Hydrogen Fuel Cell Buses: an Economic Assessment

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Introduction

Concerns over the health impacts of small particle air pollution, climate change, and oil supply security and price volatility, have combined to encourage radical changes in automotive engine and fuel technologies that offer the potential for achieving near zero emissions of air pollutants and greenhouse gas (GHG) emissions, and diversification of the transport sector away from its present heavy reliance on gasoline. The hydrogen fuel cell vehicle is one technology that offers the potential to achieve all of these goals, provided the hydrogen is derived from a non-fossil fuel source. [1]

Fuel cells convert hydrogen and oxygen directly into electricity. They have three major advantages over current internal combustion engine technology in the transport sector:

- Gains in energy efficiency. "Well to wheels" efficiency for gasoline engines averages around 14 per cent, for diesel engines 18 per cent, for near-term hybrid engines 26 per cent, for fuel cell vehicles 29 per cent, and for the fuel cell hybrid vehicle 42 per cent. Thus, up to a three-fold increase in efficiency is available relative to current vehicles.
- Near-zero emissions of greenhouse gases.
- Very low emissions of local air pollutants. Irrespective of the fuel, fuel cells largely eliminate emission of particulates and oxides of sulphur and nitrogen. All of these pollutants are associated with conventional engines.

Prototype fuel cell buses powered by compressed hydrogen are currently undergoing field trials in Australia (Perth), Japan and North America, while the European Commission (EC) is supporting the demonstration of three fuel cell buses in Iceland and three in each of nine European cities over a two-year period, which commenced in 2003.[2] In addition, the United Nations Development Program Global Environmental Facility is supporting a project to demonstrate the technology using 46 buses powered by fuel cells in the heavily polluted cities of Beijing, Cairo, Mexico City, New Delhi, Sao Paulo and Shanghai.

There are a number of reasons why hydrogen (in compressed form) and fuel cells would appear to be a suitable option for large vehicles, such as buses:

- they return regularly to a depot thus minimising fuel infrastructure requirements;
- they are "large", thus minimising the need for compactness of the technology;
- in urban areas, low or zero emissions vehicle pollution regulations will assist their competitiveness as compared with diesel-powered buses;
- subsidies may be available from urban authorities in order to demonstrate urban pollution reduction commitments;
- they avoid pollution problems specifically related to diesel buses;

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[1] If hydrogen is derived from a fossil fuel, CO_2 sequestration could still offer the near-zero emissions benefits.
[2] The Cleaner Urban Transport for Europe (CUTE) project involves Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Oporto, Stockholm, and Stuttgart. The 33 buses undergoing trials in the EU, Iceland and Perth are identical Mercedes-Benz Citaro, Ballard Proton Exchange Membrane fuel cell, buses manufactured by Daimler Chrysler.

- they operate almost continually over long periods, thus making fuel-efficient technology more attractive.

This paper presents the results of a cost benefit analysis comparing diesel, compressed natural gas (CNG) and hydrogen fuel cell (HFC) buses in the Perth bus fleet based upon the societal life cycle costs and benefits of each technology. However, the results would have general applicability for all 33 buses involved in the trials.

Technologies Assessed

The Citaro is the current Mercedes-Benz mainstream diesel-engine bus intended for public transport. The fuel cell version required some modifications, principally reinforcement of the body shell due to the three tonnes of extra load for the fuel cell drive train and the air conditioning system, and corresponding adaptation of the suspension to accommodate the higher weight and increased tendency to roll. In addition, incorporation of the fuel cell drive train and the fans of the cooling module required an increase in the height of the bus. The Perth buses have a maximum range of 250 km, a top speed of 80 kilometres an hour, and capacity for 60 passengers at a time.[3]

New additions, both diesel and CNG, to the Perth bus fleet must meet Euro 3 emissions standards (see Table 1).[4] Euro standards involve significant staged reductions in emission of pollutants, noticeably with particulates (PM_{10}) which are the prime source of human health damage arising from diesel vehicle emissions. However, this does not imply that reductions in emissions of PM_{10} will necessarily reduce health damage levels.[5]

Table 1: Euro Emission Standards and comparative emissions of diesel and natural gas fuelled buses

Standard Exhaust Gas (g/kwh)	Euro 2 From 1996	Euro 3 From 2000		Euro 4 From 2005		Euro 5 From 2008	
		ESC	ETC	ESC	ETC	ESC	ETC
NO_X	7.00	5.00	5.00	3.5	3.5	2.0	2.0
HC (NMHC)	1.10	0.66	0.78	0.46	0.55	0.46	0.55
CO	4.00	2.10	5.45	1.50	4.00	1.50	4.00
CH_4[a]			1.60		1.10		1.10
PM_{10}[b]	0.15	0.10	0.16	0.02	0.03	0.02	0.03

ESC = European Stationary Cycle; ETC = European Transient Cycle.

a. Natural gas engines only

b. Not applicable to gas fuelled engines at the year 2000 and 2005 stages.

Economic and technical specifications of an average Perth diesel and CNG bus are given in Tables 2 and 3 respectively. Comparable data for the HFC buses are given in Table 4.

The diesel buses cost A$600,000 each, with no significant additional capital requirements over their working life. A residual value of A$20,000 was assumed for the disposal of the buses after 15 years of operations. The CNG buses cost A$700,000 each, with cylinder testing assumed to be undertaken every three years. A residual value of A$15,000 was assumed.

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[3] The Perth buses would typically travel longer distances at higher speeds than their European counterparts.

[4] GHG emissions are not covered by the standards shown in the table, although some of the gases are minor greenhouse contributors.

[5] Vehicle exhaust particulate mass emissions of PM_{10} (particles with a diameter below 10 micrometres, or 10^{-6} metres) does not include those particles smaller than $PM_{2.5}$. Lowering exhaust emissions of the former, does not necessarily mean also reducing levels of the latter. Recent medical evidence (see WHO, 2003) indicates that $PM_{2.5}$ down to $PM_{0.1}$ have significantly higher detrimental impacts on human health than PM_{10}.

The non-subsidized cost of a Citaro HFC bus is in the vicinity of A$2.0 million.[6] This price reflects not only the high cost nature of the fuel cell and associated components, but also the lack of economies of scale in production. Re-building of the fuel cell stack and cylinder testing is required every three years. A residual value of zero was employed. In addition, the construction of a hydrogen fuel storage and fuel filling facility would be required. However, since a similar facility is required for the diesel and CNG buses this cost was ignored in the analysis.[7]

Table 2: Economic and Technical Specification of an Average Perth Diesel-Powered Bus

Maintenance costs	A$0.35/km A$11,000 engine replaced every 1,000,000 km		
Energy consumption	19.3 MJ/km (2.00 km/l diesel)		
Emissions (g/km)	**Combustion**	**Fuel Production**	**Total**
CO	4.44	0.44	4.88
NOx	18.22	1.93	20.15
Non Methane Hydro Carbons (NMHC)	1.62	1.09	2.71
Particulates (PM10)	0.681	0.105	0.786
CO_2 emissions	1290	370	1660 (3.32 kg/l)

Source: Emissions data from Beer et al. (2001).

Table 3: Economic and Technical Specification of a CNG-Powered Bus

Maintenance costs	A$0.50/km A$11,000 engine replaced every 500,000 km		
Energy consumption	24.8 MJ/km (1.57 km/m^3 CNG)		
Emissions (g/km)	**Combustion**	**Fuel Production**	**Total**
CO	0.074	0.17	0.25
NOx	2.82	0.64	3.47
NMHC	0.47	0.02	1.08
Particulates (PM10)	0.017	0.011	0.028
CO_2 emissions	1340	290	1630 (2.56 kg/m^3)

Source: Emissions data from Beer et al. (2001)

Table 4: Economic and Technical Specification of a Hydrogen/Fuel Cell Bus

Maintenance costs	A$0.50/km A$12,000 fuel cell stack replaced every 5,000 hrs		
Energy consumption	21.58 MJ/km (5.56 km/kg)		
Emissions (g/km)	**Combustion**	**Fuel Production** Steam Methane Reforming (SMR) with CO_2 sequestration	**Fuel Production** Onshore wind and electrolysis
CO	0.0	0.26	0.16
NOx	0.0	1.14	0.85
NMHC	0.0	0.72	0.79
Particulates (PM10)	0.0	0.015	0.0052
CO_2 emissions	0.0	0.0	170

Source: Beer (2001) and Spath and Mann (2004)

External Costs of Transportation

Delucchi (2002) has developed a Lifecycle Emissions Model (LEM) that estimates energy use, emissions of pollutants, and CO_2-equivalent GHG emissions from the complete lifecycles of fuels, materials, vehicles, and infrastructure arising from a variety of transportation technologies. Such models permit identification and calculation of the biophysical emissions, from which a total societal life cycle cost for each technology can be derived by calculating the present value of lifecycle costs (PVLC) associated with each stage; *viz*:

[6] The exact cost is commercial-in-confidence, although trade publications have provided their own estimates.
[7] The hydrogen for the Perth trial is being provided on a commercial basis from an oil refinery located at Kwinana, 50 km south of Perth.

Total Societal Life Cycle Costs ($/vehicle)
=
Initial cost of vehicle (before tax)
+ PVLC (fuel + non-fuel operation and maintenance)
+ PVLC (full fuel cycle air pollutant damages + GHG emissions damage)
+ PVLC (full fuel cycle subsidies – full fuel cycle taxes).

In the transport sector, externality costs are also incurred as a result of congestion, noise, accidents and road damage. However, since this paper assesses differences between buses based upon alternative fuels and engine technologies, the quantification of external costs will focus on emission of pollutants and assume that the other external costs noted here are common to all bus technologies and can consequently be ignored.[8]

Urban Air Quality
Ambient levels of urban air pollution arising from combustion of fossil fuels in the transport sector have been shown to be highly correlated with adverse health effects in the receptor community.[9] The effects of these pollutants on human health can be quantified using exposure-response relationships based upon epidemiological studies that link concentration of pollutants to levels of health impacts. These health effects are generally classified as premature mortality and increased levels of morbidity, both arising from respiratory problems. However, methodologies for placing a valuation on lost years of human life, or increased levels of morbidity, arising from urban pollution remain controversial.[10]

Estimated damages per tonne of pollutant for ozone, SO_2, NO_X, and particulate matter (PM) can vary greatly because of three major factors. Briefly these are:
- Quantity of vehicles and their speed, vintage of engine technologies and presence of associated emission-reducing devices;
- Population density in receptor areas for airborne pollutants; and
- Fuel type.

They can also vary according to the time of day and day of the week, particularly when non-transport sources are also considered.

Table 5 gives estimated damage costs[11] from vehicle emissions of local pollutants for the EU and Australia. The Australian estimates are significantly lower than the corresponding European values, but this is not unexpected given that urban populations in Australian cities are typically less concentrated and hence exposure numbers are lower per unit of area. The environmental footprint for diesel technology is dominated, in terms of cost, by emission of particulates which is therefore the critical value in this table. The initial damage estimate used in the CBA was A$147/kg PM_{10}.

Greenhouse Gas Emissions
External costs from the transport sector also arise from GHG emissions that contribute towards climate change with all its associated effects. Quantification of the future impacts of climate change is a contentious issue, and the range of damage estimates for the possible economic ramifications of global climate change is vast. Costs associated with climate change, such as damage from flooding, changes

[8] With regard to noise, this omission favours diesel and CNG technologies which possess noise footprints significantly higher than that of the HFC bus.
[9] The road transport sector emits (directly or indirectly) a similar range of pollutants to the electric power sector. However, the resulting impacts are not directly comparable. Power station emissions are generally from high stacks in rural areas. In contrast, road transport emission sources are more diverse, invariably closer to ground level and frequently in urban areas. There are also adverse impacts on buildings and vegetation, and ecosystems in general. A comprehensive study into damages arising from fossil fuel combustion technologies, known as ExternE, has been undertaken by the European Commission: see EC(1998) and EC(2003).
[10] See BTRE (2005) for a discussion of the issues involved.
[11] Expressed as health cost savings per tonne of reduced emissions from the transport sector.

in agriculture patterns and other effects, all need to be taken into account. However, there is a lot of uncertainty about the magnitude of such costs, since the ultimate physical impact of climate change has yet to be determined with precision. Thus, deriving monetary values on this basis of limited knowledge is an imprecise exercise.

Table 5: Estimated Damage Cost from Emission of Local Pollutants (A$)

	EU Estimated Damage Costs*			**Australian Estimated Damage Costs**		
Pollutant (A$/kg)	Average	Urban	Rural	Low	Best	Upper
NOx	15	20	12	0.3	0.9	0.9
PM_{10}	250	500	120	108	147	221
SO_2	10	17	7	n/a	n/a	n/a
Hydrocarbons	7	10	5	12	19	73

Source: EC (2003) and Beer (2002)
* Original damages quoted in euros. Rate of exchange used: A$1.00 = €0.60

Tol (2005) has reviewed 88 estimates, from 22 published studies, of the marginal cost of carbon dioxide emissions and combined them to form a probability density function. He found that the function is strongly skewed to the right, with a mode of $5/tonne of carbon (tC), a mean of US$104/tC, and a 95th percentile of US$446/tC.[12] If only peer-reviewed studies were included in the analysis, then corresponding estimates would be US$5, US$57, and US$307 respectively. Thus not only would the mean estimate be substantially reduced, but so would be the degree of uncertainty. Equity weighting[13] and changing discount rates were also shown to have significant effects on these estimates. Overall, Tol concluded that, for all practical purposes, it is unlikely that the marginal costs of CO_2 emissions would exceed US$50/tC and are likely to be substantially lower.

Based upon a constant discount rate and without equity weighting Pearce (2003) quotes a range of US$4-9/tC. Equity weighting, using a marginal utility of income elasticity of unity, changes the range to US$3.6-$22.5/tC. A time varying discount rate raised this range to US$6.5-40.5/tC. All estimates, therefore, are well below Tol's upper bound of US$50/tC. For the purpose of this study, the base-case marginal damage cost of CO_2 emissions was set at US$25/tC (A$36/tC).[14]

Oil Supply Security and Price Volatility

The economic, environmental, and social objectives of sustainable development policies have, as an underpinning tenet, a key requirement of security of energy supplies. The economic and social implications of major breakdowns in the energy delivery system can be very severe. There is a marked asymmetry between the value of a unit of energy delivered to a consumer and the value of the same unit not delivered because of unwanted supply interruption. Further, interruptions, or threats of interruptions, can swiftly lead to widespread disruption given that it is difficult and expensive to store energy. The resilience of energy systems to extreme events is a major problem confronting industrialised society.

Energy "security" is reflected in the level of risk of a physical, real or imagined, supply disruption. The market reaction to prospective disruptions would be a sudden price surge over the expected period of impact of the disruption. A prolonged period of high and unstable prices is, therefore, normally a symptom of high levels of insecurity. Interruptions to supply can also come from unexpected shocks to the energy system, such as deliberate acts of sabotage or unexpected generic faults in energy supply

[12] Divide by 3.67 to express costs in terms of tonnes CO_2.
[13] Equity weighting gives a higher weight to damages that occur in poor countries relative to the same cost of damage in a rich country. It requires the specification of a social welfare function in order derive the weights. Pearce (2003) has illustrated the effects of equity weighting on damages arising from climate change.
[14] It is widely expected that this damage cost will rise in future years due to net annual increases in the concentration of GHG in the atmosphere. To the extent that this occurs, damage estimates reported in this study will be under-estimated.

technology. There is also a time dimension to energy security, ranging from the immediate (e.g. power station breakdown) to the distant future (e.g. the low carbon economy).

It is possible to define two categories of risk in the context of energy security: strategic risks and domestic system risks. **Strategic risks** often involve the risk of interruption to the supply of imported fuels. The origin of the problem may be market power, political instability, or insufficient investment in the infrastructure of fuel exporting nations. They involve external events and circumstances. **Domestic system risks** arise from insufficient or inappropriate investment in domestic energy infrastructure, from technical failure, from terrorism, or from social disruption of the market (e.g. labour strikes).

Energy security is widely perceived as being a public good that should be provided by governments. Without such intervention, it may be argued that market imperfections would lead to an under-provision of security. In extreme cases, such as acts of terrorism, this is clearly true. However, risk is an intrinsic factor in all markets and prices should generally incorporate consumer's willingness to insure against different levels of exposure to risk.

The "cost" of oil price volatility in the international marketplace is generally assessed in terms of its potential impact on a country's Gross Domestic Product (GDP), through raising inflation and unemployment and depressing the value of financial and other assets.[15] The extent of the resulting "loss" is likely to be positively related to the country's degree of dependence on imported oil and oil products. Although the oil-GDP effect is thought to be relatively small, in absolute terms it could significantly offset higher cost competing "fuels" that are not subject to the same price volatility.[16]

Ogden et al. (2004) have estimated the societal lifecycle costs of cars based upon alternative fuels and engines. Fifteen different vehicles were considered, including fuel cell vehicles fuelled with gasoline, methanol or hydrogen (from natural gas, coal or wind power) under the assumption of mature technologies and established infrastructure. If the vast bulk of the transport sector is driven by fuel cells and hydrogen, then benefits will arise from avoidance of oil price volatility in this sector. However, it is feasible that HFC buses could operate independent of the prevailing technology in the remainder of the transport sector, similar to CNG buses today[17]. In this latter case, benefits to GDP from reductions in oil dependence from buses alone are likely to be extremely small as compared to oil requirements from the transport sector as a whole.

Imposing a hedging cost for price stability on oil and gas prices would be completely arbitrary given the time horizons involved. Thus an assessment of its value is left to the end of the analysis. If the HFC bus turns out to have a higher NPV than its fossil fuel counterparts then no additional benefits would need to be assessed. If not, then the shortfall must be addressed in terms of whether it would fully reflect the benefits of fuel price stability.

Cost-Benefit Analysis

The high capital cost of the HFC buses would clearly render them both financially and economically non-viable relative to their fossil fuel counterparts in the current technology context.[18] Both diesel and CNG buses are mature technologies with production and infrastructure facilities operating under returns to scale, a situation not applicable to the HFC buses. To enable a more realistic comparison between the conventional and the HFC buses, it was assumed that HFC buses had also reached this level in the evolution of the technology. For the base case, therefore, the difference in price between a conventional diesel bus and the HFC bus was assumed to be US$25,000. The US Department of

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[15] See Brown and Yucel (2002) for a review of the literature on oil price volatility and its impact on GDP.

[16] This issue has been raised in a series of publications by Awerbuch: see for example Awerbuch and Sauter (2006).

[17] Other specialised transport applications are also possible candidates for fuel cell and hydrogen technology, such as taxis and public utility vehicles. However, overall the resulting impact on oil requirements will remain relatively modest.

[18] In the base case, the NPV of the diesel bus exceeded that of the CNG bus by A$4,830.

Energy cost targets for fuel cell systems in 2010 are US$30/kW for the fuel cell and US$15/kW for the balance of the supporting plant. Ballard Power Systems have stated that they are on target to meet or exceed these targets.[19] If this turns out to be the case then the cost of a 300kW fuel cell system required for a transit bus would be approximately US$ 13,500. This should place the cost of a fuel cell bus at around the same cost as a CNG bus.

The CBA was undertaken on a one-bus basis with economies of scale associated with fleet purchases and operations encompassed by the above assumptions.

Hydrogen is an energy carrier that can be produced from a range of sources. The principle hydrogen production technology is currently steam reforming of natural gas, with partial oxidation (gasification) of fossil fuels and electrolysis of water having minor applications. However, steam reforming and oxidation of fossil fuels involve significant emissions of CO_2 and therefore require CO_2 sequestration in order to make them a viable proposition for near-zero emissions HFC buses. Emerging technologies for producing hydrogen, together with their estimated long-term unit retail supply costs, are given in Table 6. They reflect IEA estimates of costs for a system with full economies of scale and cost reductions achieved through progressive improvements in commercial scale production.[20] Natural gas or coal with CO_2 sequestration is the least costly option, with technologies based upon onshore wind, nuclear, and biomass in the next least-cost group. This study selected two technologies for the analysis: steam methane (i.e. natural gas) reforming (SMR) with CO_2 sequestration and electrolysis using onshore wind.

Table 6: Hydrogen Supply Cost Projections (US$)

Technology	Future fuel/elec. resource price	Fuel cost (US$/GJ)	Other prod. Costs (US$/GJ)	Transport costs (US$/GJ)	Refuelling (US$/GJ)	Future supply cost (US$/GJ)
Gasoline/diesel	$25-29/bbl	4-5	2	<1	2	8-10
Natural gas	$3-4/GJ	3-4	n/a	<1	4	7-9
H_2 (gas) CO_2 seq.	$3-5/GJ	3.8-6.3	1.2-2.7	2	5-7	12-18
H_2 (coal) CO_2 seq.	$1-2/GJ	1.3-2.7	4.7-6.3	2	5-7	13-18
H_2 (biomass)	$2-5/GJ	2.9-7.1	5-6	2-5	5-7	14-25
H_2 (wind-onshore)	3-4c/kWh	9.8-13.1	5	2-5	5-7	22-30
H_2 (wind-offshore)	4-5.5c/kWh	13.1-18.0	5	2-5	5-7	27-37
H_2 (solar-thermal)	6-8c/kWh	19.6-26.1	5	2-5	5-7	32-42
H_2 (solar PV)	12-20c/kWh	39.2-65.4	5	2-5	5-7	52-82
H_2 (nuclear)	2.5-3.5c/kWh	8.2-11.4	5	2	5-7	20-27
H_2 (HTGR cogen.)	n/a	n/a	8-23	2	5-7	15-32

Source: IEA (2003)

Results

The values assumed for the base case parameters are given in Table 7. Fuel prices (net of tax) were assumed to remain constant in real terms over the lifespan of the buses (15 years), with diesel priced at A$0.96/litres (equivalent to an oil price of about US$25/bbl). The price (supply cost) of hydrogen was set at the mid-point of the appropriate IEA range given in Table 6.

Table 8 gives the life-cycle net present value (NPV) for the external environmental costs of the three technologies. They are dominated by damage arising from emissions of local air pollutants (AP), particularly for the diesel bus.[21] By comparison, damages arising from emission of GHG are relatively modest. Fuel cell technology exhibits a significant advantage over diesel, but its advantage over CNG is very much less marked.

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[19] News Release, Ballard Power Systems Inc., March 29, 2005.

[20] The IEA did not consider “breakthrough” technologies, such as photo-electrochemical water splitting and algal systems for water production due to their speculative nature and the fact that they are unlikely to be practical options before 2050.

[21] Damage estimates were taken to be the “best” for Australia as given in Table 5.

Table 7: Base Case Parameters

Mileage per annum per bus	55,000 km
Days of operation per week	5
Lifespan of buses	15 years
Retail price of diesel	A$0.96/litre (A$0.49/litre or A$1.54/gge net of tax)
Retail price of CNG	A$0.91/$m^3$ (A$0.45/$m^3$ or A$1.39/gge net of tax)
Retail price of hydrogen (SMR with CO_2 seq.)	A$3.06/kg (A$2.40/kg or A$2.43/gge net of tax)
Retail price of hydrogen (wind/electrolysis)	A$5.00/kg (A$4.16/kg or A$4.21/gge net of tax)
Exchange rates	A$1.00 = €0.60 A$1.00 = US$0.75
Discount rate	7%
Life of fuel cell stack pair	5,000 hours (replace every 3 years)
Replacement cost of fuel cell stack pair	A$12,000[a]

a. Based upon a US DOE 2010 cost target for fuel cells of US$30/kw.

Table 8: Net Present Value of Environmental External Costs

Technology	**AP**	**GHG**	**Total**
CNG	$20,235	$3,111	$23,346
Diesel	$165,870	$9,118	$174,988
Fuel cell (SMR with CO_2 seq.)	$8,074	$0	$8,074
Fuel cell (wind/electrolysis)	$6,106	$918	$7,024

The NPV of the three technologies under the base case are given in Table 9. There is very little difference between the two fossil fuel technologies, with the lower financial cost of the diesel bus being largely offset by the lower environmental damage associated with the CNG bus. The HFC bus, with hydrogen produced from natural gas, was significantly more costly than its fossil fuel counterparts, but cheaper than when the hydrogen was derived from renewable sources.

For ***Scenario 1***, both oil and gas prices were assumed to increase by 3% per annum from their base case values. SMR depends on a feed stock of natural gas so any increase in the cost of natural gas will result in a proportional increase in the cost of hydrogen from SMR. Since natural gas feed stock accounts for around 30% of the price of hydrogen derived through reformation of natural gas where CO_2 is capture and stored, a 3% increase in the cost of natural gas would result in a 0.9% increase in the cost of H_2 derived from natural gas. The results differ little in relative magnitudes from those under the base case.

Scenario 2 assumed base case values, but with a discount rate of 3%. All NPVs increased by roughly the same percentage, thus yielding a similar ranking to the base case.

In ***Scenario 3*** the price of oil was raised to US$50/bbl. The IEA estimates given in Table 6 were based on an oil price of US$25/bbl. An oil cost of US$50/bbl would result in a diesel cost of US$13/GJ = A$0.67/l net of tax, and a pro rata increase in the cost of CNG would result in a US import price of US$6/GJ and a delivered cost of A$0.52 m^3 net of tax. This would affect the cost of hydrogen derived from natural gas by increasing its cost to A$27/GJ or A$3.21 /kg net of tax. This has a beneficial impact for the HFC bus when the hydrogen is derived from the renewable resource, but it is evident that a far greater increase in oil prices would be required to place this technology on an equal NPV footing with diesel and CNG.

Table 9: Net Present Values for the Three Bus Technologies

Technology	**CNG**	**Diesel**	**HFC** (SMR-CO_2 seq.)	**HFC** (wind/electrolysis)
Base Case	$839,705	$844,535	$950,829	$1,119,584
Scenario 1	$869,495	$870,211	$963,443	$1,119,584
Scenario 2	$971,593	$975,694	$1,094,040	$1,306,931
Scenario 3	$862,839	$890,075	$1,028,978	$1,119,584

Energy security

An "energy security premium" for hydrogen produced by electrolysis utilizing on-shore wind generated electricity could be derived by calculating the increase in fossil fuel prices required, above that of the base case, to give the HFC bus a net present value equivalent to its fossil fuel counterparts.

An additional scenario was specified which adopted base case parameters but with diesel and CNG costs set at a level that (just) resulted in a competitive social cost for the HFC bus using hydrogen based upon wind/electrolysis. The HFC bus became competitive with the diesel bus when the net of tax cost of diesel reached A$1.59/l or A$5.00/gge, which equates to a crude oil price of approximately US$160/bbl. A similar cross-over point (with a net present value of approximately A$1.12 million) was reached when the cost of CNG exceeded A$1.33/m^3 or A$4.13/gge. This equates to a US import price for natural gas of approximately US$20/GJ.

As noted earlier, an "energy security premium" is likely to be restricted to stable fuel prices for the HFC bus unless a significant proportion of Australia's transport sector is HFC-based. In the latter case, avoiding deleterious impacts of oil price volatility on GDP would produce additional benefits equivalent to the avoided damage. This would have the effect of reducing the US$160/bbl break-even point.

Conclusions

This paper has presented the results of a cost benefit analysis comparing diesel, CNG and hydrogen fuel cell buses in the Perth bus fleet based upon the societal life cycle costs and benefits of each technology. Despite its significant environmental benefits in operation, the huge initial cost of the prototype hydrogen fuel cell bus would mean that it could not compete financially with current internal combustion engine technology. The exercise was undertaken, therefore, assuming a fully developed, renewables-based, fuel infrastructure for the provision of hydrogen to fuel cell buses. It was also assumed that the buses, including the fuel cell, were produced under conditions of economies of scale and that the operating life of the fuel cell stack was significantly higher than at present.[22] The capital cost of the fuel cell bus remained higher than its diesel counterpart, but was comparable to CNG based on the DOE 2010 target of US$45/kW for a fuel cell system. The difference in cost was offset to some extent by its environmental benefits.[23]

The current capital cost difference between fuel cell buses and fossil fuel buses is dominated by the cost of the fuel cell system and the necessity to replace the fuel cells much more frequently than is necessary for diesel and CNG engines. The life cycle societal costs of fuel cell, diesel and CNG buses were only comparable when 2010 DOE targets for fuel cell system costs were used.

The major economic impediment to the competitiveness to future fuel cell bus technology is the cost of renewable hydrogen. This will be mitigated as fossil fuel cost increases due the depletion of oil and gas reserves but only if the hydrogen is derived from renewable sources and hence largely protected from increasing oil and gas prices. It can be expected that increasing fossil fuel costs and environmental concerns will drive further improvements in the fuel efficiency and pollution control technology used in internal combustion engines. This will in effect increase the challenge faced by fuel cell buses in achieving future competitiveness.

Introducing benefits associated with energy, and specifically, oil security in the form of avoidance of fuel price volatility obviously favours the renewables-based technology hydrogen technology. However such benefits are likely to be significant only if a substantial part of the transportation sector relied upon non-fossil fuel based technologies.

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[22] Anticipated improvements in fuel efficiency and emissions reduction technologies can be expected to lower both the cost of operating CNG and diesel buses, as well as their environmental impact.

[23] The off-set would have been considerably higher if "average" EU damage costs had been applied, rather than the considerably lower Australian values (Table 5).

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