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Cost and Impacts of a Transition to Hydrogen Fuel in New Zealand

1 Executive Summary

Currently, the twin issues of climate change and security of fossil fuel supply have created an environment in which the future fuelling of the transport sector must be thoroughly reconsidered on both a national and global scale. Many observers believe that the best option will be to use hydrogen gas created using renewable energy, to provide a clean and sustainable fuel source. Before embarking on such a significant change in a sector so important to the economy, it is vital to consider the possibilities and problems that may arise and how such a switch might be progressed. Hence, the Ministry of Economic Development has commissioned CRL Energy Limited to investigate the costs and impacts for New Zealand that could occur by moving from traditional fossil fuels to hydrogen based transport system.

Considerable international research, development and demonstration project work on the use of hydrogen as a transport fuel has been undertaken. This report reviews the relevant research and places it in the New Zealand context. In particular, five hydrogen supply options have been modelled, including production, transportation and distribution. The cost, energy requirement and carbon dioxide emissions associated with each supply chain have been evaluated. The current and future hydrogen vehicle options are examined on the basis of cost and efficiency. Finally, international scenarios on the uptake of hydrogen fuelled vehicles and how Government policy may affect this are discussed.

The hydrogen fuel supply chains examined here include production, transportation and distribution to the demand centre assumed to be initially sited in Auckland. Production is either small-scale at the service station forecourt or large-scale at a central facility with carbon capture and storage, connected to the supply points via a pipeline. Hydrogen is produced by electrolysis or natural gas reformation with the additional possibility of coal gasification only at a central facility. Included in the model were the costs for different sources of electricity and gas/coal and predictions of how the costs may change in the future. A carbon cost of US$55/tonne was applied, equivalent to NZ$25.05/tonne of carbon dioxide emitted, i.e. not captured and stored.

No single supply chain performed best in more than one of the three categories for which results were presented: cost, primary energy use, and carbon dioxide emissions. Coal gasification including carbon capture and storage (CCS) was the cheapest option, centralized natural gas reformation including CCS used the least primary energy, and centralized electrolysis using renewable electricity produced the lowest carbon dioxide emissions. Forecourt electrolysis using zero-emission electricity was the most expensive option, while forecourt electrolysis using grid electricity consumed the most primary energy and produced the highest carbon dioxide emissions. Each supply chain had advantages and disadvantages, which have been highlighted by this study.

The technological options for hydrogen powered vehicles include fuel cell vehicles (FCV), hydrogen fuelled internal combustion engine vehicles (ICEV), and hybrid versions with braking energy recovery. Additional costs compared to fossil fuelled vehicles are elaborated with FCVs predicted to be 60% to 200% more expensive than conventional vehicles by 2010 decreasing to between 10% and 40% more expensive by 2030. FCVs are 2 to 3 times more efficient than fossil fuelled vehicles in terms of energy use per km travelled. Hydrogen powered ICEVs are of a similar efficiency to gasoline powered vehicles and with hybridisation are more efficient than diesel powered vehicles, with significant advantage in reduced local emissions at the point of use. Studies on uptake scenarios from around the world and details of demonstration programmes are included for the US, Europe and Japan. Currently, only around 500 demonstration vehicles are in use, but major car manufacturers are preparing to include hydrogen powered vehicles within their portfolio over the next ten years.

Barriers to the uptake of hydrogen vehicles technologies were examined and can be divided into economic, technological and socio-political (regulation, public acceptance, safety). Potential solutions to these barriers include:

- Include hydrogen in support frameworks for renewable energy; exempt hydrogen vehicles from GST or other taxes; exempt hydrogen from tax; include hydrogen in biofuel targets; make funds available for demonstration projects (hydrogen refuelling station in combination with hydrogen vehicle(s))
- Introduction of a tax on greenhouse gas emissions including CO_2, or other instruments for pricing of these emissions.
- Create a financial incentive for zero-emission vehicles in areas with severe air pollution problems; create benefits such as free parking for hydrogen vehicles.
- Join and/or start R&D programme for fuel cells, hydrogen production, hydrogen storage, etc.
- Create a programme for demonstration projects; promote education and training in schools and universities.
- Create a learning/development environment where regulation and permitting is flexible.

Cost and Impacts of a Transition to Hydrogen Fuel in New Zealand

Contents

2 Introduction

Climate change issues and concerns regarding oil and gas supply security continue to represent prominent challenges for all countries. They are particularly pressing in the transportation sector, which still relies almost exclusively on oil, and are major drivers toward the introduction of new technologies which are able to produce and use energy more efficiently and cleanly. However, the role of distributed generation for electricity and heat provision, using hydrogen gas turbines and fuel cells, is also worthy of consideration. It is possible that distributed generation will be particularly important during the establishment of a hydrogen economy by increasing the initial demand for hydrogen in the short term. Distributed generation may also be important in the longer term when hydrogen may have become as commonly used as electricity for carrying energy to end users. However, this study focuses on the transportation sector where the main demand and benefits of hydrogen are likely to be realised.

Hydrogen fuelled vehicles – fuel cell vehicles (FCVs), hydrogen internal combustion engine vehicles (ICEVs), and hybrid versions of both ICEVs and FCVs in which braking energy is stored in a battery and used to power the electric engine of the vehicle – are seen by many nations as having considerable promise. Numerous R&D and demonstration projects aimed at realising this promise have been initiated globally.

The Clean Urban Transport for Europe (CUTE) programme, which concluded in May 2006, involved the testing of 27 fuel cell buses in 9 major European cities. Between them the buses ran reliably for over 64,000 hours and clocked almost 865,000 kilometres. The longest lifetime of a single fuel cell stack was in excess of 3,200 operating hours. Data obtained also showed the optimisation potential of the prototype bus with regard to fuel consumption. Simulations showed that fuel consumption could be reduced by up to 50% using hybridisation and more electric drive-train-related technology in comparison to the current fuel cell technology.

In terms of infrastructure, all but one of the filling stations was operational for more than 80% of programme time and most had availability in excess of 90%. Filling stations employed either on-site production via electrolysis, on-site production via small-scale steam reformation or off site large-scale steam reformation with the hydrogen being transported by tanker to the filling stations. A total of 192,000kg of hydrogen was supplied in more than 8,900 filling operations.

Other parts of the infrastructure performed less satisfactorily. The energy efficiency of the hydrogen production and distribution infrastructure was generally low and needs to be greatly improved. The fuel cells durability and power density also need improvement and the hydrogen storage systems need to be simplified. Prices for fuel cell buses (and FCVs generally) need to be significantly reduced in order to become cost competitive.

In the US, the immediate goal is to validate hydrogen FCVs, which have greater than a 300 mile range and 2,000 hours of fuel cell durability. The FreedomCAR programme focuses on the high-risk research needed to develop the necessary technologies, such as fuel cells and advanced hybrid propulsion systems, to provide a full range of affordable cars and light trucks that are free of foreign oil and harmful emissions, without sacrificing freedom of mobility and of vehicle choice.

One objective is to achieve 60% conversion efficiency at peak output, durable fuel cell power systems (including hydrogen storage) that achieve a power density of 325W/kg. Cost targets for fuel cells are US$45/kW by 2010 and US$30/kW by 2015 – a significant reduction from present estimated mass production costs of US$100/kW that is predicted for production volumes of over half a million 50 to 80kW units per year.

The 17 nation International Partnership for the Hydrogen Economy (IPHE) recently identified a number of critical objectives that must be met in order to facilitate a transition to a global hydrogen economy. Objectives specific to transport applications included a cost of hydrogen delivery (centralised production) less than US$1.20/kg at the pump by 2020-2030, FCVs achieving fuel cell lifetimes of 5,000 to 8,000 hours by 2015-2020 and production of sufficient hydrogen to power 15% of light duty vehicles on the road in IPHE member countries by 2030. Clusters of fuelling stations will provide hydrogen to support local market penetration by 2015-2020 and codes, standards and regulations for FCVs will ensure a level of safety at least as high as that for conventional ICE vehicles by 2015-2020.

As of late 2006 over 500 hydrogen powered vehicles were on the road worldwide. More than 200 of these were in the United States and over 150 of those were in California.

Internationally, the number of hydrogen filling stations has grown steadily. Prior to 2000 there were only 9 stations worldwide, by 2002 the number had grown to 43 and by late 2006 this had increased to 138 with a further 63 planned to come on stream in “the near future”. Since 2002 on average 20 to 25 new stations have become operational each year.

Of the existing 138 stations, 51 are in the United States (with the majority of these being in California), Germany has 22 stations, Japan 19 and Canada 9. Refuelling stations are also found in Australia, Austria, Belgium, China, Denmark, France, Greece, Hong Kong, Iceland, India, Italy, Luxembourg, the Netherlands, Norway, Portugal, Singapore, South Korea, Spain, Sweden, Switzerland and the UK. Of the planned 63 new stations, almost half are located in the United States.

A number of the major automakers have stated their intention to begin selling, or expand sales of, fuel cell passenger vehicles. These include Toyota, Honda, Nissan, Ford, General Motors, Hyundai, Daihatsu, Nissan and Daimler. Predictions vary widely on the timing and penetration of FCVs into the passenger vehicle fleet market. Automakers for the most part are predicting sometime after 2010 with the market requiring at least 5 to 8 years to develop after the introduction of the first commercial vehicle. Projections for the US have indicated that FCVs could achieve approximately 7 to 10% of the light duty vehicle stock by 2030 if current technical targets are met. It is expected that it will take several production cycles at low to medium volumes to gain experience, establish reliability and achieve maturity. Over the next decade automakers may be unwilling to commit to extensive production since early designs could become obsolete before costs are recovered fully.

The development of a hydrogen economy and a hydrogen based transport fleet poses several major infrastructural issues, such as installing sufficient capacity of the appropriate type to move the hydrogen from source to destination. Another issue is the feasibility and logistics of fitting a large number of existing petrol and diesel fuelling stations with suitable storage and equipment to dispense hydrogen. Every nation has a different mix of potential hydrogen sources, different demographics and geography. The most effective means of developing a hydrogen infrastructure will vary between countries and each nation will have to find its own solutions and plan of action. Many complex issues must be taken into consideration.

Given the size of the international push towards the development of hydrogen based energy systems, the increasing pace of progress toward realisation of this goal, and the complexity/number of issues that must be given due consideration, it is timely for New Zealand to begin to understand better the costs and impacts of the use of hydrogen in its future transport fleet.

This report considers some of these complex issues and more specifically it:

- Identifies potential hydrogen supply chains – the means whereby hydrogen is produced, transported and distributed to the forecourt.
- Identifies the costs, energy requirements and corresponding CO_2 emissions associated with each of those supply chains.
- Considers hydrogen vehicle uptake scenarios internationally and their relevance to the New Zealand situation.

3 Hydrogen Supply Options for New Zealand

3.1 Introduction

This section describes five different supply chain models for the supply of hydrogen for vehicle refuelling in New Zealand. These options were developed in consultation with the MED and selected on the basis of the abundance of the feedstock in NZ, the maturity of the technologies involved, and the ability of each option to provide a significant contribution to meeting the scale of the future demand. For example, biomass options were not chosen because the technology is not sufficiently advanced, and oil/LPG based options were not considered because the production volumes are considerably smaller than those for natural gas and coal. There are also several technologies under development based on high-temperature and solar resources which may merit future consideration as the technology approaches the demonstration or commercialisation stage.

The main difference between the options selected is the method of hydrogen production as listed in Table 1. Each supply option includes transport and distribution paths as shown in Figure 1. For electrolysis the models were further subcategorised depending on the method of production of the electricity (grid supplied electricity from a variety of sources or 100% renewable sourced).

Sections 3.2 to 3.6 detail the hydrogen production models used for the analysis. Sections 3.7 and 3.8 discuss forecourt and end use options. Note that these are simple models and are aimed at providing an understanding of the general costs and the emissions involved rather than for calculating exact quantities.

Table 1 – Five Hydrogen Supply Chains

Option Number	Supply Chain Main Descriptor
1	Forecourt hydrogen production by electrolysis
2	Forecourt hydrogen production by natural gas (NG) reformation
3	Centralised hydrogen production by advanced electrolysis
4	Centralised hydrogen production by NG reformation (including carbon capture and sequestration (CCS))
5	Centralised hydrogen production by coal gasification (including CCS)

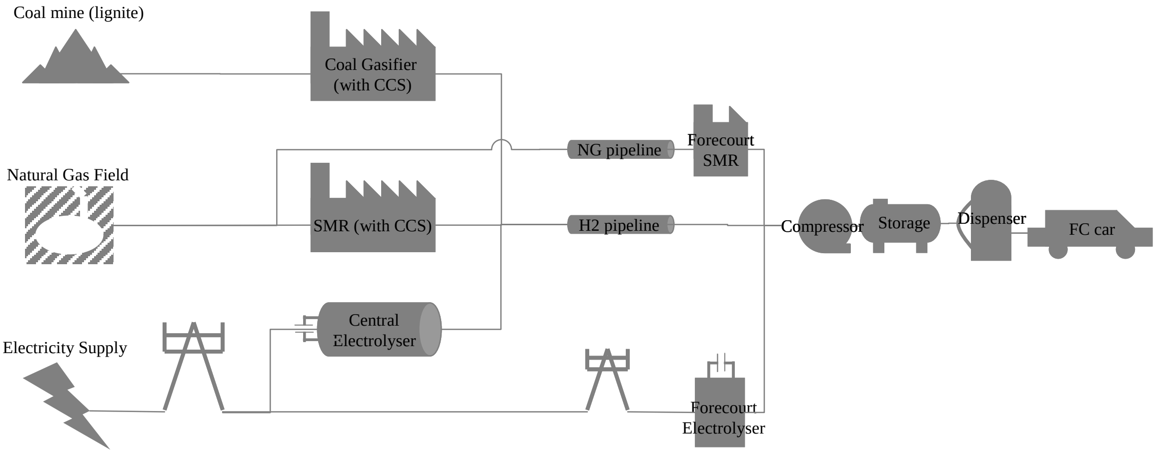

Figure 1 – Five Supply Chains for Hydrogen in New Zealand

3.2 Forecourt Hydrogen Production by Electrolysis

For this model hydrogen is produced on the forecourt using a small onsite electrolyser capable of producing up to 1,578kg of hydrogen per day (24hours). This amount of hydrogen as an energy carrier is equivalent to an output of approximately 207GJ/day or 2.4MW[1] of continuous power output [Stuart Energy, 2004].

An electrolyser is used to split water into hydrogen and oxygen gases. This size of electrolyser consumes approximately 10 litres of distilled water per minute and 27.5GWh of electricity per year from which it can be inferred that approximately 25% of the electrical energy is lost to heat. Local environmental impact should be low with a fairly low water demand at 14tonne/day and no significant emissions of solid, liquid or gas waste. The overall environmental impact depends on the source of electricity used with renewable sources minimising the impact.

It is assumed that the vehicles fuel tank at 700bar is filled from a small storage bank, where the high pressure cylinders are at 800bar. It is foreseen that this type of hydrogen supply chain will play an important role at the start the transition towards a hydrogen economy, using electricity from the national grid.

3.3 Forecourt Hydrogen Production by Natural Gas Reformation

This model is based on a forecourt natural gas reformer producing 631kg of hydrogen per day. This amount of hydrogen as an energy carrier is equivalent to an output of approximately 83GJ/day or 0.96MW [Halder Topsoe, 1998].

In the steam reforming process, methane reacts with water at 700 to 850° C (steam) in the presence of a catalyst to produce hydrogen and carbon monoxide. The carbon monoxide is then converted into hydrogen and carbon dioxide through the “water-gas shift” reaction. The hydrogen is then separated from the other gases using pressure swing adsorption (PSA)[2] and the carbon dioxide released to the atmosphere. Natural gas for the reformer is supplied by pipeline Details about the forecourt are in section 3.7. No hydrogen transport is required as the hydrogen is produced and delivered on site. The local environmental impacts of such a small plant would be minimal with a relatively small water demand for steam and the emissions consisting of carbon dioxide.

3.4 Centralised Hydrogen Production by Advanced Electrolysis

Hydrogen is produced at a centrally located electrolyser in the Tararua region, where there is a large wind energy resource. Large-scale electrolysis is used to produce hydrogen from water and electricity. Placing the hydrogen production unit close to the point where electricity is generated greatly reduces energy losses in the transmission of large amounts of electricity, although transport of the electricity to an electrolyser situated near the demand centre may be an alternative worth examining. Large-scale electrolysers provide benefits such as the ability to operate at higher temperatures and pressures with a resulting increase in efficiency. In this model 200 electrolyser units are used in parallel to produce 316 tonnes of hydrogen per day carrying 41TJ of energy at an output rate of 479MW (~0.115Mt/year). Manufacturers of electrolysis equipment currently produce large-scale plant by combining smaller modules. The hydrogen is transported to the Auckland region in an underground pipeline approximately 500km in length with several gas compressor stations *en route* to maintain the pressure. A smaller diameter pipeline, approximately 4km in length, feeds hydrogen to each refuelling station from the high-pressure pipeline. For long-term large-scale supply, tankers cannot compete economically with pipelines. The industrial scale of the plant could result in a

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[1] Assuming hydrogen carries 131 MJ/kg – this is the average of the higher heating value (HHV) and lower heating value (LHV) and is equivalent to assuming half the hydrogen will be used in fuel cells where the HHV applies and the other half used in internal combustion engines where the LHV applies.

[2] Pressure Swing Absorption separates species according to their respective molecular characteristics and affinity for an absorber. Pressure changes allow species to be absorbed then released, separating mixtures.

significant visual impact. A water demand of nearly 3000 tonnes per day could be significant locally but emissions should be minimal. As approximately 25% of the energy is lost as heat significant quantities of cooling water would be required with cooling towers, which could impact visually. Large-scale plants may have a significant impact on land use and aesthetics.

3.5 Centralised Large-Scale Hydrogen Production by Natural Gas Reformation (including CCS)

In this model a large natural gas reforming plant is located at the harbour of New Plymouth. This location provides good access to: current onshore and offshore supplies of natural gas; infrastructure that will allow large-scale liquefied natural gas (LNG) import in the future and potential carbon dioxide sinks. The reformer produces up to 555 tonnes of hydrogen per day and has an energy output of 841MW (~0.203Mt/year) [Foster Wheeler, 1992]. Natural gas could be supplied from Taranaki or imported as LNG and both these cases are considered. The reformation process is very similar to the process described in section 3.3, except that a large-scale natural gas reformer can operate at higher pressure and generally has a higher efficiency. In addition to the natural gas, the reformer also needs steam, electricity and cooling water. A Pressure Swing Adsorption (PSA) unit is used to purify the hydrogen. Carbon dioxide is captured in the reformation plant by end-of-pipe removal technology and is transported 50km to an empty gas or oil field for storage. An underground pipeline of 400km is used to transport hydrogen at 60bar to the demand centre in the Auckland region. A smaller diameter pipeline, approximately 4km in length, feeds hydrogen to each refuelling station from the high-pressure pipeline. The industrial scale of the plant results in a significant water demand as steam, although again emissions will be minimal locally. Large-scale plants may have a significant impact on land use, aesthetics and noise.

3.6 Centralised Large-Scale Hydrogen Production by Coal Gasification (including CCS)

In this model a large oxygen-blown coal gasification plant is located in the South of the South Island using lignite to produce 1,200 tonnes of hydrogen per day equivalent to an energy output of 1,819MW (~0.438Mt/year). Although complex, coal gasification is a mature and cost-effective technology.

Hydrogen is produced by an endothermic gasification reaction that produces a gas mixture[3] containing hydrogen, carbon monoxide, carbon dioxide, methane and other components. The composition depends on the type of coal used and the temperature during gasification. A water gas shift reactor is used to increase the hydrogen content by converting the carbon monoxide and steam into hydrogen and carbon dioxide. The carbon dioxide produced is captured, compressed, transported and stored nearby, for example, in an un-mineable coal seam. The hydrogen is compressed and fed into a 1,400km high-pressure pipeline (including a 100km underwater pipeline connecting South Island to North Island) that runs from the gasification plant to the demand centre in Auckland. Gas compressor stations *en route* maintain the pipeline pressure. A 4km pipeline connects the main pipeline to each refuelling station in the Auckland region. The industrial scale of the plant results in a significant local water demand for steam. Emissions would be carefully controlled by the local regulatory body to minimise impact, necessitating the use of suitable gas clean-up equipment to remove sulphur compounds, tars etc produced from the coal. Large-scale plants may have a significant impact on land use and aesthetics.

3.7 Hydrogen Forecourt

Each of the supply chains ends at an identical refuelling station with an average of eight individual pumps. The energy use, emissions and cost of the forecourt are based on sales of

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[3] Also known as "syngas"

384kg of hydrogen per pump per day[4] which is typical for New Zealand in terms of car throughput. The forecourt is located in the Auckland region and any vehicle using hydrogen can be refuelled at this forecourt.

Hydrogen compression is conducted with a 2-stage electrically powered hydraulic compressor, using inter-cooling for optimum efficiency. The station has 17 storage racks each with 16 hydrogen storage cylinders. The hydrogen forecourts are supplied with electricity from the national electricity grid unless otherwise stated.

All quantities are calculated per kg of hydrogen to simplify recalculation for different sizes of forecourt.

3.8 End Use Options

Each of the supply chains delivers hydrogen at 700bar to vehicle storage tanks. The drive-train of the vehicles can be powered by a fuel cell, an internal combustion engine or hybrid systems including battery storage (see section 5.3 for vehicle options).

4 Hydrogen Techno-Economic Data

4.1 Introduction

In this section the five different hydrogen supply chains are compared. For each chain, the cost, the primary energy use and the carbon dioxide emission in supplying a kilogram of hydrogen are calculated. These three parameters are often collectively referred to as “E3”, which stands for Economics, Energy and Emissions. Each supply chain has a value of E3 that depends on the physical layout of the chain, data for the processes involved and costs.

4.2 Input Data

For this study Auckland was assumed to be the hydrogen demand centre. The assumptions are summarised in Table 2. The annual requirement of 39.3PJ is based on 2 million cars (50% FCVs, 50% H_2 ICEVs) travelling an average of 15,000 kilometres per year. Approximately 270 hydrogen refuelling stations each with 8 individual pumps would be needed to refuel this vehicle fleet. For the central hydrogen production supply chains one large high-pressure (60bar) pipeline supplies all the refuelling stations using 4 kilometres (on average) of medium-pressure (10bar) pipeline per refuelling station. Pipeline information and cost estimates come from various sources [Parker 2004, Mintz *et al.* 2002, N.V. Nederlandse Gasunie 2004]. For electrolysis, no value is assigned to the oxygen produced as a by-product and similarly for coal gasification no account is taken of the value of sulphur captured and purified from the emissions.

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[4] Equivalent to approximately 80 cars per pump per day

Table 2 – General Assumptions

	Magnitude	Source
Carbon Tax*	50 US$/ton Carbon	[NRC/NAE, 2004]
CO_2 disposal cost	11 US$/ton	[NRC/NAE, 2004]
CO_2 emissions NZ electricity grid	198 g/kWh	[MED, 2006][5]
Average mileage	15,000 km/year	[JRC, 2004]
Hydrogen demand centre	Auckland region	
Fleet composition – H_2 ICEV: FCV (non-hybrid vehicles)	50:50	
Average fleet fuel economy	1.31MJ/km	[from Table 7 – Efficiencies 2010+ Vehicles Using Various Drive-Trains]
Annual hydrogen demand	39.3 PJ[6]	
Number of hydrogen refuelling stations (RFS) in demand centre (with 8 pumps per station on average)	270	
Average pipeline length per RFS	4 km	
Transmission pipeline cost (land)	1.78 MNZ$/km	Estimates based on European and US literature, personal communications and current projects.
Transmission pipeline cost (sea)	3.56 MNZ$/km	
Distribution pipeline cost for RFS	0.89 MNZ$/km	
Discount rate (for capital cost)	6% real	
1 NZ$ equals	0.5€ and 0.6US$	(from www.xe.com)
Income tax	Not considered	

* Note: 50$US ton Carbon equates to 55.12 $US tonne Carbon

Energy prices are also important in the calculation of the hydrogen supply cost and are listed in Table 3.

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[5] Calculated from $8,202ktCO_{2eq}$ emitted during electricity generation [MED 2006b Table 1.1.1] for a total electricity production of 41,508GWh [MED 2006a, Table G.3]

[6] Calculated from the preceding figures and equivalent to approximately 0.3 Mt hydrogen

Table 3 – Energy Prices for Five Hydrogen Supply Chains*

Forecourt hydrogen production by electrolysis	
“Zero-emission electricity” price	42 NZ$/GJ 0.15 NZ$/kWh[7]
Grid electricity price, intermediate	33.3 NZ$/GJ 0.12 NZ$/kWh[8]
Forecourt hydrogen production by NG reformation	
Natural gas price, intermediate	15.40 NZ$/GJ[9]
Grid electricity price, domestic	49.60 NZ$/GJ 0.18 NZ$/kWh[8]
Centralised hydrogen production by advanced electrolysis	
Grid electricity price, industrial	22.8 NZ$/GJ 0.082 NZ$/kWh[8]
Wind electricity price, large-scale	23.0 NZ$/GJ 0.083 NZ$/kWh[7]
Centralised hydrogen production by NG reformation (incl. CCS)	
Natural gas price, industrial	7.70 NZ$/GJ[9]
Natural gas price, LNG imports	12.00 NZ$/GJ[10]
Centralised hydrogen production by coal gasification (incl. CCS)	
South Island lignite price	1.70 NZ$/GJ[11]
Grid electricity price, industrial user	20.80 NZ$/GJ 0.082 NZ$/kWh[8]

* Does not include carbon tax.

For all supply chains the forecourt compressor and refuelling stations are powered by electricity from the national grid. Refuelling stations in the Auckland region will use electricity from a mixture of power generation sources.

4.3 Results for Cost of Hydrogen Supply Chains

Table 4 shows the results of the cost calculation for the five hydrogen supply chains, based on the modelled supply chains as described in section 3, the general assumptions from Table 2 and the energy prices from Table 3. The cost is divided into capital cost, cost for operation & maintenance, fuel or energy cost, CCS cost or a carbon tax (if applicable), hydrogen pipeline transportation cost and hydrogen distribution cost (forecourt or refuelling station). It is likely that the majority of the equipment required will be manufactured abroad.

“Future” costs take into account predicted improvements in plant efficiency and the increased experience with plant operation and maintenance (O&M), but fuel costs are kept constant for this study. Capital costs for plant or process equipment[12] are calculated using a discount rate of 6% and the lifetime of the specific process. O&M costs include all processes in the hydrogen

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[7] East Harbour (2005) reported in 2005 that by 2015 wind generated electricity would be available on large scales at <8c/kWh – cost doubled as an estimate of the retail price for a small industrial customer.

[8] MED Energy Data File January 2006, pg 146, Table I1.

[9] MED Energy Outlook 2006, Figure 3.5 energy prices by fuel type – wholesale 2015 price under business as usual scenario – price doubled for estimate of low user pricing.

[10] Calculated from formula in MED Energy Outlook 2006, Section 7.2.

[11] Solid Energy Report, Energy Options – Securing Supply in New Zealand, (2004), pg 6, Figure E7, quoted a possible price range for long term supply contract excluding delivery of 0.6 to 1.0NZ$/GJ.

[12] Electrolysers, natural gas reformer, coal gasifier, hydrogen pipeline, etc.

supply chain. The fuel costs include costs for all the energy required in the hydrogen supply. The fuels that are used are renewable and grid electricity, natural gas, and coal[13]. CCS costs include capturing, transporting and storing the carbon dioxide. A disposal cost of 18.4NZ$ (11US$) per tonne of carbon dioxide is used. For all carbon dioxide emitted, whether directly from hydrogen production or indirectly for instance from the generation of electricity used in the supply chain, a carbon charge of 91.86 NZ$ (55.12 US$) per tonne, which is equivalent to 25.05 NZ$ per tonne of CO_2, is used. The two supply chains using CCS will still involve direct and indirect carbon dioxide emissions which have been taken into account.

Table 4 – Cost for Hydrogen Supply of Five Different Hydrogen Supply Chains

Supply Chains		**Cost in NZ$/kg**						
		H_2 Prod.				**H_2 Transp.**	**H_2 Distr.**	**Total**
		Capital	**O&M**	**Fuel**	**C-tax**			
Forecourt H_2 prod. by electrolysis ("zero-emission electricity")	Current	1.65	0.17	8.00	0	0	1.15	**10.97**
	Future	0.73	0.08	8.00	0	0	0.69	**9.50**
Forecourt H_2 prod. by electrolysis (grid electricity)	Current	1.65	0.17	6.40	0.28	0	1.15	**9.65**
	Future	0.73	0.08	6.40	0.28	0	0.69	**8.18**
Forecourt H_2 prod. by NG reformation	Current	1.67	0.16	2.76	0.26	0	1.15	**6.00**
	Future	0.74	0.07	2.76	0.26	0	0.69	**4.52**
Centralised H_2 prod. by advanced electrolysis ("zero-emission electricity")	Current	0.67	0.07	3.96	0	0.19	1.15	**6.04**
	Future	0.40	0.04	3.96	0	0.19	0.69	**5.28**
Centralised H_2 prod. by advanced electrolysis (grid electricity)	Current	0.67	0.07	3.92	0.26	0.19	1.15	**6.26**
	Future	0.40	0.04	3.92	0.26	0.19	0.69	**5.50**
Centralised H_2 prod. by NG reformation (including CCS) [+]	Current	0.39	0.14	1.26	0.050 + (0.466)*	0.17	1.15	**3.63**
	Future	0.34	0.13	1.15	0.50	0.17	0.69	**2.98**
Centralised H_2 prod. by coal gasification (including CCS)	Current	0.65	0.30	0.58	0.091 + (0.481)*	0.41	1.15	**3.66**
	Future	0.51	0.25	0.34	0.51	0.41	0.69	**2.71**

* CCS costs including capturing, transporting and storing the CO_2 .

[+] LNG: All the costs remain the same except for the fuel cost which increases to 1.97 (current) and 1.80 (future).

For supply chains with central production of hydrogen the transport cost for the high-pressure pipelines includes the pipeline capital cost and the transportation cost. It is assumed that the

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[13] South Island lignite

compressors are powered with hydrogen from the pipeline itself[14] and that the medium-pressure pipelines do not require compressors.

Table 5 shows the primary energy use in GJ per kilogram hydrogen, the carbon dioxide emissions in terms of gram per kilogram hydrogen, and a repeat of the total cost of hydrogen per kilogram, for each of the supply chains. For the supply chains that use electricity to produce hydrogen, one option uses electricity from the New Zealand electricity grid, which has a carbon dioxide emission of 198g/kWh, and the other option uses "zero emission" electricity from a renewable energy source (e.g. wind power, wave power, and solar power). The efficiency of processes that convert renewable energy into electricity is assumed to be 100% (excluding biomass) and so the primary energy use from renewable sources is thus equal to the amount of electricity that is produced. The efficiency of conversion from coal, gas and oil used were 39%, 52% and 40% respectively. The overall primary energy input to electrical energy output conversion efficiency for New Zealand grid-electricity was calculated to be approximately 80% from the individual conversion efficiencies above and the percentage of total electrical generation for each energy source listed in the NZ Energy Data File [MED 2006a].

Table 5 – Primary Energy Use and Carbon Dioxide Emissions and Costs

	Primary energy use in GJ/kg				**CO2 emissions in g/kg**				**Cost in NZ$/kg**	
Supply Chains	**Prod.**	**Tran.**	**Distr.**	**Total**	**Prod.**	**Tran.**	**Distr.**	**Total**	**Now**	**Future**
Forecourt H_2 prod. by electrolysis ("zero-emission electricity")	0.192	0	0.012	**0.204**	0	0	507	**507**	**10.97**	**9.50**
Forecourt H_2 prod. by electrolysis (grid-electricity)	0.239	0	0.012	**0.251**	10559	0	507	**11066**	**9.65**	**8.18**
Forecourt H_2 prod. by NG reformation	0.175	0	0.012	**0.187**	9742	0	507	**10249**	**6.00**	**4.52**
Centralised H_2 prod. by advanced electrolysis ("zero-emission electricity")	0.172	0.006	0.012	**0.190**	0	0	507	**507**	**6.04**	**5.28**
Centralised H_2 prod. by advanced electrolysis (grid-electricity)	0.214	0.008	0.012	**0.234**	9457	337	507	**10301**	**6.26**	**5.50**
Centralised H_2 prod. by NG reformation (including CCS)	0.164	0.006	0.012	**0.182**	1423	51	507	**1981**	**3.63**	**2.98**
Centralised H_2 prod. by coal gasification (including CCS)	0.198	0.007	0.012	**0.217**	3000	107	507	**3614**	**3.66**	**2.71**

From the information in Table 4 and Table 5 the following conclusions can be drawn. Central production with carbon capture and storage was cheaper than forecourt production, because of the benefits of large-scale production and the ability to capture carbon dioxide. Coal gasification was the cheapest option followed by natural gas reformation with electrolysis the most expensive option. In terms of primary energy use natural gas reformation used least, followed

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[14] In the supply chain with natural gas transport compressor stations on high-pressure pipelines use the natural gas in the pipeline to power the compressors

by electrolysis using renewable electricity then coal gasification, with electrolysis using grid electricity consuming the most primary energy. When it comes to carbon dioxide emissions, electrolysis using renewable electricity produced least followed by centralised natural gas reformation, coal gasification, forecourt natural gas reformation, centralised electrolysis using grid electricity, and worst of all forecourt electrolysis using grid electricity. For all except the renewable electricity electrolysis option, there is significant emission of carbon dioxide relating to the energy used in hydrogen production, generation of any electricity used from fossil fuels, the transport of feedstocks, and the distribution of the hydrogen particularly for centralised production. For options with CCS, 100% capture of the carbon dioxide is impossible which adds to the carbon dioxide emissions.

In summary there is a balance to be struck between the use of resources such as coal/gas and electricity, the cost of hydrogen and the emissions from production with different supply chains offering advantages in each of these areas; there is no clear ‘winner’ from this study. In fact, the ability to produce hydrogen by different means could be crucial for both future security of hydrogen supply and effective competition to reduce the hydrogen price.

5 Hydrogen Fuelled Vehicles

5.1 Introduction

Hydrogen vehicle uptake in New Zealand will depend strongly on the cost and to be a real alternative the costs must be similar to those for fossil fuelled vehicles. Costs can be divided into two main parts: the cost for the hardware (e.g. the hydrogen storage tank) and the cost for the hydrogen itself. Hardware costs include the drive-train (fuel cell stack including an electric engine or a hydrogen ICE), hydrogen storage and a battery for hybrid systems. The fuel cell stack is the biggest contributor to the cost of hydrogen powered vehicles.

Fuel cell manufacturers are confident of bringing the cost for fuel cells down to a few hundred dollar per kW relatively quickly by doing intensive R&D. However, even at this price fuel cells are not economically competitive with internal combustion engines, for which the price averages out to 30US$/kW. The only way to bring costs of fuel cells down to competitive levels is by mass production and by using the effects of technology learning, but the potential cost reduction can only be guessed at [National Research Council and National Academy of Engineering 2004].

A major challenge to overcome is to convince consumers to purchase hydrogen powered vehicles while there is no hydrogen production and refuelling infrastructure to support the fleet or to convince suppliers to provide a hydrogen fuelling infrastructure while no demand exists. There are ways to overcome this ‘chicken or egg’ situation. For example, in some niche markets where Internal Combustion Engines (ICEs) are not an option such as forklift trucks, hydrogen powered vehicles can already compete because in those specific markets the competitors also cost more than ICEs. It may also be possible to develop demand using centrally fuelled fleets of hydrogen vehicles, such as city buses, commuter trains, or local delivery vans.

Hydrogen powered vehicles not only need to be priced competitively but they also need to meet, or exceed users’ needs and expectations by performing at least as well as fossil-fuelled vehicles in terms of driving range, start-up time, acceleration, reliability and durability. The cost of fuel cells in New Zealand will depend mainly on global advances because New Zealand has no significant fuel cell R&D programme and no established fuel cell manufacturer. Similarly, the fuel cost will also depend on developments in hydrogen production technology overseas.

5.2 Hydrogen Vehicle Uptake in New Zealand

Currently, New Zealand does not have any vehicles that run on hydrogen as a fuel. Only around 200 fuel cell vehicles are produced annually worldwide, mainly for demonstration projects, compared to approximately 50 million fossil-fuelled passenger vehicles. However, the cumulative number of FCVs has grown significantly over the past 10 years (see Figure 2).

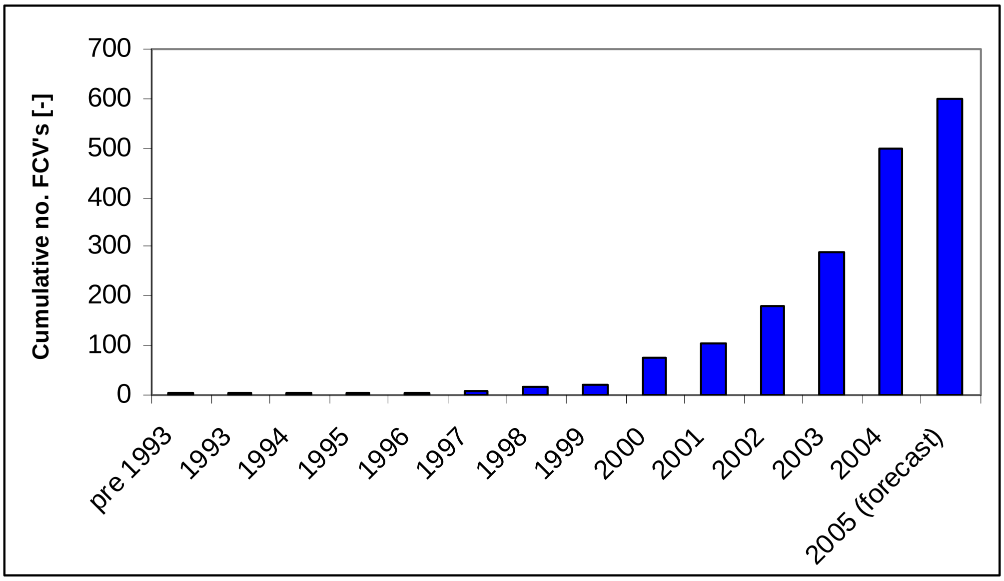

Figure 2 Cumulative Number of FCVs Worldwide

To understand how the uptake of hydrogen vehicles in New Zealand could develop it is essential to examine hydrogen vehicle uptake scenarios overseas.

Recently the HyWays consortium published its first conclusions from the hydrogen roadmap for Europe, detailing four steps for the introduction of fuel cell powered vehicles into Europe [L-B Systemtechnik 2005]:

- Today until 2010: Demonstration of fuel cell powered vehicle in captive fleets.
- 2010 – 2020: Series production of fuel cell powered vehicle for fleets (1st generation on-board hydrogen storage)
- 2020 – 2030: Series production of fuel cell powered vehicles in broad application (2nd generation hydrogen on-board storage and low-cost high temperature fuel cell systems)
- 2030 – 2040: Fuel cells become dominant technology in transport.

For success, development of the fuel cell components and hydrogen storage technologies is crucial, particularly for the transition between steps 2 and 3, which will require close collaboration and feedback between basic research components. The transition also requires a technical validation of integrated systems under demonstration programmes. In close co-operation with the car manufacturing industry, HyWays developed two possible hydrogen vehicle uptake scenarios for passenger vehicles of low and high penetration (Table 6) both following a sigmoid shaped uptake pattern [L-B Systemtechnik 2005].

Table 6 – Scenarios for the Potential Development of Hydrogen Vehicles in Europe

Total share of fleet	2010	2020	2030	2040	2050
High Penetration	-*	3.3%	23.7%	54.4%	74.5%
Low Penetration	-*	0.7%	7.6%	22.6%	40.0%

*Demonstration vehicles and fleets only

5.3 Vehicle Types

Hydrogen can be used to power vehicles either through fuel cell vehicles (FCV) with electric motors or by direct combustion in an internal combustion engine vehicle (ICEV). Both FCV and ICEV can be used as a “hybrid” where braking energy is stored in a battery. This stored energy can be used later to power the electric engine of the vehicle, which reduces the overall fuel requirements of the vehicle. The four most important hydrogen vehicle technologies are:

- PEM Fuel Cell Vehicle using hydrogen (FCV)
- Internal Combustion Engine Vehicle using hydrogen (Hydrogen ICEV)
- Hybrid version of 1 (Hybrid FCV)
- Hybrid version of 2 (Hybrid hydrogen ICEV)

Fossil fuelled vehicles use internal combustion engines with gasoline and diesel as a fuel. Four types of vehicles can be distinguished:

- Internal Combustion Engine Vehicle using gasoline (ICE Gasoline)
- Internal Combustion Engine Vehicle using diesel (ICE Diesel)
- Hybrid version of 1 (Hybrid ICE Gasoline)
- Hybrid version of 2 (Hybrid ICE Diesel)

Fuel cells vehicles can also use fuels other than hydrogen with on-board reforming. Currently no major car manufacturers are actively pursuing this option which has many technological and economic issues to overcome.

5.4 Vehicle Efficiency

Comparing vehicle efficiency is problematic as it depends on more factors than engine efficiency alone, such as the vehicle weight and drive cycle. However, the CONCAWE/EUCAR [JRC 2004] study gives valuable information on the efficiency of various drive-trains using one drive cycle. All simulations in this study are based on a common “virtual” vehicle, representing a typical European compact size 5-seater sedan comparable to a VW Golf, and a single average European drive cycle.

Vehicle efficiency varies as a function of the vehicle speed and engine loading. For example, a diesel/gasoline ICE can have an efficiency of 40% at optimal load, but efficiency decreases rapidly as operation moves away from this optimal point. Vehicles often operate at partial loads which combined with transmission losses result in an average overall efficiency at or below 23%[15]. However, fuel cell vehicles retain a high efficiency under partial loads and so have an advantage in urban traffic where vehicles brake and accelerate frequently. Modelling shows that fuel use for a FCV can be lower than for a 2001 US reference car [Ahluwalia *et al* 2004] by a factor of 2 for highway driving and 3 for urban driving (average 2.5 to 2.7). A Japanese demonstration project started in 2002 and involving 59 FCVs [METI 2005], showed FCVs to be 1.8-2 times more efficient than ICEVs on average, with the most efficient FCVs being three times as efficient as the average ICEV. A US Department of Energy project predicted that an FCV will use 2.27 times less fuel than an ICEV in 2010 and 2.95 less fuel in 2050. A joint IEA/World Business Council for Sustainable Development (WBSCD) study predicted a relative efficiency gain for FCVs compared to advanced new ICEVs in the range 46% to 66% by 2050 [WBCSD 2004].

A hybrid FCV can achieve a further 10-15% increase in efficiency over an FCV by recovery of the braking energy.

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[15] The actual value depends on the specific engine technology

Table 7 – Efficiencies 2010+ Vehicles Using Various Drive-Trains

	MJ/100km
ICE Gasoline[16]	190
ICE Diesel[17]	172
Hybrid ICE Gasoline	162
Hybrid ICE Diesel	141
ICE H2	168
Hybrid ICE H2	149
FCV H2	94
Hybrid FCV H2	84

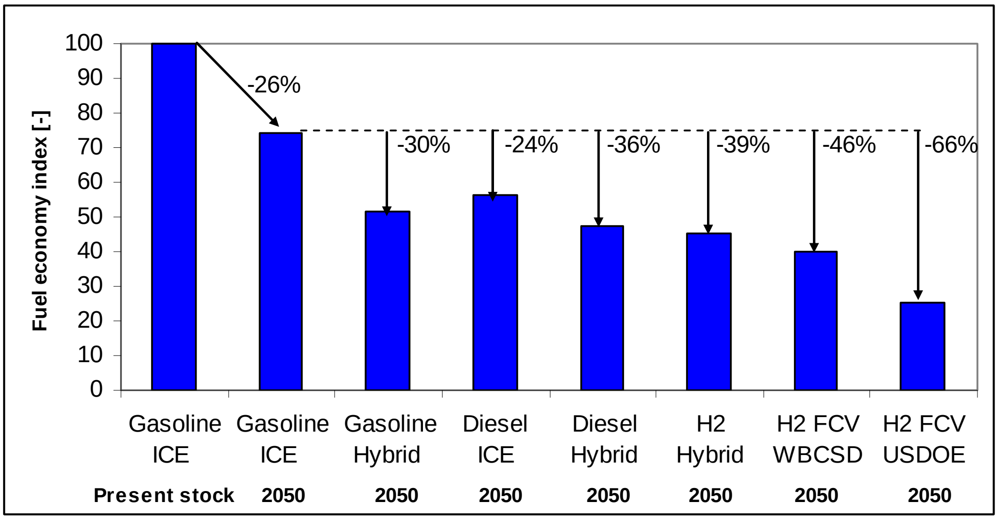

Figure 3 – Fuel Economy of Various 2050 Vehicles

5.5 Vehicle Cost

The cost of a fuel cell vehicle drive system is the sum of the costs for the fuel cell stack (including power electronics and other peripherals), the hydrogen storage system (e.g. a pressure vessel, a MeH_2 hydrogen solid storage or DME storage tank), the electric engine and the battery (for hybrid systems). An IEA study predicts that Proton Exchange Membrane (PEM) fuel cell cost could decline to between 35 and 75US$/kW by 2025 to 2040 [IEA 2005] compared to hundreds of US$/kwh today. Therefore, in 2030 the additional cost of fuel cell vehicles over a conventional vehicle could range between 2,200 and 7,625US$ per vehicle. In the short term the fuel cell stack represents the bulk of the additional cost of a fuel cell vehicle, but in time the cost for the hydrogen storage system, the electric drive system and the battery may become important. The results of this IEA study are summarised in Table 8.

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[16] 224 MJ/100km for the 2002 configuration

[17] 183 MJ/100km for the 2002 configuration

Table 8 – Estimated Costs of a Hydrogen Fuel Cell Vehicle (80kW FCV)

	2005	**2010**	**2030** Optimistic reduction	**2030** Optimistic but slower uptake	**2030** Pessimistic reduction
Costs per Unit of Capacity					
PEM fuel cell stack (US$/kW)	1,800	500	35	65	75
Gaseous hydrogen storage at 700bar (US$/kg)	1,000	500	225	375	500
Gasoline ICE (US$/kW)	30	30	30	30	30
Cost per component					
Fuel cell stack (US$)	144,000	40,000	2,800	5,200	6,000
Gaseous hydrogen storage at 700bar (US$)	4,000	2,000	900	1,500	2,000
MeH_2 hydrogen solid storage (US$)			2,000	2,000	2,000
DME storage tank (US$)	1,500	1,500	1,500	1,500	1,500
Electric engine (US$)	1,900	1,700	1,200	1,400	2,025
Cost per vehicle					
Hydrogen FCV (US$)	167,000	60,750	21,950	25,150	27,075
Hydrogen FCV drive system cost (US$/kW)	1,875	545	60	100	125
Ref. Conventional ICE vehicle (US$)	19,450	19,450	19,450	19,450	19,450
Ref. Conventional vehicle w/o engine (US$)	17,050	17,050	17,050	17,050	17,050

The concept of “learning curves” is often applied to the future cost estimations of hydrogen vehicles. A “learning curve” describes how unit costs vary with increased experience with the specific technology, as described by the “progress ratio” (PR). For example, a technology with a PR of 0.7 will see the unit price reduced by 30 percent with each doubling of the cumulative output. PR is typically observed to vary from 0.75 to 0.9.

To assess the impact of the learning rate on the total cost of fuel cell vehicles, two scenarios were developed by the IEA using an optimistic and a pessimistic learning rate. In both cases, sales of FCVs would begin after 2010 at an additional cost over similar ICE vehicles of 40,000US$. The annual rate of production increased slowly initially, but rapidly after 2020. Given the current global production of around 200 FCVs per year, the cumulative production in 2010 was set at 1,800 vehicles. Assuming that FCVs accounted for all light-duty vehicle sales in OECD regions in 2050 and half of all vehicles sales in non-OECD regions, total sales would reach 700 million by 2050. The progression-ratio was set at 0.78 in the optimistic case and 0.85 in the pessimistic case.

The results are shown in Table 9 for each five-year period between 2010 and 2050 with cumulative production levels and costs (undiscounted) over the same period.

Table 9 – Fuel Cell Vehicle Cost Reduction Scenarios

	2010	2015	2020	2025	2030	2035	2040	2045	2050
Assumptions used in both cases									
Cumulative fuel cell vehicle production, OECD (millions)	0.00	0.04	0.21	1.48	8.39	43.66	133.26	285.34	502.39
Cumulative fuel cell vehicle production, world wide (millions)	0.00	0.04	0.22	1.53	8.63	45.27	143.70	349.80	727.52
Fuel cell vehicle share of sales, OECD	0.0%	0.1%	0.2%	1.0%	5.0%	25.0%	50.0%	75.0%	100.0%
Fuel cell vehicle share of total vehicle stock, OECD	0.0%	0.0%	0.1%	0.4%	2.2%	6.3%	13.1%	21.7%	31.0%
Optimistic case results									
FCV cost, optimistic case (0.78 progress ratio) (US$/kW)	545	207	134	90	69	58	54	51	50
Total incremental cost of fuel cell vehicles, cumulative (US$ bn)	0.1	0.6	2.1	7.8	27.2	95.6	243.6	514.0	964.9
Pessimistic case results									
FCV cost, pessimistic case (0.85 progress ratio) (US$/kW)	545	284	207	148	114	92	81	74	69
Total incremental cost of fuel cell vehicles, cumulative (US$ bn)	0.1	0.9	3.4	15.3	60.0	226.1	585.2	1,2226.6	2,264.2

One conclusion from these scenarios is that the lower vehicle costs can be pushed by R&D, the lower the cost reduction needed during the commercialisation stage for success. However, relying on R&D alone to reduce costs may not be feasible and could delay market introduction of FCVs to such an extent that other technology or fuel options, such as plug-in hybrids or biofuels, could dramatically reduce the market opportunities for hydrogen FCVs.

In the HyWays project, progress ratios were derived from the automotive partners' research activities, from different comparable technologies and taken from the specifications of other research projects. The progress ratios defined for the various components of fuel cell vehicles and hydrogen ICE vehicles for fast or slow cost reduction are listed in Table 10.

Table 10 – Progress Ratios of Hydrogen Technology Components for a Hydrogen Vehicle

Component	**Low PR (fast cost reduction)**		**High PR (slow cost reduction)**	
	Initial phase	After 10years	Initial phase	After 10years
Alternative fuel tank	0.85		0.85	0.93
Electric Motor	0.90		0.90	0.98
Li-Ion battery	0.90		0.90	0.98
FC System	0.80	0.90	0.82	0.92
H2-ICE[18]	1.00		1.00	

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[18] The CONCAWE/EUCAR study uses the same production cost for gasoline and hydrogen powered engines.

Another useful comparison for vehicle cost, efficiencies and emissions for different vehicle drive-trains is the CONCAWE/EUCAR study [JRC 2004]. Relevant data is presented in Table 11.

Table 11 – Cost Breakdown of 2010+ Vehicles Using Various Drive-Trains

€/vehicle	ICE Gasoline	Hybrid ICE Gasoline	ICE H2	Hybrid ICE H2	FCV H2	Hybrid FCV H2
Baseline vehicle	16,165	15,865	16,165	15,865	15,435	15,435
Fuel tank	125	125	5,175	4,313	2,703	2,415
Engine + Transmission	2,590	2,660	2,590	2,590	8,400	8,400
Turbo	180		180	180		
Stop and Go system	200		200			
Euro IV exhaust after-treatment	300	300				
Electric motor (AC induction) + controller		600		600	2,025	2,025
Battery (Li-ion)		3,600		3,600		3,600
Powertrain and vehicle components		2,630		2,630	2,630	2,630
Total Vehicle Retail Price (€)	**19,560**	**25,933**	**24,310**	**29,778**	**31,193**	**34,505**

The assumptions made in calculating these values were:

- Prices were given for specific components are on a "supplier retail" basis (equivalent to delivered costs to vehicle manufacturers). A mark-up to include further costs, such as warranty, were not included.
- The costs were estimated from the costs of various key powertrain components, such as motors, batteries, hybrid and fuel cell systems. Costs for upgrading some vehicle components were included for some configurations.
- Costs assumed a volume of more than 50,000 units per annum and are projected for the year 2010 and after. The estimates of cost reduction through volume production for some of the key components could be optimistic. It is uncertain how much and at what rate future costs will decline under different circumstances.
- The study did not consider other associated costs beyond the key components for a certain technology. For example, vehicle body modifications are likely to vary depending on the base vehicle and the technology system integrated. More detailed cost calculations could include these additional costs.

5.6 Government Incentives

Government policy can strongly influence the uptake of hydrogen vehicles in New Zealand. A policy framework focussing on the barriers to the uptake of hydrogen energy would likely be effective. The three most important barriers and some possible solutions that could be considered on a national or local scale are:

1) Economics: there is no incentive to introduce hydrogen as an energy carrier.
    - National: include hydrogen in support frameworks for renewable energy; exempt hydrogen vehicles from GST or other taxes; exempt hydrogen from tax; include

hydrogen in biofuel targets; make funds available for demonstration projects (hydrogen refuelling station in combination with hydrogen vehicle(s))
    - Introduction of a tax on greenhouse gas emissions including CO_2, or other instruments for pricing of these emissions.
    - Local: create a financial incentive for zero-emission vehicles in areas with severe air pollution problems; create benefits such as free parking for hydrogen vehicles.
2) Technology: fuel cell and hydrogen technology is not yet commercially available.
    - National: join and/or start R&D programme for fuel cells, hydrogen production, hydrogen storage, etc.
3) Public acceptance, regulations and safety.
    - National: create a programme for demonstration projects; promote education and training in schools and universities.
    - National: create a learning/development environment where regulation and permitting is flexible.

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