expect fuel cell buses to become a commercial reality. However, as the NextHyLights analysis is based on data from industry stakeholders and is not peer reviewed, there is a clear need for independent life cycle cost analysis with full academic rigor.

4. Conclusions and Policy Implications

Many of the studies that have disregarded hydrogen as a near-term alternative transport energy technology do not include a zero-emissions target amongst the program objectives upon which their evaluations are based. This contrasts with transport programs where hydrogen vehicles are being actively developed and deployed, which commonly include a transition to zero-emissions transport as a stated critical success factor. While zero-emissions could arguably be too lofty of an objective, the data shows that even without this target there is still no one clear technology silver bullet that is emerging in the heavy-duty alternative transport space. On that basis alone further study of alternative transport fuels and drivetrains is clearly warranted.

While many hydrogen bus projects are underway in North America and Europe, it is important to note that the Australian context is different, partly due to the economics of different transport fuels in Australia, and partly due to the structure of the Australian bus transport industry. The constraints are different, the sensitivities are different, the manufacturing, disposal and duty cycles are all unique.

The economics of hydrogen delivery pathways have also been researched to a level of detail that is sufficient for inclusion in system level modelling, providing a platform upon which to base Life Cycle Costing studies for entire transportation systems. The conclusions drawn by these studies is that the cost of hydrogen fuel cell buses will be above the cost for conventional diesel buses for some time, without other incentives to change the economics such as costs on greenhouse gas emissions and local pollutants from fossil fuel combustion.

The very existence of these many and varied demonstration projects around the globe serves as proof of a level of willingness on the part of governments to pay a premium for zero emission technologies, and to support the ongoing R & D of these technologies until they are competitive in their own right. A clear trend in the literature is that fuel cell bus costs are dropping rapidly, while efficiency, durability and availability are improving, demonstrating strong progress towards commercialisation.

Combining local operational data with international results, and theoretical approximations where necessary, allows one to explore different scenarios and ultimately design the fleet of the future with full visibility on the costs, environmental impacts, and operational effectiveness of different technology options. Rather than working backwards,
after the fact, to figure out the consequences of what has been built, we can instead proceed through the design process with a full understanding of the implications of each design decision. The ultimate benefit of progressing the life cycle engineering on future transportation systems in Australia is to develop innovative ways of incorporating the practice of LCA in the policy and planning decision-making process.

Some might consider buses to be a relatively unexciting sector of the transport industry, but buses provide an ideal platform for the roll-out of new technology. They operate from a central depot where refueling and maintenance can be tightly managed, they operate on similar routes every day allowing performance to be measured, their duty cycle is rigorous with heavy loads and many start/stop sequences for durability testing, and they can serve as a prominent public display of innovation.

The Australian market presents a unique opportunity for the use of hydrogen in road transport applications, including:

- Vast renewable and non-renewable energy resources which could be used for hydrogen production, and the opportunity for variable and deferrable loads such as hydrogen production to upgrade the value of distant and non-dispatchable renewable resources.

- Declining oil production and a growing trade deficit in transport fuel present an energy security risk to the economy and a driving force to develop alternative indigenous sources of transport fuel.

- A need to find a way to reverse the trend of constant growth in greenhouse gas emissions from the transport sector.

- A very low population density, and a need for light-duty vehicles with long range capability and a short refuelling time, both of which are problematic for battery-electric EVs but could be addressed with hybridisation.

- A growing heavy-duty transport task, with an energy consumption for Australia’s trucks and buses that is growing at a faster rate than the car fleet, and which presents an opportunity for alternative technologies that can decouple the growing heavy-duty transport task from emissions growth.

Further R & D of hydrogen technologies is required to determine whether, and how, hydrogen fits in Australia’s future energy mix.

5. References

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URL http://www.fch-ju.eu/


URL http://www.transport.wa.gov.au


