New Zealand's EnergyScape

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Transitioning to a Hydrogen Economy

Hydrogen Research Strategy for Facilitating the Uptake of Hydrogen as an Energy Carrier in New Zealand

Report Number: CRL08/11047
FRST Project: CRLE0601

May 2009

CRL Energy Ltd
SCION
INDUSTRIAL RESEARCH LIMITED
GNS SCIENCE TE PŪ AO
NIWA Taihoro Nukurangi

CRL Energy Ltd

68 Gracefield Road,
PO Box 31-244
Lower Hutt
New Zealand
TEL +64 4 570 3700
FAX +64 4 570 3701
www.crl.co.nz

CHRISTCHURCH OFFICE
123B Blenheim Road
PO Box 29-415
Christchurch
New Zealand
TEL +64 3 341 2120
FAX +64 3 341 5500

HAMILTON OFFICE
C/- Ruakura Research Centre
Private Bag 3123
Hamilton
New Zealand
TEL +64 7 838 5261
FAX +64 7 838 5252

WEST COAST LABORATORY
43 Arney Street
PO Box 290
Greymouth
New Zealand
TEL +64 3 768 0586
FAX +64 3 768 0587

Transitioning to a Hydrogen Economy

Hydrogen Research Strategy for Facilitating the Uptake of Hydrogen as an Energy Carrier in New Zealand

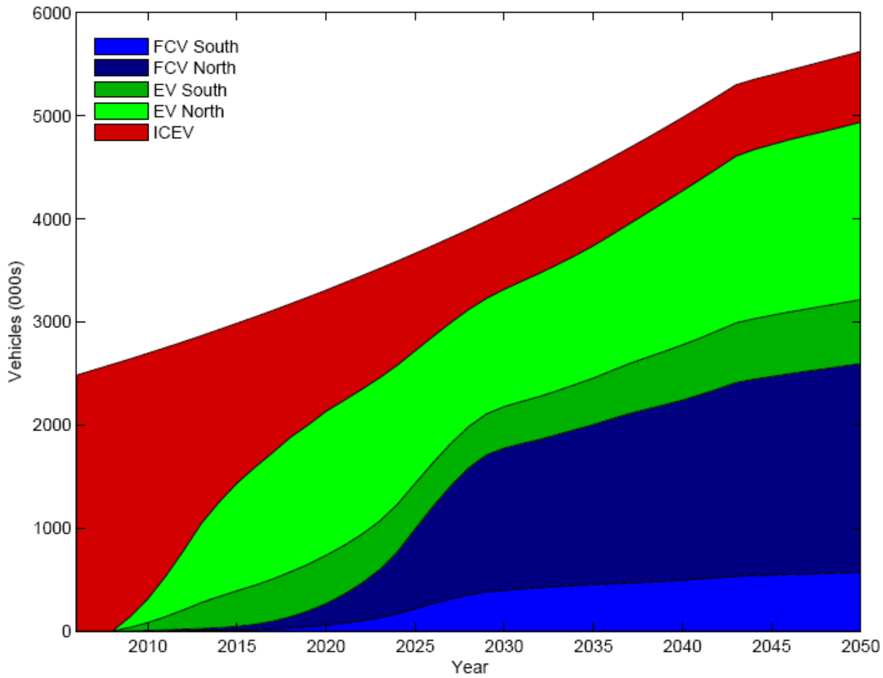
This report was compiled by:
Tony Clemens and Tana Levi of CRL Energy Ltd
Alister Gardiner and Steve Broome of IRL

Executive Summary

This report sets out a strategic research direction for hydrogen related research in New Zealand. It is the fifth and final output from the Foundation for Research, Science and Technology (FRST) programme "Transitioning to a Hydrogen Economy" that addresses 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 report builds on the conclusions of four previous reports in which a strong rationale for the early introduction of hydrogen energy into the New Zealand transport sector was developed. In particular it builds on the fourth report in the series "Hydrogen Energy Options: Scenarios, Sensitivities and Pathways" which describes the use of the UNISYD modelling package to examine future energy scenarios out to 2050. In these scenarios, a range of internal combustion engine vehicles (ICEV), 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. Scenarios were assessed against the renewable electricity generation and CO_2 emissions targets of the New Zealand Energy Strategy and selected scenarios were tested against a range of sensitivities including high oil price, consumer preference and carbon costs.

The favoured scenario, around which this hydrogen research strategy is built, is shown in the Figure below. It leads to an electric drive-train light transport fleet by 2050 comprised of approximately 2.6 million each of FCVs (blue) and BEVs (green). BEVs (referred to as EV South and EV North) dominate the change in the first half of the period (through to 2025-2030) after which FCV cost reductions and the growing infrastructure for hydrogen fuel cause a surge in FCV uptake at the expense of conventional ICE vehicles (red). For this scenario to occur, no major new advances in hydrogen energy technologies are needed.



Targeted Hydrogen Fuel Cell Vehicle Uptake Scenario

The work in this report was carried out in parallel with the BioEnergy options and Energyscape research programmes.

Pathway for Hydrogen Uptake

For New Zealand to achieve a transition involving substantial use of hydrogen energy, three overarching outcomes must be realised. These outcomes are:

- Outcome 1: Hydrogen roadmap completed
- Outcome 2: Hydrogen production pathways secured
- Outcome 3: Transition to the use of hydrogen energy achieved.

A five-stage process is envisaged. The timeframes and milestones associated with this process are:

Stage 1: Planning (2009 to 2010)

- A Government led and industry endorsed Hydrogen Roadmap.

Stage 2: Laying the Basis (2010 to 2015)

- At least one forecourt refuelling station in each of the three main centres, each capable of servicing up to 10 FCVs
- A trial of at least 100 CHP fuel cell microgenerator systems operating in North Island residences.

Stage 3: Technology Uptake (2015 to 2020)

- Installation of hydrogen fuelling capacity of 100,000 tpa, and commercial introduction of 200,000 FCVs by the end of the period
- Approximately 25,000 stationary fuel cell CHP units installed nationally.

Stage 4: Market Growth (2020 to 2035)

- Hydrogen highway initially from Wellington to Auckland with full hydrogen refuelling services
- Approximately 2 million FCVs on the road
- First large scale centralised hydrogen plant constructed
- First industrial tri-gen (heat, power, hydrogen) plants constructed.

Stage 5: Market Consolidation (2035 to 2050)

- Approximately 2.6M FCVs (and similar numbers of BEVs or plug-in hybrids) on the road
- Approximately 700 hydrogen equipped stations, servicing an average of 500 FCVs per day
- Approximately 530,000 tpa hydrogen produced (New Zealand currently produces 55,000 tpa)
- Further large-scale production plants come on line as required
- Hydrogen infrastructure development completed.

April 2008 - Light duty fuel cell vehicle technology reaches acceptable levels of performance in refuelling convenience and vehicle range.

Toyota Motor Corp's FCHV was driven 560km on a single filling and finished with 30% of the hydrogen still in the tank. It has a cruising range of 830km.

Honda FCX Clarity FCVs are being rolled out to the first lease customers.

Mercedes B-Class with FC technology passed a series of winter tests in Sweden. Mercedes plans to launch its first commercial FC vehicle in 2010. Daimler expects to be producing 100,000 FCVs/yr by 2015.

Hyundai Kia Group has announced that it will start selling fuel cell vehicles in 2012 and will currently increase the number in the test stage to 500.

Internationally, many countries are already moving to Phase 2 – Laying the Basis of a hydrogen infrastructure. At least six countries are progressing with the installation of initial "Hydrogen Highways" that will allow public refuelling of hydrogen vehicles over a stretch of highway between major cities.

Recent strong progress towards commercialisation of hydrogen and fuel cell technologies illustrates that there are now no fundamental technology "show stopper" barriers to the large-scale uptake of hydrogen and fuel cell technologies. Much of the international research effort is now being applied to technology cost reduction, systems analysis and planning.

Results of the operational performance trials of hydrogen fuel cell light vehicle fleets around the globe (for example, Wipke et al 2007), indicate that this decade and in particular the year 2008 may well prove to the defining point for the role of FCVs in a new global transport infrastructure.

Strategic Themes and Research Priorities

The role of research investment in realising the overarching outcomes is developed by identifying strategic hydrogen energy activities or themes, the knowledge gaps associated with those themes and the priority research needed to fill those knowledge gaps. This research is classified under a slightly modified form of the four-level classification used in the Ministry of Research, Science and Technology publication: Energy Research - Roadmaps for Science (MoRST 2006). Three levels are used: *New Zealand Led, Fast Follower, or Niche.*

Our *New Zealand Led/Required* classification is the same as the MoRST "New Zealand Lead" classification - RS&T that because of its specificity can only be, or is best undertaken, in New Zealand.

Our *Fast Follower* classification encompasses RS&T to achieve both the "Fast Adapter" and "Emerging Opportunities" status of the MoRST report. The combined *Fast Follower* level includes RS&T that ensures New Zealand is actively involved with new and emerging energy developments that arise internationally, and positions and enables New Zealand in a timely and efficient way to utilise, adopt or adapt science related knowledge for use and further development in New Zealand It is an essential component of a hydrogen research strategy because of the breadth and depth of transformation required, and because much of the new technology will be at international scale.

Our *Niche* classification is the same as the MoRST "Niche/Commercial Opportunity" classification - areas of RS&T where New Zealand has developed particular expertise and may have commercial or intellectual property value. It may also provide solutions for New Zealand's immediate knowledge or energy needs.

In reality, both *Fast Follower* status and *Niche* opportunities result from *New Zealand Led* RS&T. *Niche* opportunities also result from *Fast Follower* RS&T. In combination, niche opportunities can deliver substantial future economic benefit to New Zealand, through high value manufacturing and services activities.

Three technology focussed strategic hydrogen energy themes to which research needs to be applied were identified. These are:

- Hydrogen Production
- Hydrogen Distribution/Storage
- Hydrogen Utilisation

In addition, two cross-cutting themes were also identified. These are:

- Regulations, Codes and Standards
- Planning, Outreach and Demonstration

Hydrogen Research Strategy

A research strategy must contribute to the three overarching outcomes needed for transitioning to the use of hydrogen as an infrastructure fuel. The research priorities and the knowledge gaps that must be filled are aligned below under the relevant outcome. It is during the time up to 2015 that government research investment is most critical.

It is also recognised that the parallel development of business opportunities for New Zealand companies is critical and the Research Strategy must facilitate this as much as it is possible to do so.

Outcome 1: Hydrogen roadmap completed

Strategic Theme: *Planning, Outreach and Demonstration*

Because it involves the planning for integration of a new energy system into New Zealand's existing infrastructure, research contributing to Outcome 1 must be New Zealand led.

Research Priority:

- Modelling and analysis of hydrogen technologies and systems. (New Zealand led)

This Priority is required to fill knowledge gaps including:

- how to integrate hydrogen into the future energy system
- coordinated understanding of why hydrogen is an important energy carrier
- economic and environmental factors associated with liquid fossil and biofuels, hydrogen and electricity
- latest vehicle options including hybrid combinations and plug-ins
- costs associated with maintaining the existing system, oil price scenarios, late transformation to alternative fuels, sunk assets and safety compliance
- impacts of transferring the transport energy supply chain from external to internal resources.

The research investment supports:

- A comprehensive internationally benchmarked roadmap to hydrogen uptake (2010).

Outcome 2: Hydrogen production pathways secured

Because supplies of hydrogen will be New Zealand specific, key research contributing to Outcome 2 needs to be New Zealand led.

Strategic Theme: *Hydrogen Production*

Research Priorities:

- Electrolysis using renewable electricity (New Zealand led)
- Coal gasification (New Zealand led)
- Biomass gasification (New Zealand led)
- Syngas clean-up and hydrogen separation (Fast follower)
- CO_2 capture from coal feedstocks (Fast follower)
- CO_2 sequestration (New Zealand led)
- Business opportunities from hydrogen production (New Zealand led).

These Priorities are required to fill knowledge gaps including:

- Integration and impacts of hydrogen production on the existing and future energy resources and infrastructure, including renewable resources and electricity supply

- In-depth understanding of behaviour of New Zealand biomass and New Zealand coal during gasification
- Applicability to local resources
- Role of biomass in hydrogen production
- Carbon footprints and means for reduction
- Business opportunities (including export).

The research investment delivers:

- Proof of concept technology packages involving early engagement of New Zealand technology providers (2015).

The research investment subsequently leads to

- Pilot scale demonstrations (2020)
- Large scale centralised and industrial tri-generation plants (2035).

It is important to achieve development of proof of concept technology early to allow sufficient time for industry buy-in, up-scaling and trialling at pilot scale and subsequent construction, commissioning and operation of full-scale plant necessary to achieve the overarching outcome. Inclusion of industry in the building of experimental plants and research into business opportunities creates the base for a new support industry sector to develop.

Outcome 3: Transition to the use of hydrogen energy achieved

Because the RS&T associated with the distribution and use of hydrogen energy is so extensive and much of it is being undertaken internationally, key research contributing to Outcome 3 needs to be a mix of New Zealand led and fast follower. Several strategic hydrogen energy themes are involved.

Strategic Theme: *Hydrogen Distribution and Storage*

Research Priorities:

- Storage in chemical and metal hydrides (Fast follower / Niche)
- Transmission and distribution by pipeline (Fast follower).

Strategic Theme: *Hydrogen Utilisation*

Research Priorities:

- Fuel cell technology and systems (Fast follower)
- Other end-use technologies (Fast follower/Niche).

Strategic Theme: *Regulations, Codes and Standards*

Research Priority:

- Applicability of RCS to Safety of Hydrogen Energy Use in New Zealand. (New Zealand led).

Strategic Theme: *Planning, Outreach and Demonstration*

Research Priorities:

- Modelling and analysis of hydrogen technologies and systems (New Zealand led)
- Hydrogen energy system demonstrations/ pilots (New Zealand led)
- Education and training (New Zealand led/required)
- Comparison of technology requirements with New Zealand industry capability (New Zealand led).

To fill knowledge gaps related to:

- Fuel cell, refuelling station and vehicle safety
- Understanding of hydrogen markets, commercialisation policy and business strategy
- Integration of overseas technologies into New Zealand market conditions
- Business opportunities for New Zealand developed IP.
- Introduction and running of small-scale CHP installations
- Specific knowledge of hydrogen and fuel cell applications
- Improved storage density
- Pipeline distribution
- Improved fuel cell performance and durability.

The research investment contributes to:

- Three refuelling stations (2015)
- A 100 unit residential CHP trial (2015).

The research investment subsequently leads to:

- 200,000 FCVs on the road (2020)
- 2.6 million FCVs on the road (2050)
- 700+ refuelling stations (2050)
- 25,000 residential CHP units in place (2020)
- hydrogen CHP units installed in up to 5% of residential and commercial sites (2035).

The investment also leads to significant local manufacturing input into the New Zealand hydrogen infrastructure and further develops export opportunities for New Zealand businesses.

Beyond 2015 the proportion of government investment in research gradually tails off as industry investment in infrastructure and large-scale production plants increases. During 2015 to 2020 there is an on-going need for government investment into process improvement – development of better hydrogen production and separation technologies, development of improved materials and catalysts, improved electrolysers and fuel cell stacks, and into systems analysis, technology performance and social and environmental impacts.

Research related to the development of the Hydrogen Highway and the early stages of market uptake also occurs prior to 2020. The period 2015 to 2020 also sees improved understanding of activities and costs associated with integration of hydrogen and research support for industry in planning infrastructure investments.

The stages beyond 2020; Market Growth (2020 to 2035) and Market Consolidation (2035 to 2050) are characterised by the commercialisation of the research investment made in the previous three stages. Continued improvements to hydrogen production and utilisation technologies are needed and will require some on-going government investment but the majority will come from global industry stakeholders.

Our overall conclusions from the Transitioning to a Hydrogen Economy programme are that:

- Hydrogen will make its biggest contribution in the transport sector. It is a robust and cost-effective option.

- Substantial economic benefits accrue under a 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.

- A significant level of vehicle penetration will take 15 to 20 years to achieve but for the benefits to be realised, preparation must start now.
- Scenarios involving both FCVs and BEVs contribute to NZ Energy Strategy objectives. Moving forward with both the FCV and BEV options represents a good risk mitigation strategy for New Zealand.
- Of the new transport options available for reducing and eventually removing oil dependency, the FCV is the only one presently able to match conventional light duty vehicles in terms of range and refuelling time, and also outperform them in terms of reduced emissions and improved efficiency.
- Both the biofuels and battery electric options, are increasingly facing formidable challenges internationally. The battery electric option requires a major scientific advance in order to deliver the energy densities needed to match the range and refuelling performance of existing ICE engine vehicles and fuel cell vehicles. The heightened interest in battery electrics is a positive step towards increased electrification of the transport fleet and the use of hydrogen as an oil replacement. Biofuels face challenges related to sustainability particularly in regard to land and water use.
- A potential additional use for hydrogen is in the upgrading of biofuels. The extent to which this is required will depend on the balance between biofuels and hydrogen FCVs in the future transport mix.
- The hydrogen option provides security, resiliance and price stability. New Zealand has an ideal resource mix to obtain hydrogen competitively from at least four major resources (intermittent renewable electricity, natural gas, coal with carbon capture and storage and biomass). The diversity of production guards against placing a heavy load on the electricity system while the cost, efficiency and CO_2 emissions levels associated with these .supply chains compare very favourably with those associated with conventional ICE vehicles running on petrol and diesel.
- There are now no serious technology showstoppers to the development of a hydrogen energy infrastructure in New Zealand, but research is needed to reduce costs and achieve implementation..
- A five-stage process can be implemented to facilitate the uptake of hydrogen into the future energy system.
- Government research investment is most critical for bringing about this uptake during the first two stages (to 2015) and Government leadership is essential. Both New Zealand led and fast follower research are critical to the introduction of a new hydrogen energy infrastructure.
- There is an urgent need to look more closely into the role hydrogen energy can play in filling the transport energy gap and the issues associated with the introduction of a new fuel supply infrastructure.
- Research effort should continue to be invested in understanding the hydrogen production pathways best suited to New Zealand, implementing high profile hydrogen pilots/demonstrations, and development of a government-led industry endorsed hydrogen roadmap for New Zealand.
- There is significant business opportunity potential for New Zealand manufacturing and servicing industry to participate in this development and early consideration in the research phase will maximise this engagement.

The findings that led to these conclusions are discussed in detail in the preceding reports.

Contents

1 Introduction

This report sets out a strategic research strategy for hydrogen related research in New Zealand. It is the fifth and final report of the "Transitioning to a Hydrogen Economy" programme. The overall programme describes how hydrogen may become a part of New Zealand's energy future and identifies the role of research investment in making that vision a reality. The term "Hydrogen Economy" is not intended to imply that hydrogen is the only energy carrier in the future energy system – but that it will be a significant one. In essence the overall study addresses the question "when does hydrogen make sense for New Zealand?" and outlines the role of research investment in realising that future.

The first four outputs from the programme are:

- Output 1: An awareness raising Issues Document (CRL07/11009 of May 2007). This document describes:
    - what a hydrogen energy system is
    - what the drivers for hydrogen energy are
    - the major issues relating to its uptake and international research to address these issues
    - the present hydrogen market in New Zealand and the increased market arising from uptake of a hydrogen as an energy carrier for transport and stationary applications
    - the potential hydrogen supply chain options for meeting that increased demand.

- Output 2: Identification of Preferred Hydrogen Supply Chains (CRL 07/11034 of November 2007). This document describes the use of the E3 model framework to identify the Economics, Efficiencies and Emissions associated with hydrogen supply chains. It is the major tool being used to develop a Hydrogen Roadmap for Europe. It was adapted to New Zealand conditions and used for detailed Well to Wheels and Source to User analyses of the range of potential individual hydrogen supply chains identified in the Issues Document. The result is identification of nine chains preferred on the basis of being cost effective long term options for the energy future of New Zealand. The E3 data for these chains and appropriate baseline chains (based on oil price of $US 40 a barrel) is shown in Table 1.

- Output 3: Unitec report "System Dynamics Modelling of Pathways to a Hydrogen Economy in New Zealand" (June 2008). This report identifies the combined contributions over time (from the present to 2050) of the preferred supply chains primarily in terms of meeting future energy scenarios characterised by varying mixes of hydrogen fuel cell, battery electric and liquid fuelled mechanical drive vehicles. It also calculates the costs associated with each scenario and ability to meet Government renewable electricity generation and CO_2 emission reduction targets. Several scenarios are also subjected to sensitivities including oil price, carbon charge and consumer preference. The complete set of assumptions used and a detailed description of the modelling methodology is contained in a companion Unitec report "Regional Scenarios for the Development of a Hydrogen Economy in New Zealand" produced under FRST programme "Hydrogen Energy for the Future of New Zealand". In deriving vehicles numbers, heavy vehicles are defined as those over 3.5 tonnes tare weight, growth rates for both heavy and light vehicles are based on historic values of slightly greater than 2% per annum while limits of vehicle ownership per capita are set at 0.8 and 0.2 for light and heavy vehicles respectively.

- Output 4: "Hydrogen Energy Options: Scenarios, Sensitivities and Pathways (CRL 08/11029 of November 2008). This report analyses the findings of the Unitec System Dynamics Modelling of Pathways report. The findings are that:
  - Stationary applications are likely to play an important role in the early stages of hydrogen uptake but it is in the transport sector that the biggest benefits from a hydrogen energy carrier will be realised
  - 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 hydrogen fuel cell vehicle 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 (Figure 1) 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 for the road transport fleet 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

Table 1: E3 data for preferred transport and stationary supply chains

Feedstock	Hydrogen Production Method	CCS	Hydrogen Transport Method	End Use	Energy Use kWh/km	Emissions CO_2 eq g/ km	Economics NZ$/km
Natural gas	Central Reformation	No	Tanker	Transport	0.43	87.4	0.035
Natural gas	Central Reformation	Yes	Pipeline	Transport	0.40	18.1	0.024
Coal	Central Gasification	Yes	Pipeline	Transport	0.67	14.8	0.025
Biomass	Central Gasification	No	Tanker	Transport	0.61	25.6	0.064
Wind electricity	Central Electrolysis	N/A	Pipeline	Transport	0.45	3.6	0.062
Grid electricity	Central Electrolysis	N/A	Tanker	Transport	0.61	92.2	0.066
Wind electricity	Refuelling Site Electrolysis	N/A	Direct Use	Transport	0.49	0.0	0.083
Crude oil petrol				Transport	0.71	197.1	0.049
					Energy Use kWh/kWh	**Emissions CO_2 eq g/kWh**	**Economics NZ$/kWh**
Biomass	Central Gasification	No	Pipeline	Stationary	2.53	37.9	0.15
Natural Gas	FC CHP with reformation	No	Direct Use	Stationary	1.22	90.4	0.093
Grid electricity to heat				Stationary	1.59	237.8	0.068
Grid electricity to electricity				Stationary	1.51	225.9	0.065

It was decided, after feedback from stakeholders, that the hydrogen research strategy should be developed to enable the uptake profile of Figure 1 to be realised.

A similar methodology is also applied in two concurrent programmes – BioEnergy Options and EnergyScape – in which likely chains for biomass and other energy resources are identified and analysed and, in the case of BioEnergy Options, a Research Strategy developed. The relationship between the two strategies is also considered in this report.

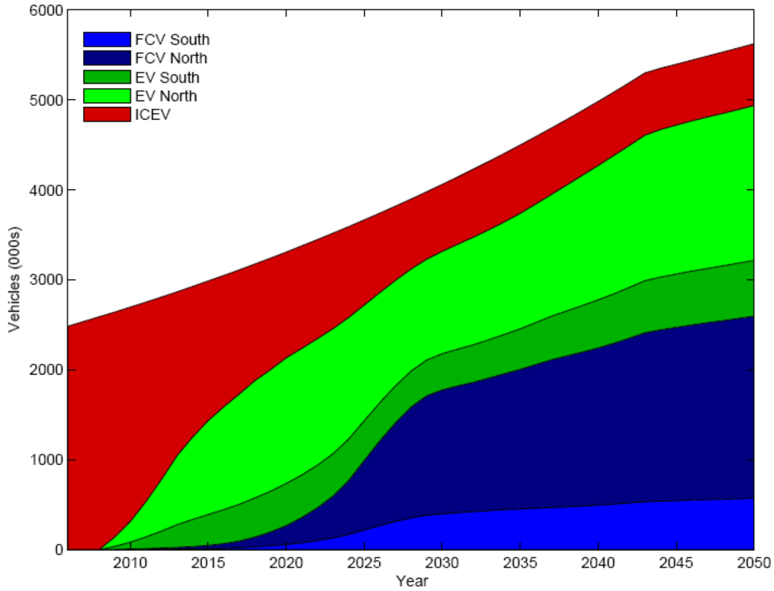


Figure 1: Targeted Hydrogen Fuel Cell Vehicle Uptake Scenario

2 A Pathway for Uptake of Hydrogen Energy

Based on the proposed uptake scenario of Figure 1, the next step is to identify achievable milestones and timeframes for the introduction and uptake of hydrogen energy. This is done by breaking the activities into five stages and identifying milestones that indicate when each stage is completed.

> ***Hydrogen Energy Vision:***
>
> *Development of a national hydrogen roadmap or hydrogen vision is a key step in the planning, outreach and stakeholder education process.*

This is outlined in Figure 2, where five stages overlay a graph of fuel cell vehicle uptake profile which the earlier modelling (Unitec 2008) indicates is feasible, and economically viable. Also shown for comparison are the predicted total light transport fleet numbers and a BEV vehicle uptake profile used in a recent Electricity Commission scenario. The five stages are briefly discussed in the following section.

2.1 A five stage pathway to hydrogen uptake (2008 to 2050)

The first stage – *Planning* – is completed by 2010. At the end of this stage a fully detailed, government led and industry-endorsed national Hydrogen Roadmap will be in place and several high profile demonstrations will be identified and planned.

The second stage – *Laying the Basis* – is completed by 2015. At the end of this stage there will be at least one pilot scale refuelling station in each of the three main centres (Auckland, Wellington and Christchurch) each capable of servicing up to 10 FCVs, and a small number of FCVs on the road (approximately 30). A 100 unit residential CHP fuel cell trial will be in operation.

The third stage – *Technology Uptake* – is completed by 2020. At the end of this stage there will be refuelling capacity of 100,000 tpa for 200,000 FCVs, and commercial introduction of FCVs. Approximately 25,000 stationary fuel cell CHP microgeneration units will be installed nationally.

The level of hydrogen production will still be insufficient to warrant the beginning of a central production and pipeline infrastructure. Vehicles will initially consist of delivery service activities, central and local government fleets, light public transport, and increasingly light private vehicles. Most distribution, if required, will continue to be by tanker truck. Major industry players begin to uptake the technologies and there is a rapid increase in stationary applications. In addition to the 25,000 small scale CHP units there may also be growth in commercial and industrial scale CHP MCFC fuel cell installations running on a range of renewable fuels including ADG (biogas) and bioethanol.

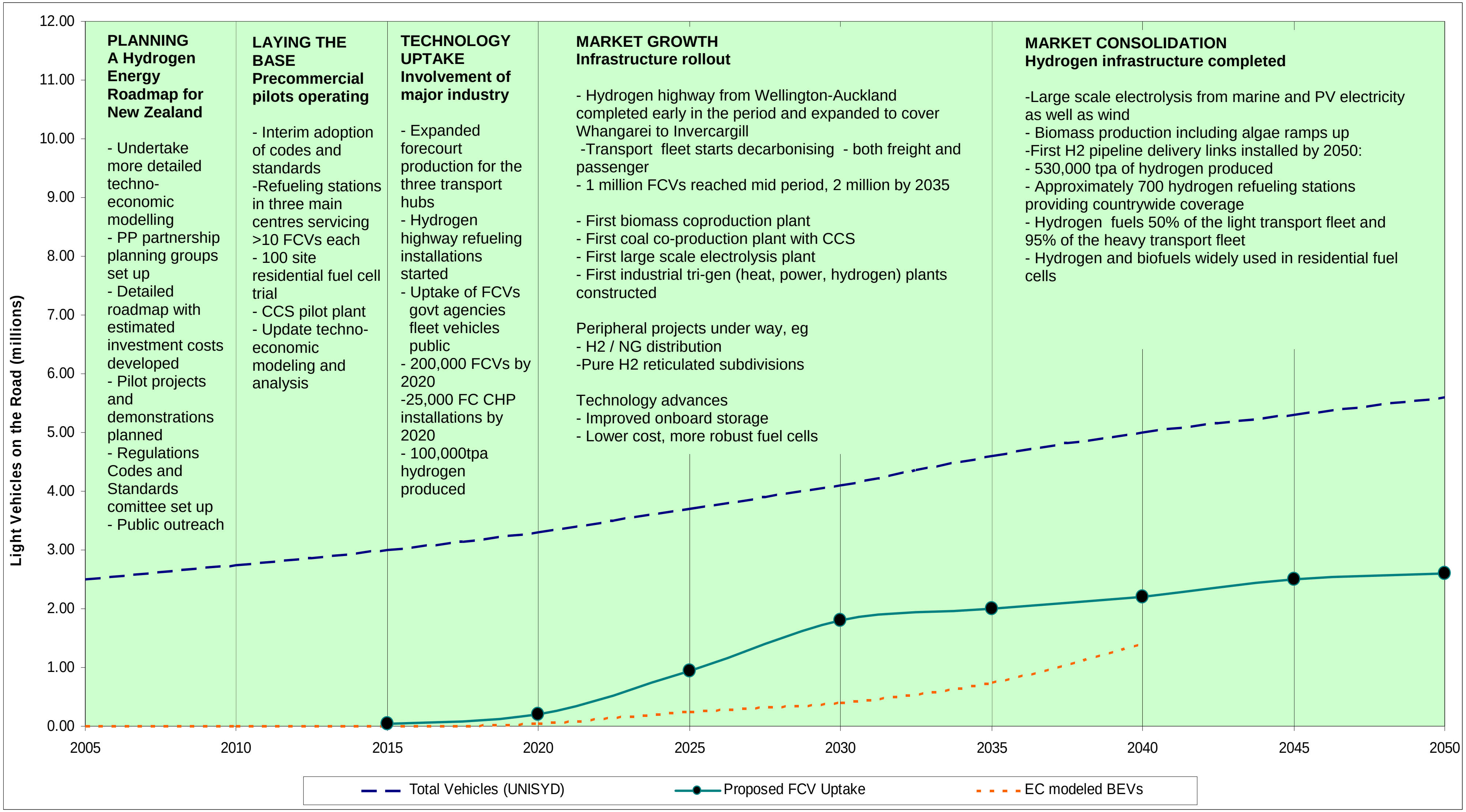


Figure 2: Key stages in the hydrogen uptake pathway

During the fourth stage - *market growth* (2020 to 2035) - the first large scale hydrogen production plants based either on electrolysis, coal based co-production with carbon capture and storage, or biomass based production, will come online. Hydro, wind and geothermal will contribute significantly to the mix of grid electricity used for hydrogen production by electrolysis (and will also support the substantial fleet of short range battery electric vehicles on the roads). A major activity during this time is the development of a fully serviced *Hydrogen Highway* from Whangarei to Invercargill. This becomes the backbone on which the hydrogen infrastructure will continue to be built. The first stage initiated early in the period runs from Auckland to Wellington. By the end of the period there are 2 million FCVs on the road and up to 5% of residential and commercial sites have hydrogen CHP units installed. The first industrial tri-generation (heat, power and hydrogen) plants will come on line during this period.

Hydrogen Highway:

By 2035, sufficient refuelling stations are in place to rapidly service hydrogen vehicles operating out of Auckland, Hamilton, Wellington and Christchurch, and to allow all-transport refuelling facilities along a SH1 "hydrogen highway" extending from Whangarei to Invercargill.

The final stage - *market consolidation* (2035 to 2050) – will see a consolidation in hydrogen demand. Additional large scale hydrogen production plants will be built as required – including one in the South Island – and by the end of the period there will be at least 2.6 million FCVs on the road. Hydrogen production will be approximately 530,000 tonnes per annum. By then an adequate hydrogen refuelling infrastructure will be in place throughout the country. To cater for 2.6 million hydrogen vehicles, New Zealand will need approximately 700 hydrogen equipped stations servicing 500 vehicles on the average per day. Based on current performance of FCVs, short term fuel use targets and vehicle design learning curve expectations, it may be deduced that the more remote stations would service a lower vehicle rate than this average, but will be able to be sparsely distributed since the full-tank range of hydrogen cars will by then exceed that of conventional vehicles.

Hydrogen Fuel Demand:

By 2050, there will be 2.6 million FCVs on the road in New Zealand.

The hydrogen required to fuel these vehicles will be only about 10 times the current production at the Marsden Pt refinery, but will be GHG neutral if required.

It is during the first two stages that government research investment is most critical.

Table 2 summarises these stages of a hydrogen energy uptake pathway. It also gives an indication of the potential scale of combined government and commercial investment required. No attempt is made here to separate government investment from private investment but it is recognised that the parallel development of business opportunities for New Zealand companies is critical. It is important to note that the initial investment (in the order of $20 million through to 2015) which must be government led, is crucial to trigger the transformation. It is a very small portion of the total. It also represents a fraction of the potential benefits accruing to New Zealand from timely introduction (estimated to be in the vicinity of $18 billion to $57 billion (CRL Energy Report 08/11029, 2008). Note that this table does not represent a roadmap – but it is helpful to identify a timeline of key activities around which a matching research plan can be formulated.

Table 2: A hydrogen energy infrastructure investment plan

Period	Uptake Actions and Key Endpoints	Approximate Level of Investment*
Planning To 2010	**Key Activities:** Government commitment to an energy futures plan that sees hydrogen fuel as a direct and rapid substitute for imported oil. Planning for both stationary and transport demonstrations. Detailed systems modelling undertaken. Increase active role in international IPHE and IEA hydrogen organisations to maximise political and industry support and buy-in for New Zealand as an adopter-proactive market. Consultants and committee costs - Roadmap debated and developed, regulations, codes and standards committees set up and working to targets. **Endpoint:** A hydrogen energy roadmap with energy industry buy-in. Several demonstrations selected and in the planning stages.	Allocation of time from government. agency operational budgets $200,000 pa staffing in government energy agencies plus $500,000 pa
Laying the Basis 2010 to 2015	**Key Activities:** Pilots/Demonstration under way: Three small capacity (~2tpa ea) single dispenser city refuelling stations each with fleets of approximately10 FCVs fully operational. Auckland – forecourt NG reformation Wellington – forecourt electrolysis Christchurch - forecourt electrolysis Users: a mix of private and government vehicles and at least one shuttle style bus service. A 100 unit residential CHP fuel cell trial in operation by 2012 with devices at several urban locations, e.g. Auckland, Wellington and Christchurch. Planning in hand for the first stage of the SH1 hydrogen highway: Wellington-Auckland Public education and outreach campaign. Early engagement of New Zealand technology providers Identification of New Zealand business opportunities. **Endpoint:** Strong public awareness of hydrogen energy. Industry mobilised. Refuelling station codes and standards set. Stationary application codes and standards selected.	Time allocated in government agency budgets $20 million for FCV fleet and refuelling stations $3 million for a residential CHP trial

Period	**Uptake Actions and Key Endpoints**	Approximate Level of Investment*
Technology Uptake 2015 to 2020	**Key Activities:** Refuelling stations in the main centres upscale to service the fleet growth in Auckland, Wellington and Christchurch. First stage of the hydrogen highway progressively installed by extending refuelling points on SH1 out from Auckland and Wellington. Vehicles are now commercially competitive, hydrogen distribution starts occurring from forecourt hubs by tube trailer. **Endpoint:** Distributed production capacity for 100,000 tpa of hydrogen in place Sales of light FCVs to the public- 200,000 in service Expansion of NG fuelled residential CHP units in the NI -20,000 Installation of LPG fuelled residential CHP units in the SI -5,000 Base created for development of a new support industry sector	$100 million + for investment in supply infrastructure Vehicle purchases are based on commercial choice
Market Growth 2020 to 2035	**Key Activities:** SH1 Hydrogen Highway services available over the complete distance from Auckland to Wellington in 2020, then extended to link up between Whangarei and Invercargill mid period. Refuelling stations continue to expand out from this backbone to all main centres by the end of the period. Construction of first centralised hydrogen production plants. First industrial tri-gen plants come on-line. Fuel cell bus and heavy vehicle demand ramps up. **Endpoint:** Production capacity of 400,000 tpa in place 2M light FCVs on the road Dedicated hydrogen support industry sector in place and growing	$10 billion + (includes investment in the first centralised production and distribution infrastructure)
Market Consolidation 2035 to 2050	**Key Activities:** Construction of additional production plants as required. Refuelling to other South Island centres expanded. Hydrogen distribution to main centres by pipeline. Advanced renewable production technologies commercialised. **Endpoint:** A competitive FCV market is in place with 2.6M vehicles on the road. National fuelling infrastructure completed. Established industry for support and maintenance of the hydrogen infrastructure	$10 billion +

- Estimates based on $2 million per forecourt production plant, $2 billion per centralised plant, pilot FCVs $200,000 each, pilot CHP units $20,000 each. These are starting point estimates only.

3 Themes and Research Priorities

3.1 The International Situation

New Zealand is fortunate in having strong ties to the international hydrogen research community through its membership of the International Partnership for the Hydrogen Economy (IPHE) and IEA Hydrogen Implementation Agreement. Many of the findings of these international organisations are as relevant to New Zealand as to the rest of the world and it is worth reviewing them here before developing a New Zealand specific research strategy.

Many countries, including the US, Canada, EU and its member states, Japan and Korea have recently undertaken modelling studies similar to the one carried out within the Transitioning to a Hydrogen Economy programme. Although the scenario and sensitivity analysis were undertaken using different computer models and techniques, the major outcomes of our modelling is remarkably similar to other studies (e.g. Contaldi, 2008). Even Brazil, far better endowed than New Zealand to pursue a bio-energy future and much further ahead in implementing one, has committed to a parallel hydrogen energy roadmap. Similar conclusions were also reached by another recent USA based study (Thomas, 2008) in which FCVs were found to be the best future transport option under a number of measures.

The IPHE has recently identified four overarching strategic priorities for the outcomes of the research it sanctions. The priorities reflect the recognition by international research agencies that informing and influencing policy makers and government leadership is vital for implementation. The IPHE Hydrogen and Fuel Cell Brief for Policymakers, attached as an Appendix to this report provides more detail.

The overarching IPHE priorities are:

SP1 - Accelerate the market penetration and early adoption of hydrogen and fuel cell technologies and its supporting infrastructure

SP2 –Raise the Profile of hydrogen and fuel cell technologies with Policy-Makers and the Public - Continuing Education and Outreach Efforts

SP3 – Encourage development of policy and regulatory actions to support widespread deployment

SP4 – Monitor and publicise Hydrogen, Fuel Cell and Complementary Technology Developments.

Maintaining an updated snapshot of the "State of the Nation" in regard to international developments in hydrogen supply and end use technologies is an on-going activity of the international community. These findings are also highly relevant to New Zealand. A brief summary of the current status follows.

3.1.1 Feedstocks

A current review of European stakeholder views on the key challenges to the introduction of hydrogen (Seymour, 2008) concludes that the major challenges relate to carbon capture and storage, high temperature production technologies (including gasification), and hydrogen pipeline development. The most common feedstocks for hydrogen production are identified as natural gas, biomass, wind electricity and coal – essentially the same four as identified for New Zealand by the scenario analysis stage of this programme.

3.1.2 End use technologies - Light Duty Vehicles

Substantial advances have been made in the past five years in fuel cell design and integration into the basic electric vehicle platform. Light duty FCVs are now in the preparation stage of commercial production. Leading auto-makers Honda and Toyota have demonstrated functionally acceptable FCVs with adequate cold start capability, range, performance and refuelling times for light duty requirements (particularly under New Zealand climatic conditions). Honda claim a fuel efficiency at least 3 times that of a typical petrol ICE vehicle and 2 times that of a Prius type hybrid. At least 6 vehicle manufacturers are known to have products at a similar state of commercial readiness. Overall it is estimated that 550 FCVs

On-Board Vehicle Storage:

Current technology for onboard hydrogen gas storage uses very high strength cylinders certified to 350 bar (5,000 psi) or 700 bar.

As a result of improvements in fuel cell vehicle efficiency these tanks now provide adequate range.

Cost reduction is the main challenge for use of such tanks in vehicles.

were manufactured and released to users in 2008 (Fuel Cell Bulletin 2008). This represents a doubling in numbers produced in 2007 and brings the number of FCVs evaluated on the road to over 2,000. The newly released vehicles will be evaluated while manufacturing systems are geared up for mass production, slated to begin in 2012-2015.

Hydrogen Infrastructure:

The cost of installing a hydrogen refuelling infrastructure is likely to be lower than first thought. A 2008 study by GM has shown that just 40 stations in the LA metropolitan area and along the major highway corridors would provide a hydrogen fuelling point within 3.5 miles of most of the population.

At a cost of $US4 million each, this is significantly less than the refurbishment investment required for maintaining conventional fuel services over the next decade.

An interim report (Wipke et al 2007) released in July 2007 summarises the initial results from the US DOE FreedomCAR industry trials which commenced in Q2 2005. This report removes any doubts that fuel cell vehicles are technically very close to introduction-readiness. At the time of data collection cut-off (Dec 06), *first* generation vehicles from four manufacturers had travelled 573,064 miles, composed of 141,000 individual vehicle trips. The vehicles achieved fuel economy figures (adjusted to a “window sticker standard”) of 67 to 90 km/kg and recorded efficiencies of around 55%, very close to the DOE target of 60%. Over 3,700 refuelling events were recorded and analysed, yielding an average rate of 0.71kg/min, which is approaching the DOE target of 1kg/min. *Second* generation vehicles, entering the test fleet now, will obviously exceed these acceptable figures, and are expected to get very close to the DOE 2009 driving range target of 250 miles (400km).

3.1.3 End use technologies -Heavy Duty Vehicles

The 13-city fuel cell bus trial (EU Cute project) has been completed with generally satisfactory results. Five fuel cell buses have been ordered for the London Olympics. Two were used at the Beijing Olympics. China, Canada, USA, Spain and UK have all recently announced new bus projects. Compressed gas tanks of 350 bar provide adequate range. On the down side, fuel cell durability needs to be improved in order to reduce vehicle costs. Fuel cells are also expected to play a role in the near future in Auxiliary Power Units (APUs) providing continuous power to electrical systems within these and heavy transport vehicles.

3.1.4 Infrastructure

There are now over 220 refuelling stations in place globally (Marban, 2008). Just over one hundred of these are in the United States with 49 being in California. The California experience is that the installation of 40 refuelling stations in the regions covered by Los Angeles would cost $US160 million and provide access to a fuelling site within 3.5 miles for most of the residents. A cost of $US4 million per forecourt production refuelling station suggests that hydrogen infrastructure can be progressively installed at a cost well below the ongoing investment by oil companies in replacement and upgrading of existing transport fuel infrastructure.

In 2005, Dr W Reitzle, President and CEO of Linde AG stated: “A transition to hydrogen is economically feasible”. To service 6.1 million FCVs by 2020 in Europe, about 2,800 filling stations will be required. In Germany, the infrastructure to supply 1.9 million cars would cost 870 Million Euros (Reitzle 2005). The estimated cost per filling station is about 1 million Euro.

These estimates and experiences offer a good guide to potential New Zealand requirements. Most major economies represented within the International Partnership for the Hydrogen Economy (IPHE -17 nations, representing 80% of the world economy and 85% of its energy use) are pushing ahead with the development or implementation of a hydrogen roadmap strategy. While the broad thrusts around a FCV transport solution are common, each has their own specific objectives in choice of supply, stationary applications, timing and infrastructure roll out. A common theme is to implement at least one section of a national hydrogen highway by 2010-2012. Countries and regions that have announced plans include several US states, Norway, Denmark, UK, Germany, Spain, Korea, Japan, Canada and Iceland. The forecourt refuelling stations are initially predominantly natural gas reformers but a considerable number of electrolysis systems are also in place or planned. Both of these types of system can now be bought off the shelf, although prices are still high. The aim of each country is to set up refuelling sites in high density population areas, where vehicle manufacturers can sell/lease the first crop of FCVs. Lack of fuelling infrastructure, along with planned (i.e government led) investment is seen by vehicle manufacturers as the main impediment to the volume introduction of FCVs (Seymour, 2008).

3.1.5 Stationary Applications

These are widely regarded as an important early step in the uptake of a hydrogen energy carrier. Japan is pushing ahead with its Large Scale Residential FC (microCHP) programme. It has moved from the pilot field trial stage involving several hundreds of units from four manufacturer-gas supplier groups to a commercialisation phase. A standardised product operating on natural gas is being commercialised for the Japanese market by a number of companies including Matsushita (Panasonic), Sanyo and Ebara Ballard. Systems are nominally 1kWe, with co-produced domestic hot water. LPG and possibly kerosene versions are planned. The FC technology used in the first generation systems is low temperature PEM with a front end reformer. Some systems have achieved an overall peak LHV efficiency of 85%, almost double that of gas use in a central power plant. Government support is now being switched from developers to adopters. The Japanese residential market is expected to be 300,000 units in 2015, and prices per unit are projected to be around $US6,000 by that time. The Japanese government expects these systems to be installed in over 10 million homes, a quarter of all Japanese households, by 2020.

In the USA, Germany, Japan and Korea, MCFC (molten carbonate) technology is being commercialised for distributed CHP power. Korea, in particular, has started a commercial production programme that will eventually see a capacity of 50MW/yr produced. Installation of these 250-300 kW units commenced at the end of 2008. Fuels are natural gas and ADG (biogas). Claimed efficiency for these systems is 47% electrical and 85% overall through the external use of the co-produced heat.

3.1.6 Fuel Cell Technology Status

PEM fuel cell performance has now reached an adequate level of performance for compact vehicle applications. Most manufacturers have settled on 80-90kW as the market entry size. Adequate durability for vehicles of 5,000 hours is close to being achieved, but further work is required to achieve the 80,000 hours or 10 years service life desired for stationary applications. Governments are continuing to invest in both basic research to improve fuel cell technologies, but are also encouraging public-private partnership programmes to get vehicle applications in place. The major public-purse investment continues to come from Japan, USA, EU and individual EU States, with Korea, Russia, China and Brazil also active. Total public investment is well in excess of $2 billion per annum. Private investment is believed to be considerably greater although exact figures are not readily available.

> ***Future Research Focus:***
>
> *There remains no major technology show-stopper to the full introduction of hydrogen and fuel cells into light duty vehicle fleets.*
>
> *Vehicle R&D from this point will largely be focused towards the major goals of reducing costs and improving performance.*

Internationally, it is recognised that there are five major hydrogen energy thematic areas where RS&T advances are required. These are:

- Hydrogen production
- Hydrogen distribution and storage (both within the distribution system and on board vehicles)
- Hydrogen utilisation - fuel cell cost and performance and other end use technologies
- Development of appropriate regulations, codes and standards for safe utilisation of hydrogen as an energy carrier
- Public outreach - including pilots and demonstrations to increase acceptance of hydrogen and fuel cell technologies.

These themes are as relevant to New Zealand as they are to the international community. The following section considers New Zealand knowledge gaps associated with the themes, and identifies the priority research needed to fill them. It also considers existing capabilities and categorises the research needed to fill these gaps as being either:

- New Zealand specific (and therefore requiring a New Zealand led programme)
- Fast follower status
- A niche opportunity for New Zealand.

The knowledge gaps are also categorised as being driven by the need to address either:

- Technology showstoppers – where a major technology barrier needs to be overcome because there is no practical technology available
- Emissions focused – where the main focus is a need to reduce GHG and other air quality emissions
- Resources focused – where the main need is to extend or protect remaining resources including fuels, embodied materials, land use, etc. through measures such as energy efficiency and reduced use of limited resources in manufacture
- Economic focused – where the main focus is improved economic performance through lower costs.

3.2 Theme: Hydrogen Production

Hydrogen Production:

The four hydrogen production pathways best suited to New Zealand are:

- *Natural gas steam reforming*
- *Water electrolysis*
- *Coal gasification*
- *Biomass gasification*

The scenario analysis phase of the programme ("Hydrogen Energy Options: Scenarios, Sensitivities and Pathways (CRL Energy Report 08/11029) identified four hydrogen supply chains that are best placed to meet New Zealand hydrogen energy demand associated with the uptake scenarios. These are:

- Forecourt steam reformation of natural gas – in which natural gas is transported by pipeline to the service station, and converted in a small-scale steam reformer into hydrogen. It provides between 5 and 30% of hydrogen production needs across all scenarios.
- Electrolysis – in which grid electricity is used to convert water to hydrogen at a centralised plant and then piped to the point of use. It provides between 15 and 60% of hydrogen requirements.
- Coal Gasification – in which coal is gasified to produce syngas from which the hydrogen is separated and then piped to the point of use. This process requires the partnering CO_2 capture and sequestration technology to also be developed. It provides between 0 and 50% of hydrogen requirements.
- Biomass Gasification – in which biomass is thermally gasified to produce syngas from which the hydrogen is separated and then piped to point of use. It provides between 0 and 30% of hydrogen requirements.

The mix of chains varies with scenario and time. Initial commercial production will be through forecourt methods at existing or new service stations, either from electrolysis or steam methane reforming with the larger scale centralised plant based on gasification and electrolysis coming on-stream as demand grows.

The status of each technology, the issues and the research needed to resolve them are as follows.

3.2.1 Forecourt steam reformation of natural gas – knowledge gaps and priorities:

Steam reformation is a process in which natural gas is combined with water vapour endothermically at high temperature (700 to 850°C) to principally produce hydrogen and carbon monoxide. The process is normally carried out over a selective catalyst. A water gas shift reactor then converts the carbon monoxide to additional hydrogen (and carbon dioxide). The hydrogen is then separated and stored for dispensing.

While large-scale steam reformation is a mature technology widely used in the chemical and refinery industries, small-scale steam reformation is also a commercially available technology although at lower efficiencies and higher cost than its large-scale counterpart. Efficiency improvement requires improvements to the reformer. This requires development of improved catalysts for the reformer process. New Zealand has limited research capability in this area and fast follower status through international links is the most appropriate option.

Autothermal reformation is a high temperature (950 to 1100°C) and pressure (up to 100 bar) reformation process. This technology has the potential for higher conversion efficiencies particularly at the small scale suitable for distributed production (either for combined heat and power or at the forecourt). It is a complex process currently at the R&D stage. New Zealand has no particular research capability in this area and fast follower status through international links is again appropriate.

The reformation process, like the coal and biomass gasification processes considered below, requires hydrogen to be separated from the mix of gaseous products and purified. Improved membranes and adsorption materials for separation are required. New Zealand has a capability in high efficiency nano-porous membrane supports and selective surface deposition and this represents a niche opportunity.

Overall, the steam reformation process is seen as a low priority research area for New Zealand. We can reach fast follower status in this area by pilots/demonstrations identified under the Planning, Outreach and Demonstration theme. The niche opportunity in separation technologies can be addressed within research programmes relating to hydrogen production from coal and biomass.

3.2.2 Electrolysis – knowledge gaps and priorities:

Electrolysis is a mature large-scale technology in which electricity is used to split water into hydrogen and oxygen. If the electricity is produced from renewable resources such as wind and hydro, the hydrogen produced has a very low carbon footprint. Electrolysis is therefore of great relevance to New Zealand for production of renewable hydrogen both for use as an energy carrier and potentially for the upgrading of biofuels. The two main types of electrolyser that are currently commercially available at large scale are alkaline and polymer electrolyte membrane (PEM) electrolysers. New Zealand has capabilities relating to both alkaline and PEM electrolysers. Fast follower status is relevant for systems level technology, and there are niche opportunities in both cell and system development, including production of electrocatalytic particles for use in PEM electrolysis and deposition of hydrogenase on electrode surfaces.

A range of less mature electrolyser technologies could also provide improved conversion efficiency and assist the integration of hydrogen energy into existing energy systems. To this end, there is considerable interest in development of electrolysers that operate at elevated temperatures (700 to 1000°C) in which some of the water splitting electrical energy requirement can be replaced with heat. Potential sources include geothermal, solar and waste heat from fossil (or nuclear) power plants. Solid oxide electrolyser cells are of particular interest as a component of the high temperature process but there are challenges relating to the thermal stress limits of the materials used in the cells. New Zealand has limited capability and fast follower status is appropriate in high temperature electrolysis.

The use of large-scale energy storage to address the intermittency of electricity supply associated with wind, marine and wave power is also of increasing interest [Hynet, 2004, Zerta, 2007, Karlsson, 2008]. Hydrogen is produced when there is an excess of renewable electricity, which may then be used for transport or regeneration of electricity when demand exceeds supply. Recycling the hydrogen as grid electricity is not particularly cost effective due to the round trip conversion losses of over 50%, but sale of the hydrogen as a high-grade (low carbon) transport fuel is more attractive. This concept is particularly relevant to New Zealand, which plans to substantially increase the generation of wind sourced electricity. New Zealand has capability relating to use of electrolysers for load shifting and storage and the relevance of these techniques to intermittent renewable electricity generation in the New Zealand energy system warrants New Zealand led research status.

Indeed the "utopian" concept of two clean energy vectors, electricity and hydrogen operating in parallel, with electricity produced predominantly from intermittent renewables and hydrogen produced predominantly from hydrocarbon feedstocks, fits better with New Zealand situation than almost any other nation. Electrolysers at all scales are a key technology in this concept, providing the means to turn surplus intermittent electricity into stored hydrogen for transport fuel.

3.2.3 Coal gasification:

Large scale coal gasification is a mature technology in which carbon in coal reacts with steam to produce syngas – a mixture of hydrogen and carbon monoxide. It is used mainly for chemical production although it also forms the basis of the coal to transport fuels process that has operated commercially in South Africa since the 1950s and that is now beginning to expand to other areas of the world. There is also increasing interest in coal gasification as the enabling technology for reduced emissions electricity production – and a number of these plants are currently running as full scale demonstrations.

Production of hydrogen from coal for use as an energy carrier is a much less established technology and co-production of hydrogen with electricity or transport fuels is considered the best option for making hydrogen production from coal cost-competitive. Many of the more efficient gasification processes use oxygen rather than air as feedstock and a significant portion of the cost relates to the oxygen separation unit. Research is underway into development of oxygen separation membrane technologies. New Zealand has no particular expertise in oxygen separation membranes and fast follower status is appropriate.

An alternative solution is to feed the gasifier with oxygen produced from electrolysis – an option that is beginning to receive attention internationally, since the electrolysis "byproduct" hydrogen can be used directly as a high quality transport fuel. Use of low-cost surplus wind energy in the electrolysis plant could offer a strong synergy with the high wind penetration future planned for the New Zealand electricity system. New Zealand has capability in both electrolysis and coal gasification and the development of an integrated technology represents a significant niche opportunity.

In addition to containing hydrogen and carbon monoxide, syngas, as it emerges from the gasifier contains reduced sulphur gases, particulates, condensables, CO_2 and a range of trace impurities. There is considerable research into development of improved hot gas desulphurisation methods, improved shift reactor catalysts for increasing the yield of hydrogen, and improved hydrogen separation membranes – some of them capable of combined shift reaction and hydrogen separation. New Zealand has no particular research expertise in these areas but it is important to maintain fast follower status. Hot desulphurised syngas is highly corrosive and this is becoming an issue. New Zealand has expertise in corrosivity of reduced sulphur gases and a niche opportunity exists.

There is considerable research internationally into the development of improved, lower cost technologies for pre-combustion CO_2 capture (i.e. capture from syngas). New Zealand has capability in sorbent bed technology and a niche opportunity exists. In terms of options for geological sequestration of the CO_2 once captured – these are unique to every country. New Zealand has expertise relevant to CO_2 sequestration and a New Zealand led research programme is a high priority for filling this knowledge gap.

Variations in coal properties and the coal resource in each country means different behaviours during gasification. New Zealand has expertise in coal gasification and a New Zealand specific, New Zealand led research programme is a priority in addressing this knowledge gap.

3.2.4 Biomass Gasification:

Biomass gasification is a less mature process than coal gasification. It is also a fundamentally different one in that, rather than reacting with carbon (from biomass), the steam reacts with volatiles released from the biomass – in essence a form of steam reformation.

Nevertheless many of the gasification, clean-up and separation issues relevant to coal gasification are relevant to the biomass process as well. Many of the considerations applied above to coal again apply although the mandatory requirement for CO_2 capture and sequestration no longer exists and desulphurisation is likely to be much less of an issue. However processes to separate the hydrogen from CO_2 are still essential. The New Zealand capability in sorbent bed technology again represents a niche opportunity.

Research into co-gasification of biomass and coal is a rapidly emerging area internationally. One advantage of co-firing is that it spreads the risks of biomass availability and cost against a reduction in CCS requirements. The biomass resource, like the coal resource is New Zealand specific and has it own behaviour under gasification conditions. The behaviour of combined biomass/coal feeds will be even more unpredictable. New Zealand has capability in both coal and biomass gasification and a New Zealand led research programme is required to address knowledge gaps related to both biomass and coal/biomass co-gasification for hydrogen production.

Biofuel feedstocks can be converted directly to hydrogen by reformation, potentially improving the supply chain efficiency. New Zealand has expertise in this area and this represents a niche opportunity. The potential role of biomass in a New Zealand hydrogen energy system is relatively unknown and needs to be better defined. This represents a New Zealand led research requirement.

The situation in relation to Hydrogen Production research priorities is summarised in Tables 3 to 6.

Table 3: Knowledge gaps and NZ capability in hydrogen production from natural gas

AREA *Fuel: Natural Gas*	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Steam Methane Reforming	Efficiency improvement of small scale SMR systems	Catalysts	Economic	No - Fast follower	None
Autothermal Reformation	Improved high temperature performance	Reactor design	Economic	Yes - Fast follower	
Reformation	Improved hydrogen separation	Membranes and adsorption materials	Economic	Yes - Niche	

Table 4: Knowledge gaps and NZ capability in hydrogen production by electrolysis

AREA *Fuel: Electricity*	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Electrolysis	Improved alkaline electrolyser systems	Robust, high efficiency lower cost pressurised systems	Economic	Yes - Niche	Electrolysis using renewable electricity New Zealand led
Electrolysis	Improved PEM electrolysers	New high pressure cell stack design and lower cost polymer materials.	Economic	Yes - Niche	
High Temperature Electrolysis	High electrical conversion efficiency	Thermal stress and corrosion resistant materials, ionic conduction membranes	Technology / Economic	No - Fast follower	
Electrolysis systems integration	Hydrogen production from intermittent renewable electricity supply	H2 production and storage for buffering intermittent energy flows	Resource / Economic	Yes - New Zealand led	

Table 5: Knowledge gaps and NZ capability in hydrogen production from coal

AREA *Fuel: Coal*	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Gasification	Lower cost oxygen supply	Technologies for oxygen separation	Economic	Yes - Fast follower	Coal gasification New Zealand led
Gasification	Improved plant lifetimes	Corrosion resistant materials	Economic	Yes - Niche	
Gasification	Improved gasification performance	Catalysts for shift process	Economic	No - Fast follower	
Gasification	Applicability to local resources	Understanding coal behaviour	Economic	Yes - New Zealand led	
Hydrogen Separation	Improved hydrogen separation performance	Desulpuristion and separation technologies	Economic	Yes - Fast follower	Syngas cleanup and hydrogen separation Fast follower
CO2 Capture	Reduced cost CO2 separation	New and improved separation technologies	Economic/ Emissions	Yes - Niche	CO2 capture from coal feedstocks Fast follower
CO2 Sequestration	CO2 sequestration sites and capacity unknown	Improved models for geological structures, experimental verification	Emissions	Yes - New Zealand led	CO2 sequestration New Zealand led

Table 6: Knowledge gaps and NZ capability in hydrogen production from biomass

AREA *Fuel: Biomass*	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Preprocessing	Reduced processing costs	Woody biomass handling processes	Emissions	Yes - Fast follower	Biomass gasification New Zealand led
Gasification	Improved gasification performance	Improved catalysts for shift process	Emissions	No - Fast follower	
Gasification	Applicability to local resources	Understanding of biomass behaviour - cogasification	Emissions	Yes - New Zealand led	
Liquid Bio-fuels	Efficiency improvement of small scale systems	Reformation processes: microCHP,forecourt and central production	Emissions/ resource	Yes - Niche	
Best use of resource	Role of biomass in hydrogen production	Techno-economic modelling of the tree to wheel processes in NZ	Emissions	Yes - New Zealand led	
Hydrogen Separation	Improved hydrogen separation performance	Separation technologies	Emissions	Yes - Niche	Syngas cleanup and hydrogen separation Fast follower

3.3 Theme: Hydrogen Distribution and Storage

Hydrogen is distributed in cryogenic liquid form by tankers and as a gas using pipeline infrastructure. There is interest in use of existing natural gas pipelines for distribution. Research issues are related to embrittlement and diffusion losses. Since large scale distribution and storage are critical hydrogen technologies it is essential that the latest findings are applied in a timely manner, and so a fast follower role is appropriate for New Zealand.

For light vehicles compressed storage in high pressure tanks is viable and car companies such as Honda and Toyota are now demonstrating good driving range – and achieving the target 300 miles or 500 km - using high pressure tanks in their FCVs. BWM uses liquefied hydrogen storage in their H2-ICE BMW Series 7 vehicle. The energy cost for compression is not as high as commonly thought since it is frequently confused by the media with cryogenic liquefaction. Distribution and storage compression energy cost can be as low as 5 to 10% of the production hydrogen energy, due to pre-compression at manufacture. Research into reducing the costs of high compression technologies continues. New Zealand's role is that of a fast follower. This is not seen as a priority area for New Zealand research investment and new developments can be rapidly accessed through international linkages. New Zealand's role is that of a fast follower.

Both metal and chemical hydrides can achieve better volumetric hydrogen storage density than compressed gas or liquefied hydrogen. Metal hydrides work by distributing the hydrogen throughout the metal lattice. They are heavy and take time to charge, but have the ability to absorb and release hydrogen many times without deterioration. Chemical hydrides can store hydrogen energy at very high weight percentages (20% or more) but are difficult to manufacture and recycle due to various side reactions. This is a large research area internationally. New Zealand has capabilities in both metal and chemical hydride storage and these represent niche opportunities – probably through involvement within one of the large international programmes. Nano-composites are a further option for improved on-board hydrogen storage – a fast follower role for New Zealand is indicated in regard to that priority.

The situation is summarised in Table 7.

Table 7: Knowledge gaps and NZ capability in hydrogen distribution and storage

AREA	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Compression	Higher efficiency lower cost compression	mechanical, desorption and electroactive membrane compression technolgies	Economic	No - Fast follower	None
Storage	Improved storage density	Nanocomposites for high density physical storage	Economic	Yes - Niche	Storage in chemical and metal hydrides Fast follower / Niche
Storage	Improved storage density	Release and uptake mechanisms in chemical hydrides	Economic	Yes - Fast follower	
Storage	Improved storage density	Improved metal hydride storage	Economic	Yes - Niche	
Distribution	How to use existing and new pipelines	mixed delivery in NG pipelines, performance of new pipeline materials	Economic	Yes - Fast follower	Transmission and distribution by pipeline Fast follower

3.4 Theme: Hydrogen Utilisation – Fuel Cells and Other Technologies

The two key issues for hydrogen utilisation are fuel cell cost reduction and improved durability. For transport systems, cost reduction is the major issue with a 5 to 10 fold reduction still necessary. On the other hand, for stationary applications durability needs to be increased 5 to 10 fold to achieve 10 years operational life.

Early markets for power fuel cells (as opposed to portables) are in remote communication site back up power, fork lift trucks, natural gas CHP cogeneration and a range of small vehicles/scooter applications.

Hydrogen Fuel Cells:

The main research challenges are cost and durability. These are now being addressed in a commercialisation environment – but still with substantial injections of materials research and technology demonstration funding from governments concerned abut the international competitiveness of their future industries, and their transport fuel options.

Most of the priorities relate to improved cost and performance of fuel cells – including reduction in catalyst loadings, metal recovery and use of non-noble metal catalysts. New Zealand has limited capability in the area of fuel cell development but understanding the relevance of fuel cells is a priority area. Fast follower status can be maintained by direct involvement in pilots and demonstrations involving fuel cells. A niche opportunity exists in relation to hydrogen utilisation in other technologies including hydrogen engines and combustion systems.

The situation is summarised in Table 8.

Table 8: Knowledge gaps and NZ capability in hydrogen energy utilisation

AREA	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Fuel cells	Fuel Cell failure modes	Causes of off-specification fuel cell performance	Resource/ Economic	No	Fuel cell technology and systems Fast follower
Fuel cells	Improved Solid Oxide Fuel Cells (SOFCs)	Lower temperature, more robust SOFC stacks	Resource/ Economic	No	
Fuel cells	Improved Proton Exchange Membrane (PEM) fuel cells	High temperature PEMs	Economic	No	
Fuel cells	Improved Proton Exchange Membrane (PEM) fuel cells	Membranes for wider range of temperature and humidity	Economic	No	
Fuel cells	Smaller, lighter fuel cells for portable application	Improved methanol fuel cells	Economic	No	
Hydrogen turbines	Large scale stationary generation	Heat resistant materials and coatings, maximised efficiency	Emissions	No	Other end-use technologies Fast follower
Hydrogen reciprocating engines	Improved efficiency and lower emissions	Engine systems and management	Resource	Yes - Niche	
Hydrogen burners	Safe, efficient, low emission combustors for heat production	Combustion systems and management	Resource	Yes - Niche	

3.5 Theme: Regulations, Codes and Standards

Hydrogen is a common industrial gas, and has been in use for over a century in a wide variety of work environments. However for widespread integration into the energy supply infrastructure appropriate local standards must be developed or adopted. Existing general hazardous gas regulations are designed specifically for industrial installations. Technical standards and guidelines are primarily required for fuel cell systems in two areas – hydrogen safety and electrical safety and interconnection. For hydrogen safety this relates to clearly defining ventilation and explosion proofing requirements for hydrogen in a non-industrial setting. An immediate issue relates to the safety for small-scale own use systems, as these are likely to be the first to be introduced. For electrical safety, framework regulations are already in place for small (< 10 kW) units, but some special measures may be necessary for hydrogen fuelled electrical systems.

For transport systems, vehicles will be manufactured to standards that apply in the country of origin. However, refuelling station standards will need to addressed in the New Zealand context. The IPHE and IEA are active in attempting to standardise hydrogen refuelling station codes and standards and this is an important area for further effort. In most cases New Zealand will play a role of fast follower but the regulations, codes and standards developed internationally will have to be incorporated into a New Zealand framework. This requires a New Zealand led programme but the capability needs to be developed. The situation is summarised in Table 9.

Table 9: Knowledge gaps and NZ capability in hydrogen energy regulations, codes and standards

AREA	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Codes and standards	Lack of consistency in fuel cell assessment methods	Benchmarking and validation of methods for characterising FC systems	Economic	No	None
Codes and stardards	Benchmarking and performance of storage systems	Synthesis, handling and utilisation risks for storage materials	Economic	No	
Regulations	Fuel cell system safety	Standardised approvals for fuel cell system safety	Economic	No - Fast follower	Applicability of RCS to safety of hydrogen energy in New Zealand New Zealand led
Regulations	Fuelling station safety	Standardised technical guidelines and approvals for fuelling stations- to ISO standard	Economic	No - Fast follower	
Regulations	Vehicle safety	Hydrogen leakage modes and crash performance in vehicles	Economic	No - Fast follower	
Regulations	Adaptation of RCS to country framework	Understanding of the relevance of RCS to New Zealand	Economic	No - New Zealand led	

3.6 Theme: Planning, Outreach and Demonstrations

Internationally, public outreach covers a wide range of activities and target audiences including policy makers, industry, educators, and the general public. The message needs to be pitched to the appropriate level for each.

Planning for a hydrogen infrastructure and development of national roadmaps is also seen as a key priority for government involvement. Roadmaps inform policy makers, industry and the general public of the nature and implications of a transition to hydrogen energy and identify the key steps in getting there. Roadmaps must be based on the most accurate and up to date information available on technology expectations and cost projections, and the analysis of country specific hydrogen production routes, supply chains and consumer use. Energy system modelling is required to understand the impact of hydrogen as a parallel energy vector. Many countries have already developed and endorsed their roadmaps – each varies considerably in terms of focus and breadth. Some are primarily based on technology improvement, some on the role of hydrogen within future energy systems. Integration of hydrogen energy systems into the New Zealand energy mix is a New Zealand specific activity requiring New Zealand led research involvement.

High profile demonstrations of hydrogen and fuel cell technologies – whether as part of a transport fleet trial or in a stationary application – are critical in raising awareness and acceptance of fuel cell and hydrogen technologies. New Zealand currently has no such profile in regard to transport but needs to develop it. In terms of stationary demonstrations New Zealand does have capabilities and these should be included within niche opportunity based research activities.

Education is a broad topic and of necessity needs to be New Zealand specific. Engineering and trade educational courses will need to be set up to prepare the skills base for the technology uptake phase. Hydrogen energy needs to be on the curriculum of schools, polytechnics and universities. The situation is summarised in Table 10.

Table10: Knowledge gaps and NZ capability in hydrogen energy outreach

AREA	INTERNATIONAL KNOWLEDGE GAP	RESEARCH ACTIVITIES	MAIN NZ DRIVER	NZ CAPABILITY AND NEED	NZ RESEARCH FOCUS
Outreach	Coordinated understanding of why hydrogen is an important energy carrier	Analysis of hydrogen technologies and systems to identify best options for New Zealand	Economic/ Resource/ Emissions	Yes - New Zealand led	Modelling and analysis of hydrogen technologies and systems New Zealand led
Planning	How to integrate hydrogen into the future energy system	Systems modelling and analysis to contribute to a New Zealand roadmap	Economic/ Emissions	Yes - New Zealand led	
Planning	Understanding of hydrogen markets, commercialisation, policy and business strategy	Systems modelling and analysis	Economic	Yes - New Zealand led	
Demonstration	Lack of specific knowledge of residential, commercial and industrial hydrogen energy and fuel cell applications	Demonstrations and analysis of residential, commercial and industrial fuel cell applications	Economic/ Emissions	Yes - New Zealand led	Hydrogen energy system demonstrations /pilots New Zealand led
Demonstration	Lack of specific knowledge of fuel cell vehicle applications	Demonstrations and analysis of fuel cell vehicle applications	Economic/ Emissions	No - New Zealand led	
Outreach	Lack of formal education and training programmes	Input to the development of programmes at all levels of society - masterclasses, courses, seminars, workshops	Economic/ Emissions	No - New Zealand led	Education and training New Zealand led

Virtually all of the technology based research needs identified in these tables are aimed at achieving cost reductions to make hydrogen energy more competitive. The remaining “show stopper” barriers to hydrogen energy and fuel cell are now primarily political and institutional.

The above sections have:

- Identified a target hydrogen uptake profile
- Identified the major themes, knowledge gaps and priority research areas associated with hydrogen as an energy carrier
- Identified the means for addressing them either through New Zealand led research, maintaining fast follower status or exploring a niche opportunity.

A research strategy is now discussed. It is recognised that the parallel development of business opportunities for New Zealand companies is critical and the Research Strategy must facilitate this as much as it is possible to do so. Activities for early engagement with New Zealand technology providers, the building of a new support industry sector and the identification and development of business opportunities – including export opportunities – are included in the Strategy.

4 A Hydrogen Energy Research Strategy

A research investment strategy is required to enable many of the milestones associated with the vision for hydrogen uptake to be realised. This section combines the findings relating to the targeted hydrogen uptake profile, required outcomes, strategic themes, knowledge gaps and priority research areas to develop a research strategy.

4.1 The period to 2015.

Outcomes may not be realised until the *Uptake, Market Growth* and *Consolidation* stages, but it is in the initial stages - *Planning* and *Laying the Basis* – that government policy commitment and research investment are most critical. Private investment in production plants and infrastructure requires the confidence that there will be a growth in demand engendered through government leadership in transformation of the transport system.

During the period to 2015, in order to support the three major hydrogen energy uptake outcomes identified, investment is required in each of the five strategic themes. New Zealand already has a developing capability in most of the priority area within each theme. Priority areas where this is not the case are designated "Required."

A research strategy must contribute to the three overarching outcomes needed for transitioning to the use of hydrogen as an infrastructure fuel. The research priorities and the knowledge gaps that must be filled are aligned below under the relevant outcome. It is during the time up to 2015 that government research investment is most critical.

Outcome 1: Hydrogen roadmap completed

Strategic Theme: *Planning, Outreach and Demonstrations*

Because it involves the planning for integration of a new energy system into New Zealand's existing infrastructure, research contributing to Outcome 1 must be New Zealand led.

Research Priority:

- Modelling and analysis of hydrogen technologies and systems (New Zealand led)

This Priority is required to fill knowledge gaps including:

- How to integrate hydrogen into the future energy system
- Coordinated understanding of why hydrogen is an important energy carrier
- Economic and environmental factors associated with liquid fossil and biofuels, hydrogen and electricity
- Latest vehicle options including hybrid combinations and plug-ins
- Costs associated with maintaining the existing system, oil price scenarios, late transformation to alternative fuels, sunk assets and safety compliance
- Impacts of transferring the transport energy supply chain from external to internal resources.

The research investment supports:

- A comprehensive internationally benchmarked roadmap to hydrogen uptake (2010).

Outcome 2: Hydrogen production pathways secured

Because supplies of hydrogen will be NZ specific, key research contributing to Outcome 2 needs to be New Zealand led.

Strategic Theme: *Hydrogen Production*

Research Priorities:

- Electrolysis using renewable electricity (New Zealand led)
- Coal gasification (New Zealand led)
- Biomass gasification (New Zealand led)
- Syngas clean-up and hydrogen separation (Fast follower)
- CO_2 capture from coal feedstocks (Fast follower)
- CO_2 sequestration (New Zealand led)
- Business opportunities from hydrogen production (New Zealand led)

These Priorities are required to fill knowledge gaps including:

- Integration and impacts of hydrogen production on the existing and future energy resources and infrastructure, including renewable resources and electricity supply
- In-depth understanding of behaviour of New Zealand biomass and New Zealand coal during gasification
- Applicability to local resources
- Role of biomass in hydrogen production
- Carbon footprints and means for reduction
- Business opportunities (including export).

The research investment delivers:

- Proof of concept technology packages including early engagement of New Zealand technology providers (2015).

The research investment subsequently leads to

- Pilot scale demonstrations (2020)
- Large scale centralised and industrial tri-generation plants (2035).

It is important to achieve development of proof of concept technology early to allow sufficient time for industry buy-in, up-scaling and trialling at pilot scale and subsequent construction, commissioning and operation of full-scale plant necessary to achieve the overarching Outcome. Research into business opportunities and inclusion of industry in the building of experimental plants creates the base for a new support industry sector to develop.

Outcome 3: Transition to the use of hydrogen energy achieved

Because the RS&T associated with the distribution and use of hydrogen energy is so extensive and much of it is being undertaken internationally, key research contributing to Outcome 2 needs to be a mix of New Zealand led and fast follower. Several strategic hydrogen energy themes are involved.

Strategic Theme: *Hydrogen Distribution and Storage*

Research Priorities:

- Storage in chemical and metal hydrides (Fast follower / Niche)
- Transmission and distribution by pipeline (Fast follower)

Strategic Theme: *Hydrogen Utilisation*
Research Priorities:

- Fuel cell technology and systems (Fast follower)
- Other end-use technologies (Fast follower/Niche)

Strategic Theme: *Regulations, Codes and Standards*
Research Priorities:

- Applicability of RCS to Safety of Hydrogen Energy Use in New Zealand (New Zealand led)

Strategic Theme: *Planning, Outreach and Demonstration*

Research Priorities:

- Modelling and analysis of hydrogen technologies and systems (New Zealand led)
- Hydrogen energy system demonstrations/ pilots (New Zealand led)
- Education and training (New Zealand led/required)
- Comparison of technology requirements with New Zealand industry capability. (New Zealand led)

to fill knowledge gaps related to:

- Fuel cell, refuelling station and vehicle safety
- understanding of hydrogen markets, commercialisation policy and business strategy
- Integration of overseas technologies into New Zealand market conditions
- Business opportunities for New Zealand developed IP
- Introduction and running of small-scale CHP installations
- Specific knowledge of hydrogen and fuel cell applications
- Improved storage density
- Pipeline distribution
- Improved fuel cell performance and durability.

The research investment contributes to:

- Three refuelling stations (2015)
- A 100 unit residential CHP trial (2015).

The research investment subsequently leads to:

- 200,000 FCVs on the road (2020)
- 2.6 million FCVs on the road (2050)
- 700+ refuelling stations (2050)
- 25,000 residential CHP units in place (2020)
- hydrogen CHP units installed in up to 5% of residential and commercial sites (2035).

The investment also leads to significant local manufacturing input into the New Zealand hydrogen infrastructure and further develops export opportunities for New Zealand businesses.

4.2 Beyond 2015

During the Technology Uptake Stage (2015 to 2020), the need for government investment in research for large-scale co-production plants gradually tails off as industry investment in infrastructure increases. There will be an on-going need for improving processes – development of better hydrogen separation techniques, development of improved materials and catalysts, improved electrolysers and fuel cell stacks – in some cases New Zealand will be a fast follower through its on-going involvement in the international research community but in others, niche opportunities will arise.

Detailed infrastructure planning, with co-funding from industry, to support the development of the New Zealand Hydrogen Highway begins during this period.

During the Market Growth (2020 to 2035) and Market Consolidation (2035 to 2050) phase, the benefits of the research investment made in the previous three phases will be seen through commercialisation. Improvements will continue to be made to the hydrogen production and utilisation technologies. These may require some level of government investment but much of the investment will come from global industry stakeholders.

An overview of the above research strategy is summarised in Figure 3. It is arranged as two main work streams. The first work stream consists of short-term research programmes necessary to provide early and intermediate input to roadmap activities. The second work stream is a set of ongoing longer-term programmes designed to have impact in both the short and the longer term. The shading is intended to convey the transition from government to industrial end user research investment.

The overall role of the research strategy in contributing to a transition to hydrogen energy is shown in Figure 4. The role of the research strategy is to inform and support the development of a roadmap and support the implementation of an overall hydrogen energy strategy designed to achieve the required outcomes.

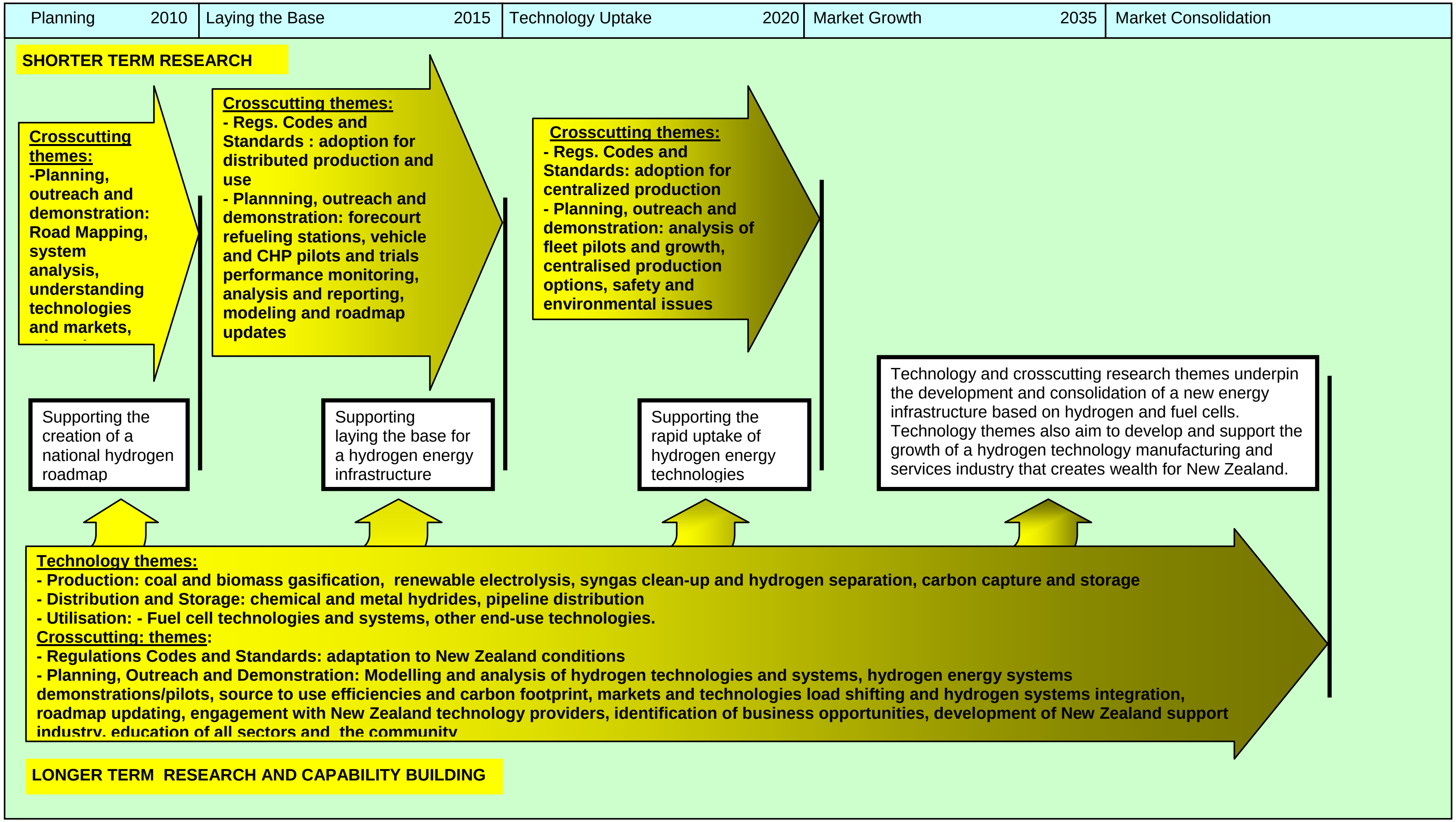


Figure 3: Proposed Research Plan for the uptake of hydrogen energy and fuel cells in New Zealand

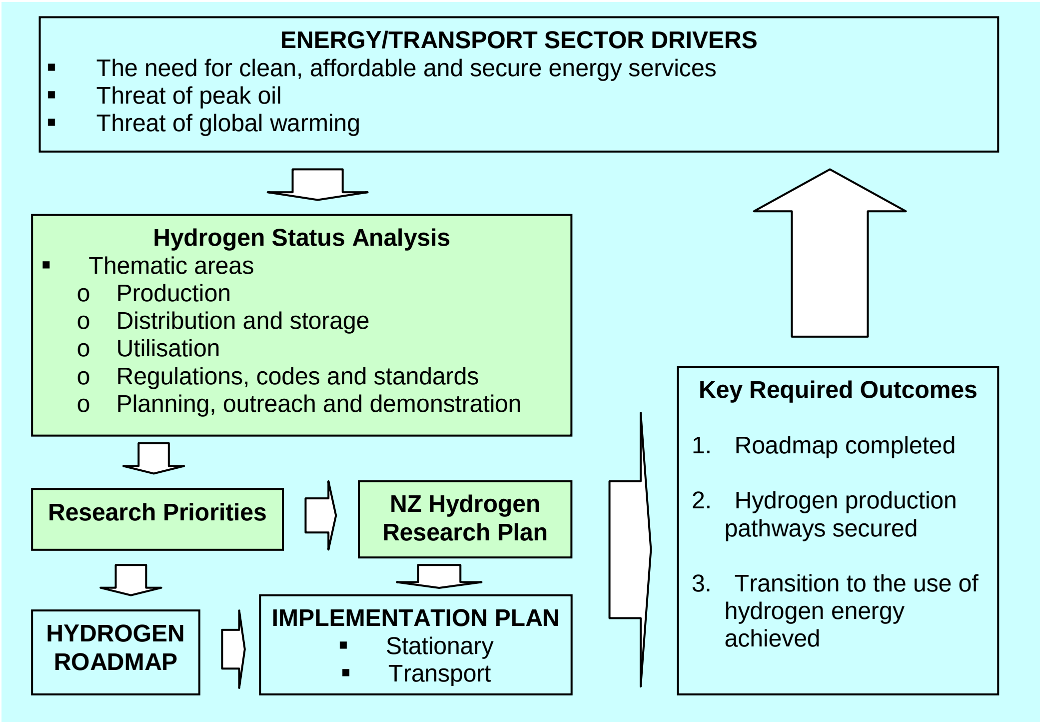
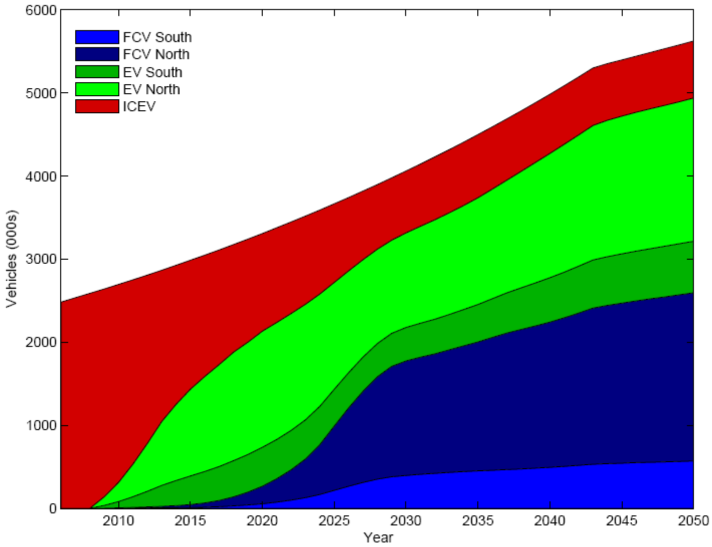


Figure 4: Role of Research in the Hydrogen Energy Transition

5 Alignment with the BioEnergy Strategy

The present study was undertaken in the context of the Energyscape suite of research assessments, involving a broad view of the future energy needs of New Zealand, and the role of research in contributing to them. In order to see where the hydrogen strategy aligns with these broader programmes it is helpful to reconsider the future transport uptake scenario around which the strategy is designed (Figure 1 reproduced below).



The preceding sections of this report concentrate solely on the role of research investment in supporting the hydrogen FCV uptake curve (the blue areas). Similar questions in relation to battery electric vehicles (the green areas) are considered within the NIWA led Energyscape programme.

The Bioenergy R&D strategy developed by SCION and the hydrogen strategy align in two ways. One is the ongoing future use of biofuels in a portion of the conventional ICE fleet. Biofuels research can address the need to ensure that the fuel used within the remaining ICE fleet (the red area in the above Figure) transitions to renewable sources. The bioenergy strategy assumes that future demand for biofuels will be greater than that in the above Figure, but whatever the final mix between ICE, FCV and BEV, it is necessary to ensure that ICE vehicles ultimately use renewable fuels. It should also be noted that a potential additional use of hydrogen is in the upgrading of biofuels. The importance of this use, as against use as an energy carrier, will depend on the balance between demand for biofuels and hydrogen FCVs in the future transport mix.

One of the potential hydrogen supply chains involves biomass. The Bioenergy strategy proposes that much of the biomass energy resource in New Zealand is likely to come from purpose grown forests. Studies suggest that an energy chain involving direct use of hydrogen in fuel cell vehicles, produced by gasification of woody biomass crops, provides both a high energy out for energy in ratio, and low overall GHG emissions. Prospective wood to hydrogen energy efficiencies of 30-60% have been reported (Lv et. al., 2007). If large scale process technology can be developed to deliver this performance the option should be given close examination in the New Zealand context. It will be recalled that biological routes from biomass to hydrogen were not chosen by the scenario analysis carried out during the development of the Hydrogen strategy, because they are not sufficiently mature to allow realistic assessment. Anaerobic digestion and fermentation processes for production of liquid biofuels are assessed under the BioEnergy strategy. The conversion of liquid biofuels to hydrogen is receiving increased attention due to the relatively high potential efficiency.

Figure 5 shows the alignment between the biomass and hydrogen studies. The hydrogen research strategy addresses the red lines, the bioenergy strategy addresses the green lines.

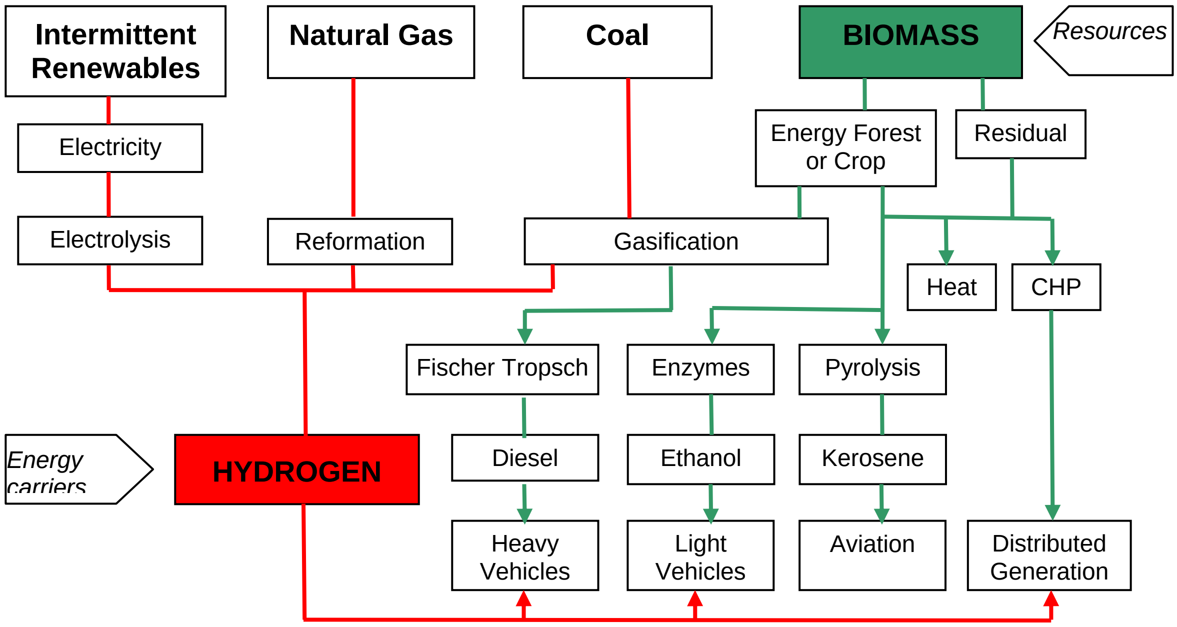


Figure 5: Alignment of Hydrogen and BioEnergy Research Strategies

The Figure shows that the biomass and hydrogen energy strategies are complimentary:

- Gasification of biomass (wood residues in particular) could be a significant source of renewable hydrogen
- Reformation of bio-ethanol is another means of hydrogen production and also represents an opportunity for closer integration of research in these two areas. The reformation process can be applied to unrefined aqueous feedstock.

Keeping options open is an important risk mitigation strategy for New Zealand. Both liquid biofuels and hydrogen are likely to have a significant role in oil replacement.

6 Concluding Remarks

Overall, the Transitioning to a Hydrogen Economy programme confirms that hydrogen can contribute strongly to transitioning away from the present dominance of imported oil for fuelling New Zealand's transport fleet. Continuing high and fluctuating oil prices will ultimately force the transport fleet to undergo major changes. With planned and timely uptake, hydrogen FCVs offer a robust and economic option capable of delivering significant cost benefits and emission reductions.

New Zealand can choose to be either an early or late adopter of hydrogen fuel cell vehicles. This study shows that the cost of being late could be very high.

A significant level of vehicle penetration will take 15 to 20 years to achieve. If we begin planning now for the introduction of FCVs as soon as they become available, the New Zealand economy can hugely benefit by avoiding continued dependence on imported oil, as well as providing a further flexible option for decarbonising the energy sector and reducing CO_2 emissions.

The cost of moving forward now is very modest in relation to the future benefits.

The steps required to move forward are outlined in this document.

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8 List of Project Publications

1. Transitioning to a Hydrogen Economy – Issues Document.
CRL Energy Report # CRL 07/11009
May 2007.

2. Transitioning to a Hydrogen Economy – Identification of Preferred Hydrogen Chains
CRL Energy Report # CRL 07/11034
November 2007.

3. Regional Scenarios for the Development of a Hydrogen Economy in New Zealand
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9 Acknowledgments

We would like to thank the Foundation for Research Science and Technology for their investment into this project.

We also wish to thank the programme Steering Group and Targeted Stakeholder Group for their many helpful insights and guidance throughout the duration of this project.

Appendix: The IPHE Hydrogen and Fuel Cell Brief for Policymakers

An introduction for policy makers prepared by the International Partnership for the Hydrogen Economy

International Partnership for the Hydrogen Economy

HYDROGEN AND FUEL CELL BRIEF FOR POLICYMAKERS

HYDROGEN AND FUEL CELL BRIEF FOR POLICYMAKERS

I. Executive Summary

Hydrogen and fuel cell research and development focuses on enabling the widespread use of hydrogen as an energy carrier to increase energy security and improve the environment by reducing greenhouse gases and other emissions. This brief for policymakers summarizes the state of existing hydrogen-related technologies; the main technical and socio-economic challenges that remain; and offers a comparison and contrast of hydrogen and fuel cells with conventional energy technologies for stationary and transportation applications.

A review of the existing hydrogen infrastructure and the use of stationary and fuel cell applications worldwide shows that hydrogen production is around 60 million tons per year (TPY), energy equivalent to 4.3% of current oil production per year. The fuel cell industry to date has produced 3000 portable, 800 large stationary fuel cell units, well over 3000 small stationary units, 600 light duty fuel cell vehicles, 62 fuel cell buses and more than 600 small mobile applications. In addition, the current hydrogen infrastructure includes 3000 kilometers (1864 miles) of hydrogen pipeline primarily dedicated to hydrogen use for industrial activities and 100 operating hydrogen fueling stations to support vehicular applications.

Governments and industry are increasing investments in research and development (R&D) to meet cost and performance requirements for technologies that produce, deliver, store, and use hydrogen in fuel cells for stationary, portable, and transportation applications. Investments are being made to address the barriers outlined below in order to build a hydrogen delivery infrastructure, develop safety codes and standards, and educate decision-makers, customers, and the future workforce about hydrogen and fuel cell technologies. Global public and private R&D investment for hydrogen and fuel cells is estimated to be 1.0 billion and 3-4 billion US$ per year, respectively. Additionally, ongoing demonstration projects are assessing hydrogen and fuel cell technologies, helping to identify key issues and provide feedback to researchers. These projects also serve to familiarize and educate the public on hydrogen and fuel cell technology.

Accelerating the adoption of hydrogen and fuel cell technologies cannot occur without the support of a policy framework that emphasizes critical research and development, creates business opportunities that encourage investors' confidence, and facilitates market development. Government policies are needed to 1) enhance societal benefits such as global climate change, reduction of oil combustion and clean air quality; 2) help build infrastructure in areas where there is limited demand and a need for additional fueling stations; and 3) support the initial production of fuel cell vehicles and stationary fuel cell applications, and stimulate early market development by purchasing first generation products.

II. Introduction

Hydrogen Vision

A vision for widespread hydrogen and fuel cell use…..

> *Imagine driving a fuel cell vehicle, which is indistinguishable from vehicles currently available with one notable exception, the fuel cell vehicle drives virtually silent and emits zero pollution. The local hydrogen refueling station also looks and operates the same as today's gasoline fueling station - a hose attaches to the vehicle, a lever is turned to create a seal and pumping begins. Upon returning home, the garage door is opened using electricity supplied through a stationary fuel cell powered by hydrogen delivered to your house through a pipeline system modeled after the current natural gas distribution system. In fact, the stationary fuel cell provides electricity and heating needs for the entire home and has the potential to feed electricity into the regional electrical grid.*

We are close to achieving this vision with existing technologies but at a price too high for the average consumer. To achieve this vision, several technical, economic and institutional challenges must be overcome. Policymaking can play a crucial role by fostering international cooperation and by directing industrial development in the areas of research, development and deployment (RD&D), setting legal requirements and stimulating early market development by purchasing first generation products

The energy needed to produce hydrogen can be obtained from many sources, including fossil fuels and renewable energy. When combined with carbon capture and storage, hydrogen production holds the promise of a plentiful fuel that will help safeguard the world's climate system. A growing number of countries have recognized the benefits of hydrogen technologies and have committed resources to accelerate the development of hydrogen and fuel cell technologies to improve their energy, environmental and economic security. Seventeen governments are currently participating in the International Partnership for the Hydrogen Economy (IPHE), which serves as a mechanism to organize and implement effective, efficient, and focused international research, development, demonstration and commercial utilization activities, to accelerate the development and commercialization of hydrogen and fuel cell technologies (more information is available at www.iphe.net).

The main objective of this brief is to serve as a guide to policymakers and stakeholders as they address the research and commercialization of hydrogen-related technologies. It briefly summarizes the state of existing technologies; the main technical, economical and institutional challenges; and it offers a comparison and contrast of hydrogen and fuel cell technologies with existing energy technologies for stationary and transportation applications.

III. Current Hydrogen and Fuel Cell Technology Applications in the Marketplace

Energy Conversion Technologies

Hydrogen can be converted to energy via traditional internal combustion engines (ICE), generating mechanical energy, and via fuel cells, producing electricity. Engines can combust hydrogen in the same manner as gasoline or natural gas - but with a higher efficiency and without producing harmful emissions. Hydrogen combustion applications being developed today include the re-design of combustion equipment for power generation turbines, allowing them to use hydrogen fuel, and ICEs for vehicles. Many countries consider hydrogen internal combustion technologies to be a transitional technology; the ultimate goal is to use fuel cells because of their greater efficiency when compared to ICEs. Fuel cells use the chemical energy of hydrogen to produce electricity and thermal energy. There are many types of fuel cells with differences primary based on their components, i.e. membrane materials or electrolytes. As a result, each fuel cell type offers its own operating characteristics and has different application opportunities. For example, some fuel cells have the potential to replace batteries for consumer electronics, some types can be used for stationary power sources for homes and buildings, and others have promising applications in the transportation sector.

Today, most hydrogen is produced from natural gas and is utilized in the industrial sector for non-energy purposes. The total worldwide hydrogen production is estimated to be around 60 million tons per year (TPY). [i] This is energy equivalent to 4.3% of current yearly oil production. To put this into perspective, to supply worldwide demand for the current estimate of 600 million passenger cars, approximately 120 million tons of hydrogen - twice the current production level - will need to be produced annually.[ii] There are now about 3000 kilometers (1864 miles) of hydrogen pipeline worldwide, which are primarily dedicated to hydrogen delivery for industrial activities. This represents about 0.23% of the existing pipeline infrastructure for natural gas (1,295,421 kilometers, 804,937 miles).[iii] In addition, some new hydrogen infrastructure has been built for demonstration projects. For example, there are about 100 hydrogen fueling stations currently operating worldwide[iv] that look much like modern gas stations, only with a gaseous or liquid hydrogen dispenser instead of traditional gasoline or diesel hoses. In most of these stations, hydrogen is either delivered to the station via truck from a centralized location, similar to gasoline, or is generated on-site through the use of reformers, which produce hydrogen from natural gas or other liquid fuels, or using electrolyzers that use electricity to produce hydrogen from water. The hydrogen is then stored in tanks that are sited either below-ground like gasoline, or above-ground, like propane gas. A recent experiment comparing a hydrogen fuel cell car experience with that of a traditional car confirmed that refueling a fuel cell car is not much different from refueling a traditional car in terms of daily driving demands, in that the pumping is similar and the process only takes a few minutes.[v]

Stationary Applications

Hydrogen turbine technology coupled with carbon sequestration is an environmentally sound alternative that allows for central and distributed power generation from fossil fuels with zero emissions. In the process, fuels like heavy oils, residue coke or coal are first converted to hydrogen and CO_2 gases, the gases are then separated, the CO_2 is captured and sequestered while the hydrogen gas stream can be used to fuel a gas turbine to generate electricity. Alternatively, the hydrogen can be used as feedstock in transportation fuel cells. Design studies performed by major turbine manufacturers have indicated that the modifications needed to convert existing combustion turbines are technically feasible today.

Stationary fuel cells are essentially compact power plants that offer the benefit of producing power close to the end user, rather than connecting to the electrical grid. Stationary fuel cell units use pure hydrogen or hydrogen-rich fuels to produce electricity. They can be used not only to provide power but also to produce heat. These energy systems are scaled according to their output capacity - larger units can generate electricity greater than 10kW and smaller units generate from 1kW up to 10kW of electricity. The benefits of stationary fuel cells include lower emissions, lower noise, and higher efficiencies compared to conventional technologies. Residential stationary fuel cell units have been designed to be easily moveable through standard doorways and are similar in size to standard boilers or water tank systems. These are adapted to fit the current home energy model and can be fueled by natural gas or propane. At the end of 2005, there were close to 800 large stationary fuel cell units and well over 3000 small stationary units being demonstrated around the world.

Transportation Applications

Prototype hydrogen-powered vehicles come in all shapes and sizes, and include passenger cars, light trucks, sport utility vehicles and buses. Hydrogen-powered vehicles are on the road today and people may not have even noticed anything unique about them. In most cases, their exterior and interior characteristics are similar to traditional models, with a key difference concealed - the vehicle is powered by hydrogen. In the case of fuel cell vehicles, there is an electric engine rather than an internal combustion engine. During the Clean Urban Transport for Europe (CUTE) trial project, bus drivers found that fuel cell bus characteristics were the same or better than conventional buses. In 2003, there were at least 66 prototype hydrogen-powered vehicles with modified internal combustion engines (ICE) on the road.[vi] In 2004, there were an estimated 600 light duty demonstration fuel cell vehicles worldwide[vii] and at least 65 fuel cell buses and 50 hydrogen powered ICE operating on a daily basis worldwide.[viii]

Early Markets and Portable Applications

Early market fuel cell applications include a broad range of systems including auxiliary power units, uninterruptible power supply, forklifts, locomotives, maritime applications, scooters/motorbikes, wheelchairs, robots and bicycles. These applications have two major advantages 1) they provide an initial revenue stream for companies, which are often small and medium enterprises without much capital stock, and 2) the early market experience contributes to the development of the technology. The use of materials handling equipment like forklifts has been recognized as a promising niche market and as an important stepping stone to the broader commercial introduction of fuel cell technology in vehicular applications. For example, demonstration projects have shown that conventional battery-operated forklifts outfitted with fuel cells have demonstrated advantages in refueling downtime and power consistency.[ix] Moreover, a recent market analysis on forklifts estimated that 260,000 battery-powered forklifts will be sold in 2005, increasing to 350,000 by 2010, and that the market for forklift batteries is worth between $2 billion and $3 billion a year. The cumulative number of niche fuel cells in transportation systems in 2005 was estimated to be well above 600 units.[x]

Another market for fuel cells is portable devices. Tiny fuel cells that act like batteries have the potential to power small appliances like laptop computers, cameras, and flashlights, and can be refueled using small hydrogen or methanol cartridges that are inserted into the device. In 2005, close to 3,000 of these new portable fuel cells were manufactured worldwide.[xi]

IV. Technical Barriers to Full Market Penetration

Many of the technical barriers to a commercially viable hydrogen economy span the functional areas of production, storage, and use. These individual segments mutually support one another; therefore, overcoming the barriers requires an integrated approach in which advances in one area stimulate progress in another. Today, governments and industry are increasing investments in technology R&D to meet cost and performance requirements for technologies that produce, deliver, store, and use hydrogen in fuel cells for stationary, transportation, portable and early market applications. In addition, investments are also being made to build a hydrogen delivery infrastructure, develop safety codes and standards, and educate decision-makers, customers, and the future workforce about hydrogen and fuel cell technologies.

Hydrogen Production, Delivery, and Storage

Researchers are developing a wide range of technologies to overcome technical barriers to large-scale hydrogen production. Because most hydrogen produced today is generated from hydrocarbons, its production results in a great deal of carbon dioxide (CO_2) being released into the atmosphere. In order to realize the full environmental benefits of hydrogen, it is critical to improve the efficiency and reduce the cost of production, while enabling technologies that either capture and store carbon from fossil fuel sources, or that use renewable resources like solar power, wind, or nuclear energy to generate hydrogen via electrolysis.

An important advantage to using hydrogen as an energy carrier is that it can be produced either at a large centralized plant, or on-site with small distributed production units at the point of use. Hydrogen produced at centralized large facilities can be distributed efficiently in large volumes via pipeline, similar to natural gas and oil. However, because current market demand is low and transport can be expensive, hydrogen is generally used at the same site it is produced. In the near future, as demand increases, hydrogen will be economically produced in semi-central locations (25-100 miles from point of use) and transported to the end user in trucks as compressed gas or super-cooled liquid or by using existing infrastructure including pipelines.

A critical barrier to the use of hydrogen as a transportation fuel is finding safe, low-cost, light-weight, and low-volume hydrogen storage technologies. Existing high pressure hydrogen storage systems in prototype hydrogen-powered vehicles offer limited driving ranges and less cargo space than conventional gasoline-powered vehicles. Alternative storage methods, such as materials-based technologies, have the potential to store more hydrogen than a traditional tank of similar size filled with liquid or hydrogen gas. Another benefit of material-based technologies is the ability to store hydrogen at pressures much lower than those used in today's prototype vehicles. Research is currently underway to improve these technologies and make them more competitive with conventional vehicles.

Cross-cutting Issues of Hydrogen

Infrastructure Investment: The shift to a hydrogen-based energy system requires a large investment in infrastructure for widespread delivery. Building a hydrogen infrastructure as extensive as the current railroads and oil and gas pipelines will likely require decades, since hydrogen pipelines or fuel stations will not become economically viable until demand grows.

Business Development: The establishment of a supply chain is also essential to expand the use of fuel cell technology. The supplier industry will provide needed components, materials, and labor for the engineering and manufacturing of production equipment. The existing industry supply chain for hydrogen production and fuel cells is generally underdeveloped. One strategy to accelerate the development of a supplier industry is to establish clusters of related companies that can benefit and grow through their proximity to each other and to sources of public and private funding.

Regulation, Safety, Codes and Standards: Existing hydrogen regulations are based on the industrial uses of hydrogen. Current efforts target the development of regulation, codes and standards for hydrogen use as a fuel source that would guarantee its safe use. Moreover, the adoption of hydrogen and fuel cell technologies in the private sector requires the development of regulations, codes and standards that are harmonized on an international basis. This would standardize technology interfaces, help to ensure safety, inform experts on liability risks determine insurance rates, and facilitate local and municipal permitting. Current activities in this area are focused on the creation and harmonization of criteria for certifying hydrogen vehicles, fuel cells and ICEs, developing standards and regulations for hydrogen filling stations and filling station-vehicle interfaces.

Education and Training: The further adoption of hydrogen and fuel cells depends on the education of key audiences. Education of communities surrounding demonstration projects will facilitate greater understanding of the benefits of hydrogen and fuel cell technologies. Education is also essential to the development of a skilled workforce, for example certified professionals/maintenance personnel for hydrogen related equipment. Training is also required for safety and code officials, government, educators, and students. Currently, hydrogen education efforts are focused on building a foundation for the future educational needs of key audiences through web-based and printed documents, multimedia informational sources, and hydrogen and fuel cell related curricula and coursework.

Demonstration projects are not only a means for technology assessment, but they also provide an opportunity to familiarize and educate the public on hydrogen and fuel cell technology. For example, the CUTE bus demonstration, which reported use by more than 4 million people during a two year period, included dissemination activities and materials to inform a diverse public about hydrogen and fuel cells. Surveys examining the effect of hydrogen demonstrations on public awareness and attitudes have indicated that, in general, public attitudes toward using hydrogen fueled buses is highly positive. Some passengers even indicated that they would wait additional time at the bus stop for the opportunity to ride one of the silent and non-polluting "hydrogen" buses.[xii]

V. Policy Options

Accelerating the adoption of hydrogen and fuel cell technologies cannot occur without the support of a policy framework that emphasizes R&D, creates business opportunities that encourage investors' confidence, and facilitates market development. Government policies are needed to 1) enhance societal benefits such as reduction of oil consumption, global climate change and air quality; 2) help build the infrastructure in areas where there is less demand; 3) support the initial production of fuel cell for transportation, stationary and, in particular, early market applications that can pave the way for other uses.

Government programs can accelerate the development of hydrogen and fuel cell technologies by:

- Promoting international cooperation in RD&D, and networking across organizations including business, academia and non-profits to share information and leverage resources.

- Investing in R&D needed to overcome technical barriers.
- Facilitating and encouraging demonstration projects that help validate hydrogen and fuel cell technologies, provide feedback on codes and standards issues in “real world” implementation, facilitate acceptance by educating the public.
- Supporting research examining the role of fiscal policy in facilitating hydrogen market development. This includes analysis of various policy options and their potential role in facilitating the market shift for development of infrastructure and commercial penetration of hydrogen-related technologies.
- Becoming early adopters of hydrogen.
- Developing, adopting, harmonizing and promoting national and international codes and standards to facilitate deployment of hydrogen technology through existing international cooperation and agreements.[xiii]

Financial Incentives and government policy examples:

- Governments can institute programs that include financial support such as:
    - Tax incentives for early purchasers, i.e. graduated vehicle excise and company car tax favoring low CO_2 vehicles and capital allowances for infrastructure installations.
    - Per-kilowatt-hour fuel cell production incentives, designed with the applicable hydrogen and fuel cell business cycle taken into account. For example, the business cycle for a stationary fuel cell development is about two years. Any tax credit policy needs to consider this norm in the expiration of the credit.
    - Government loan guarantees and other financial management tools to target mitigation of specific business risks for early adopters of hydrogen technologies.
- Governments may enact decisive policies for reducing CO_2 emissions and using fossil fuels, such as emission restrictions, incentives for emission saving, emission trading, energy security and diversification targets. For example, in the transportation sector these can be undertaken through:
    - Environmental labeling of new vehicles i.e. environmentally friendly vehicles (EFVs)
    - Deployment and government public procurement of EFV (making forward commitments to fund technology developments).
    - Local policies such as free parking and exemption road pricing for EFVs, i.e. London’s Congestion Charge.

VI. Conclusion

Using hydrogen as an energy carrier has the potential to provide many benefits including additional energy security, reducing greenhouse gas and other emissions, and providing us with a diversity of options for energy production. To realize these benefits, however, there are many barriers to overcome. These include technical challenges in the areas of hydrogen production, delivery, and storage, as well as cross-cutting issues such as infrastructure investment, supply chain development, education and training, and development of regulations, codes, and standards. In order to help realize the potential of hydrogen, first in early market applications such as portable devices, and later in longer-term uses like transportation and stationary fuel cells, government leadership is needed. Policymakers can help achieve the vision of hydrogen by enacting policies that support hydrogen research, promote international cooperation, encourage demonstration projects and early adoption of hydrogen technologies, and exploring policy options that facilitate market development.

VII. Endnotes

[i] IEA Hydrogen Implementing Agreement Executive Committee Meeting in October 2005.

[ii] The number of global passenger cars in 2003 was estimated at 600 million based on statistics from the Korea Automobile Manufacture Association, 2005. The annual average mileage of passenger was assumed to be on an average 20,000 Km or 12,500 miles. The mileage driven per kg of hydrogen was estimated to be 100 Km or 62.5 miles based on Hydrogen Energy R&D Center in Korea, 2004. Using these data, we calculated the annual production of hydrogen required annually to fuel all the passenger vehicles in the world, to be 120 million tonnes of hydrogen by applying the following formula: (600 million vehicles)*(12,500 miles / vehicle) / (62.5 miles/kg hydrogen.

[iii] Data estimates on hydrogen pipeline infrastructure from American Society of Mechanical Engineers (ASME) 5th Annual International Pipeline Conference and Exposition (IPC&E) will be held October 4-8, 2004 in Calgary, Alberta, Canada.

[iv] Quantity of hydrogen fueling stations based on Fuel Cell Today Survey Automobile Hydrogen Infrastructure, 2005. From article in the New York Times, Car of the Future? Published November 15, 2005.

[v] Questions and Answers. California Fuel Cell Partnership. www.cafcp.org

[vi] Potential for Hydrogen as Fuel for Transport in the Long Term (2020-2030). Report by the Institute for Prospective Technological Studies.

[vii] Quantitative information on vehicles and buses from Fuel Cell Today Surveys on Buses, 2004.

[viii] Quantitative information on vehicles and buses from Fuel Cell Today Surveys on Light Duty Vehicles, 2005.

[ix] Data on Fuel Cell Forklift from The Fuel Cell Review article, Heavy lifting on the factory floor: Fuel cells shape up against batteries in the industrial materials-handling market, August/September 2005 issue.

1.1.1 [x] Quantitative information on Niche Transport applications from Fuel Cell Today Surveys on Niche Transport part I and II, 2005.

[xi] Quantitative information on Portable applications from Fuel Cell Today Survey, Portable Applications, 2005.

[xii] Icelandic New Energy's 4th newsletter, Public Perception of Hydrogen Buses in Five Countries presentation at the International German Hydrogen Energy Congress 2004 11.-12. February 2004 in Essen, Germany.

[xiii] UNECE-WP.29.