A Cost-Benefit Analysis of Perth's Hydrogen Fuel Cell Buses

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EXECUTIVE SUMMARY

- This report presents the results of a cost benefit analysis comparing diesel, compressed natural gas and hydrogen fuel cell buses in the Perth bus fleet based upon the life cycle societal costs and benefits of each technology.

- Despite its significant environmental benefits in operation, the high initial cost of the prototype hydrogen fuel cell bus means that it could not compete financially with current internal combustion engine technology. Therefore, the study was undertaken assuming a fully developed, renewables-based, fuel infrastructure for the provision of hydrogen to fuel cell buses, although non-renewable sourced hydrogen was also considered. It was also assumed that the buses, including the fuel cells, were produced under conditions of economies of scale and that the operating life of the fuel cell stack was significantly higher than at present. It is anticipated that this could reasonably be the case between 10 and 15 years time.

- The capital cost of the fuel cell bus remained significantly higher than its fossil fuel counterparts, but the difference was partially offset by its environmental benefits. The “offset” was complete with oil prices in the vicinity of US$120 a barrel in the case of a fuel cell bus using a completely renewables-based supply of hydrogen. Benefits arising from avoidance of the detrimental impacts of oil price instability were not assessed, because these would only be significant if the bulk of the transport sector were based upon hydrogen and fuel cell vehicles.

- Long operating hours for buses favour the hydrogen fuel cell technology due to the volume of pollutants emitted, per bus, per year, by the fossil fuel technologies.

- Internalising the environmental externalities of the road transport sector would benefit near-zero emission technologies such as hydrogen and fuel cells. Emissions taxes, combined with minimum vehicle tailpipe emissions standards, would be a possible instrument for “internalising externalities”, but the resulting higher fuel prices would be likely to generate considerable public opposition to such a policy.

- Although the study focuses on the three Perth buses, the results would have general applicability for the three buses operating in Iceland and in each of the nine European cities in the trials if suitable adjustments were made for the local cost of damages from urban air pollution.

- The application of the higher European Union damages from air pollutants raised the hydrogen fuel cell bus to the position of preferred technology, returning a lower life cycle societal cost than both fossil fuel technologies. This result supports the adoption of such buses in Europe, and elsewhere, when local air pollution involves significant damage to human health and the environment.

- Failure to impose a cost on fossil fuels to reflect damages arising from their combustion effectively amounts to a subsidy and consequently an inefficient use of energy resources. The “polluter pays principle” is an irrefutable concept.

ABBREVIATIONS

bbl	barrels (of oil)
BTRE	Bureau of Transport and Regional Economics
C	carbon
CBA	cost benefit analysis
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CUTE	Cleaner Urban Transport for Europe
DOE	(US) Department of Energy
EC	European Commission
ESC	European Stationary Cycle
ETC	European Transient Cycle
FCV	fuel cell vehicle
GDP	Gross Domestic Product
gge	gallon of gasoline equivalent
g/kwh	grams per kilowatt hour
GHG	greenhouse gas
GJ	gigajoules
H_2	hydrogen
HFC	hydrogen fuel cell
HTGR	high temperature gas reactor
ICEV	internal combustion engine vehicle.
IEA	International Energy Agency
kg	kilograms
km	kilometre
km/l	kilometres per litre
km/m^3	kilometres per cubic metre
kW	kilowatt
l	litre
LCA	life cycle analysis
LEM	Lifecycle Emissions Model
MJ/km	megajoules per kilometre
NMHC	non-methane hydro carbons
NO_X	nitrogen oxide
NPV	net present value
PM	particulate matter
PV	photovoltaics
seq.	sequestration
SMR	steam methane reforming
SO_2	sulphur dioxide
STEP	Sustainable Transport Energy for Perth
t	tonne
THC	total hydrocarbons
WHO	World Health Organisation

Note on Financial Data

All financial data used in the ensuing analysis are based upon constant, or real, dollars. In other words, the impact of inflation has been removed from the analysis. All dollars are Australian, unless otherwise denoted.

BACKGROUND

This study is one of five major projects undertaken as part of the evaluation programme of the Perth Fuel Cell Bus Trial. Its principal objective was to analyse the full economic costs and benefits to the community of the implementation of a hydrogen powered fuel cell bus fleet in Perth. The other four evaluation projects were:

- Public perception;
- Bus operations;
- Government systems analysis; and
- Industry development opportunities.

Progress reports on these projects can be accessed via the following web site: http://www.dpi.wa.gov.au/ecobus/1718.asp

THE METHODOLOGICAL APPROACH

Cost-Benefit Analysis

A cost-benefit analysis is typically undertaken in order to assess the net value of a potential project to society, where non-financial (e.g. environmental) attributes are an important component in determining its viability and justification of the allocation of investment funds. Thus the cost-benefit analysis contained in this report could be viewed as an ex-poste assessment, since acquisition of the three hydrogen fuel cell buses by the Government of Western Australia was made prior to the commissioning of this study. However, the high initial cost of these three prototype buses, together with the high cost of their associated fuel production and delivery infrastructure, rendered them non-viable from both financial and societal perspectives. Consequently, the analysis was undertaken on the assumption that all technologies involved had reached maturity and were benefiting from economies of scale in production.

The United States Department of Energy (2005) envisions a phased transition to hydrogen, with a commercialisation decision in 2015. Success is broadly defined as validation by 2015 of technologies for:

- Hydrogen production at competitive costs with gasoline and no adverse environmental impact;
- Hydrogen storage for more than 300-mile vehicle range with affordable cost; and
- Fuel cell vehicle engines at less than US$50/kW, with appropriate durability.

While the full extent of hydrogen benefits would not be achieved for decades, meeting these requirements in 2015 would enable industry to move towards the commercialisation of hydrogen fuel cell vehicles and the development of the required infrastructure. Thus, it could be anticipated that benefits of scale and a maturing industry status for hydrogen fuel cell vehicles could occur over a time horizon of around 10 to 15 years.[1] In that context, this study is a “typical” cost-benefit analysis.

The Reference Scenario

A research project such as this must necessarily make a substantial number of assumptions regarding future technological and financial variables. These “best estimate” assumptions form the basis of the reference scenario. To the extent that reality differs from the assumptions made in the reference scenario, the analysis will be in error. To permit assessment of the significance of such errors, a number of alternative scenarios have been specified. However, any one of these could have been designated the reference scenario so no particular importance should be given to the order in which the scenarios are presented.

Oil Prices

At present, uncertainty surrounding the near-term outlook for oil prices is unusually pronounced. The annual average West Texas Intermediate oil price rose from US$31.12/barrel in 2003, to US$41.44 in 2004, and US$56.49 in 2005,[2] peaking at almost US$70/barrel in September 2005. In the Reference Scenario, the price is assumed to ease to US$36/barrel[3] as new crude oil production and refinery capacity come on-stream. It should be noted that the veracity of this assumption is not critical to the analysis, since an alternative scenario is specified that calculates the oil price required to render the hydrogen fuel cell bus economically viable compared with its fossil fuel counterparts. This result may then be interpreted in terms of alternative expectations of future oil prices. However, it must be emphasised that cost-benefit-analysis is concerned with the undistorted resource value of a factor of production. Cartel practices, terrorist acts, political conflicts, etc., distort markets and consequently cause a divergence between the true factor cost and its market-based cost. To the extent that such distortions are currently having a significant impact on international oil prices, price adjustments to correct this situation would be required.

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[1] For automobiles the time horizon is likely to be significantly longer than for buses due to much greater transition costs. See IEA (2005a) for costs and associated time horizons for hydrogen and fuel cell technologies.

[2] US Energy Information Administration.

[3] This is the figure used in IEA (2005b), which is the most recent edition of the IEA’s *World Energy Outlook*.

INTRODUCTION

Concerns over the health impacts of small particle air pollution, climate change, oil supply security and oil 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 oil. 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 or, if derived from a fossil fuel, CO_2 sequestration is a financially viable technology. [4]

This report presents the results of a cost benefit analysis comparing a hydrogen fuel cell (HFC) bus with its diesel and compressed natural gas (CNG) counterparts 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 if adjusted for different damage levels in receptor areas arising from emissions of local (as opposed to global) pollutants.[5]

Fuel cells convert hydrogen and oxygen directly into electricity.[6] They have three major advantages over current internal combustion engine technology in the transport sector:

- Gains in energy efficiency. The IEA (2005) reports that the average overall on-road efficiency of gasoline and diesel internal combustion engines vehicles (ICEVs) is at or below 23%, depending upon the specific engine technology. Average fuel consumption of a fuel cell vehicle (FCV) ranges from a factor of two to three times lower than ICEs in highway and urban traffic respectively (with hybrid FCVs achieving an additional 10-15% efficiency), although these values are sensitive to the drive cycle characteristics.[7] Both the efficiency of FCVs and ICEVs are expected to improve over time. A comparison of their

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[4] The battery-powered electric vehicle is a more mature near-zero emissions technology under the same proviso, but current capacity restrictions with batteries have imposed a serious constraint on battery vehicle range. Thus having a fuel cell providing on-board electricity appears to hold considerable long-term potential.

[5] In the context of this study, global pollutants refer to emissions of the uniform-mixing so-called greenhouse gases whose damage is independent of the source of the emissions. Local pollutants are those exhaust gases whose damage is dependent upon the geographic location of source and receptor points.

[6] The basic operation of the hydrogen fuel cell is explained in Larminie and Dicks (2003).

[7] Reported in Ahluwalia et al. (2004).

future efficiency is complicated by a number of factors relating to the range of potential new technologies in vehicle design.[8]

- Near-zero tailpipe 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)[9], 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.[10] 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;
- they operate almost continually over long periods, thus making fuel-efficient technology more attractive.

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[8] See IEA (2005) for an overview and relevant references.

[9] The Sustainable Transport Energy for Perth (STEP) project.

[10] 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 Evo, Ballard Proton Exchange Membrane fuel cell, buses manufactured by Daimler Chrysler.

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 HFC buses have a manufacturer-specified maximum range of 250 km, a top speed of 80 kilometres an hour, and capacity for 60 passengers at a time.[11]

The current Perth bus fleet comprises CNG buses that meet Euro 4 or Euro 2 emissions standards, diesel buses that meet Euro 2 standards and use ultra low sulphur diesel, and some older CNG and diesel buses that pre-date the Euro standards (see Table 1). [12]

Table 1:
Euro Emission Standards and Comparative Emissions of Diesel and Natural Gas 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
THC	1.10	0.66		0.46		0.46	
NMHC			0.78		0.55		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

Source: Summary of European Commission directives.
ESC = European Stationary Cycle; ETC = European Transient Cycle
* Commencing 2006, Australian new diesel vehicle emission standards will be harmonised with the *Euro 4* standard.
a. Natural gas engines only
b. Not applicable to gas fuelled engines at the year 2000 and 2005 stages.

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[11] Note that the Perth buses would typically travel longer distances at higher speeds than their European counterparts.

[12] GHG emissions are not covered by the Euro Emission Standards shown in the table, although some of the gases are minor GHG contributors.

New additions to the Perth bus fleet will be CNG buses that meet Euro 4 emissions standards.[13] The Euro standards involve significant staged reductions in emissions of local pollutants, noticeably particulates which are the prime source of human health damage arising from diesel vehicle emissions. Vehicle exhaust mass emissions of particulates are generally expressed in terms of PM_{10} (particles with a diameter below 10 micrometres, or 10^{-6} metres) This classification includes particles smaller than $PM_{2.5}$, the so-called "fine particles". The proportion of total particulates that can be classified PM2.5 changes depending on a range of factors, including emission reduction measures. Thus reducing emissions of PM_{10} through diesel fuel modifications may not necessarily reduce health damage levels if, as a result, higher emissions of fine particles occur.[14]

Economic and technical specifications, together with emission footprints, of an average Perth diesel and CNG bus are given in Tables 2 and 3 respectively. Comparable data for the HFC bus are given in Table 4, based upon two alternative methods for manufacturing hydrogen: steam methane reforming of natural gas with CO_2 sequestration (henceforth denoted by "HFC (gas)") and electrolysis using electricity produced by on-shore wind plants ("HFC (wind)"). Emissions data for the three technologies (four fuel cycles) are shown graphically in Figures 1 to 5, by each major pollutant.[15]

The current cost of a Perth diesel bus is $360,000, with no significant additional capital requirements over its working life. A residual value of $20,000 was assumed for the disposal of the bus after 15 years of operations. The CNG buses cost $414,000 each, with cylinder testing required to be undertaken every three years. A residual value of $15,000 is assumed.[16]

The cost of the Perth Citaro HFC buses is in the vicinity of $2.0 million each.[17] 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. In addition, re-building of the fuel cell stack and

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[13] Source: Transperth, which is the brand name through which the Western Australian Government provides public passenger transport services in the Perth metropolitan region.

[14] 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}.

[15] Emissions data are given in terms of physical units. For this study these are only relevant in the context of the financial damage per physical unit arising from emissions of each pollutant.

[16] The $5000 difference in the residual value of the two buses reflects the fact that the CNG bus would require a further cylinder replacement at that time in order to continue in operation elsewhere.

[17] The exact cost is commercial-in-confidence, as are the extent of subsidies provided by Ballard and Daimler Chrysler.

cylinder testing is required every three years. A residual value of zero was employed. Although the construction of a hydrogen fuel storage and fuel filling facility would be necessary, since a similar facility is required for the diesel and CNG buses this cost was ignored in the analysis.[18]

Table 2:
Economic and Technical Specification for the Average Perth Diesel-Powered Bus

Maintenance costs	$0.35/km $11,000 engine replaced every 1,000,000 km		
Energy consumption	19.3 MJ/km (2.00 km/l diesel) $0.28/km @ $0.57/l (net of tax)		
Emissions (g/km)	**Combustion**	**Fuel Production**	**Total**
CO	4.44	0.44	4.88
NOx	18.22	1.93	20.15
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 for Perth from Beer et al. (2001).

Table 3: Economic and Technical Specification for the CNG-Powered Bus

Maintenance costs	$0.50/km $11,000 engine replaced every 500,000 km		
Energy consumption	24.8 MJ/km (1.57 km/m^3 CNG) $0.36/km @ $0.57/$m^3$ (net of tax)		
Emissions (g/km)	**Combustion**	**Fuel Production**	**Total**
CO	0.074	0.17	0.24
NOx	2.82	0.64	3.47
NMHC	0.47	0.60	1.07
Particulates (PM10)	0.017	0.011	0.028
CO_2 emissions	1340	290	1630 (2.56 kg/m^3)

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

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[18] 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.

Table 4: Economic and Technical Specification for the Hydrogen/Fuel Cell Bus

Maintenance costs	$0.50/km $12,000 fuel cell stack replaced every 5,000 hrs		
Energy consumption	11.99 MJ/km (10 km/kg) $0.42/km @ $4.16/kg (net of tax): H_2 from wind/electrolysis		
Emissions (g/km)	**Combustion**	**Fuel Production** Steam Methane Reforming (SMR) with CO_2 sequestration	**Fuel Production** Onshore wind and electrolysis
CO	0.0	0.14	0.09
NOx	0.0	0.64	0.47
NMHC	0.0	0.40	0.44
Particulates (PM10)	0.0	0.0081	0.0029
CO_2 emissions	0.0	99.8	95

Source: Beer et al. (2001) and Spath and Mann (2004)

EXTERNALITIES

Externalities are defined as benefits or costs generated as an unintended by-product of an economic activity that do not accrue to the parties involved in the activity and where no compensation takes place. Environmental externalities are benefits or costs that manifest themselves through changes in the physical-biological environment.

Pollution emitted by road vehicles and by fossil fuel fired power plants during power generation is known to result in harm to both people and the environment. In addition upstream and downstream externalities, associated with securing fuel and waste disposal respectively, are generally not included in power or fuel costs. To the extent that the ultimate consumers of these products do not pay these environmental costs, nor compensate others for harm done, they do not face the full cost of the services they purchase (i.e. implicitly their energy use is being subsidised) and thus energy resources will not be allocated efficiently.

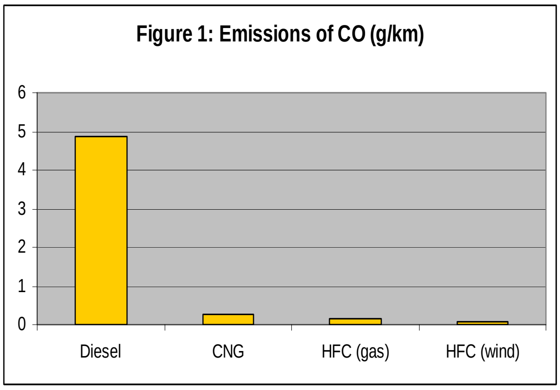

Figure 1: Emissions of CO (g/km)

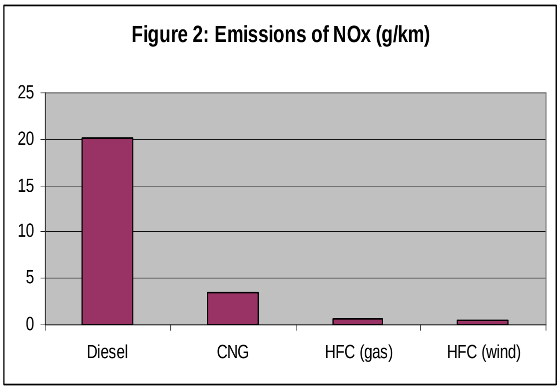

Figure 2: Emissions of NOx (g/km)

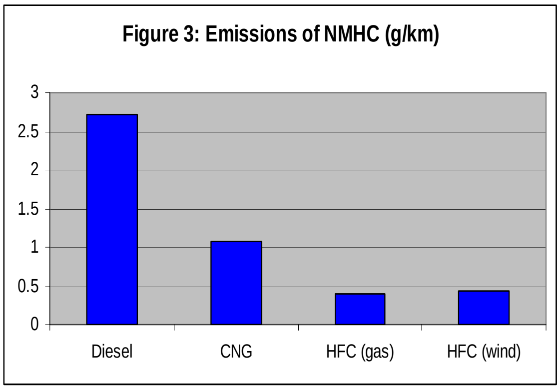

Figure 3: Emissions of NMHC (g/km)

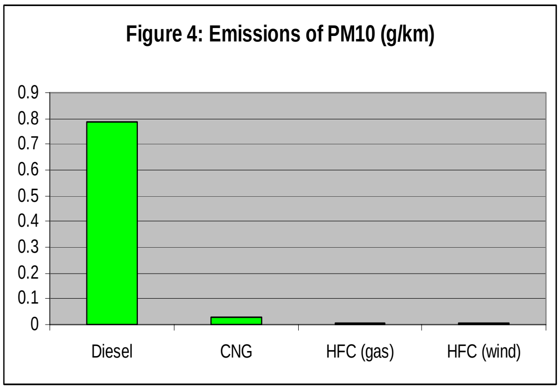

Figure 4: Emissions of PM10 (g/km)

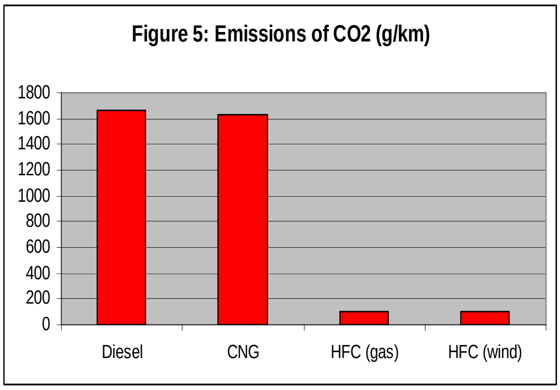

Figure 5: Emissions of CO2 (g/km)

The origin of an externality is typically the absence of fully defined and enforceable property rights. However, rectifying this situation through establishing such rights is not always an easy task. In such circumstances, at least in theory, the appropriate corrective device is a tax equal to marginal social damage levied on the generator of the externality. If the tax is subsequently used to compensate the sufferer(s), then the externality is said to have been “internalised”.[19]

LIFE CYCLE ANALYSIS

When comparing the environmental footprints of alternative energy technologies and fuels, it is important that the combustion stage of the technology not be isolated from other stages of the “cycle”. For example, fuel cells emit virtually no greenhouse gases (GHGs) in their operation. However production of their “fuel” (hydrogen) from fossil fuels may involve increases in GHG emissions in excess of those that would arise from using current commercial fossil fuel technologies to meet the same level of transport demand. To avoid such distortions, the concept of life cycle analysis has been developed.

Life cycle analysis (LCA) is based upon a comprehensive accounting of all energy and material flows, from “cradle to grave”, associated with a system or process. The approach has typically been used to compare the environmental impacts associated with different products that perform similar functions, such as plastic and glass bottles. In the context of an energy product, process, or service, a LCA would analyse the site-specific environmental impact of fuel extraction, transportation and preparation of fuels and other inputs, plant construction, plant operation/fuel combustion, waste disposal, and plant decommissioning. Thus it encompasses all segments including upstream and downstream processes and consequently permits an overall comparison (in a cost benefit analysis framework) of short- and long-term environmental implications of alternative energy technologies. Central to this assessment is the valuation of environmental externalities of current and prospective fuel and energy technology cycles. It should be noted, however, that only material and energy flows are

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[19] For a comprehensive analysis of environmental externalities in the context of the energy sector, see Owen (2004).

assessed in an LCA, thus ignoring some externalities (such as supply security) and technology reliability and flexibility.

For the purpose of this report, life-cycle analysis will involve the following methodological steps[20]:

- Definition of the product cycle's geographical, temporal, and technical boundaries;
- Identification of the environmental emissions and their resulting physical impacts on receptor areas; and
- Quantifying these physical impacts in terms of monetary values.

Environmental emissions (or burdens) from the energy sector that are capable of causing some form of impact can be identified in the following broad categories:

- Solid wastes;
- Liquid wastes;
- Gaseous and particulate air pollutants;
- Risk of accidents;
- Occupational exposure to hazardous substances;
- Noise; and
- Others (e.g. exposure to electro-magnetic fields, emissions of heat).

All potential physical impacts of the identified burdens for all fuel chains must be analysed comprehensively, and it is possible to produce several hundred burdens and impacts for the various fuel chains. Thus, for practical reasons, the analysis must concentrate on those that are considered to be non-negligible in terms of their externalities.

The first task is to identify, both in terms of activities and geographic locations, the various stages of the fuel/technology cycle. The precise list of stages is clearly dependent on the fuel

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[20] These steps describe a "bottom up", as distinct from a "top down", methodology for life cycle analysis. Top-down studies use highly aggregated data to estimate the external costs of pollution. They are typically undertaken at the national or regional level using estimates of total quantities of emissions and estimates of resulting total damage. The proportion of such damage attributable to certain activities (e.g. the transport sector) is then determined, and a resulting monetary cost derived. The exercise is generic in character, and does not take into account impacts that are site specific. However, its data requirements are relatively minor compared with the "bottom up" approach. The latter involves analysis of the impact of emissions from a single source along an impact pathway. Thus all technology data are project specific. When this is combined with emission dispersion models, receptor point data, and dose-response functions, monetised values of the impacts of specific externalities can be derived. Data requirements are relatively large compared with the "top down" methodology, and therefore omissions may be significant.

chain in question, but would include both “upstream” and “downstream” activities in addition to the fuel combustion stage itself. “Upstream” activities would include stages such as exploration, extraction, refining and transportation of fuel. “Downstream” activities would include the treatment and disposal of wastes and by-products and, ultimately, refinery demolition and site restoration impacts.

The extent to which the boundaries of the LCA must encompass indirect impacts is determined by the order of magnitude of their resulting emissions. In theory, externalities associated with the construction of plants to make the steel that is used in the construction of gasoline delivery trucks should be included. In reality, however, such externalities are likely to have a relatively insignificant impact

The LCA boundaries will also have spatial/geographical and temporal dimensions. These will have major implications for the analysis of the effects of air pollution in particular. For many air pollutants, such as ozone and SO_2, the analysis may need to focus on a regional, rather than local, scale in order to determine their total impact. For emissions of GHGs, the appropriate range is clearly global. Impacts must also be assessed over the full term of their impact, a period that may extend over many decades or even centuries in the case of emissions of GHGs and resulting changes in climate. This introduces a significant degree of uncertainty into the analysis, as it requires projections to be made of a number of variables that will determine the future socio-economic structure of society. Among these would be the size of the global population, the level of economic growth, technological developments, the sustainability of fossil fuel consumption, and the sensitivity of the climate system to anthropogenic emissions.

EXTERNAL COSTS OF TRANSPORTATION

Comparisons of alternative transport technologies utilising LCA are generally standardised as emissions per vehicle km in order to allow for different technologies and emission profiles. However, data used to quantify burdens are, to varying degrees, technology specific. For example, emission of CO_2 from cars depends only on the efficiency of the equipment and the carbon/hydrogen ratio of the fuel; uncertainty is negligible. Conversely, emissions of SO_2 can vary by an order of magnitude depending on the grade of oil and the extent to which emission abatement technologies have been incorporated in the vehicle. In general, one would adopt the best available technology currently in use in the country of implementation.

Quantifying the physical impacts of emissions of pollutants requires an environmental assessment that ranges over a vast area, extending over the entire planet in the case of CO_2 emissions. Thus the dispersion of pollutants emitted from fuel chains must be modelled and their resulting impact on the environment measured by means of dose-response functions. Ideally, in the context of damages to humans, such functions are derived from studies that are epidemiological, assessing the effects of pollutants on real populations of people. However, the relevance and reliability of current methodologies for putting financial estimates on human suffering in terms of increased levels of mortality and morbidity has been the subject of some debate.[21]

In the transport sector, typically a "well-to-wheel" analysis is undertaken to assess the impact of a technology rather than a comprehensive LCA. The former excludes the analysis of material and energy flows and emissions from the fuel and vehicle supply infrastructure, which is the first stage of a LCA, and the dismantling and disposal of supply infrastructure and vehicles, which is the last stage. In the context of this study, even if the data were available, these omissions are of minor importance relative to the fuel production and vehicle operation stages of the analysis. The life cycle analysis undertaken in this study, therefore, is a well-to-wheels analysis although the term "life cycle" will continue to be used.

In brief, the process involves calculating the present value of societal lifecycle costs (PVLC) *viz*:

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 report assesses differences between buses

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[21] Pearce (2003) has raised concerns with the methodology used to derive monetary estimates of health impacts.

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.[22]

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.[23] 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.[24]

Estimated damages per tonne of pollutant for ozone, SO_2, NO_X, and particulate matter (PM) can vary greatly depending on the population density in receptor areas for these particular airborne pollutants. 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[25] 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 damage costs, by emission of particulates which is therefore the critical value in this table. The “best” damage estimate, \$147/kg PM_{10}, was used in this study.

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[22] With regard to noise, this omission favours diesel and CNG technologies which possess noise footprints significantly higher than that of the HFC bus.

[23] 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).

[24] See BTRE (2005) for a discussion of the issues involved.

[25] Expressed as health cost savings per tonne of reduced emissions from the transport sector.

Table 5: Estimated Damage Cost from Emission of Local Pollutants

	EU Estimated Damage Costs[a]			**Australian Estimated Damage Costs**[b]		
Pollutant ($/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
NMHC	7	10	5	12	19	73

Source: EC (2003) and Beer (2002)

a. Original damages quoted in euros. Rate of exchange used: A$1.00 = €0.60

b. "Low", "Best", and "Upper" refer to minimum, modal and maximum estimates of damage costs, respectively.

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 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.

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 US$1.4/tonne of carbon dioxide (tCO_2), a mean of US$28.3/$tCO_2$, and a 95th percentile of US$121.5/$tCO_2$.[26] If only peer-reviewed studies were included in the analysis, then corresponding estimates would

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[26] Original estimates were quoted in tonnes of carbon (tC). To retain consistency of units in this report, they have been changed to tCO_2. To return to the original values, multiply by 3.67.

be US$1.4, US$15.5, and US$83.7 respectively. Thus not only would the mean estimate be substantially reduced, but so would be the degree of uncertainty. Equity weighting[27] and declining 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$13.6 tCO_2 and are likely to be substantially lower.

Based upon a constant discount rate and without equity weighting Pearce (2003) quotes a range of US$1.1-2.5/$tCO_2$. Equity weighting, using a marginal utility of income elasticity of unity, changes the range to US$1.0-6.1/$tCO_2$. A time varying discount rate raised this range to US$1.8-11.0/$tCO_2$. All estimates, therefore, are well below Tol's upper bound of US$13.6/$tCO_2$. For the purpose of this study, the base-case marginal damage cost of CO_2 emissions was set at US$7.71/$tCO_2$ ($10.28/$tCO_2$).[28]

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 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 energy insecurity. Interruptions to supply can also come from unexpected shocks to the energy system, such as deliberate acts of sabotage

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[27] 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.

[28] 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.

or unexpected generic faults in energy supply technology. There is also a time dimension to energy security, ranging from the immediate (e.g. oil refinery breakdowns resulting from Hurricane Katrina in August 2005) 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.[29] 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 the higher cost of competing “fuels” that are not subject to the same price volatility.[30]

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 to hydrogen-

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[29] See Brown and Yucel (2002) for a review of the literature on oil price volatility and its impact on GDP.
[30] This issue has been raised in a series of publications by Awerbuch: see for example Awerbuch and Sauter (2006).

based technologies 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. 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. [31]

An alternative approach would be to impose a hedging cost for price stability on oil and gas prices, although this would be an arbitrary exercise given the time horizons involved. Thus an assessment of the value of fuel price stability was left to the end of the analysis. If the HFC bus turns out to have a lower (negative) 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[32]

The CBA was undertaken on a one-bus basis with economies of scale associated with fleet purchases and operations encompassed by the above assumptions. Given the assumption that financial "benefits" (i.e. passenger revenues) arising from bus operations are equivalent for all three bus technologies and can therefore be ignored, the analysis is essentially based upon comparing the PVLC costs (both financial and environmental) of the three technologies. Thus, the preferred technology from a societal standpoint would be that yielding the smallest (negative) NPV.[33]

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-

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

[32] A brief overview of the principles of cost benefit analysis is given in Annex 2.

[33] For convenience, negative signs are omitted in the presentation of the results.

zero emissions HFC buses. Emerging technologies for producing hydrogen, together with their estimated long-term unit retail supply costs, are given in Table 6.

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$/GJ)**	**Retail refuelling (US$/GJ)**	**Future supply cost (US$/GJ)**	**Bus fuel cost (US$/km)**
Gasoline/diesel	$36/bbl	6	2	<1	2	11	0.21
Natural gas	$6/GJ	6	n/a	<1	4	11	0.27
H_2 (gas) CO_2 seq.	$6/GJ	7.58	1.95	2	6	17.5	0.21
H_2 (coal) CO_2 seq.	$1-2/GJ	1.3-2.7	4.7-6.3	2	5-7	13-18	0.16-0.22
H_2 (biomass)	$2-5/GJ	2.9-7.1	5-6	2-5	5-7	14-25	0.17-0.30
H_2 (wind-onshore)	3-4c/kWh	9.8-13.1	5	2-5	5-7	22-30	0.26-0.36
H_2 (wind-offshore)	4-5.5c/kWh	13.1-18.0	5	2-5	5-7	27-37	0.32-0.44
H_2 (solar-thermal)	6-8c/kWh	19.6-26.1	5	2-5	5-7	32-42	0.38-0.50
H_2 (solar PV)	12-20c/kWh	39.2-65.4	5	2-5	5-7	52-82	0.62-0.98
H_2 (nuclear)	2.5-3.5c/kWh	8.2-11.4	5	2	5-7	20-27	0.24-0.32
H_2 (HTGR cogen.)	n/a	n/a	8-23	2	5-7	15-32	0.18-0.38

Source: Adapted from IEA (2003)

The data in Table 6 reflect IEA estimates of costs for a system with full economies of scale and cost reductions achieved through progressive improvements in commercial scale production.[34] Natural gas or coal with CO_2 sequestration is the least costly option for H_2 production, 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.

RESULTS

The high capital cost of the prototype Perth HFC bus would clearly render it both financially and economically non-viable relative to its fossil fuel counterparts in the current technology

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[34] 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.

context.[35] 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 bus. To enable a more realistic comparison between the conventional and the HFC buses, it was assumed that the HFC bus had also reached this level in the evolution of its technology.

The US Department of 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.[36] Assuming 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. The HFC bus would attract other costs above a standard diesel bus, such as strengthening of the body to accommodate roof top tanks and improving suspension to account for increased weight. When these additional construction costs and fuel cell system costs are taken into consideration, this should place the cost of a fuel cell bus at around the same cost as a CNG bus.

The current Citaro HFC buses contain geared electric traction systems using many friction producing power transfers. Effectively this lowers fuel efficiency of the buses and hence their “full-tank” range relative to more efficient traction systems. For this analysis it was assumed that the HFC bus would achieve an efficiency of 10km/kg, although double this figure may be feasible within the specified time horizon.[37]

The values assumed for the reference scenario 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 $0.57/litres (equivalent to an oil price of US$36/bbl). The price (supply cost) of hydrogen was set at the mid-point of the appropriate IEA range given in Table 6.

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[35] In the reference scenario, the NPV cost of the CNG bus exceeded that of the diesel bus by $27,000. However, both technologies produced NPVs significantly lower than the initial capital cost alone of the HFC bus.

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

[37] The trial buses are currently achieving an efficiency of around 4-5 km/kg.

Table 7: Reference Scenario Parameters

Mileage per annum per bus	55,000 km
Days of operation per week	5
Lifespan of buses	15 years
Retail price of diesel	\$1.04/litre (\$0.57/litre or \$1.78/gge net of tax)
Retail price of CNG	\$1.05/m^3 (\$0.57/m^3 or \$1.79/gge net of tax)
Retail price of hydrogen (SMR with CO_2 seq.)	\$5.00/kg (\$4.16/kg or \$4.21/gge net of tax)
Retail price of hydrogen (wind/electrolysis)	\$5.00/kg (\$4.16/kg or \$4.21/gge net of tax)
Exchange rates	\$1.00 = €0.60 \$1.00 = US\$0.75
Discount rate	7%
Life of fuel cell stack pair	5,000[a] operating hours
Replacement cost of fuel cell stack pair	\$12,000[b]

a. A Ballard estimate of 20,000 hours is reported in Knights et al. (2004), but this may not be realistic within the timeframe of this study.
b. Based upon a US DOE 2010 cost target for fuel cells of US\$30/kW.

Table 8 gives the “well-to-wheels” net present value (NPV) for the private costs and external environmental costs of the three bus, four fuels, technologies. The data are illustrated in Figure 6. The NPV of the capital and maintenance costs of the diesel bus are appreciably lower than those of the other technologies, and consequently render it the preferred option on the basis of financial viability alone. Conversely, the diesel bus produces appreciably higher environmental damages than the other technologies, with damage arising from emissions of local air pollutants (AP) the main source.[38] By comparison, damages arising from emission of GHG are relatively modest. Overall, in the context of environmental externalities, fuel cell technology exhibits a significant advantage over both fossil-fuel based technologies, with the extreme diesel damage value being particularly noticeable.

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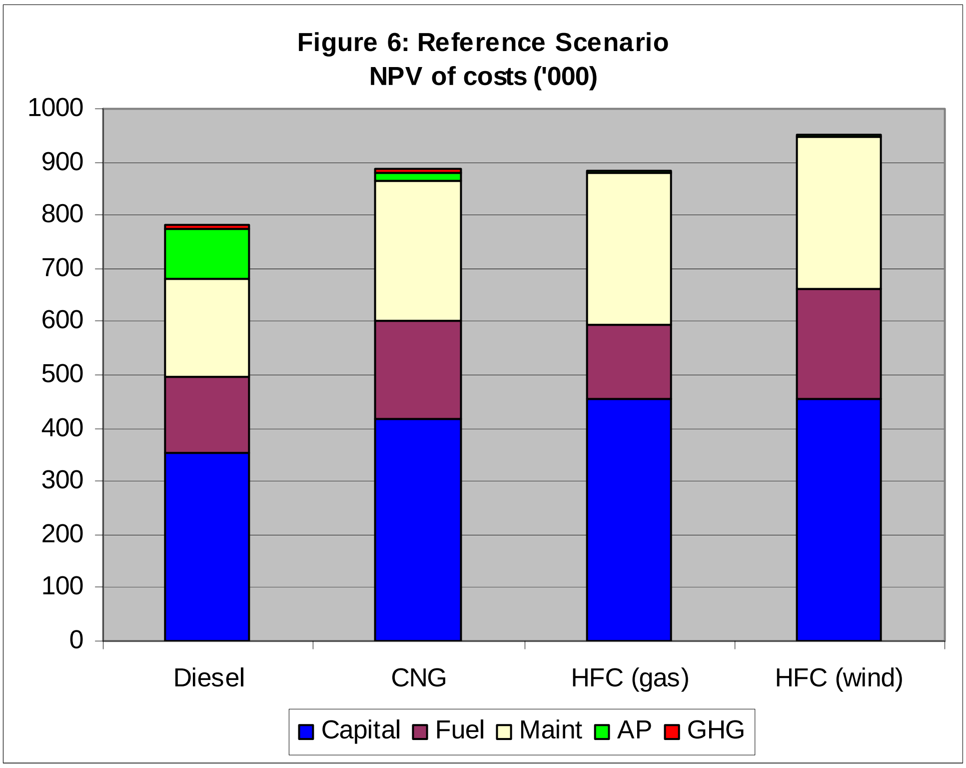
[38] Damage estimates were taken to be the “best” for Australia as given in Table 5.

Table 8: Net Present Value of Private and External Costs: Reference scenario ($'000)

	Capital	Fuel	Maint.	**Total Private**	AP	GHG	**Total External**
CNG	418.4	182.0	265.5	**865.8**	14.2	8.5	**22.7**
Diesel	352.8	141.8	185.8	**680.3**	93.5	8.7	**102.1**
HFC (gas)	453.7	140.3	284.1	**878.0**	4.9	0.5	**5.4**
HFC (wind)	453.7	208.4	284.1	**946.1**	4.8	0.5	**5.3**

The NPVs of the three technologies under the reference scenario are illustrated in Figure 6, disaggregated into their capital, fuel, maintenance, and external component costs. Diesel is the preferred technology based upon lowest societal "well-to-wheels" cost (largely because of its comparatively low capital and fuel costs), with CNG and HFC (gas) both about 13 percent more costly, and HFC (wind) around 22 percent more costly.



Aggregate values for the NPV of the three bus technologies under six additional scenarios to the reference case are presented in Table 9, illustrated in Figure 7, and discussed below.

Table 9: Net Present Values for the Costs of the Three Bus Technologies ($'000)*

Technology	**CNG**	**Diesel**	**HFC** (gas)	**HFC** (wind)
Reference scenario	$888.5	$782.4	$883.4	$951.4
Scenario 1	$924.0	$810.1	$890.9	$951.4
Scenario 2	$1,034.0	$911.6	$1,020.0	$1,108.9
Scenario 3	$986.5	$858.6	$944.0	$951.4
Scenario 4	$894.8	$788.9	$883.8	$951.8
Scenario 5	$915.6	$1,071.6	$884.0	$950.9
Scenario 6	$921.9	$1,078.0	$884.4	$951.3

* Least cost technology highlighted in yellow; next lowest cost in blue.

For ***Scenario 1***, both oil and gas prices were assumed to increase by 3% per annum from their reference scenario values.[39] 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 diesel and CNG bus NPVs both increased by approximately 3-4 percent while the HFC bus using natural gas based hydrogen increased by less than one percent. This resulted in the NPV for the HFC (gas) bus becoming about 4 percent lower than for CNG. The NPV for the HFC bus using renewables-based (i.e. wind) hydrogen was unchanged and remained the bus with the highest societal cost. Thus a gradual but sustained increase in fossil fuel prices reduced the societal advantages of the fossil fuel technologies, but not sufficiently for them to lose their lowest societal cost status.

Scenario 2 assumed reference scenario values, but with a discount rate of 3%.[40] All NPVs increased by roughly 16 percent, thus yielding a similar ranking to the reference scenario. This reflects the fact that the annual costs for all technologies exhibits a very similar time pattern.

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[39] This scenario could be interpreted as an application of the Hotelling rule: *c.f.* Pearce and Turner (1990).

[40] This permits analysis based upon the lowest justifiable discount rate that could be applied to an "environmental" project (*cf.* Pearce (2003)).

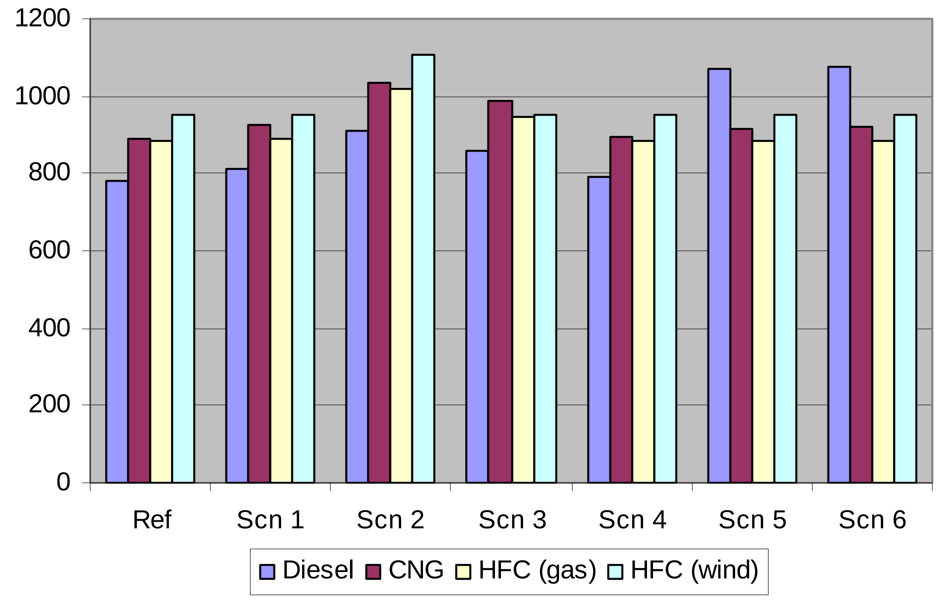
Figure 7: NPV of costs for each technology ($'000)

In ***Scenario 3*** the price of oil was doubled to US$72/bbl. The IEA estimates given in Table 6 were based on an oil price of US$36/bbl. An oil price of US$72/bbl would result in a diesel cost of US$17/GJ = $0.87/l net of tax. Similarly, doubling the price of natural gas would raise the cost of CNG to US$12/GJ and a delivered cost of $0.88 m^3 net of tax. This would affect the cost of hydrogen derived from natural gas by increasing its cost to $25/GJ or $4.01/kg net of tax. This has a beneficial impact for the HFC bus when the hydrogen is derived from a renewable resource, but it is evident that a greater increase in oil prices would be required to place this technology on an equal NPV cost footing with diesel and CNG.

Scenarios 4 and 5 raised, separately, damage costs for CO_2 and local pollutants, respectively, above their reference scenario values, whilst for **scenario 6** these increases were imposed together. Scenario 4 applied Tol's high value of US$13.6/tonne CO_2 for CO_2 damages, with a resulting (minor) narrowing of the gap between the NPVs of the fossil and non-fossil fuel technologies.

Scenario 5 used EU estimated damage costs in urban areas for local pollutants arising from bus operations.[41] The NPV of environmental external costs under this scenario are given in Table 10. For the diesel bus, the change from the reference scenario (Australian-based)

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[41] Although pollution costs arising from the fuel production stage were assumed to be those quoted for EU rural damages.

damages given in Table 9 is quite dramatic, and delivers the HFC (gas) bus the lowest social cost of all three technologies.[42] Adding in the higher CO_2 damage costs (scenario 6) further benefited this technology.

Table 10:
Net Present Value of Environmental External Costs: Scenario 5 ($'000)

Technology	**AP**	**GHG**	**Total**
CNG	41.3	8.5	49.7
Diesel	382.6	8.7	391.2
HFC (gas)	5.5	0.5	6.1
HFC (wind)	4.3	0.5	4.8

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 reference scenario, to give the HFC bus a net present value equivalent to or less than its fossil fuel counterparts.

An additional scenario was specified which adopted reference scenario parameters but with diesel and CNG fuel costs set at a level that (just) resulted in a competitive social cost for the HFC bus using hydrogen based upon wind/electrolysis.[43] The HFC (wind) bus became competitive with the diesel bus when the net of tax cost of diesel reached $1.24/l or $3.9/gge, which equates to a crude oil price of approximately US$120/bbl. A similar cross-over point was reached when the cost of CNG exceeded $0.77/m^3 or $2.4/gge. This equates to a US import price for natural gas of approximately US$9.8/GJ. However, as illustrated by scenarios 5 and 6, these results are very sensitive to values applied to damages arising from air pollutants and in the context of EU damages the HFC (wind) bus could be the least societal cost option with oil at $36/bbl, irrespective of oil security considerations.

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[42] The 55,000 km a year distance travelled by the HFC bus was the major factor influencing this result. Cars generally travel much shorter distances in a year, and therefore the benefits of lower emissions of local pollutants from HFC cars would not be as pronounced as for buses with increasing damage values.

[43] Here, the focus is on HFC (wind), rather than HFC (gas), technology because it gives a near-zero life-cycle emissions footprint combined with negligible reliance on fossil fuels. Essentially, this is the ideal scenario for a "hydrogen economy".

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 from those impacts. This would have the effect of reducing the US$120/bbl break-even point from a societal cost perspective.

CONCLUSIONS

This report 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 very high initial cost of the prototype Perth HFC bus renders it financially non-viable compared with current internal combustion engine technology. The exercise was undertaken, therefore, assuming a fully developed, near-zero net CO_2 emissions, fuel infrastructure for the provision of hydrogen to the 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 longer than at present.[44] The capital cost of the fuel cell bus remained higher than its diesel counterpart, but was comparable to CNG based on the US DOE 2010 target of US$45/kW for a fuel cell system.

A major economic impediment to the competitiveness of HFC bus technology is the cost of hydrogen. This will be mitigated if fossil fuel prices increase due the depletion of relatively low-cost conventional oil and gas reserves and the associated requirement to invest in higher-cost conventional and non-conventional sources, but only if the hydrogen is derived from renewable sources and is thus largely insulated from oil and gas price increases.

Thereafter, the difference in life cycle costs between the technologies was largely determined by assumptions relating to their respective environmental benefits, particularly where buses operate in intensively populated cities with, consequently, relatively high levels of damage from local pollutants emitted by diesel buses. The long operating periods for buses favoured

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[44] Although anticipated improvements in fuel efficiency and emissions reduction technologies can be expected to occur with CNG and diesel buses by the time HFC buses reach this point, damage estimates will not necessarily decline in the context of higher (real) damage values being placed on environmental degradation due to increased atmospheric concentrations of both global and local pollutants.

the HFC technology due to the volume of pollutants emitted, per bus, every year. However, greenhouse gas damages were considerably lower than damages arising from emission of local pollutants.

Introducing benefits associated with energy, and specifically oil, security in the form of avoidance of the economic impacts of fuel price volatility would clearly favour the renewables-based 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.

Overall, HFC buses would appear to offer substantial societal benefits where they operate in cities with high population concentrations where high levels of air pollution from the transport sector impact negatively on human health. For cities such as Perth, the benefits are less marked. Moreover, in the absence of economic instruments that can effectively internalize the externalities of the road transport sector, the benefits of using near-zero emissions technology outside of public sector buses would appear to be limited.[45]

As noted earlier, since this report assesses differences between vehicles based upon alternative fuels and engines, externality costs that are incurred as a result of congestion, accidents and road damage were assumed to be common to all vehicles and consequently ignored. In addition, this report also ignored the important interaction between urban transport policy and near-zero emission transport technologies, which is beyond the scope of this particular study.

On the basis of this study, it is evident that the societal benefits arising from the introduction of near zero emissions bus technologies based upon hydrogen rely heavily on their environmental benefits to offset their private cost disadvantages. Unfortunately, the precision of such benefits is uncertain due a range of complex methodological issues and the absence of markets in environmental “goods”. Nevertheless, the degree to which fossil fuels are either directly or indirectly subsidised is a significant factor in assessing the commercial viability of emerging alternative technologies. Failure to impose costs associated with environmental damage following their combustion is, effectively, providing these fuels with a subsidy.

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[45] Policy options for “internalising” environmental externalities from the energy sector are discussed in Owen (2004), pp. 148-154.

Conversely, justification of energy subsidies to developing technologies may be based upon the desire of a government to achieve certain environmental goals (e.g. enhanced market penetration of low GHG emissions technology), to “level the playing field” by offsetting implicit and explicit fossil fuel subsidies, or for enhancing levels of domestic energy supply security. However, in general, case specific direct action is likely to give a more efficient outcome. Thus penalising high pollution emitting technologies not only creates incentives for “new” technologies, but it also encourages the adoption of energy efficiency measures with existing technologies and consequently lower emissions of pollutants per unit of output. In addition, if the existence of market failures is restricting the diffusion of zero or low emission energy technologies, then (again) addressing those failures directly should provide an efficient outcome.

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ANNEX 1

DETAILS OF THE WORK

Objectives

An evaluation of the economic and social costs and benefits of operating fuel cell buses utilising hydrogen in Perth, relative to conventional buses. The social benefits are largely environmental; *viz*: reduced levels of greenhouse gas emissions, air pollutants and noise. An extension of the analysis will use cost projections for the buses and hydrogen under the assumption of mature technologies, operating under economies of scale, for both. The latter will assist in forming policy decisions regarding the future for fuel cell buses in Perth.

Outcomes

Specific objectives of the Work include:

1. Enumeration of the net financial costs of operating fuel cell buses in Perth.
2. Enumeration of the net social benefits of operating fuel cell buses in Perth. These benefits will be expressed in terms of physical measure relating to reductions in greenhouse gas emissions, local air pollution, and noise.
3. Enumeration of the net social benefits of operating fuel cell buses in Perth, translating the “physical” benefits from step 2 into financial terms.
4. Derivation of the Net Present Value and sensitivity analysis to assess the robustness of the results to the study’s assumptions.
5. Repeat previous step utilising long-term “mature” technology assumptions for the cost of the buses and hydrogen.
6. Production of a Final Report containing all the information outlined in Outcomes 1 to 5 above.

The Final Report and all associated documentation will be provided electronically in a form determined by the Department.

Three printed and bound copies of the report will also be provided.

ANNEX 2

COST BENEFIT ANALYSIS[46]

The term cost benefit analysis (CBA) refers to the social appraisal of projects. A firm evaluates a project in terms of its market-determined costs and benefits (i.e. revenue). CBA evaluates according to the relative social values of the input and output streams. Under ideal conditions the two approaches would be equivalent, since market prices would be identical to relative social valuations. However, since real economies are characterised by market failure, in practice the divergence between the two may be great.[47]

There are five basic elements to a CBA:
1. Project definition and identification;
2. Complete enumeration of the physical consequences of the project proceeding;
3. Aggregation over consequences at each time period in the project's life to get time series for project costs and benefits in monetary terms;
4. Aggregation of the discounted cost and benefit streams over time to get a figure for the project's net present value (NPV);
5. Sensitivity analysis.

A *project* is an item of investment that can be analysed as an independent unit. Such projects may be physical (e.g. new oil refinery), educational, medical, agricultural, etc. The project must be defined so as to ensure that all of the direct and indirect financial and economic costs and benefits of the investment are incorporated within the project definition.

The *enumeration* stage involves identification and measurement of the physical consequences of the project. Prices are then used to *aggregate* over the benefits (B) and the costs (C) over the project lifetime (T years). All costs and revenues are expressed net of taxes and subsidies, since these are merely transfer payments within an economy and do not therefore reflect resource use.[48]

The project's *NPV* can then computed, where:

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} = (B_0 - C_0) + \frac{(B_1 - C_1)}{(1+r)} + \frac{(B_2 - C_2)}{(1+r)^2} + ... + \frac{(B_T - C_T)}{(1+r)^T}$$

and r is the discount rate.[49] Projects with a positive NPV are deemed to be socially desirable. For two or more competing projects, that with the higher NPV should be preferred.

The final stage of a CBA is to test the impact on the NPV of changes in the values of key input variables: the *sensitivity analysis*.

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[46] See Perkins (1994) for a comprehensive introduction to cost-benefit analysis.

[47] Market failure generally arises from incomplete market information, the existence of public goods, monopolistic practices, or market externalities. In this report, the latter is particularly important in the context of environmental externalities.

[48] The exception to this practice is where the tax or subsidy is specifically designed to offset (or “internalise”) an externality. In such a situation they do reflect resource use (or abuse) and must be included.

[49] The value selected for r can have a substantial impact on the viability of environmental projects, particularly for those whose major benefits occur some distance into the future but whose major costs occur early in the project cycle. See Pearce (2003) for a brief discussion of the issues involved.