New Zealand's EnergyScape





2000 2005 2030 2050

Transitioning to a Hydrogen Economy

Hydrogen Energy Options: - Scenarios, Sensitivities and Pathways

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Hydrogen Energy Options: Scenarios, Sensitivities and Pathways

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Executive Summary

This report to stakeholders is the fourth output from the Foundation for Research, Science and Technology (FRST) project Contract CRLE601, "Transitioning to a Hydrogen Economy". The project identifies how hydrogen could become a significant contributor to New Zealand's energy system by 2050 and the role of research investment in realising that future. The term "Hydrogen Economy" refers to an energy future in which hydrogen is used as an energy carrier. It is not intended to imply that hydrogen will be the only energy carrier – but that it will be a significant one.

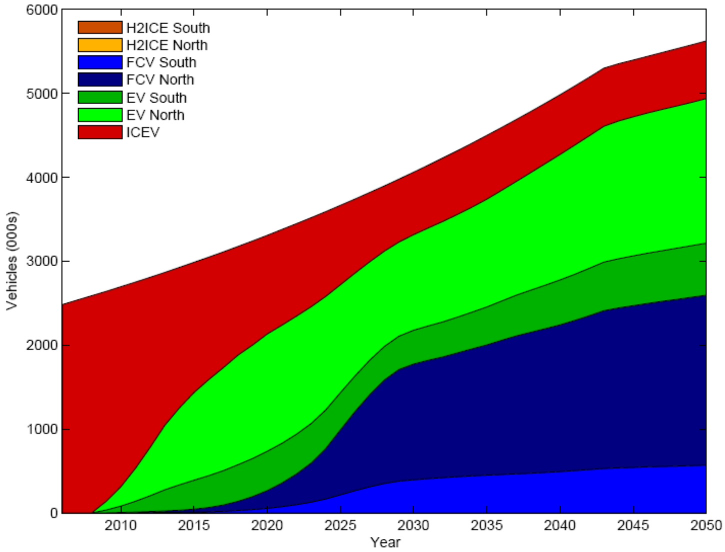
Hydrogen is likely to make its biggest contribution as an energy carrier in the transport sector and the recent reversal of the previously held view of the IEA that conventional oil supplies are not in danger of decline underlines the urgent need for an alternative transport fuel infrastructure.

The third output of the programme was a report (Unitec New Zealand "Systems Dynamic Modelling of Pathways to a Hydrogen Economy in New Zealand" June 2008). This report documented the results of UNISYD modelling to examine future transport scenarios in which a changing mix of internal combustion engine (ICE), battery electric vehicles (BEV) and fuel cell vehicles (FCV) make up the light transport vehicle fleet over the period between the present day and 2050. The model took account of the electricity generation requirements and costs associated with each scenario, the resources used to meet that requirement and the renewable content of that electricity generation mix over time. It also calculated the carbon dioxide emission reductions associated with each scenario.

This report analyses the results contained in the Unitec report. The main findings are that:

- Scenarios involving high penetration of FCVs can achieve close-to NZ Energy Strategy targets for renewable electricity generation by 2025 and transport related emission reductions by 2040.
- Scenarios involving both FCVs and BEVs also meet the NZ Energy Strategy objectives. Two extreme case scenarios were studied – one in which the transport fleet of 2050 is comprised mainly of FCVs and one in which it is comprised mainly of BEVs. Both scenarios are robust against high oil price and carbon costs. Moving forward with both the FCV and BEV options open represents a good risk mitigation strategy.
- The influence of consumer preference, modelled by a "Fleet Starting Preference" (FSP) function, is a very significant factor in determining the uptake profiles of new transport technologies.
- The FCV is the only option currently available that can match the performance of conventional vehicles in terms of range, refuelling time and customer expectation. It can also outperform them in terms of reduced emissions and improved efficiency.
- Substantial economic benefits accrue under high oil price scenario if the switch to new technologies is made as soon as possible - accelerating the uptake of FCVs by 10 years leads to cumulative reductions in transport fuel costs of between $18 and $57 billion through to 2050. The lower figure applies under an $80 per barrel oil price plateau, the upper figure to a $200 per barrel plateau. Associated savings in CO_2 emissions of up to 85 million tonnes will also be realised.
- There is a high (greater than 70%) penetration of fuel cells into the 2050 heavy transport fleet under all scenarios and sensitivities.
- A scenario in which both the BEV and FCV options contribute significantly (see figure below) is also robust against high oil and carbon costs. The scenario leads to an "electric-drive train" light transport fleet comprised of approximately 2.6 million FCVs and a similar number of BEVs in 2050. Under this scenario BEVs start appearing as soon as commercially available, primarily due to subsidies promoting initial uptake. They grow rapidly during the period 2010 to 2020. Their contribution continues to grow through to 2050. FCVs appear in small numbers by 2015. Their initial uptake rate is slow primarily due to the high introductory cost of fuel cell vehicles. Over the period 2020 to 2030 there is rapid growth in FCVs due to cost reductions.
- The hydrogen demand in 2050 corresponding to this scenario is 530,000 tpa (approximately 10 times the amount currently produced in New Zealand). It costs $6.00 per kg wholesale and is produced from a mix of:

- Forecourt steam reformation of natural gas
- Grid electrolysis
- Coal gasification with CCS
- Biomass gasification



Targeted uptake scenario

This rapid uptake scenario was generally agreed by stakeholders to represent a challenging, but achievable target, where substantial economic benefits and GHG emission reductions are achieved.

It is recommended that the hydrogen research strategy be designed to support the uptake of this scenario.

Contents

1 Introduction

This report is the fourth output from the Foundation for Research, Science and Technology (FRST) project Contract CRLE601, "Transitioning to a Hydrogen Economy". The term "Hydrogen Economy" refers to an energy future in which hydrogen is used as an energy carrier. It is not intended to imply that hydrogen will be the only energy carrier – but that it will be a significant one.

In essence the overall programme addresses the question "when does hydrogen make sense for New Zealand?" and identifies the role of research in realising that future. The programme uses a methodology similar to that used by the European Union in their development of a hydrogen roadmap (the Hyways programme). It involves identification of the individual hydrogen supply chains most likely to contribute to hydrogen uptake, the use of modelling to determine the contributions of these chains in achieving certain hydrogen uptake scenarios, determination of knowledge gaps in the chains with the greatest contribution, and the role of research investment in filling those knowledge gaps. The process involves considerable interaction with stakeholders at key points throughout.

The first three outputs were:

- An awareness raising Issues Document (CRL07/11009 of May 2007)
- Identification of Preferred Hydrogen Chains (CRL 07/11034 of November 2007)
- Unitec report System Dynamics Modelling of Pathways to a Hydrogen Economy in New Zealand (June 2008)

This report analyses the results of the Scenario Modelling and identifies a future hydrogen uptake scenario around which a hydrogen research strategy should be designed.

A subsequent fifth and final report develops the research strategy.

1.1 Summary of Previous Findings

1.1.1 Raising Awareness of Hydrogen

The Issues Document was presented to targeted stakeholders for feedback and subsequently to a wider range of stakeholders at a public forum in August 2007. The report described:

- *What a hydrogen energy system is* – an energy system in which hydrogen is used as an energy carrier in the same way as electricity and petroleum are used within the existing energy systems.
- *What the drivers are* – energy security and environmental issues were identified as the biggest. Hydrogen fuel has the potential to decarbonise and significantly improve the efficiency of the transport fleet. Elemental hydrogen is not freely available in nature but it can be produced from indigenous renewable resources and fossil resources (with carbon capture and storage) in a carbon neutral manner and in sufficient volumes to readily meet future long-term demand. Technology advances, economic growth, increased population and energy demand, political will, and industrial opportunities were also seen as important drivers.
- *What the major issues relating to introduction of hydrogen into a future energy system are* – these relate to production of hydrogen at a price to make it commercially viable as an energy carrier when competing against traditional liquid fuels, lower cost on-board hydrogen storage, the necessity for a new distribution infrastructure, reduced cost and improved reliability of fuel cells, improved public understanding and requirement for a robust set of regulations, standards and codes of practice for use of hydrogen as an energy carrier.
- *International and national research activities to address these issues* - significant progress has recently been made in many of the above areas – particularly in terms of vehicle range and performance – to the extent that there are now no "show-stopper" technology barriers to the large-scale uptake of hydrogen and fuel cell technologies.
- *The hydrogen market in New Zealand* – currently we produce approximately 55,000 tonnes per annum – the vast majority of that being used onsite at the New Zealand Refinery at Marsden Point. Fifty-five thousand tonnes is approximately 10% of the amount required to support the predicted

light duty road transport fleet of 2050. Globally over 50 million tonnes of hydrogen are already manufactured and traded each year for non-fuel use. This is already approximately 100 times the predicted need for New Zealand's 2050 road transport fleet.

- *Hydrogen supply chains for transport* – from well-to-wheels - that could potentially be used to produce and distribute hydrogen in New Zealand. While it is possible to envisage a very large number of potential chains, a first pass assessment, supported by input from stakeholders led to selection of 24 chains, covering a wide spectrum of possible options.
- *Stationary power generation using hydrogen as a fuel* – this mainly centred around fuel cells in distributed combined heat and power applications although there may be a future application for hydrogen gas turbines in a decarbonised economy. A selection of source-to-user supply chains for stationary application (distributed generation and small scale combined heat and power (CHP) systems) were also included. While it is in the area of transport applications and increased security against rising imported oil costs that hydrogen uptake is likely to be of most benefit in the longer term, its use within stationary fuel cells is a likely means of facilitating the early adoption of fuel cell technologies into the energy system.
- *The potential of hydrogen as a future transport technology for New Zealand* - in 2006 the New Zealand transport sector accounted for 44% (220PJ) of consumer energy, and was responsible for 44% (14,821 kt CO_2-e) of the energy sector greenhouse gas emissions. The energy sector accounted for 43% of total GHG emissions, putting transport at 19% overall (MED 2007, NZ Energy Data File). Hydrogen as an energy carrier is completely emission free at the point of use, with the only other conversion products being water and heat. It may be converted into electricity at up to 80% efficiency in fuel cells, offering an efficient, emission free and entirely new transport infrastructure.
- *The broad options available for future automotive transport technology* - vehicles that use a relatively conventional mechanical drive train, and those that are based on electric drives (EVs). The former include fossil-fuelled internal combustion engine (ICE) vehicles and could involve low emission but relatively inefficient ICE vehicles powered by either biofuels or hydrogen. The EV option includes hybrid vehicles (such as the Toyota Prius) and a range of more advanced electric options using combinations of battery only, hydrogen fuel cell (FC) or ICE vehicles driving a generator or the wheels directly. The FC and ICE power packs can include varying degrees of battery storage, turning battery electric vehicles (BEVs) into hybrid electric vehicles (HEVs). Battery and fuel cell powered options offer a step change improvement in fuel efficiency over the ICE alternative and can be practically emission free, and for these reasons are likely to ultimately dominate.

1.1.2 Selection of preferred hydrogen supply chains

The second output of the programme (CRL07/11034 Identification of Preferred Hydrogen Chains, November 2007) described:

- *The Selection Process* - the analysis of the 24 chains identified at the first pass screening was carried out using the economic, emissions and energy (E3) model developed by the EU for their HyWays programme (L-B Systemtechnik, 2005). The E3 model required each supply chain to be described to a high level of detail and then worked out the costs, CO_2 emissions and energy requirements associated with every step in the chain. It then summed them to generate its results. The results were compared with those from E3 modelling of reference chains that are used within the existing NZ energy system. This relied on the quality of data in the extensive accompanying E3 database – where necessary the European figures were modified to better reflect New Zealand conditions and prices. For transport applications the end point was envisaged as hydrogen being injected into a fuel cell vehicle and for the stationary applications either a conventional fuel (e.g. natural gas) or hydrogen was fed to a fuel cell for distributed generation or small-scale combined heat and power generation.
- *Conclusions from transport selection process.* In terms of both energy use (or "well to wheels" efficiency) and cost, the feedstock used was more important than the details of the chain which include options relating to carbon capture and storage (CCS) and carbon cost, type of production

plant, hydrogen delivery option (pipeline or truck) and distance delivered. The majority of the transport chains chosen were based on the most cost-effective long-term options. They involve centralised hydrogen production and large-scale delivery and usage infrastructure. To evaluate early market transition costs, forecourt production chains involving NG reformation and grid electrolysis were selected.

- *Conclusions from stationary selection process*. Thermal fuel use and greenhouse gas (GHG) emissions could be greatly reduced by using fuels directly in on-site hydrogen fuel cell CHP "appliances" instead of either generating electricity from central locations (and wasting two thirds of the thermal energy) or converting to hydrogen and then transporting it for CHP. In the longer term, if centralised production of hydrogen from biomass becomes an accepted part of the transport infrastructure, use of this hydrogen for distributed stationary energy services becomes feasible and may be worthy of further investigation.

The individual chains selected as most likely to contribute to the future energy system in New Zealand were:

Feedstock	Hydrogen Production Method	CCS	Hydrogen Transport Method	End Use
Natural gas	Central Reformation	No	Tanker	Transport
Natural gas	Central Reformation	Yes	Pipeline	Transport
Coal	Central Gasification	Yes	Pipeline	Transport
Biomass	Central Gasification	No	Pipeline	Stationary
Biomass	Central Gasification	No	Tanker	Transport
Wind electricity	Central Electrolysis	N/A	Pipeline	Transport
Grid electricity	Central Electrolysis	N/A	Tanker	Transport
Wind electricity	Refuelling Site Electrolysis	N/A	Direct Use	Transport
Natural Gas	FC CHP with reformation	No	Direct Use	Stationary

Table 1: Preferred individual hydrogen chains

These results were presented and discussed at stakeholder and programme Steering Group meetings in December 2007 and March 2008.

1.1.3 Scenario Modelling

The third report (Unitec New Zealand "Systems Dynamic Modelling of Pathways to a Hydrogen Economy in New Zealand, June 2008) identified:

- contributions of each of the above chains to meeting the hydrogen demands associated with a range of targeted 2050 energy scenarios.
- changes in the contribution from each chain between the present day and 2050 and the varying costs of hydrogen production.
- electricity generation requirements and costs associated with each scenario, the resources used to meet that requirement and the renewable content of that electricity generation mix over time
- the carbon dioxide emissions associated with each scenario.

The full Unitec report is available online at:

www.unitec.ac.nz/fms/research/1_10%20Pathways%20Report.pdf

2 UNISYD Scenario Modelling

Energy scenario modelling was carried out using UNISYD - a dynamic regional model of the New Zealand energy system developed at Unitec. The model is used to select the lowest cost option leading to a defined end point – in this case varying mixes of vehicles powered by technologies based on conventional mechanical drive ICE engines or electric technologies using either fuel cells (i.e FCVs) or batteries (i.e BEVs).

The UNISYD model is structured such that economic, technological and socio/political drivers of a hydrogen economy impact four main sectors: the transport fleet, electricity production, hydrogen production and energy resources. In its present form it can cater for most forms of stationary and transport energy flows and technologies, including battery electric and hydrogen fuel cell vehicles.

The UNISYD model is a partial-equilibrium economic model focused on the NZ energy system, currently using weekly time steps from 2008 to 2050. The primary sectors of the model are the electricity, hydrogen, and vehicle fleet markets. Each of the 13 regions of New Zealand is modelled separately, allowing for a more detailed treatment of potential electricity generation sites and regional variation in electricity and hydrogen prices. The electricity generation options available in the model are coal, natural gas, hydro, geothermal, hydrogen/electricity cogeneration, biomass, solar PV, wind, solar hot water, combined heat and power, and hydrogen and natural gas based micro-generation, and with a sequestration option available for fossil generation. Electricity prices are set so that supply equals demand within each region after transmission of electricity as needed from other regions. New generation capacity is installed based on the expected profitability of the generation type, within political feasibility constraints.

Hydrogen production pathways include on-site steam methane reforming, on-site electrolysis, centralised biomass gasification, coal gasification and steam methane reforming. The centralised plants can be based on co-generation of hydrogen and electricity and or process heat. Sequestration is available for all centralised generation. Demand for hydrogen is primarily from hydrogen fuel cell vehicles. Wholesale hydrogen prices are based on demand and set in a similar manner to electricity prices, i.e. wholesale prices are set in both the North and South Islands, based on the lowest cost production routes.

The vehicle fleet technologies modelled are hydrogen fuel cell, battery, petrol/diesel and hydrogen fuelled internal combustion engine. The vehicle fleet for each of the vehicle technology types is divided into light duty imported used vehicles, light duty new vehicles, and heavy duty vehicles. The fleets with the exception of petrol/diesel ICEs are further divided into North Island and South Island fleets due to the variation in fuel price for these technologies. The total vehicle fleet grows exogenously until vehicle per capita saturation limits are reached. Consumers purchase vehicles based on regional annual cost of owning and operating a vehicle and the intrinsic preference parameter for the vehicle technology type based on a logit share allocation model. The intrinsic preference parameter captures qualitative factors that affect consumer preference for one vehicle technology type over another. These factors include availability of refuelling infrastructure, range and reliability of vehicle.

2.1 Assumptions used in UNISYD modelling

As with all modelling environments there are limitations, and assumptions must be made to define constraints and boundaries, and future developments in technology. These are fully detailed in Leaver (2008) but for an understanding of the results discussed here, some of the key assumptions, the reasons for them and their limitations, are listed below.

2.1.1 Energy Sources and Fuels

Renewable resource availability is based on the 2005 report "Availabilities and Costs of Renewable Sources of Energy for Generating Electricity and Heat" by East Harbour Management Services.

Coal price rises from \$3.8/GJ in 2008 to \$4.0/GJ in 2015 and remains at that price to 2050. The model assumes that it is easier (cheaper) to transport coal than hydrogen between or to the North and South Island. This may not be the case long term, but within the present analysis this is often the factor that leads to a decision as to where a coal hydrogen co-production plant is sited, bearing in mind that the model sees no electricity capacity constraints, and a relatively small inter-region transport penalty.

Domestic natural gas is supplied at a base wellhead price of \$7.75/GJ. When demand is greater than the supply of domestic gas, the wellhead price is replaced with price of imported LNG (MED 2006).

$$LNG = [2.003 + 0.0493 \times (US\$Oil\ Price/bbl - 1)+1.25]/Exchange\ rate$$

Gas prices are average cost per customer for each class and include the pipes charge in the \$/GJ figure. The model does not cater for variable pricing with volume – the effects of this approximation for residential fuel cell systems are discussed later.

Under baseline modelling, oil prices are assumed to remain steady at \$US80/barrel through to 2030 and then increase at between 4 and 8% per annum thereafter up to \$US200/barrel. Under a high oil price scenario, the price increases from \$US80/barrel at 6% per annum, reaching \$US200/barrel in 2020 and remaining constant thereafter (Figure 1 shows a 4% post 2030 rise).

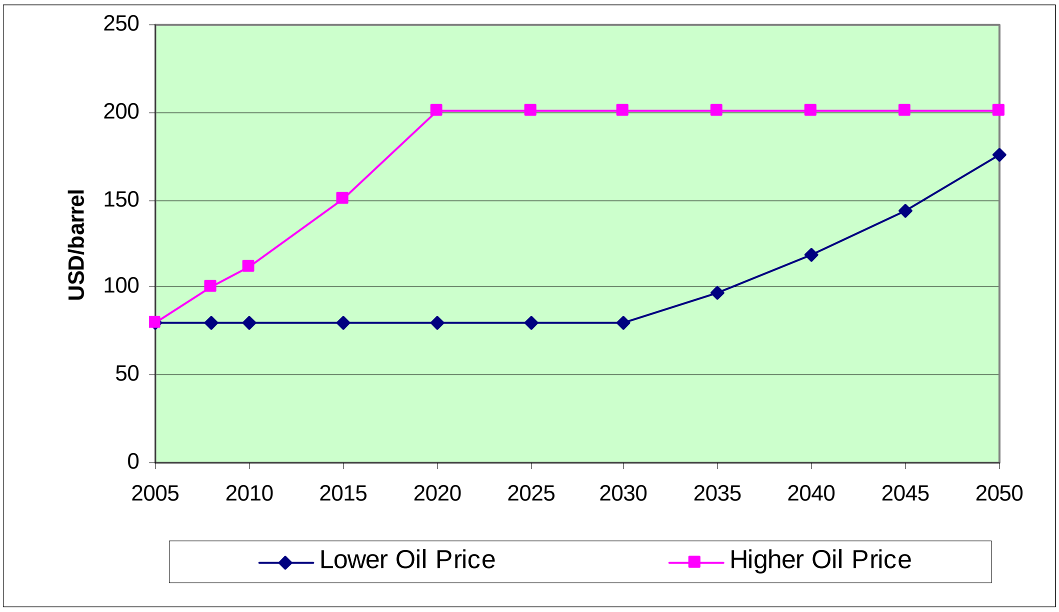


Figure 1: Oil price pathways

The model has the option to allow or prohibit new large scale fossil plant. In almost all cases it assumes that no new large scale fossil plant is permitted before 2018.

2.1.2 Hydrogen

The model provides for inter-regional transport of hydrogen but does not allow the transport of hydrogen via tanker or pipeline between the North and South Islands. It makes the inherent assumption that it will be less costly to transport coal than hydrogen.[1] This assumption also means that there are separate hydrogen prices for the North Island and the South Island. The central hydrogen plant construction is undertaken having regard to the optimal technology, region, and plant size triplet to meet the need at the lowest hydrogen production cost. For a triplet to qualify, the electric region can have no other centralised hydrogen plant currently under construction. Triplets will also only qualify if the technology's production cost in a particular region is less than a three-year futures price of hydrogen scaled up or down by the tightness or looseness of the current supply market, similar to the scaling in the electricity sector. Triplets involving plant sizes larger than the projected hydrogen need—a forecast of hydrogen demand three years into the future based on a running average of the previous three years—are also disqualified.

The model then builds the optimal qualified triplet. After a predetermined amount of construction time, that amount of hydrogen will become available in the trucked hydrogen market on the island in question.

Baseline assumptions are that no centralised fossil based hydrogen production will be allowed in Auckland, Bay of Plenty, Nelson/Marlborough and Canterbury due to environmental constraints. This does not cover forecourt steam methane reforming to manufacture hydrogen (SMR), which is permitted under all scenarios.

The model adds on 15% to costs of hydrogen production to account for the costs associated with building the necessary level of hydrogen infrastructure.

2.1.3 Electricity

The model assumes that the electricity grid has no transmission constraints, i.e. that there are no inherent transmission constraints anywhere between regions. It assumes a standard fixed loss component for moving electricity between any two regions irrespective of distance. Baseline assumptions are that no centralised fossil based electricity generation will be allowed in Auckland, Bay of Plenty, Nelson/Marlborough, and Canterbury due to environmental constraints.

Huntly is assumed to have a refurbish life through to 2050, and is allowed to operate under any moratorium on building new plants.

Electricity price assumptions are based on those of the MED (MED 2007). The price ratio between each class of consumer is:

Industrial = 1
Commercial = 1.54 Industrial
Retail = 1.94 Industrial

2.1.4 CO_2 Sequestration

CO_2 sequestration capacity in NZ is estimated at approximately 1.2 Gt. The CO_2 sequestration capacity for the deep coal seam and aquifer options is determined from the international average capacity in coal seams and aquifers per area overlain with the more well-characterised regionalised capacity for depleted oil and gas fields. Cost of sequestration increases as capacity is reached and once capacity within a region is used up the model assumes the CO_2 will be

[1] Energy security concerns may dictate that the bulk of the hydrogen generation resides on the lignite fields of Otago/Southland. If this is the case the vehicle fleet profiles would not be expected to change by more than 10% although this would need to be tested with further modelling.

released. If the calculated cost of sequestration is higher than the carbon cost, the model also assumes the CO_2 will be released rather than sequestered.

2.1.5 Transport Application

Fleet Starting Preference (FSP): This LOGIT function is used to reflect consumer attitudes toward new technologies. It is set on a scale ranging from 0 to 100 where 100 represents customer preference for the status quo (e.g. a petrol fuelled car). It has the effect of inhibiting the uptake of unproven and unfamiliar technology. Initial settings for fuel cell vehicles and other alternatives would normally be less than 100 to reflect the natural reluctance of the consumer to invest in a new vehicle technology involving a new and restricted refuelling infrastructure. As a particular technology becomes taken up, the FSP setting automatically rises towards 100, reaching this value when penetration levels have reached 20%. This mimics observed customer behaviour where reluctance to embrace new technology dissipates as the technology becomes more familiar.

FC Vehicle Fuel Efficiency: Fuel economy is modelled dynamically for all vehicle technologies. The fuel economy for new FCVs is modelled so it adjusts to the price of hydrogen via the same fuel price elasticity that is used for ICE vehicles. Imported used vehicles are again modelled to have the same fuel economy as new vehicles seven years prior and, for lack of other data, their initial fuel economy is set to be the same as new light vehicles. Fuel use for heavy vehicles is assumed to be 3.5 times that for light vehicles.

Production Learning Curves and Vehicle Capital Costs: Figure 2 shows the relative cost reductions assumed for FCVs, BEVs and ICEs. Because the FCV technology is new, it follows an exponential technology learning cost reduction as production numbers build up. The uptake trigger point is more strongly linked to vehicle capital cost than fuel cost, because this primarily determines the cost of ownership in the early years. The curve shown here assumes a slow or low learning rate. A high learning rate (used in a number of the scenarios) results in a faster cost reduction, where the lowest cost (horizontal portion of the curve) is reached about 20 years earlier.

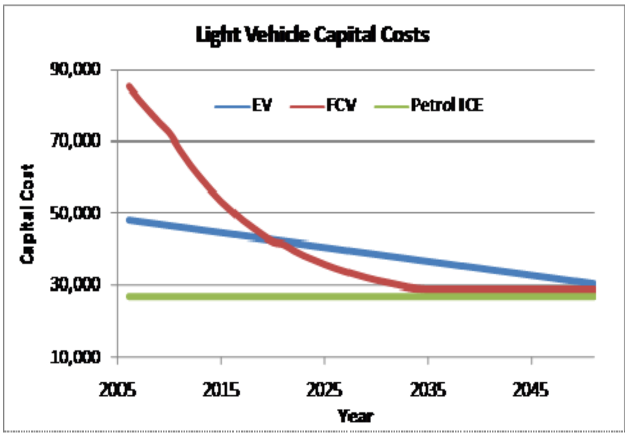


Figure 2: Learning curve cost reductions

For BEVs, battery cost is currently a major impediment to uptake (as is energy density, to which cost is related). A linear 70% reduction in battery cost is assumed, from 2008 to 2050. This is based on the understanding that batteries are a mature technology and are therefore on the lower part of a technology learning curve. The costs predicted by this linear decrease are in accord with industry predictions which see battery pack costs dropping from present levels of US$236/kWh to $US150 per kWh by 2030 (NRC 2005). The 70% straight-line reduction chosen may in fact be optimistic after 2030 as some industry sources limit the cost reduction possible to just 50% (Kromer 2007). The model allows for Low, Medium and High technology learning curves, to test the sensitivity effects of slower or more rapid technology development. These change the uptake timeframe, but not the end point value.

BEV charging infrastructure costs are not considered in the model (NREL 2006). It is assumed that charging infrastructure requirements are minimal – that the vehicles are charged from home, and that any metering or charging equipment is already installed, built into the electricity price, or comes with the vehicle. This again may be optimistic, since while initial short range BEVs can be charged from the home, mass market uptake of longer range vehicles will require a substantial investment in new public and private infrastructure (Kromer 2007).

2.1.6 Stationary Application

Uptake of residential CHP fuel cell systems is linked to new housing growth only – this limits the uptake rate to the housing stock replacement rate, irrespective of the competitiveness of the capital cost or the fuel price. Existing housing stock also represents a potential market, but a model change would be required to incorporate this. The model assumes a fixed natural gas pricing structure, which penalises higher residential consumption as would be the case for homes with fuel cell based CHP systems installed.

2.1.7 Other Model Constraints

Battery and fuel cell technologies are both likely to be subjected to recycling, both for environmental reasons and to recover the expensive metals involved in their manufacture (e.g. lithium and platinum respectively). This may represent an additional cost or a disposal benefit associated with ownership. At present no mechanism for this is included in the modelling, but this feature could be added under future work.

Biofuel vehicles were not directly modelled. It was assumed that biofuel would form part of the fuel mix in conventional liquid fuelled ICE vehicles. For clarity, the scenarios were all run on the assumption of zero biofuel mix.

2.2 Scenarios

The scenarios modelled are shown in Table 2.

In order to test the robustness of the FCV and BEV electric drive technologies, two scenarios, one leading to a significant uptake of FCVs (Scenario 5) and one in which BEVs become the dominant technology (Scenario 13), are subjected to a number of sensitivities including carbon tax, oil price and consumer preference. These two scenarios are highlighted in Table 2.

It is recognised that these represent extreme scenarios and that a more likely uptake scenario is one in which both of these electric drive transport technologies make a significant contribution. Scenario 3 (also highlighted) comes closest to meeting that situation and it is also analysed.

Stationary energy chains using hydrogen fuel cells are evaluated within the same scenarios by adjusting ownership costs to achieve a 20% uptake. This identified the technology cost necessary for economic viability**.**

UNISYD Scenario	Target % FCVs in light fleet	Target % Fossil ICEVs in light fleet	% EVs in light fleet	% domestic & commercial CHP	Ratio Achieved FCV/ICEV/EV
1	90	10	0	20	76:21:3
3	50	0	50	20	46:12:42
5	50	50	0	20	68:30:2
7	25	50	25	20	28:49:23
9	25	25	50	20	22:26:52
11	50	25	25	20	53:20:27
13	0	50	50	20	1:50:49

Table 2: Scenarios

2.2.1 Scenario Results

The full set of results including a description of each scenario, the national hydrogen demand, the costs of producing that hydrogen and the mix of supply chains required to do so are contained in the full Unitec Report. Also included are the electricity generation mix and cost, CO_2 emissions profiles and vehicle fleet makeup for each scenario. This level of analysis allows each scenario to be assessed for its alignment with the objectives of the New Zealand Energy Strategy, - 90% renewable electricity generation by 2025 and 50% CO_2 emission intensity per vehicle reduction by 2040.

The summarised results, for all scenarios, along with the underlying model conditions are shown in Table 3.

Scenario	1	3	5	7	9	11	13
Hydrogen:							
Hydrogen Required, kt per annum	650	530	725	450	400	620	180
Hydrogen Production, SMR:Coal:Biomass:Grid, %	10:35:35:20	10:55:5:30	15:30:5:50	10:60:5:25	15:55:5:25	10:50:5:35	30:45:0:25
NI (SI) Wholesale Hydrogen Price, Ave.$/kg 2030-2050	8.2 (7.0)	6.0 (7.8)	5.6 (7.2)	6.2 (6.6)	6.0 (7.3)	6.0 (6.9)	6.6 (7.1)
Electricity:							
Electricity Production, PJ	230	240	250	230	230	260	225
Average Wholesale Price, ave.c/kWh 2020-2050	11.3	11.7	11.2	7.2	11.7	11.3	9.3
Renewables Generation % in 2025 (2050)	94 (91)	94 (89)	88 (86)	84 (85)	91 (91)	87 (85)	86 (94)
CO2:							
CO2 Reduction in 2050, % (% sequestered)	36 (15)	30 (17)	24 (16)	31 (26)	54 (39)	34 (16)	38 (19)
Model Conditions:							
FCV Learning Curve	Low	Low	High	Low	Low	Low	High
EV Capital Tax (%)	0	-30	0	0	-10	-5	20
Starting Preference, FCV:EV	90:70	80:90	80:65	51:62	54:64	66:78	50:78
Oil Price 2008 ($/bbl)	80	80	80	80	80	80	80
Oil Price Rise from 2030 (% per annum)	8	8	4	4	6	2	6
Carbon Tax Post 2012, $/t CO2	150	150	75	25	100	75	50

Table 3: Summarised results for all scenarios

Figures 3 and 4 illustrate the volumes of hydrogen and electricity required in 2050 under the various scenarios and the resources selected by the model to produce these amounts. It can be noted that for hydrogen production, the mix produced via the four main supply chains is quite variable, indicating a robust hydrogen supply. The average price of hydrogen production over 2030-2050 differs between North and South by around 10-25%. This is a realistic outcome given that hydrogen is not permitted, in the model, to be transported across Cook Strait. The reasonably constant wholesale price of hydrogen indicates low cost sensitivity to different production pathways. As would be expected, the hydrogen demand is higher for those scenarios that favour FCVs (Table 3, Scenarios 1-5, 11).

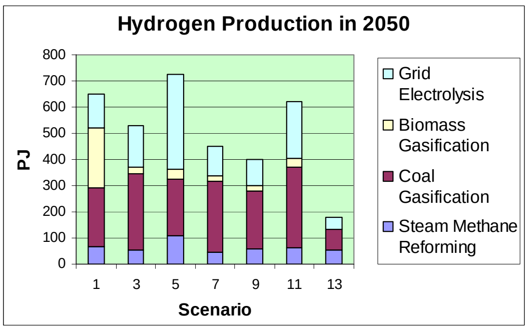


Figure 3: Hydrogen required in 2050

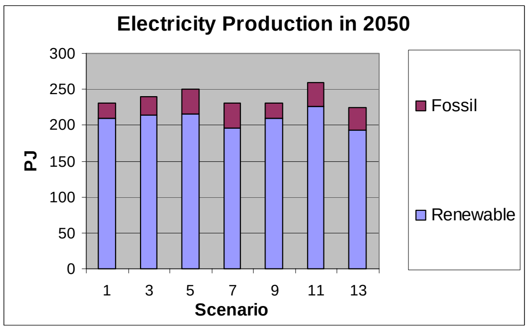


Figure 4: Electricity required in 2050

2.2.2 The two extreme scenarios - FCV uptake favoured

Under scenario 5 the model achieves a mix of 68% FCVs, 30% ICEs and 2% BEVs in the 2050 light duty transport fleet.

In order to deliver this outcome, the full set of required input parameters is:

- Fleet Starting Preference (FSP) for FCVs 80% against a BEV setting of 65%, and a high fuel cell learning curve;
- Oil price $80/bbl to 2030 and then increasing at 4% per annum until it reaches $200/bbl;
- Natural gas price $7.75/GJ to 2030 and then increasing at 4% per annum until it reaches $19.50/GJ;
- A carbon tax starting at $25/t in 2008 through to 2012, then increasing to $75/t and staying steady thereafter.

The resulting fleet profile data is shown in Figure 5.

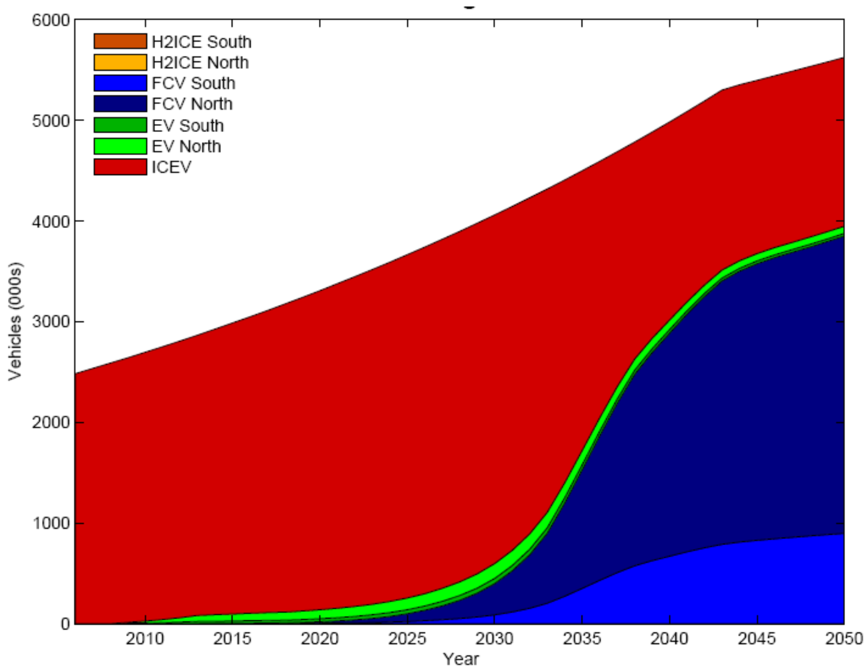


Figure 5: Composition of light vehicle fleet to 2050 (Scenario 5)

Very little FCV uptake occurs before 2020 but the FCV option becomes more competitive during 2020-2030 and thereafter, uptake accelerates rapidly. This results in a hydrogen demand of 725,000 tpa in 2050 at an averaged wholesale price (over 2030-2050 of $5.6/kg for the North Island and $7.2/kg for the South Island. In 2050 the hydrogen is produced (Figure 6) by a combination of 50% grid electrolysis, 15% forecourt steam methane reforming, 30% coal gasification with cogeneration of electricity, and 5% biomass gasification with cogeneration.

The electricity demand in 2050 is 250PJ, with an average electricity price of 11.2c/kWh over the period 2020-2050. Supply is 88% renewables in 2025 but drops slightly to 86% by 2050 (Figure 7).

The overall reduction of energy related CO_2 equivalent emissions by 2050 is 24%, with 16% CO_2 sequestered.

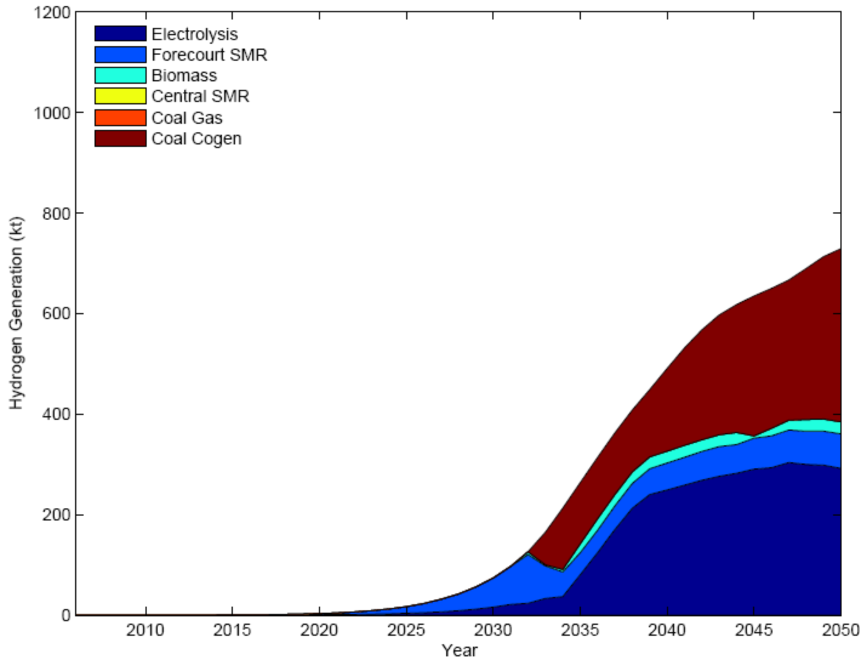


Figure 6: Hydrogen production chains (Scenario 5)

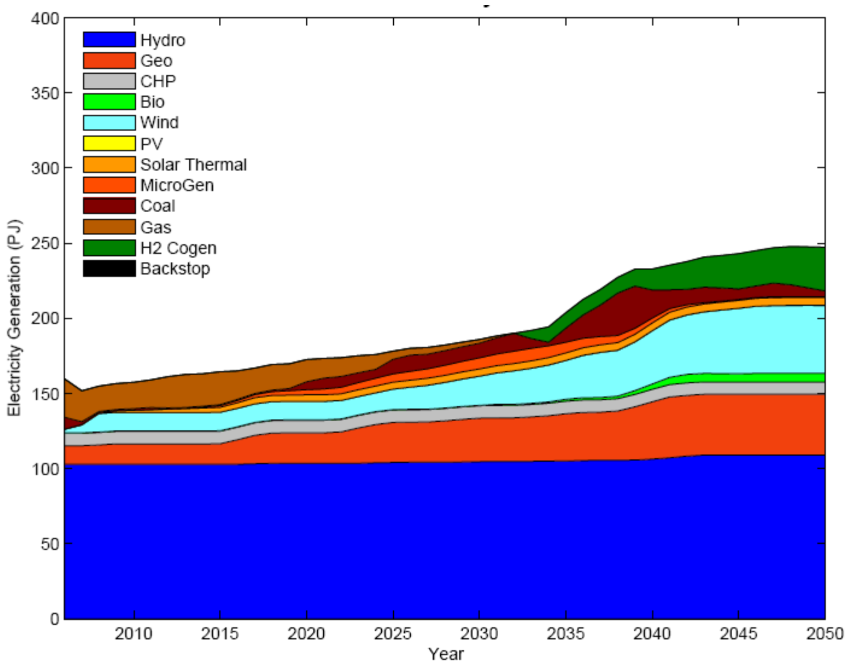


Figure 7: Electricity generation to 2050 (Scenario 5)

2.2.3 The two extreme scenarios –BEV favoured

Under scenario 13 the model achieves a mix of 1% FCVs, 50% ICEs and 49% BEVs in the 2050 light duty transport fleet.

In order to deliver this outcome, required input parameters are:

- Fleet Starting Preference (FSP) for FCVs 50% against 78% for BEVs, with a high fuel cell learning curve and a 20% capital tax on BEVs;
- Oil price \$80/bbl to 2030 and then increasing at 6% per annum until it reaches \$200/bbl;
- Natural gas price \$7.75/GJ to 2030 and then increasing at 6% per annum until it reaches \$19.50/GJ;
- A carbon tax starting at \$25/t in 2008 through to 2012, then increasing to \$50/t and remaining steady thereafter.

The resulting fleet profile data is shown in Figure 8.

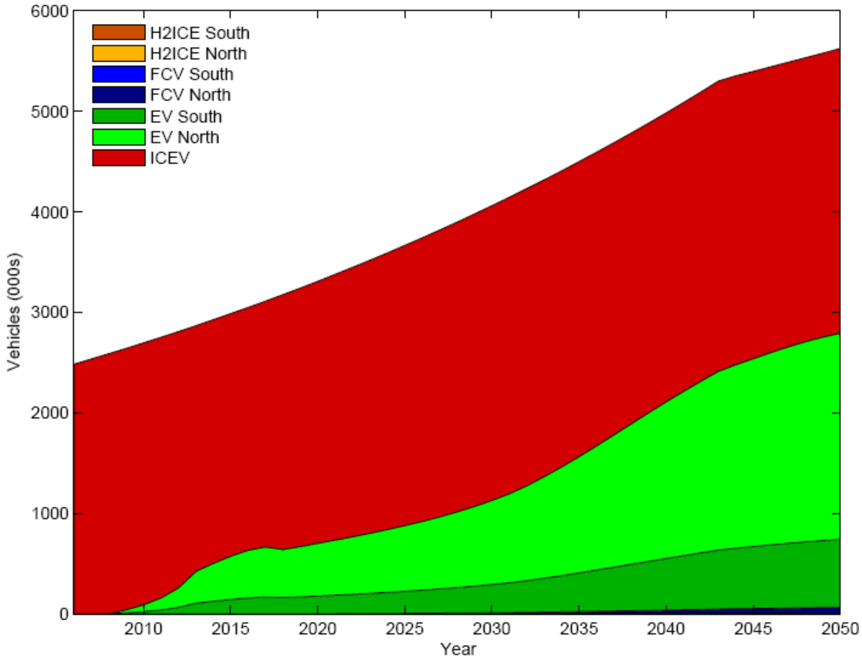


Figure 8: Composition of light transport fleet to 2050 (Scenario 13)

Three of the four hydrogen supply chains are required, with some variations in the contributions from each (Figure 9). Total hydrogen requirement is greatly decreased – and nearly all of that is required for the heavy transport fleet (see below).

Although the presence of BEVs is much more prevalent than under Scenario 5, the corresponding electricity demand in 2050 (Figure 10) is decreased by 25PJ to 225PJ, with an average electricity price of 9.3 c/kWh over the period 2020-2050. This reduction is due mainly to the diminished hydrogen production from electrolysis, off-setting the increased electricity demand from the BEV fleet. The renewables component of supply drops slightly to 86% in 2025 but reaches 94% by 2050, as the reduced electricity demands is able to be met without the advent of new thermal generation.

There is an overall 38% decrease of energy related CO_2 equivalent emissions by 2050 % with 19% CO_2 sequestered.

Both scenarios are clearly capable of delivering outcomes that align reasonably well with the New Zealand Energy Strategy. The following section subjects them to a sensitivity analysis.

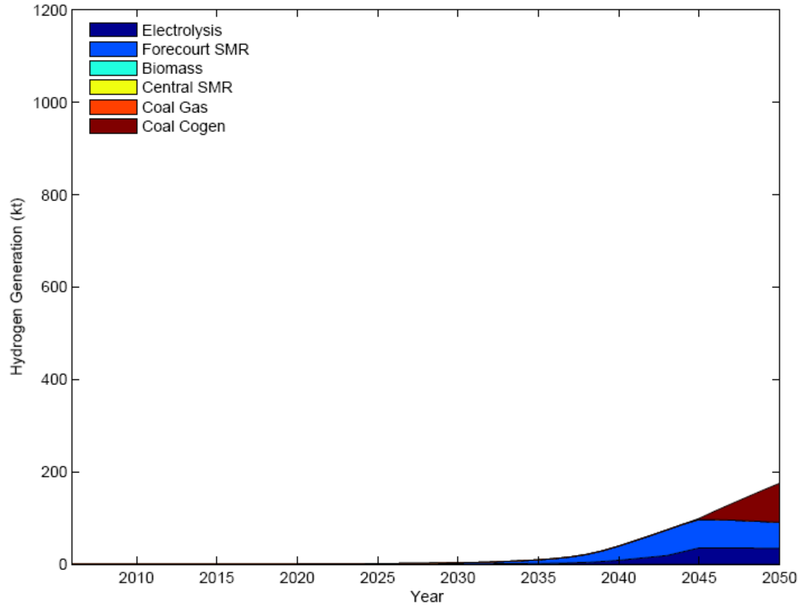


Figure 9: Hydrogen Production to 2050 (Scenario 13)

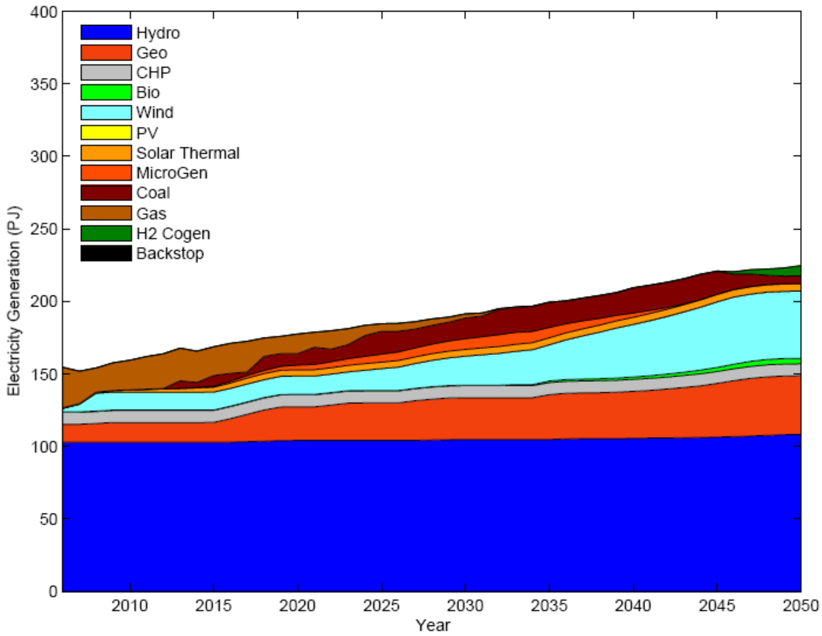


Figure 10: Electricity generation to 2050 (Scenario 13)

2.3 Sensitivity Analyses

2.3.1 Sensitivity of the FCV favoured scenario

Scenario 5 sensitivities are summarised in Table 4 and discussed below.

High Oil:

Under the high oil sensitivity option, oil price increases at 6% per annum from a base level of \$100/ barrel in 2008, reaches \$200 per barrel in 2020 and remains constant thereafter. All other parameters remain unchanged.

Under these conditions the percentage of light FCVs on the road in 2050 drops from 68% to 59%, ICEs drop from 30% to 19% and BEVs increase from 2% to 22%. The uptake profile for FCVs is not greatly impacted but the BEV profile shows a sharp increase at the expense of ICEs around 2020 when the full force of continued high oil prices is being felt (Figure 11).

Scenario 5 - FCVs Favoured	Base Case	High Oil	Early Uptake	High Carbon	No Fossil
Light Transport Fleet Profile (FCV/ICE/EV) %	**68:30:2**	59:19:22	74:25:1	70:28:2	67:31:2
Hydrogen:					
Hydrogen Required (kt per annum)	**725**	740	700	750	600
Hydrogen Production (SMR/Coal/Biomass/Grid)	**15:30:5:50**	35:40:5:20	10:40:30:20	10:40:0:50	10:0:25:65
Average NI (SI) Wholesale Hydrogen Price ($/kg)	**5.6 (7.2)**	5.8 (6.9)	8.4 (6.6)	5.4 (7.1)	8.2 (8.3)
Electricity:					
Electricity Production (PJ)	**250**	230	230	260	250
Average Wholesale Price (2020 to2050) (c/kWh)	**11.2**	11.8	9.6	14.3	14.9
Renewables Generation 2025 (2050) %	**88 (86)**	82 (87)	93 (89)	90 (85)	88 (86)
CO2:					
CO2 Reduction in 2050, % (% sequestered)	**24 (16)**	34 (17)	44 (26)	37 (29)	24 (0)
Model Conditions:					
FCV Learning Curve	**High**	High	Low	High	High
EV Capital Tax (%)	**0**	0	0	0	0
Starting Preference (FCV/EV) %	**80:65**	80:65	90:65	80:65	80:65
Oil Price 2008 ($/bbl)	**80**	100	80	80	80
Oil Price Rise from 2030 (% per annum)	**4**	6**	4	4	4
Carbon Tax Post 2012 ($/t CO2)	**75**	75	75	150	75

** Oil Price Rise is from 2008.

Table 4. Summary of scenario 5 sensitivities

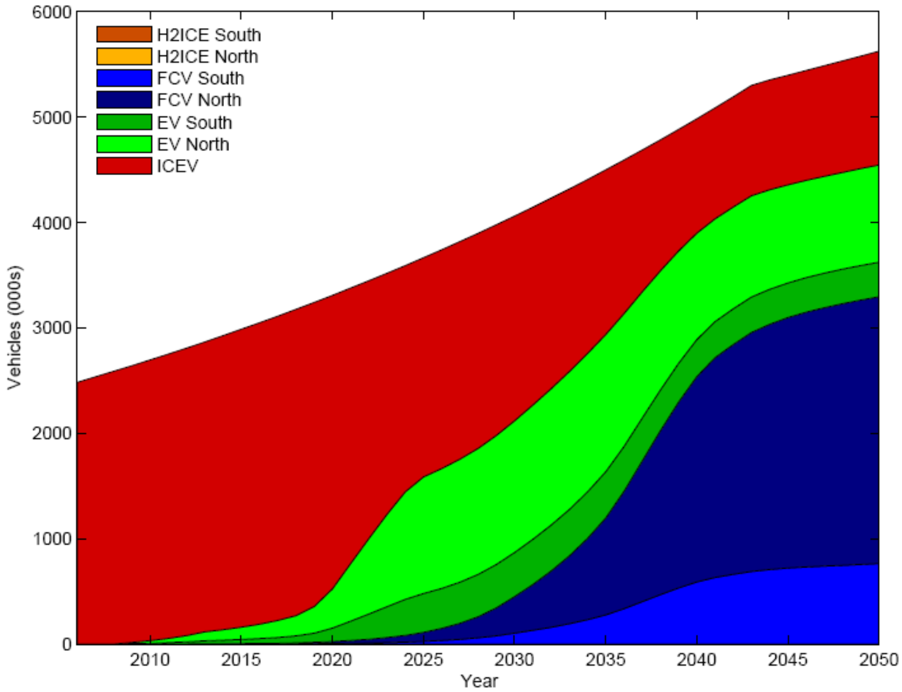


Figure 11: Composition of light transport fleet to 2050 (Scenario 5 High Oil)

Hydrogen demand at 2050 drops to 700,000 tpa and is met by the same four supply chains as in the base case, although each now makes a different level of contribution. The price of hydrogen increases slightly.

National wholesale electricity price over the period 2020 to 2050 increases slightly relative to the base case and averages 11.8 c/kWh over the period 2020 to 2050. The percentage of renewable electricity at 82% remains similar to the base scenario of 88% in 2025, and increases slightly to 87% by 2050.

Other sensitivities:
Increasing fleet starting preference for FCVs from 80% to 90% (against an unchanged BEV setting of 65%) increases the light FCV uptake from 68% to 74% by 2050 and accelerates uptake to as early as 2017 (Figure 12). The same four hydrogen production supply chains are again required, with hydrogen production from biomass making a much larger contribution than in previous cases. Electricity demand drops slightly and prices drop significantly from 11.2 to 9.6 c/kWh due to the introduction of cost effective hydrogen-electricity co-production. Renewable content increases from 88% to 93%, and CO_2 reduction and sequestration profiles also improve from 24% to 44%.

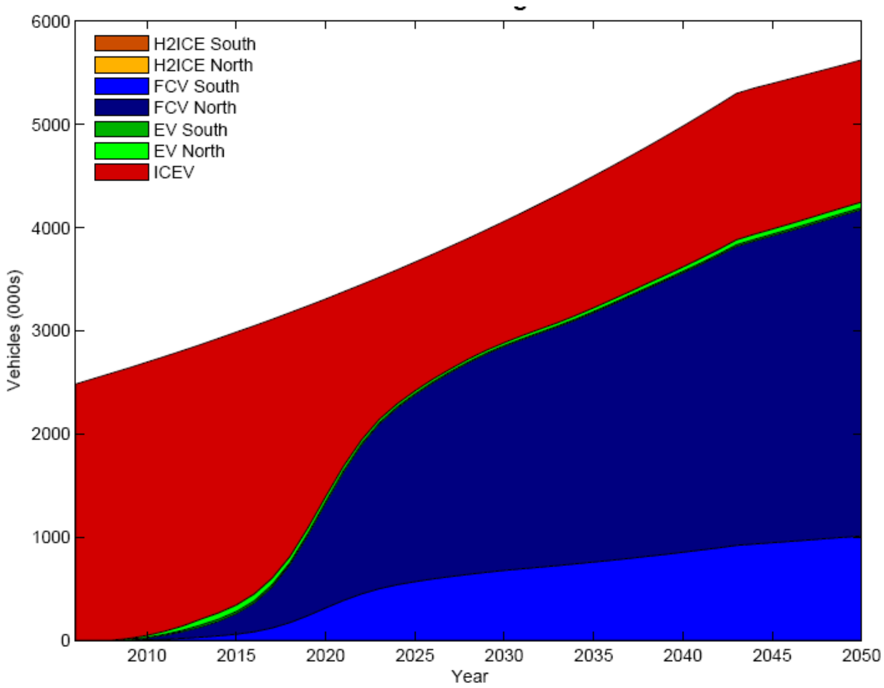


Figure 12: Composition of light transport fleet to 2050 (Scenario 5 Early Uptake)

The main impacts of increasing the carbon charge to $150 per tonne in 2012 are seen in terms of increased wholesale electricity prices (from 11.2 to 14.3 c/kWh) and increased carbon sequestration giving a reduction in energy sector CO_2 emissions over 2006 levels of 37% (as compared to 24%). Electricity prices increase from 11.2 to 14.3 c/kWh but the mix of vehicles, hydrogen demand and required supply chains is not greatly impacted. Renewable electricity reaches 90% in 2025 but falls back to 85% by 2050.

The modelling was carried out at a time when a moratorium on large-scale fossil plant was in place and considered the impacts of an indefinite extension. The effect is to remove the coal co-production option and place increased reliance on grid electrolysis for hydrogen production. Hydrogen production costs increase to $8.20/kg (as against $5.60 in the base case) and electricity prices also increase from 11.2 to 14.9c/kWh. In terms of the transport fleet, the two effects offset each other and the overall mix of light vehicles on the road in 2050 is not significantly different from that seen in the base case.

The impact of any of the above changes to the composition of the 2050 light duty transport fleet is not particularly significant with FCVs achieving a high and consistent level of penetration ranging from 59% to 74% (Figure 13). Of the sensitivities tested, the Fleet Starting Preference is the only one to dramatically accelerate the uptake of FCVs to the point where over 2 million are already on the road by 2025. The FSP parameter models customer behaviour including the influence of policy settings, and is a very significant factor (at least within the modelling environment) in determining the uptake of new transport technology.

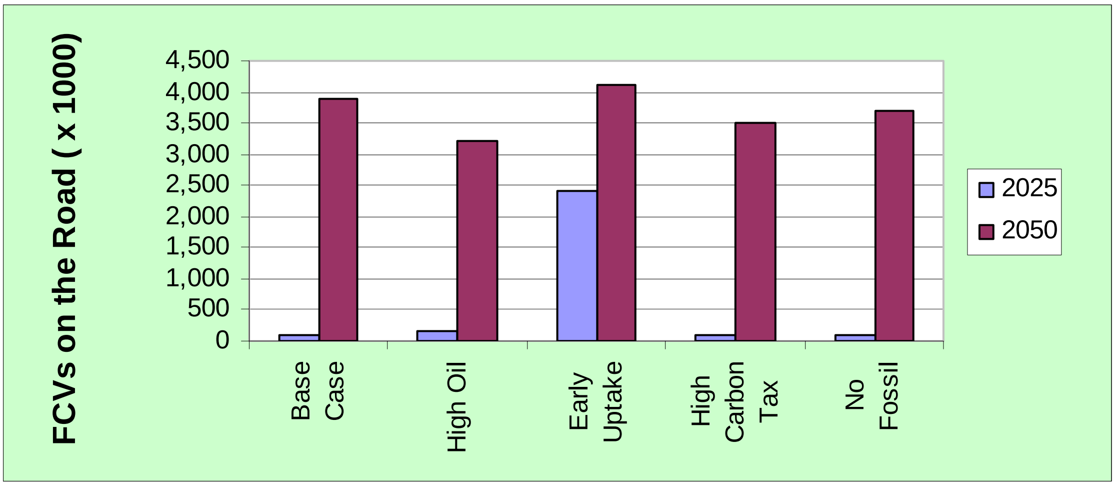


Figure 13: Uptake sensitivity analysis for scenario 5

2.3.2 Sensitivity of the BEV favoured scenario.

Scenario 13 sensitivities are summarised in Table 5 and discussed below.

Scenario 13 - EVs Favoured	Base Case	High Oil	High Carbon	Low Pref.	Med. Pref.	No Fossil
Light Transport Fleet Profile (FCV:ICE:EV) %	**1:50:49**	1:47:52	1:49:50	3:94:3	2:81:17	1:51:48
Hydrogen:						
Hydrogen Required (kt per annum)	**180**	275	180	180	180	180
Hydrogen Production (SMR/Coal/Biomass/Grid)	**30:45:0:25**	20:60:10:10	30:50:0:20	10:35:5:50	30:50:0:20	34:0:0:60
Average NI (SI) Wholesale Hydrogen Price ($/kg)	**6.6 (7.1)**	6.0(6.5)	7.1 (7.7)	6.6 (7.0)	6.6 (7.0)	7.2 (7.5)
Electricity:						
Electricity Production (PJ)	**225**	225	225	210	210	230
Average Wholesale Price (2020 to2050) (c/kWh)	**9.3**	11.1	13.1	9.0	9.1	9.5
Renewables Generation 2025 (2050) %	**86(94)**	83 (83)	91 (96)	87 (96)	86 (95)	86 (90)
CO2:						
CO2 Reduction in 2050 (%) (% sequestered)	**38(19)**	37(26)	50(25)	28 (18)	28 (18)	8 (0)
Model Conditions:						
FCV Learning Curve	**High**	High	High	High	High	High
EV Capital Tax (%)	**20**	20	20	20	20	20
Starting Preference FCV:EV	**50:78**	50:78	50:78	50:60	50:66	50:78
Oil Price 2008 ($/bbl)	**80**	100	80	80	80	80
Oil Price Rise from 2030 (% per annum)	**6**	6**	6	6	6	6
Carbon Tax Post 2012 ($/t CO2)	**50**	50	150	50	50	50

** Oil Price Rise is from 2008.

Table 5. Summary of scenario 13 sensitivities

High Oil:

The composition of the 2050 light vehicle fleet remains essentially unchanged at 1:47:52 as against the base case 1:50:49 although there is an increased demand for hydrogen to fuel the heavy transport fleet which converts to FCVs in response to the high oil price. It may be expected that on-going exposure to high oil prices would drive the light fleet more decisively toward BEV uptake. Evidently the increases in electricity price are sufficient to suppress this change. Electricity demand remains at 225 PJ per annum and wholesale price increases from

9.3 to 11.1 c/kWh. Hydrogen wholesale prices remain essentially unchanged from the base case, as do levels of CO_2 emission reduction.

Other Sensitivities:
Reducing the fleet preference setting level for BEVs from 78 to 60% (Low Preference) against an unchanged FCV setting of 50% has a dramatic effect on the composition of the 2050 light vehicle fleet with the FCV:ICE: BEV ratio of 1:50:49 becoming 3:94:3. Increasing the BEV preference setting to 66% (Medium Preference) results in a 2:81:17 mix. Further increasing the preference setting to 72% (not shown in Figure 14 essentially restores the base case 2050 fleet composition.

The fleet composition is not significantly impacted when an increased carbon charge is applied (High Carbon) but electricity costs increase from 9.3 to 13.1 c/kWh. Renewable content increases from 86 to 91% in 2025 and reaches 96% by 2050. CO_2 emission reductions reach 50% with 25% sequestration as against base case 38% reductions with 19% sequestration.

An indefinite extension to the moratorium on large scale fossil plants raises the average wholesale electricity price during 2020 to 2050 while the composition of the 2050 light transport fleet remains essentially unchanged at 1:51:48 as against the base case 1: 50:49.

The BEV favouring Scenario, like the FCV favouring Scenario, emerges as being robust against peak oil, extended fossil moratorium and high carbon charge sensitivities. BEV uptake is sensitive to changes in FSP settings (Figure 14). FCV uptake sensitivity to FSP was not similarly tested but it is likely to show similar behaviour.

The conclusion from the above analysis is that a risk mitigation pathway for new transport technology is to keep both the battery and fuel cell electric vehicle options in the mix.

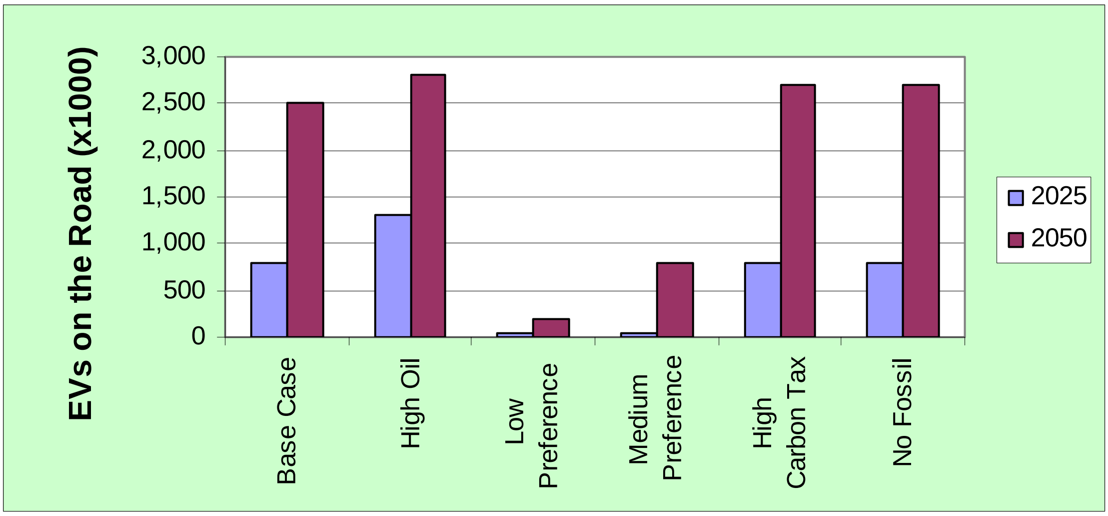


Figure 14: Uptake sensitivity analysis for scenario 13

2.4 A balanced uptake Scenario

Scenario 3 was designed to evaluate a combined uptake of FCV and BEV technologies. It achieves a mix of 46% FCVs, 12% ICEs and 42% BEVs in the 2050 light duty transport fleet (Table 3) and is representative of how the fuel for a range of plug-in and hybrid vehicles platforms might be produced.

In order to deliver this outcome (Table 4), the full set of input parameters are:

- Fleet Starting Preference (FSP) of 80% for FCVs against 90% for BEVs, with a low fuel cell learning curve;
- A capital subsidy of 30% on BEVs to encourage early uptake;
- Oil price \$80/bbl to 2030 and then increasing at 8% per annum until it reached \$200/bbl;
- Natural gas price \$7.75/GJ to 2030 and then increasing at 8% per annum until it reached \$19.50/GJ;
- A carbon tax starting at \$25/t in 2008 through to 2012, then increasing to \$150/t and staying steady thereafter.

The resulting fleet profile data is shown in Figure 15. BEVs start appearing as soon as commercially available due to strong subsidies to promote initial uptake. They grow rapidly during the period 2010 to 2020. Their contribution continues to grow through to 2050. FCVs appear in small numbers by 2015. Their initial uptake rate is slow primarily due to vehicle cost. Over the period 2020 to 2030 there is rapid growth due to cost reductions. The end result is a highly electrified light transport fleet by 2050 comprised of approximately 2.6 million each of FCVs and BEVs.

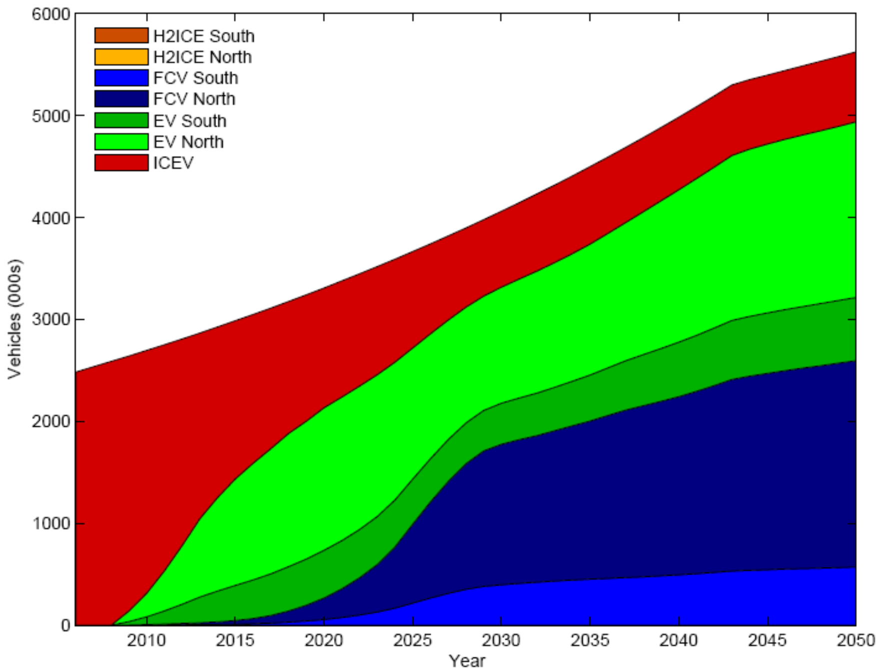


Figure 15: Composition of light vehicle fleet to 2050 (Scenario 3)

The hydrogen demand reaches 530,000tpa in 2050 at an averaged wholesale price (over 2030-2050) of \$6.00/kg for the North Island and \$7.80kg for the South Island. Approximately 55% of the hydrogen comes from coal gasification, 30% from grid electrolysis, 5% biomass gasification and 10% from forecourt steam reformation of natural gas (Figure 16). Fuel consumption and electricity generation profiles are shown in Figures 17 and 18 respectively.

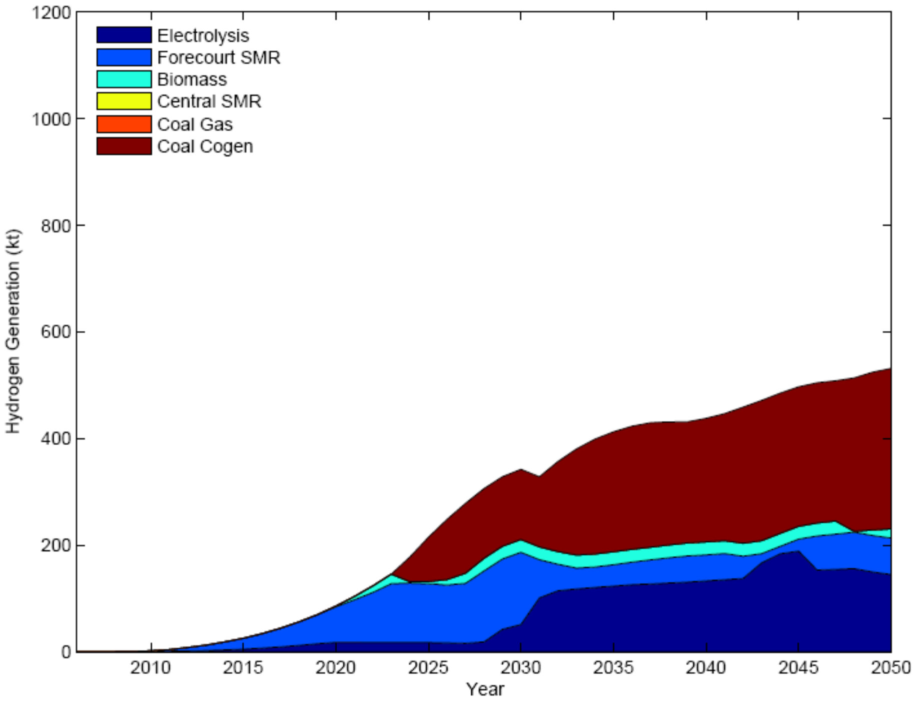


Figure 16: Hydrogen production to 2050 (Scenario 3)

It may be noted from Figure 17 that although the vehicle fleet numbers continue to increase the fuel energy content requirement drops significantly due to the much higher tank to wheels efficiency of electricity and hydrogen in the mixed FCV/BEV fleet as against the petroleum fuelled ICE mechanical drive vehicles of the present day.

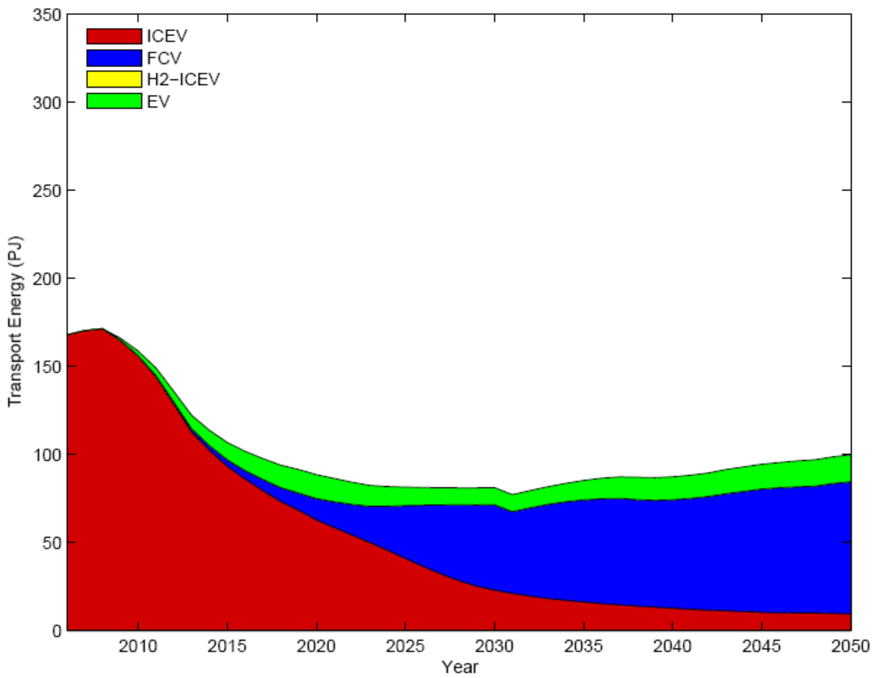


Figure 17: Transport fuel consumption to 2050

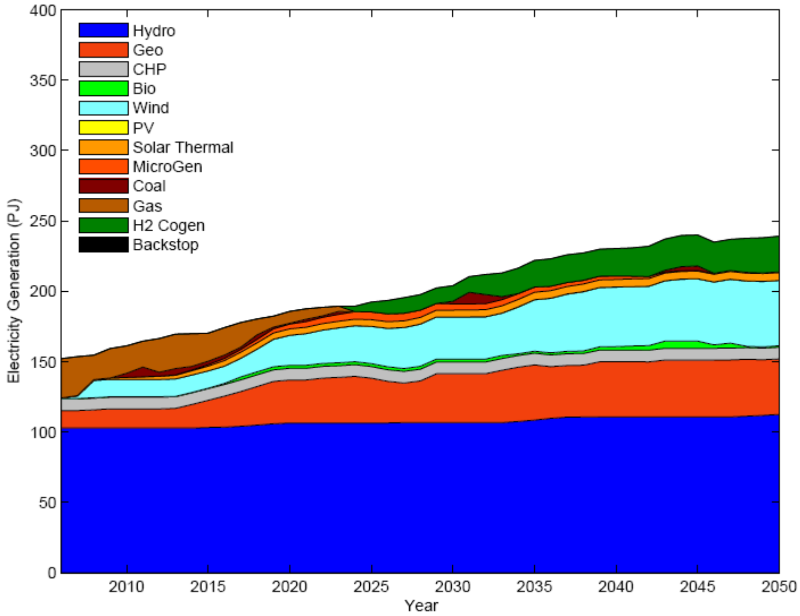


Figure 18: Electricity Generation to 2050

Electricity demand is 240 PJ per annum in 2050 at an average wholesale price of 11.7 c/kWh over the 2020 – 2050 period. Renewable electricity reaches 94% by 2050. CO_2 emission levels in 2050 are 30% lower than present day with 17% of emissions being sequestered.

In view of the sensitivity analyses described in previous sections, in which the need for a balanced uptake profile is identified, this could be regarded as a desirable and achievable scenario for New Zealand's transport future.

On this basis and from stakeholder feedback, Scenario 3 is selected as the basis of the Hydrogen Research Strategy to be developed in the final output report from the Transitioning to Hydrogen programme.

2.5 Other options for hydrogen in the transport fleet

2.5.1 Hydrogen in ICE powered Vehicles

The model is also used to identify conditions under which the H2-ICE vehicle technology makes a significant transitional contribution.

To achieve this outcome the following parameters are used:

- Fleet Starting Preference (FSP) for both FCVs and H2-ICEs of 80%; against a BEV FSP of 65%, with a high fuel cell learning curve;
- Oil price $100/bbl and increasing at 6% per annum until it reaches $200/bbl (i.e the high oil price setting);
- Natural gas price $7.75/GJ and increasing at 6% per annum until it reaches $19.50/GJ;
- A carbon tax starting at $25/t in 2008 through to 2012, then increasing to $75/t and remaining steady thereafter.

Under these conditions H2-ICEs reach 30% to 35% penetration throughout 2020 to 2030 and then drop back to 19% of the 2050 fleet due primarily to the increased use of FCVs post 2030. The uptake profile is shown in Figure 19.

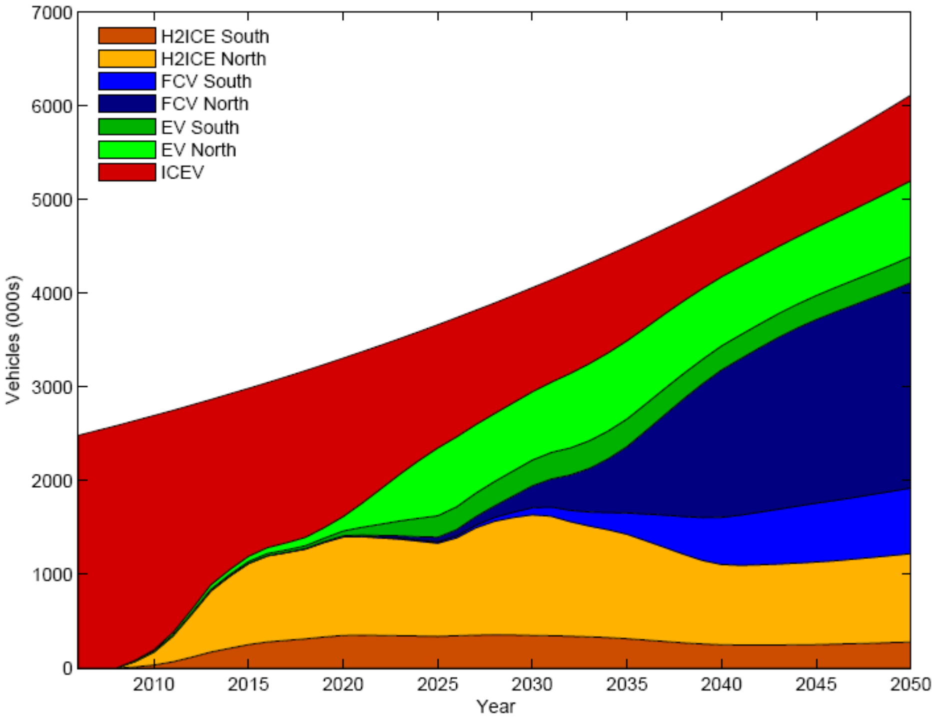


Figure 19: Uptake of H2-ICE Technology

Hydrogen demand in 2050 increases from 725,000 to almost 1,000,000 tpa – a reflection of the much lower efficiencies associated with the use of hydrogen in ICEs as against fuel cells. Wholesale price of hydrogen over the 2030 to 2050 period drops slightly from 5.6 to 5.2 c/kWh. The four hydrogen production chains are again required. Compared with the extreme FCV favoured scenario, electricity demand and wholesale price remain unchanged at 225 PJ and 11.1c/kWh respectively as does the renewable electricity contribution.

Overall the H2-ICE option appears to have merit as a transition technology – possibly in the form of a H2-ICE hybrid EV or hybrid PEV. While not as efficient as a FCV, the vehicle technology is more mature and likely to be durable and robust. Further modelling is required to evaluate the impact on CO_2 emission levels. Continuing significant use of H2-ICEs through to 2050 with unregulated emissions results in the highest CO_2 emissions of all the scenarios examined, although these are still much lower than those of a BAU petroleum based ICE fleet.

2.6 The Heavy Transport Fleet

The model indicates a high (greater than 70%) penetration of fuel cells into the 2050 heavy transport fleet under all scenarios and sensitivities. For light duty vehicles the assumed cost of the high pressure fuel tank is an important factor, but for heavy duty vehicles the size, weight and cost of the fuel tank are less important. There is ample room for long tubular high pressure tanks which can be more cheaply manufactured than those required for the light fleet although there still needs to be an improvement in fuel cell performance to meet the power output profile needed for the heavy fleet.

It can be noted that although battery electric vehicles are prevalent in the light transport fleet under the BEV favouring scenarios, they do not appear at all in the heavy fleet. Heavy duty BEVs are found to be uncompetitive due largely to rising electricity costs, which form a substantially greater proportion of operating costs for the heavy transport fleet than for light duty BEVs.

2.7 Stationary (Heat and Electricity) Chains

It is recognised internationally that stationary hydrogen fuel cell applications involving electricity generation are likely to appear ahead of uptake in transport applications. Although these will have low impact on overall energy use, they will initially have to operate without any hydrogen production and delivery infrastructure in place and represent an important first step for generating product sales and advancing the technology learning curve.

The stationary chains investigated in the scenario analysis included residential and industrial CHP fuel cell generation systems of kilowatt and megawatt scale respectively. Two basic fuelling options were considered: systems fuelled from natural gas or ethanol delivered to the end-use site at which the fuel cell generator is located, and future direct use of pipeline hydrogen produced centrally from biomass. The key feature of these systems is that they must satisfy a local heat demand to maximise the overall energy efficiency, as well as provide electricity. Based on the technology cost estimates used, only the natural gas fuelled residential system showed potential competitiveness and is the only chain further discussed here. The lack of knowledge about the form and cost of hydrogen delivery systems for stationary applications may have contributed to the non-appearance of the pipeline hydrogen supply chain - generalised assumptions on pipeline costs were extrapolated from limited available published data.

As indicated in the Section on Modelling Assumptions, gas prices used for each class are average-cost per customer and include the fixed pipes charge in the $/GJ figure. The model does not cater for a pricing plan that varies with volume – for residential CHP systems in particular this produces a misleading result due to the relatively high fixed charge that residential customers pay. The effect is to underestimate the price of supply for low usage and overestimate it for higher usage. Installing a micro-CHP unit substantially increases the gas use by a consumer (fuel switching from electricity to gas) which reduces the effective energy cost. This reduced "variable" price is not represented in the model. It was found that under these model constraints, which discourage micro-CHP uptake, up to 30% capital "subsidy" on the projected cost of fuel cell micro-CHP systems was required to trigger stationary fuel cell CHP generation uptake. Based on actual New Zealand residential prices, it can be shown that this reasonably closely offsets the effect of the overestimated cost for higher gas consumption, and is sufficient to demonstrate where this chain becomes commercially competitive under varying scenarios. The other constraint which affects this result is mentioned in the section on Assumptions – at present the model assumes that these systems will only be installed in new housing, which severely inhibits the potential uptake rate.

Within these model constraints, it is found that natural gas fuel cell residential CHP generation is consistently installed over the period ranging from 2015 to 2040. Uptake is initiated when the technology cost reduced sufficiently due to production learning. At the end of this period, rising natural gas prices make operating on NG fuel uncompetitive. It is envisaged that by this stage hydrogen gas networks will replace natural gas in many areas and direct hydrogen fuel cell CHP systems will become the home generator system of choice. The results are summarised in Table 6. The peak installed capacity achieved (limited to new residences only) is 5-7 PJ pa. Since this includes 5-7 PJ of heat supply, it represents 10-14 PJ of total residential energy supply, which is a substantial contribution. The 80% end use efficiency of this supply chain means that it consumes only half the energy and produces only 50% of the GHG emissions created by central gas generation.

The scenario target of 20% residential and commercial demand is not reached (due to the uptake rate assumptions identified earlier).

Sc	Starts year	Peak CHP (PJe pa)	At year	Total Supply (PJe pa)	Annual CO_2 reduction (tpa)	% Electricity CO_2 reduction	Ends at year	Comments
1	2015	7	2025	180	584,000	5.1%	2042	Residential
3	2015	7	2035	190	584,000	4.8%	2050	Residential
5	2016	6	2032	190	500,000	4.1%	2045	Residential
7	2015	7	2035	210	584,000	4.3%	2045	Also some commercial CHP in 2003 to 2005.
9	2015	6	2032	260	500,000	3.0%	2045	Residential
11	2015	5	2032	240	417,000	2.7%	2045	Residential
13	2015	6	2032	240	500,000	3.3%	2040	Residential

Table 6: Stationary Fuel Cell CHP Uptake

The conclusions for stationary generation are that fuel cell residential micro-generation could make a contribution to reduction in CO_2 emissions and extension of natural gas supplies. Further modelling of the economic viability of micro-generation within an environment that allows retrofitting to existing buildings, and includes more accurate natural gas pricing and hourly electricity pricing is required. This may show a different pattern in the uptake of fuel cell micro-generation. Future use of bio-ethanol feedstock for home fuelling of micro-CHP systems is a possibility, particularly if hydrogen fuel cells dominate in the transport sector. Ethanol fuelled CHP would further reduce GHG emissions associated with electricity production. Home fuel cell generator systems with built in natural gas reformers could conceivably manufacture hydrogen in a distributed manner for FCV refuelling.

3 When Does Hydrogen Energy Make Sense for New Zealand?

3.1 Risk mitigation in transport fuels

The three major challenges and constraints faced in the transport sector are:

- supply security
- the need to reduce GHG emissions,
- the economic cost resulting from future high oil prices.

It may be argued that the situation of sustained high, or rapidly fluctuating oil prices will not eventuate, and that a mixture of new discoveries and enhanced refining capacity will ensure that "peak oil" will not happen. The IEA appears to no longer think so. Their May 2008 analysis, reinforced by their follow-up release of November 2008 (Birol (1) 2008, Birol (2) 2008) foresees on-going worldwide inability to meet oil demand, continued fluctuating oil prices and lowered economic growth. This will contribute to inflation and unemployment within the OECD should its members continue to rely on oil.

There are three recognised alternative fuel options to transition us away from reliance on oil. These are biofuels (using modified and conventional ICEs), electricity, and hydrogen. All options have specific associated uncertainties and risks and there are dangers associated with attempting to pick a winner at this time**.**

For example, while biofuels will meet a key component of future transport needs the benefits in terms of reduced CO_2 emissions from uptake may not be as great as initially hoped. For BEVs, significant battery technology advances are still required to achieve a vehicle performance that will meet the expectations of a substantial portion of the market. Present battery storage is well short of that required for an acceptable general purpose vehicle range (Yang, 2008). For hydrogen, the current high cost of FCVs and the lack of infrastructure are still seen as substantial barriers. On the other hand, FCVs are now able to match fossil fuelled ICEs in terms of range and refuelling time, and to exceed them in terms of efficiency and reduction of emissions[2] (Clemens and Gardiner (2007) Zerta, (2007), Thomas (2008), Seymour (2008), NREL (2006), NRC (2005), Reitzle (2005), Marban (2006).

The introduction of hydrogen can effectively address all three challenges:
- Hydrogen is indigenously produced and therefore offers high security of supply,
- Hydrogen as an energy carrier can be mandated to deliver any desired level of CO_2 emission reduction, and when used in fuel cell vehicles is 100% free from health damaging emissions,
- Hydrogen price is stable under a wide range of fuel prices

This flexibility is not readily offered by other fuels.

Recent hydrogen refuelling demonstrations with latest generation vehicles (Wipke, 2007) show that there are now no fundamental technology barriers to the large-scale uptake of hydrogen and fuel cells in transport. The issues for hydrogen now relate more to economics - reducing costs

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[2] The Honda Clarity – range 500 kms, rapid refuelling time, capable of 200 km per hour with good storage space - is an example of the current status of FCV. Over 500 similar vehicles are planned for production in 2008 – more than twice the number made in 2007 [The Fuel Cell Bulletin, May 2008]

of fuel cells and infrastructure building – than to the removal of fundamental technology barriers. Research and development will play a substantial part in achieving these goals.

Given the time lag between recognising the need to introduce a new fuelling infrastructure and its implementation (maybe 10-20 years) the development of an ongoing hydrogen vehicle and transport infrastructure programme is now urgent. If New Zealand plans to position itself to take up the hydrogen energy transport option, planning action is required now.

3.2 Stationary Applications

Fuel cell based micro-CHP residential generators offer a substantial improvement in efficiency of natural gas use for electricity production. Early market stationary technologies will operate without the need for any hydrogen production and delivery infrastructure and represent an important first step for generating product sales and advancing the technology learning curve.

3.3 Potential for significant cost savings through accelerated uptake of hydrogen

Economic benefits may be derived from timely introduction of new transport technology to substitute for depleting oil supplies. The modelling strongly suggests that accelerated replacement of fossil fuelled ICEs will not only mitigate GHG emissions but also provide major economic benefits through reduced oil costs.

To illustrate this point, the difference in fuel costs associated with an accelerated FCV uptake rate intermediate between the base case FCV favoured scenario and the early uptake sensitivity was evaluated (Figure 20) – it has a very similar uptake profile to that associated with Scenario 3.

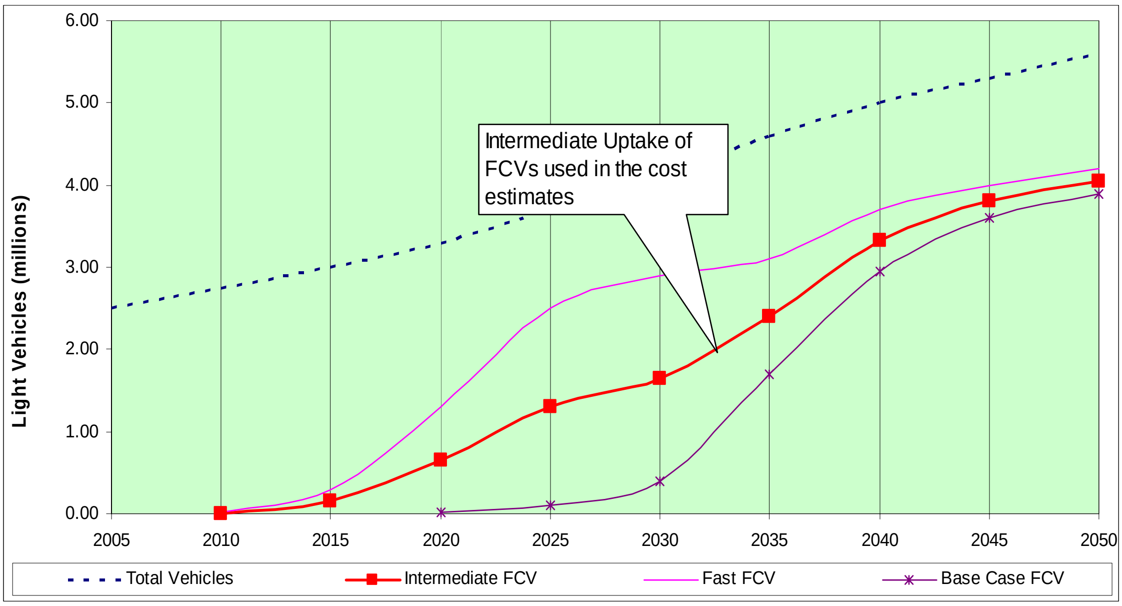

Figure 20: Various predicted vehicle growth profiles

The cumulative fuel cost differences between the intermediate uptake and base case rates through to 2050 are shown in Figure 21. Under a low oil price sensitivity the difference is $31 billion. Under the high oil price sensitivity it comes to $69 billion.

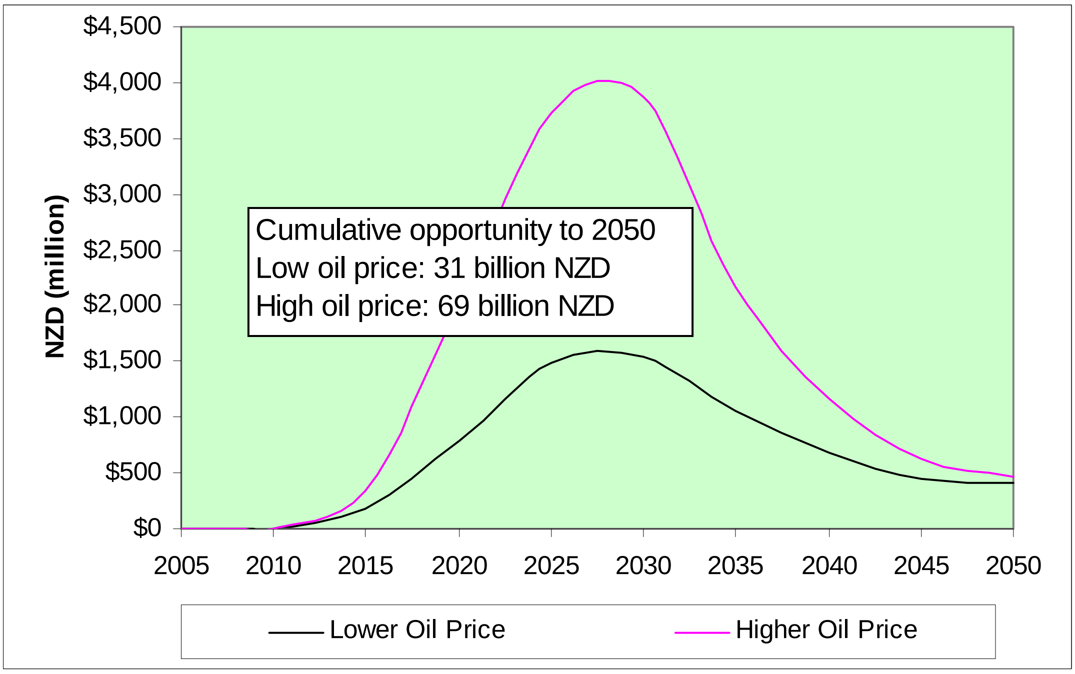

Figure 21: Difference in oil import costs between intermediate and base case FCV uptake rates

The cost of hydrogen production needs to be offset against this. When estimates are made of the difference in the total transport fuel cost (oil plus hydrogen) between the intermediate and base case FCV uptake rates the savings come to $18 billion under low oil and $57 billion under high oil (Figure 22).

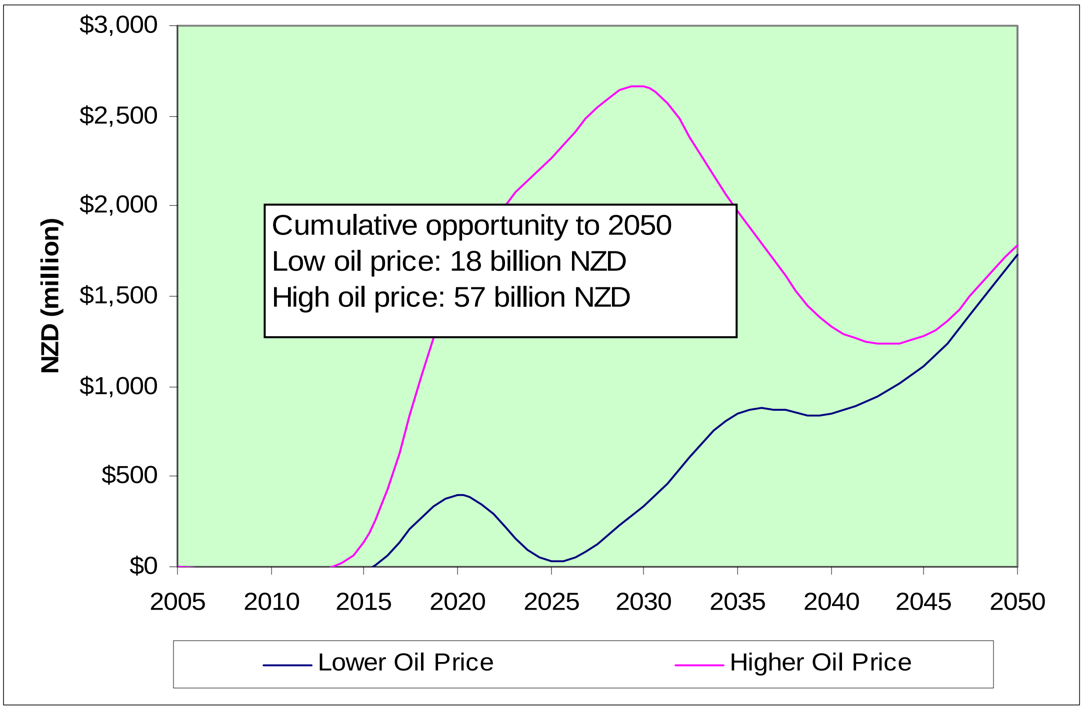

Figure 22: Net fuel cost savings under a modestly accelerated FCV uptake rate

It can be seen that under the lower oil price trend, early savings fluctuate because of the cost of hydrogen production relative to initial low oil prices, but the impact of higher oil prices from 2020 onward leads to net benefits that continue to grow rapidly from 2030. Savings under a high oil price scenario ramp up immediately.

The trends suggest that there is an uptake rate of new vehicle technology that will tend to minimise overall fuel costs during the transition from a 100% oil based transport economy to one that is no longer dependent on oil. In the early years, new technology introduction costs will be high, but since there is an unavoidable delay involved in market growth, if uptake is not initiated soon enough, the imported fuel cost for the remaining oil fuelled fleet may rapidly outstrip the initial investment cost required to trigger the transition. The prudent answer to the question ***when*** should we be prepared for the introduction of a hydrogen and fuel cell infrastructure may be, from an economic viewpoint, "***as soon as possible***".

The effect of a more rapid uptake of FCVs on reduction of CO_2 emissions under these scenarios is positive. Associated savings in CO_2 emissions of up to 85 million tonnes can also be realised, dependent on the mix of hydrogen production routes chosen.

Fatih Birol chief economist of the IEA foresees on-going worldwide inability to meet oil demand, leading to continued high prices and the lowered economic growth, rising inflation and unemployment within the OECD [April, 2008]:

"leave oil before oil leaves us."

www.energybulletin.net/4360

4 Conclusions

It is essential that New Zealand move forward with a balanced portfolio of transport energy options such as that depicted in Figure 1. The FCV scenario modelling analysis demonstrates that the FCV option is a robust and economic option under all oil price situations, is capable of delivering significant cost benefits through accelerated uptake, and represents a strong risk mitigation option against failure of other options to deliver. New Zealand can choose to be either an early or late adopter of hydrogen fuel cell vehicles. The benefits of being early could be very high. Conversely the cost of being late could be very high.

A hydrogen research strategy is required to enable the FCV uptake profile of Figure 1 to be realised. This is developed in the final report of the Transitioning to a Hydrogen Economy programme.

5 References

Birol (1), 2008: German media interview with Fatih Birol, May 2008- translation reported on: www.energybulletin.net/43604.html

Birol (2), 2008: Overview of the IEA World Energy Outlook Update, November 2006

Clemens and Gardiner 2007: Transitioning to a Hydrogen Economy: Identification of Preferred Hydrogen Chains, November 2007

Hemery, 2008: Impact of Plug-in Hybrid Vehicles on the New Zealand Grid, Erwan Hemery and New Zealand Energy Outlook to 2030, 2006: Ministry of Economic Development (MED), 2006

HyNet, 2004: Executive Report, HyNet–Towards a European Hydrogen Energy Roadmap, 2004

Karlsson, 2008: Optimal investment paths for future renewable based energy systems – using the optimising model Balmorel, Kenneth Karlsson, Peter Meibom, International Journal of Hydrogen Energy 33 2008

Kromer, 2007: Electric Powertrains:Oportunities and Challenges in the US Light-Duty Vehicle Fleet, Matthew A Kromer and John B Heywood, Massachusetts Institute of Technology, May 2007

Leaver, Baglino and Cunningham, 2008: Regional Scenarios for the Development of a Hydrogen Economy in New Zealand, July 2008

L-B Systemtechnik, 2005: Co-ordinator HyWays, HyWays: a European roadmap, Assumptions, visions and robust conclusions from project Phase I, HyWays Consortium, Ottobrun, www.hyways.de, 2005

Marban, 2007: Towards the Hydrogen Economy? Gregorio Marban, Teresa Valdes-Solis, International Journal of Hydrogen Energy 32, 2007

MED, 2006: NZ Energy Outlook to 2030, Ministry of Economic Development (MED) 2006

MED, 2007: NZ Energy Data File: Ministry of Economic Development (MED) June 2007

NRC, 2005: National Research Council, Review of the research programme of the freedom car and fuel partnership, Washington DC, 2005, 0-309-09730-4, 2005

NREL, 2006: Report NREL/CD-540-40658, December 2006. Energy Storage Requirement Analysis for Advanced Vehicles (Fuel Cell, Mild Hybrid, and Plug-in Hybrid) Milestone, December 2006

Reitzle, 2005: Dr W Reitzle, CEO Linde AG, HyWeb, Berlin 2005

Seymour, 2008: Key challenges to the introduction of hydrogen – European stakeholder views, Seymour, Murray, Fernandes, Intl. Journal of Hydrogen Energy, 33, 2008

Thomas, 2008: Comparison of transportation options in a carbon-constrained world: hydrogen, plug-in hybrids and biofuels, C E Thomas NHA Meeting, Sacramento March 2008

Wipke et al, 2007: Learning Demonstration Interim Progress Report – Summer 2007, Technical Report NREL/TP=550-41818, July 2007

Yang, 2008: Hydrogen and electricity: Parallels, interactions, and convergence, Christopher Yang, International Journal of Hydrogen Energy 33, 2008

Zerta, 2007: Alternative World Energy Outlook (AWEO) and the role of hydrogen in a changing energy landscape, Martin Zerta, Patrick Schmidt, Christoph Stiller, Hubert Landinger, International Journal of Hydrogen Energy 33, 2008.

6 Glossary

Vehicle related terms:

ICEV	Internal Combustion Engine Vehicle, fuelled with either petrol, diesel, gas or biofuels
ICE	Internal Combustion Engine
EV	Generic term for any vehicle using an electric drive train.
BEV	Battery Electric Vehicle (where the battery is the only on-board energy source so the battery must be charged from an external source, usually the grid supply)
FCV	An electric drive vehicle that uses a fuel cell as its energy source. There may also be a battery on-board for buffering energy demand which may or may not be externally rechargeable
H2-ICE	Hydrogen fuelled ICE
HEV	Generic hybrid electric vehicle. The vehicle has a battery for buffering the power flow, and is powered in a range of possible configurations by a separate on-board power plant (eg ICE or FC)
PHEV	Generic plug-in hybrid electric vehicle (the vehicle battery can also be charged from the external electricity infrastructure)

Other terms:

GHG	Greenhouse Gas
CCS	Carbon Capture and Storage (or Sequestration)
CHP	Combined Heat and Power
E3	A database used to assess Energy use, Economics and Emissions for processes
SMR	Steam Methane Reformation
FC	Fuel Cell
tpa	Tonnes per annum

Hydrogen Characteristics:

1 kg of hydrogen contains 142MJ HHV combustion energy and occupies 11.987 m^3 at STP. (1 kg petrol contains 48MJ HHV and occupies ~ 1 litre)