New Zealand's EnergyScape

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Transitioning to a Hydrogen Economy

Issues Document

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Transitioning to a Hydrogen Economy: Issues Document

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1 Executive Summary

The aim of this project is to identify how hydrogen could become a significant contributor to New Zealand's energy system, what needs to be achieved in order to successfully transition to a hydrogen energy system and the role of research investment in bringing this about. This includes the conditions that would lead to the establishment of a hydrogen energy system, what such a system would look like and what issues would have to be overcome and how, during the transition. The aim is not to debate the merits of transitioning to a hydrogen energy system or whether or not that will happen.

The project consists of 5 Stages: Stage 1, the identification of preferred energy supply chains using hydrogen as an energy carrier; Stage 2, energy, emissions and economic analysis of the preferred supply chains to select a smaller number of best options for the forecast New Zealand situation; Stage 3, the integration of the various best supply chain options to meet a number of future implementation scenarios; Stage 4, the identification of the gaps and barriers in understanding or in resources to meet the developed scenarios; and Stage 5, developing a plan to address these gaps and barriers. The end product of the project is a vision of how hydrogen may be a part of New Zealand's energy system and an understanding of the research needed to make this vision a reality.

In Stage 1, this Issues Document is designed to raise awareness and understanding among government and industry stakeholders by providing information on the use of hydrogen for energy purposes under the following headings:

- What a hydrogen energy system is and the drivers for it.
- What the major issues relating to hydrogen production, storage, utilisation, codes and standards and public outreach are.
- What international and national research activities are being undertaken to address these issues.
- The extent of the present hydrogen market in New Zealand.

Most importantly, the Issues Document introduces the concept of "energy pathways"; pathways from the base energy resource through to final demand. For hydrogen energy systems, "energy pathways" are more commonly referred to as "hydrogen supply chains" or simply "chains" to reflect the fact that the focus is on the supply of the hydrogen rather than the supply of energy. Hundreds of potential hydrogen chains were considered and prioritised using a first pass assessment process based primarily on sustainability, cost effectiveness of feedstock, status of conversion technology and relevance to New Zealand (Section 7). This has lead to a list of 24 chains, listed in the table overleaf.

We now seek your feedback on this initial selection. We are not asking you to prioritise the 24 chains but we do want you to:

- Identify chains that should be added.
- Identify chains that should be deleted.
- Give reasons for proposed changes.
- Identify chains you believe essential.
- Comment upon any other issues you feel are relevant

Using a combination of your feedback and an economic, emissions and energy modelling technique, the list will be reduced to a smaller number of favoured hydrogen chains in Stage 2. Reference chains and competitive chains will also be modelled and the selected chains will be assessed against these.

Please address all feedback on this Issues Document to Tony Clemens at CRL Energy Ltd., PO Box 31-244, Lower Hutt by 22nd June 2007 (email t.clemens@crl.co.nz).

Chain Codes*	**Feedstock**	**Conversion Process**	**Distribution**	**End Use**
1a - d	Natural gas	Central reformation	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Small-scale FC CHP d) Distributed power FC
2 a - d	Natural gas	Central reformation	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
3 a - d	Natural gas	Central reformation + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
4 a - d	Natural gas	Central reformation + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
5 a - d	Coal	Central gasification	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
6 a - d	Coal	Central gasification	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
7 a - d	Coal	Central gasification + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
8 a - d	Coal	Central gasification + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
9 a - d	Biomass	Central gasification	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
10 a - d	Biomass	Central gasification	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
11 a - d	Biomass	Central gasification + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
12 a - d	Biomass	Central gasification + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC

Chain Codes*	**Feedstock**	**Conversion Process**	**Distribution**	**End Use**
13 a - d	Wind generated electricity	Central electrolysis	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
14 a - d	Wind generated electricity	Central electrolysis	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
15 a - d	Grid electricity mix	Central electrolysis	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
16 a - d	Grid electricity mix	Central electrolysis	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
17 a - d	Wind generated electricity	Refuelling site electrolysis	None	a) FC vehicle b) H_2 ICE vehicle
18 a - d	Grid electricity mix	Refuelling site electrolysis	None	a) FC vehicle b) H_2 ICE vehicle
19 a - b	Natural gas	Refuelling site reformation	None	a) FC vehicle b) H_2 ICE vehicle
20	Coal	Central IGCC + H_2 gas turbine + CCS	Direct use	Electricity for grid
21	Biomass	Central IGCC + H_2 gas turbine	Direct use	Electricity for grid
22 a - b	Natural gas (piped)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC
23 a - b	LPG (by tanker)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC
2 4 a - b	Ethanol (by tanker)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC

* a, b, c & d refer to the end use

Contents

GLOSSARY

AFC	Alkaline Fuel Cells
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage (or Sequestration)
CGH2	Compressed Gaseous Hydrogen
CHP	Combined Heat and Power
CMR	Compact Mixed-Reactant
DMFC	Direct Methanol Fuel Cell
E3	A database used to assess Energy use, Economics and Emissions for processes
FC	Fuel Cell
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
HIA	Hydrogen Implementation Agreement
IEA	International Energy Agency
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IGCC	Integrated Gasification Combined Cycle
IPHE	International Partnership for the Hydrogen Economy
LH2	Liquid Hydrogen
LPG	Liquefied Petroleum Gas
MCFC	Molten Carbonate Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PSA	Pressure Swing Adsorption
SMR	Steam Methane Reformation
SOEC	Solid Oxide Electrolyser Cells
SOFC	Solid Oxide Fuel Cells
StU	Source-to-Use
USDoE	United States Department of Energy
WtW	Well-to-Wheel

2 Introduction

In February 2007, the Government awarded a contract to CRL Energy "Transitioning to a Hydrogen Economy" [1] to develop a comprehensive understanding of what New Zealand needs to achieve in order to prepare for and transition to a hydrogen energy system and to identify a pathway for this to be implemented. The aim of this project is to consider the conditions that would lead to the establishment of a hydrogen energy system, what such a system would look like and what issues would have to be overcome and how during the transition; the aim is not to debate the merits of transitioning to a hydrogen energy system or whether it will or will not happen.

At the end of this contract (June 2008), New Zealand will have taken a number of steps towards developing a harmonised vision for transitioning to a hydrogen economy, identified the existing knowledge gaps and New Zealand specific barriers to transition together with the means to tackle them, and identified which of these means will come from within New Zealand and which from outside. This project will closely follow the process used in "HyWays" [2], a multi-nation project that developed a roadmap for the uptake of hydrogen in Europe.

This Issues Document represents the first stage in the process. Its purpose is to improve stakeholder understanding of what a hydrogen energy system is, what it can offer in terms of clean and secure energy, the generic barriers to introduction of hydrogen energy systems, the risks associated with such a transition, and the extensive range of hydrogen energy related research activities being carried out globally to address them. It also introduces a range of potential hydrogen supply chains that may be of relevance to New Zealand should we undergo our own transition to a hydrogen energy system.

In the second stage of the process, a smaller number of favoured hydrogen supply chains will be selected from among the potential chains introduced in the Issues Document. This selection will be based upon economic, energy and emissions analysis of the various chains and upon feedback from targeted New Zealand stakeholders.

The third stage of the process – transition analysis – identifies conditions under which a transition to a hydrogen energy system may take place within New Zealand, and the likely timeframe of the transition. Again, following the European "HyWays" methodology, this starts by identifying the country specific issues relating to the transition process by using a hydrogen scenarios approach based on the chosen hydrogen supply chains. This highlights the mix of supply chains that could be employed and how the mix varies over time.

Having identified a plausible future and a route for getting there, the fourth stage will then identify the knowledge gaps and New Zealand specific barriers to transition. The fifth, and final, stage of the process involves production of an action plan to address these barriers most efficiently.

This Issues Document is divided into several sections: Section 3 includes descriptions of hydrogen energy systems, Section 4 describes the critical barriers to their implementation; Section 5 covers the international and national research efforts underway; Section 6 contains information on the present hydrogen market in New Zealand and how it compares with the likely situation under a hydrogen energy system. In particular, Section 3 introduces the concept of "energy pathways"; pathways from the base energy resource through to final demand. For hydrogen energy systems, "energy pathways" are more commonly referred to as "hydrogen supply chains" or simply "chains" to reflect the fact that the focus is on the supply of the hydrogen rather than the supply of energy. The Appendices provide more detailed information on some of these areas.

Section 7 is the most important section both in terms of stakeholder input and for the programme going forward. It identifies a wide range of hydrogen supply chains – from energy resource to end user – and begins the process of identifying those deemed to be most likely to play an important role in New Zealand. Our first pass assessment of what these chains may be is included. We seek your feedback on these choices. During the next stage of the programme the agreed range of potential chains will be subject to more in depth assessment and the favoured chains identified.

3 What are a Hydrogen Energy System and its Drivers?

The potential of a hydrogen based energy system is clean energy, both in terms of local pollution and global greenhouse gas emissions, coupled with long-term energy security. At a time of raised awareness of local and global impacts of pollution, political instabilities and uncertainties of supply, this is an extremely attractive prospect. This, combined with significant advances in development of high efficiency fuel cell technologies for converting hydrogen to electricity, has led to an enormous amount of international research aimed at converting the potential of hydrogen based energy systems into a reality.

To appreciate why a hydrogen-based energy system offers clean and secure energy requires an understanding of energy systems. Energy systems are comprised of a number of energy pathways, each of which is devised to do the same thing – use the energy sources available to deliver services required. Each pathway requires a technology to convert natural energy resources into an energy carrier and a technology to enable the consumer to utilise that energy once delivered. Two examples from the current energy system are shown in Figure 1.

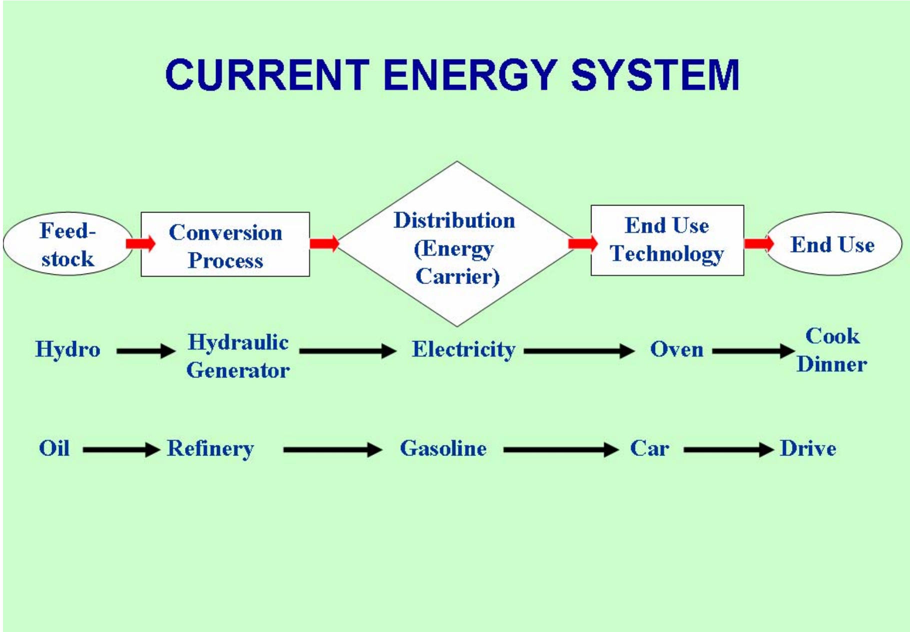

Figure 1: Examples of Two Energy Pathways in the Current Energy System

In the first energy pathway, the food preparation required by the consumer begins with a hydro lake, then through a generator to produce electricity, which carries the energy to the consumer's home where it powers an oven. In the second line, the requirement to get from one place to another begins with a supply of oil, then through a refinery to produce petrol that carries the energy to the consumer's car.

As previously mentioned, when hydrogen is used as an energy carrier, the "energy pathway" is commonly referred to as a "hydrogen supply chain" or simply "chain"; this convention will be used for the remainder of the Issues Document. A number of possible supply chains providing the same services under a hydrogen energy system are shown in Figure 2. The first chain remains largely unchanged. The big change occurs in the second chain where petrol is replaced as an energy carrier by hydrogen and the transport fleet is decarbonised (at the point of use). This leads to a new situation where the two major energy carriers in the system, electricity and hydrogen, are inter-convertible, with hydrogen offering the benefit of energy storage.[1] This provides significant flexibility to the energy system.

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[1] Simplistically, electricity passing through water picks up a proton to produce hydrogen and hydrogen passing through a fuel cell releases the electron to produce electricity – the combination of these processes allow a choice of energy medium.

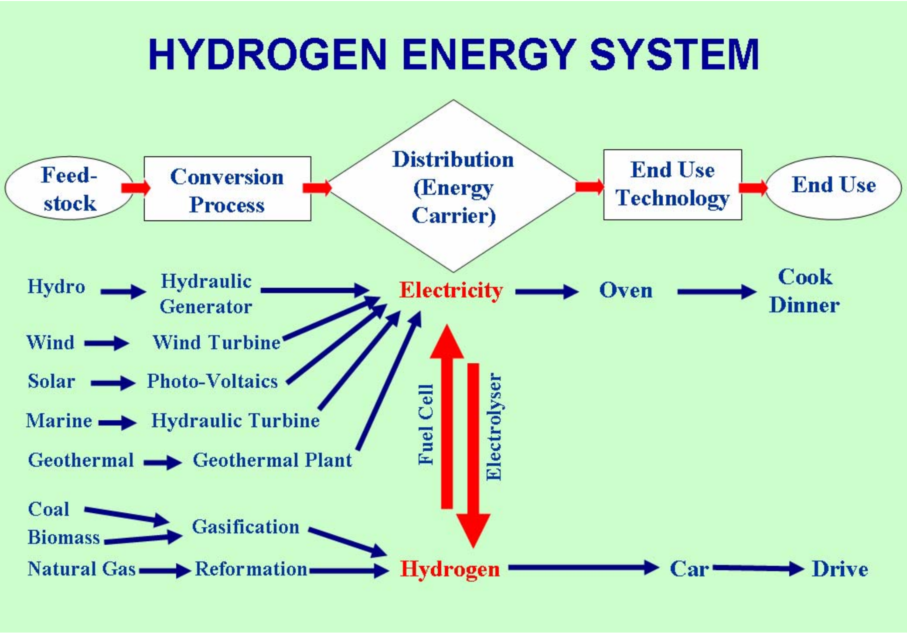

Figure 2: Examples of Two Energy Supply Chains in a Hydrogen Energy System

The potential of clean energy coupled with long term energy security now emerges. “Secure” as every nation has an abundance of at least one of the listed energy sources from which to produce its hydrogen and “clean” as water is the only significant by-product of the end use conversion process when hydrogen is used to carry energy. It should also be noted from the above discussion that hydrogen may be regarded as a means of storing electricity as well as carrying energy and that it can be made from any available primary energy source.

The main drivers for an international and New Zealand hydrogen energy system are broadly similar and can be identified as shown below in Figure 3. There is a global consensus [3, 4] that energy security and environmental concerns are the most pressing of these.

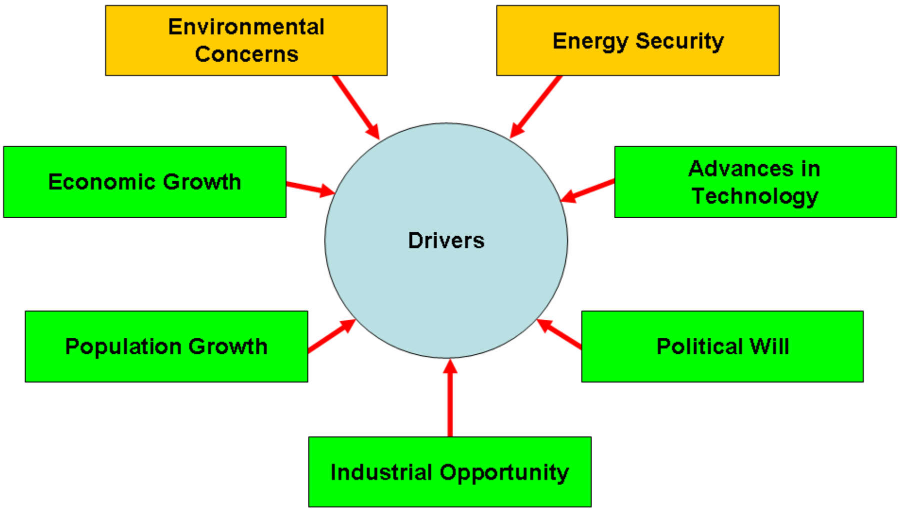

Figure 3: Drivers for the Introduction of Hydrogen Energy Systems

3.1 How Will We Know When We Have Got a Hydrogen Energy System?

The International Partnership for the Hydrogen Economy [5] (IPHE, see Section 5.1.1), has identified a range of objectives that are considered internationally to signify the transition to a hydrogen energy system. Of these, the objectives identified as critical by the IPHE include:

- Ensure a standard of safety that is at least as high as that required from conventionally fuelled vehicles on a worldwide basis by developing codes, standards and regulation for transportation related hydrogen and fuel cells.
- Stationary fuel cell systems that achieve a lifetime of 40,000 to 80,000 hours.
- Produce sufficient hydrogen to fuel 15% of the light duty vehicles.
- 70% of the hydrogen being used as an energy carrier comes from carbon neutral resources (i.e., renewable resources or fossil resources with carbon capture and sequestration).

3.2 Sequence of Events

The critical objectives capture another aspect of the transition to hydrogen based energy systems, which is internationally accepted as important; the final objective is to decarbonise the transport fleet. However, it is likely that stationary fuel cell applications will become established prior to this. The reason for this is the relative cost of the technologies fuel cells are trying to replace. Table 1 lists comparative cost data from 2003 [6] which show that fuel cells could only have been able to replace laptop batteries cost-effectively at that time. Replacing internal combustion engines for transport applications will be difficult on a cost basis because of the extremely low cost of the current transport technology.

Table 1: Comparative Costs for Fuel Cell and Conventional Power Technologies in 2003 [6]

Technology	**Cost (US$/kW)**
Laptop batteries	11,000
Fuel cells	4,000
Small-scale distributed generation	2,000
Large-scale conventional power generation	1,000
Conventionally fuelled internal combustion engines	30

The United States Department of Energy (USDoE) targets in 2003 for mass produced fuel cell costs were US$1000/kW by 2010 and US$30/kW by 2015. It is difficult to provide a definitive current cost as fuel cell prices have decreased substantially since this forecast. A current estimate could be as low as US$120/kW for high volume mass production. Matching the cost of conventional internal combustion engines by 2015 will still require significant and rapid development in fuel cell technology.

It should be appreciated that a competitive hydrogen energy system will be based on the commercial establishment of mass market fuel cells. Several different fuel cell technologies are likely, in a similar fashion to heat engine technologies where two stroke, petrol, gas and diesel variants all play a role.

4 Hydrogen Energy System Issues

Internationally, the main issues regarding the transition to a hydrogen based energy system are divided into six areas:

- Hydrogen Production.
- Hydrogen Delivery.
- Hydrogen Storage.
- Conversion Technology.
- Education and Public Outreach.
- Regulations, Codes and Standards.

The issues recognised internationally to be relevant to each area are discussed in detail in Sections 4.1 to 4.6. Issues which cut across the 6 identified areas are briefly described below.

An issue relevant to all of the first four areas is whether investors will put money into capital items which may end up as “stranded investment” e.g. distributed hydrogen production technology may be essential to kick-start a hydrogen energy system, but it may be rendered uncompetitive by centralised hydrogen production with pipeline distribution once sufficient demand is generated.

A significant general issue is how other sustainable technologies might affect the development and uptake of hydrogen as an energy carrier by competing for the same end markets. For example, the development of bioethanol and biodiesel fuel supply chains may be readily achieved, particularly as their incorporation into the existing distribution and supply networks as blends with gasoline or diesel will require relatively slight modification to modern vehicles and the existing refuelling infrastructure compared to that needed for hydrogen.

A country specific issue is the size and availability of the feedstocks and energy sources available for production of hydrogen. This cannot be discussed in a general manner, other than that each country can only use the resources available to it to meet security of supply objectives. Hence, resource availability will be covered in Section 7.2, where the situation specific to New Zealand will be discussed and used in selection of the hydrogen energy chains for further consideration.

Another issue frequently raised is that of the “best use” for the resources from which hydrogen can be made. For example, wind energy can be used to generate electricity that can be used to power electrolysis units to produce hydrogen for transport fuel, but it may be possible to make significantly larger savings in greenhouse gas emissions by using this same wind power generated electricity connected to the national grid to replace a demand that might otherwise have to be met by building a new fossil-fuelled power station. These issues will be addressed during the scenario modelling phase of the project.

4.1 Hydrogen Production

No existing technology can currently produce and deliver the required quality of hydrogen at a low enough price to make it commercially viable as an energy carrier when competing against traditional liquid fuel prices. Virtually all the hydrogen currently produced is made from fossil fuels by reformation or gasification with the remainder from electrolysis of water. These hydrogen production techniques are well proven, and large scale demand is expected to produce further innovation and refinement which could lead to some cost reduction. The available methods of hydrogen production and their issues are collated in Table 2. More detail on the issues surrounding each technology can be found after the table and details of the various hydrogen production processes can be found in Appendix A.

Table 2: Summary of the Current State of Hydrogen Production Technologies [7 - 10]

Process	**Natural Gas Reformation**	**Electrolysis (alkaline/PEM[2])**	**Coal Gasification**	**High-T + Thermochem. Water Splitting**	**Biomass Gasification**	**Photo-electrolysis**	**Photo-biological**	**Liquid Fuel Reformation**
Technological Maturity	Commercial	Commercial	Commercial (not for pure H_2)	Development stage	Biomass power plant demonstrated but not for H_2	R&D only	R&D only	Commercial at large scale/ developmental at small scale
Process Inputs	Methane, water, heat	Electricity, water	Coal, water, heat	Water, heat	Biomass, water, heat	Water, sunlight	Water, sunlight, biomass as nutrient	Hydrocarbon fuel, water
Scale (for centralised or distributed production)	Large and small scale	Large and small scale	Large-scale (for CCS[3])	Not known	Medium scale	Not known	Not known	Large and small scale
Carbon Dioxide Emission	CCS potential with large scale only	None if using renewable electricity	CCS potential for large-scale plant	None if heat source used is non-fossil fuel based	Neutral but potentially carbon-negative if CCS used	None	None	CCS potential with large scale, not required with renewable fuels (e.g. biodiesel, ethanol, methanol)

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[2] PEM – Polymer Electrolyte Membrane

[3] CCS – Carbon Capture and Storage, where carbon dioxide is separated and pumped into underground storage sites, such as depleted gas or oil wells, where it will remain

Process	**Natural Gas Reformation**	**Electrolysis (alkaline/PEM^2)**	**Coal Gasification**	**High-T + Thermochem. Water Splitting**	**Biomass Gasification**	**Photo-electrolysis**	**Photo-biological**	**Liquid Fuel Reformation**
Hydrogen Purity	Requires gas clean-up/purification	High-purity	Extensive gas clean-up/ purification required	High-purity	Extensive gas clean-up/ purification required	High-purity	Some gas clean up required	Extensive gas clean-up/ purification
Cost	Relatively low cost	High cost	Higher than steam methane reformation	High	Higher than for coal	High	High	Large scale relatively low cost, small scale costly
Conversion Efficiency (no compression)	Large-scale 85%, small scale 75-80%	~50 to 70% (theoretical max. ~85%)	>~50%	Low	Not known	Not known	Not known	Can be up to 80% depending on fuel type
Issues	H_2 cost, gas quality, conversion efficiency, fossil fuel use, future gas price	H_2 cost, cell cost, conversion efficiency, equipment lifetime	H_2 cost, complexity of gas clean-up and separation, large-scale only, CCS required	H_2 cost, low efficiency, materials heat exchange and corrosion resistance, cheap high-T sources	H_2 cost, biomass cost and preparation, , technology immature, complexity of gas clean up	H_2 cost, technology immature, low efficiency, semiconductor lifetime	H_2 cost, technology immature, low efficiency, genetic engineering required	H_2 quality, fossil fuel use, future oil price, small scale technology cost and durability

4.1.1 Natural Gas Reforming

Commercially, hydrogen is produced from natural gas by steam methane reformation combined with the water-gas shift reaction. The technology is available over a wide range of scales and at large scale conversion efficiency can reach 75% [8]. Advanced thermal reactors are being developed to give higher conversion efficiencies on smaller scales. The cost is slightly cheaper than for coal gasification and much lower than for electrolysis, although the cost of natural gas is expected to rise with respect to coal in the future. The syngas produced requires separation and clean-up for energy use. New catalysts, adsorption materials and separation membranes are under development to increase the process efficiency and the quality of the gas and reduce their deactivation and poisoning by gas impurities such as sulphur. It is considered that carbon capture and storage will be considerably more expensive on small scales because of the need to transport the relatively small amounts of carbon dioxide captured to a central storage site.

4.1.2 Electrolysis

Electrolysis is a well-established commercial process for producing high-purity hydrogen and oxygen gases over a wide range of scales of production. Larger plants yield higher conversion efficiencies up to ~70% [8]. The main issues are the high cost of the electrolyser cells and the electricity required, the modest efficiency of conversion and the length of the equipment lifetime. Efficiencies close to the maximum theoretical value of 85% [8] are predicted for PEM electrolysers with the development of new materials and new stack designs. High-temperature steam electrolysers are being developed with the promise of high conversion efficiencies. High pressure electrolysers are also under development which will reduce the large amount of energy required to pressurise the hydrogen, often quoted as 10-30% of the embodied energy in the fuel, depending on storage pressure [8].

4.1.3 Coal Gasification

Coal gasification is also commercially mature (not yet as a method for producing pure hydrogen, but rather to produce syngas mixtures), but more complicated and therefore slightly more expensive than natural gas reformation. Gas separation and gas clean-up are necessary to produce hydrogen of a fuel-quality standard. Large-scale plants give the benefits of economy of scale and the potential to capture and store the carbon dioxide produced. Efficiencies of hydrogen production can be 50-70% [8]. New catalysts for water-gas shift reactors and membranes for hydrogen separation are under development and could improve the conversion efficiency and reduce the energy needed for gas separation. Carbon capture and storage is generally seen as an essential part of the process of hydrogen production from coal. CCS is most effective when the gasifier is fed with pure oxygen. This makes carbon dioxide capture less difficult but requires cheaper methods of oxygen production to be developed.

4.1.4 Biomass Gasification

None of the proposed biological and thermochemical processes for converting biomass to hydrogen have been commercialised, although several integrated gasifier-combined cycle gas turbine (IGCC) projects for power generation have been successfully demonstrated burning impure syngas rather than separated hydrogen. The main issues for biomass gasification are in the feedstock cost, quality control, preparation and transport, making costs significantly higher than for coal gasification or natural gas reformation. Competition for land use and for the biomass itself could be serious issues, although for New Zealand significant quantities of plantation forest residues could provide a useful feedstock.

4.1.5 High-Temperature Water Splitting and Thermochemical Cycles

There are many possible thermochemical cycles which can be used to produce hydrogen, usually by extracting hydrogen from water molecules. Several techniques for splitting water using high temperatures and multistage conversions have been proposed but are still in the experimental stage. Conversion efficiencies are currently low and materials need to be developed for improved heat transfer and corrosion resistance. Cheap sources of high-temperature (up to and beyond 1000°C) will be required to make the processes cost effective.

4.1.6 Photo-electrolysis

This technology is still in the research phase with low conversion efficiencies (~10% at bench level). Development of semiconductor materials to increase efficiency and cell lifetime will be required if photo-electrolysis is to make a significant contribution to hydrogen production.

4.1.7 Photo-biological Production

To date, this method has only been demonstrated at the laboratory scale and it is too early to predict costs and conversion efficiency for commercial-scale plant. Metabolic or genetic engineering of the organisms is essential for progress of this technology beyond the laboratory. Large-scale bio-reactors could produce significant quantities of hydrogen.

4.1.8 Liquid Fuel Reformation

Liquid fuels can be reformed using a variety of processes similar to natural gas reformation. Feedstocks can include the full range of petroleum oils, alcohols and liquid petroleum gas (LPG). In fact the hydrogen produced in oil refineries for fuel upgrading by hydrocracking comes from petroleum feedstocks, using steam reformation. The New Zealand Oil Refinery alone produces around 50,000 tonnes of hydrogen per year by these methods. At the very small scale, microreformers have received considerable research attention in the past decade due to interest in on-board production of hydrogen for fuel cells from fuels such as petrol, diesel, LPG, methanol and ethanol.

4.2 Hydrogen Distribution

After production, hydrogen needs to be delivered to the point of storage or use in a reliable, safe, convenient and cost-effective manner.

Centralised (large-scale) hydrogen production will require distribution through pipelines as a compressed gas, or in a tanker (via road, rail or sea) as a compressed or liquefied gas. While reliability, safety and convenience can already be satisfied by pipeline or tanker transport, it is likely that initially, the most economical method of distribution will be by tanker. Once the hydrogen energy system becomes established, pipelines will become increasingly cost effective.

For central production supplying large quantities of hydrogen to an area of large demand, pipelines are the most cost effective. Hydrogen pipelines of hundreds of kilometres have been used successfully for over 50 years [8]. Hydrogen is incompatible with some metals, alloys and polymers commonly used in natural gas pipelines; it can cause embrittlement of some steels by carbon removal or blistering of some polymers. Also, hydrogen can diffuse through some polymers used for natural gas pipes. Therefore, the choice of materials for pipelines is critical. However, some components of existing natural gas distribution systems would be suitable for use with hydrogen.

Hydrogen gas has a comparatively low volumetric energy density and so compression and transport use more energy than for natural gas. Over long distances the gas in the pipeline will require re-pressurising and it is estimated that 10% of the energy carried by the hydrogen would be used in transporting it through 1200km of pipeline [8]. The overriding issue for pipelines is the installation cost, which may be prohibitive in the early development stage of a hydrogen energy system, when the cost relative to throughput can be very high. Therefore a transition phase where hydrogen is either generated locally or produced centrally and moved to the point of use in bulk by road, rail or ship is expected.

Hydrogen is already transported as a compressed gas in tankers or as a liquid in cryogenic tankers. The main issues are the high costs of these transport methods and the high energy consumption for compression/liquefaction. Currently, to liquefy hydrogen uses 30-40% of the energy it carries (this may be reduced to 20% in the future) and there is an additional loss of 0.2 to 0.4% of the hydrogen per day by evaporation [8]. Compressing hydrogen for transport uses 10-15% of the energy carried by the hydrogen depending on the pressure required.

The costs for moving hydrogen in bulk are high and distance dependent, including the fuel for the tanker/truck and the wages for the driver. However, some areas may never become economic for pipeline connection and for them, bulk supply by tankers may be the only economic and practical option.

An alternative to large-scale centralised production is small-scale distributed hydrogen production. For distributed production there will be no further hydrogen distribution requirement other than perhaps temporary or buffer storage and any refuelling station needs. Many proponents of a hydrogen economy consider that this is the most likely model through which larger scale demand will develop to the point where installing pipeline becomes economic. Distributed production will utilise the existing water, gas and electricity infrastructure to bring the raw materials to the site, with no subsequent requirement for transport of the hydrogen. Naturally, this advantage over centralised production must be compared to the disadvantages of higher cost, lower efficiency and more expensive carbon capture and storage for small-scale plant.

4.3 Hydrogen Storage

The critical issue facing hydrogen storage is that for a hydrogen system to be easily accepted, whichever method is chosen, sufficient hydrogen storage is required to provide a similar level of service as the system that is replaced. For example, sufficient storage would be required to allow similar distance travelled between refuelling for vehicles (this does not necessarily require the same amount of energy to be stored as the original system due to different energy efficiencies).

Existing storage techniques include cryogenic liquid (for large scale), pressurised cylinders (small scale general distribution and vehicles) and metal hydrides (specialised stationary and small transportable quantities). Figure 4 illustrates the ranges in volumetric and gravimetric energy density for hydrogen (also providing that for diesel as a reference). The USDoE have set industry guidelines of 70kg/m^3 and 9% weight hydrogen. Further detail is provided in Appendix B [9, 11, 12, 13].

Hydrogen storage for transport is a critical area where improvements are needed. Substantial research is being undertaken, particularly into chemical and physical adsorption/absorption storage techniques. For transport applications, large quantities of hydrogen will be required to be moved from the point of production to the point of distribution. Hydrogen must then be transferred as smaller volumes for storage in an on-board fuel tank.

For stationary applications, no storage may be necessary if the production is used directly for electricity generation (e.g. with CCS), or distributed directly via a pipeline. Partial storage can be achieved through pressure fluctuations in a pipeline infrastructure, buffering supply from demand. Hydrogen production can be deliberately used as a peak load reduction or shifting technique for balancing electricity supply and demand through electrolysis. In this case large quantities must be stored with many charge-discharge cycles.

For remote area energy uses, a convenient, easily recycled high density storage technology also still needs to be found.

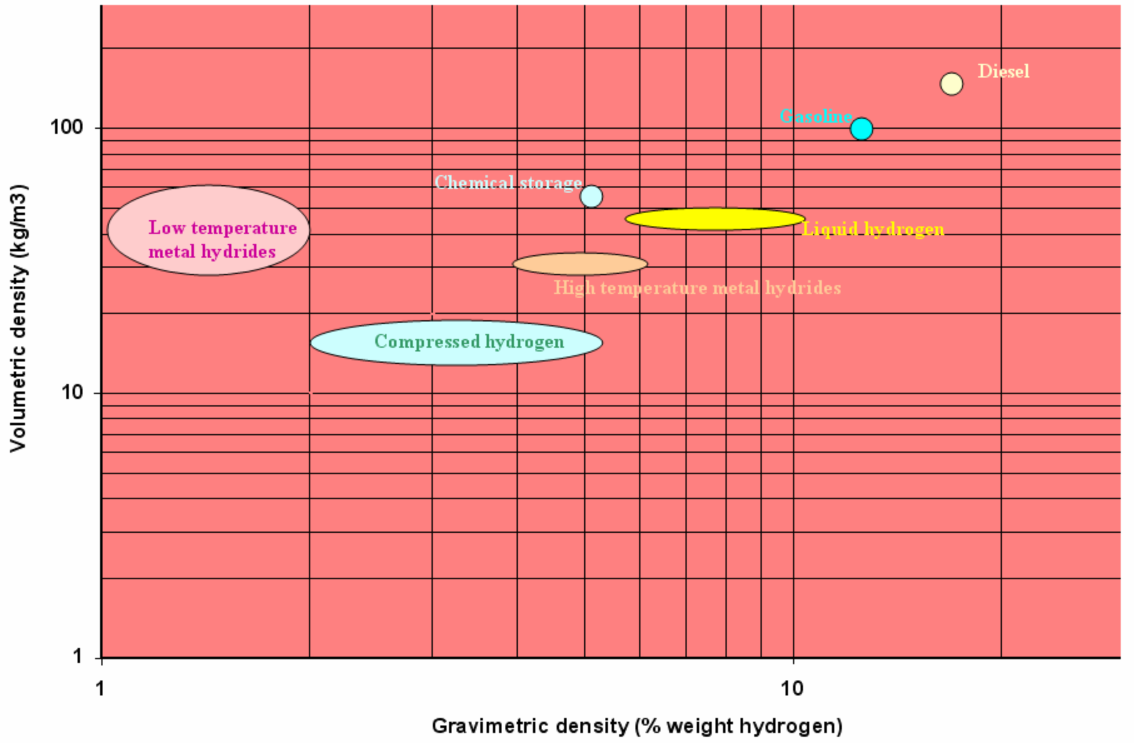

Figure 4: Ranges in Volumetric and Gravimetric Energy Density for Hydrogen, Petrol and Diesel.

4.4 End Use Conversion Technologies

Critical issues facing end use conversion technologies are those of cost and reliability/durability as well as the development of improved materials and coatings able to withstand increased operating temperatures and system designs that increase efficiency and power output. The end use conversion technologies can be roughly divided into four areas:

- Fuel cells (FC) for portable, stationary and transport applications
- Internal combustion engines (ICE)
- Gas turbines
- Combustors (flame and catalytic)

These four areas cover the use of hydrogen [14, 15] for transport, electricity, and heat. It is expected that those end use technologies that involve the direct combustion of hydrogen (ICEs, gas turbines and flame combustors) will be phased out in the medium to long term as more efficient fuel cell technologies evolve. They may however provide an important transition role. For example, BMW currently use ICEs in their vehicle demonstration projects, providing a robust technology that is available today, but one that is less efficient than what can be achieved through the use of fuel cell and hybrid combinations. Combined heat and power (CHP) technologies provide both heat and electricity at very high combined efficiency (to the order of 70–90%), because the heat generated is utilised rather than wasted and may also provide long-term high efficiency use of hydrogen.

A key reason for a hydrogen economy is ultimately to deliver transport power that is carbon free along the whole supply chain.

4.5 Education and Public Outreach

The crucial issue is to educate stakeholders, technical specialists and laypeople with the knowledge necessary to play their parts in the transition to a hydrogen-based energy system. For many people, hydrogen represents a dramatically different energy currency. In order to gain public acceptance, extensive education programmes are needed to teach both the fundamental concepts of a hydrogen economy as well as the specialised information and skills required [16].

Identification of target audience groups is paramount as each will have distinct educational needs ranging from general to technical and broad-based to narrow focussed. Timetables for action will also vary and certain groups will require special attention in the near term (e.g. R&D and demonstration efforts) whilst others will learn over the longer term. The following identifies audience groups that should be targeted and the key educational needs:

- National, regional and local government officials.
- Safety and code officials.
- Communities hosting hydrogen demonstration projects.
- University and technical college students.
- Industrial stakeholders.
- Primary and secondary teachers and students.
- General public.

The key approach to meeting the educational needs for each target group is to:

- Assess current levels of understanding and awareness.
- Identify specific educational needs.
- Identify and catalogue currently available resources.
- Consider opportunities to advance understanding and awareness.

Figure 5 depicts the progression of educational needs among the identified target groups.

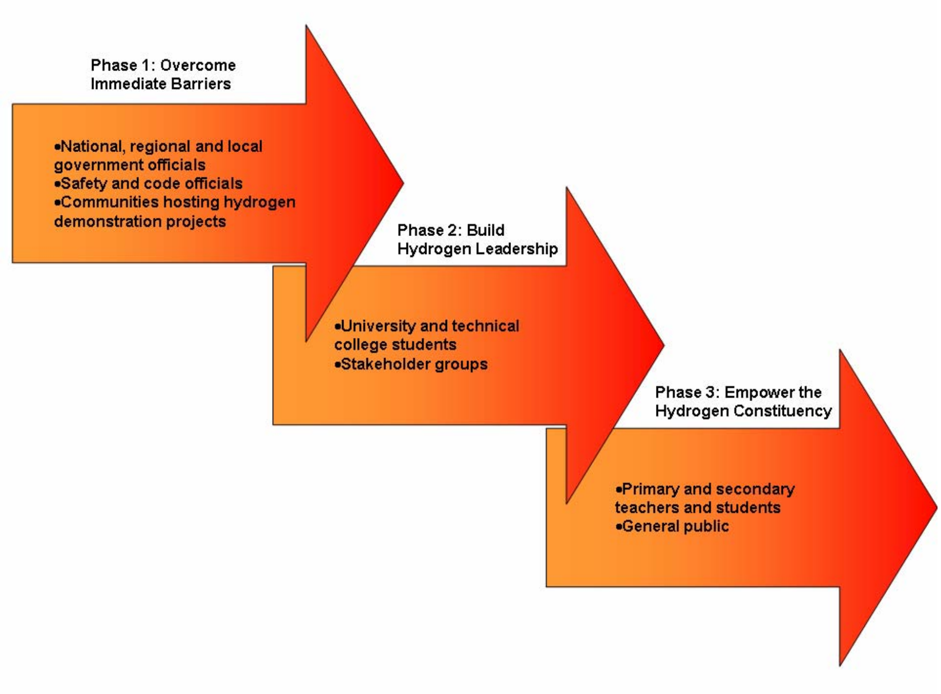

Figure 5: Three Phases of Education for a Hydrogen Energy System

In Phase 1, education efforts should be targeted towards specific barriers to near-term validation and demonstration activities with regulatory infrastructure being given priority. Phase 2 involves expanding the involvement of those groups that will participate actively during the transition to a hydrogen energy system. Phase 3 targets education at a widespread audience.

There are also some private company initiatives aiming to introduce the general population to hydrogen technology for the transport and energy sectors e.g. BMW is actively promoting its

"Hydrogen 7 Series" of vehicles via news and trade articles, exhibitions and targeted promotions.

4.6 Regulations, Standards and Codes of Practice

The crucial issue surrounding standards, codes of practice and regulations regarding a fully integrated hydrogen energy system is that there are none addressing wide spread public use of hydrogen energy. Some regulations have been developed within the European Union and codes and standards exist for hydrogen handling (e.g. ISO TC58) and transportation (e.g. ISO TC22) but these are for very specific quantities and applications. As an entirely new energy infrastructure, there is now the opportunity to develop a common global set of codes and standards. This means that it is important for countries contemplating a hydrogen energy economy to be involved from the outset in international standards development.

Some countries (notably Germany, USA and Japan) are already well down the track in the revision and extension of existing codes to address broader use of hydrogen in energy end use applications. For example, these countries already have residential fuel cell standards in place and are working on transport requirements.

New Zealand currently has no involvement in any international hydrogen standards working groups.

5 Hydrogen Research Activities

Research has focussed on addressing all the issues identified in Section 4 and significant progress has been made. On-going research continues to improve scientific and technological knowledge.

5.1 International Hydrogen Research

5.1.1 International Partnership for the Hydrogen Economy (IPHE).

The International Partnership for the Hydrogen Economy (IPHE) was launched in Washington DC in November 2003 as a mechanism to coordinate international hydrogen research and hydrogen technology development and deployment. The intention is to allow members to organise, coordinate and implement effective, efficient, and focused international research, development, demonstration and commercial utilisation activities related to hydrogen and fuel cell technologies. New Zealand joined early in 2005. The full list of the current member countries is shown in Table 3.

Table 3: IPHE Membership as at March 2007

Australia	Brazil	Canada	China
European Commission	France	Germany	Iceland
India	Italy	Japan	Republic of Korea
New Zealand	Norway	Russian Federation	United Kingdom
United States			

The IPHE is also a forum for advancing policies, common technical codes and standards providing the potential to accelerate the cost-effective transition to a hydrogen energy system. It also aims to educate and inform stakeholders and the general public on the benefits of, and challenges to, establishing a hydrogen economy. Member countries must demonstrate at the highest level a political commitment and government leadership in planning and taking steps towards transitioning to a clean hydrogen energy future.

Among the many important activities carried out within the IPHE are facilitated discussions between members to identify the highest priority critical objectives for transitioning to a hydrogen based energy system [5]. So far, nine critical objectives have been identified:

- The development of codes, standards and regulation for transportation related hydrogen and fuel cells to ensure a standard of safety that is at least as high as that required from conventionally fuelled vehicles on a worldwide basis.
- Stationary fuel cell systems will achieve a lifetime of 40,000 to 80,000 hours.
- Each member country is able to produce sufficient hydrogen to fuel 15% of the light duty vehicles on its roads.
- 70% of the hydrogen being used as an energy carrier within each member country comes from carbon neutral resources (renewable resources and fossil resources with carbon capture and storage).
- Reductions in cost of vehicular fuel cell systems (including auxiliaries) down to US$25 to $45/kW projected high volume manufacture.
- Vehicular fuel cells with lifetimes of 5,000 to 8,000 hours.

- Installed costs of stationary fuel cells (including the hydrogen production componentry) down to US$1,200 to $1,800/kW (industrial) and US$2,400/kW (residential).
- Delivered hydrogen costs from carbon neutral sources at US$3 to US$5 per mile driven or per kWh for stationary applications.
- Cost of hydrogen delivery (from a centralised production site) to be less than US$1.20/kg (or gallon of gasoline equivalent) at the pump.

Major technical objectives underpinning these critical objectives were identified. For the areas related to hydrogen production and delivery these included:

- Carbon capture and storage.
- Improvements in low temperature electrolyser efficiency and costs.
- Ability to support a sufficient density of fuelling stations – defined either in terms of x% existing stations converted to hydrogen or y fuelling stations per square mile as a function of population density.
- Improvements to catalysts and membranes for producing and separating hydrogen from syngas (the product of biomass and coal gasification).
- Improved efficiency and overall process optimisation.

In the area of fuel cells for stationary applications, major technical objectives included:

- Development of more robust fuel cell stack materials.
- Better identification of performance degradation mechanisms of fuel cell stacks.
- Lower cost and more robust fuel supply componentry.
- Lower cost and more robust heat exchanger materials better able to tolerate aggressive and/or high temperature environments.

In the area of fuel cells for transportation applications major technical challenges included:

- Cost-effective on board storage systems.
- Development of non-precious metal catalysts for use in fuel cells.
- Improved fuel cell system durability under all operating conditions (high temperature/ freeze tolerant fuel cell membranes.

Another activity of the IPHE is recognition of large international projects by IPHE branding. An evaluation team comprised of IPHE members from the United States, United Kingdom, European Commission, Russian Federation, Iceland, Germany and New Zealand evaluate proposals on the basis of impact, extent of international collaboration, scientific quality, management and financial structures. As of March 2007 a total of 23 projects covering the main hydrogen-related issues have received official IPHE recognition. Between them these projects provide a good indicator of where much of the major international research effort in hydrogen is being directed. The most recent of these projects are outlined in more detail in Appendix E.

5.1.2 International Energy Agency's Hydrogen Implementation Agreement

The International Energy Agency (IEA) has had hydrogen research programmes going on for 30 years. New Zealand joined the IEA Hydrogen Implementation Agreement (HIA) in 2005. The strategy of the IEA's Hydrogen Programme is to facilitate, coordinate, and maintain innovative RD&D activities through international cooperation and information exchange [17]. Seven areas are targeted: technology, energy security, environmental, economic, market, deployment, and outreach. The specific completed, current and future tasks are shown in Appendix F and the strategic objectives and actions for each area are as follows:

Technology Objective: To promote acceptance of hydrogen as an energy carrier

- Conduct R&D to address important barriers to hydrogen's acceptance.
- Foster and maintain a balanced portfolio of hydrogen technologies.

- Develop safe, efficient, and cost-effective hydrogen storage systems.
- Demonstrate integrated hydrogen systems.
- Collect, disseminate, and analyze information on hydrogen technologies.
- Develop direct hydrogen production technologies.

Energy Security Objective: Contribute to global energy security

- Fuel cell urban transit bus and hydrogen refuelling station.
- Facilitate the transition from fossil fuel energy systems to sustainable hydrogen-based energy systems.
- Provide resources for converting intermittent and seasonal renewables to base-load, load-following, or peak-load power supplies, and to transportation fuels.
- Assist developing countries in evaluating sustainable, indigenous resources for hydrogen production.

Environmental Objective: Exploit the environmental benefits of hydrogen

- Carry out R&D on renewable hydrogen production techniques.
- Promote hydrogen as a "clean" fuel.
- Perform life-cycle assessments of hydrogen technologies and energy systems.
- Conduct R&D on technologies that lead to the decarbonisation of fossil fuels.

Economic Objective: Develop cost-effective hydrogen energy systems that can compete in global markets

- Encourage industry participation to obtain market-oriented input for prioritizing RD&D activities.
- Develop and utilize analysis tools to evaluate and optimize hydrogen systems.
- Increase involvement of industry in the Hydrogen Implementing Agreement's activities.
- Foster clean-system incentive policies.
- Identify secondary benefits of hydrogen energy systems, such as a reduction in the use of military force to ensure petroleum supplies.

Market Objective: Identify and overcome barriers for hydrogen's penetration into the energy and fuel markets

- Contribute to the scientific and technical basis for approved codes and standards.
- Promote hydrogen infrastructure for supply, maintenance, and operation.
- Pursue technologies that will lead to increased market penetration for hydrogen.
- Initiate safety-related educational and technology assessment activities.

Deployment Objective: Promote deployment of hydrogen technologies with important local and global energy benefits

- Provide design support for hydrogen demonstrations.
- Conduct cost-shared and task-shared deployment activities for hydrogen energy systems.
- Act as an information resource for ongoing and proposed hydrogen demonstration activities, including performance analyses.
- Conduct case studies for hydrogen systems in developing countries.

Outreach Objective: Advertise the benefits of hydrogen

- Increase involvement of private and public organizations in the IEA Hydrogen Program.
- Use media tools to promote hydrogen education.
- Establish collaborative R&D projects that promote international networks.

- Collaborate with other IEA Implementing Agreements to increase the effectiveness of cross-cutting R&D activities.
- Increase cooperation to reach "critical mass" in R&D activity.

In essence, the areas covered by the IEA HIA and the IPHE are identical but because the IEA HIA has been operating much longer and has grown more organically, the way its tasks and objectives are organised appears less logically structured than for the more recent IPHE structure. In several areas the two bodies are looking to pool their resources in combined programmes.

5.1.3 International Industrial Hydrogen Research

Many privately owned industrial companies are involved in collaborations under the IPHE and IEA HIA programmes but will also have their own commercially-sensitive research programmes aimed at generating intellectual property and new products for market. It should be noted that overall private spending on R&D dwarfs spending by governments. The companies undertaking research can be divided into the groups:

- Automotive manufacturers – all of the major companies - including General Motors, Ford, Daimler-Chrysler, Toyota, Honda, Mitsubishi, BMW, Fiat, and Hyundai – have active programmes to develop hydrogen vehicles.
- Energy companies – including BP, Shell, Elf, ExxonMobil, Chevron Texaco, Rio Tinto.
- Fuel cell companies – including Ballard, United Technology Corporation Fuel Cells, Plug Power, ReliOn, Millenium Cells, Ceramic Fuel Cells etc.
- Other – covering hydrogen production, distribution and storage technology companies – including Stuart, Norsk Hydro, Praxair, Air Products, Linde, Johnson Matthey etc.

Usually, the current research is not disclosed until a new product is ready for launch but the areas being addressed will cover the practical issues described previously for each technology. Some examples of research for each group are given in more detail in Appendix G.

5.2 Hydrogen Related Research in New Zealand

The current New Zealand research and development programmes involving hydrogen are summarised in Table 4. These cover research, development and demonstration projects for a range of hydrogen producing technologies. Most of the programmes are funded by the New Zealand Government but some are funded by other bodies e.g. the Coal Association of New Zealand (CANZ). There does not appear to be any exclusively commercial funded hydrogen energy research being undertaken within New Zealand at present.

Table 4: Hydrogen Related Research in New Zealand [18]

Project Title	**Project Objective**	**Project Participants**
Hydrogen Energy for the Future of New Zealand	To build the technology platform, knowledge and expertise necessary to underpin the introduction of a hydrogen energy economy into New Zealand	Industrial Research Limited CRL Energy Limited Unitec
Thermochemical Production from Renewable Resources	To investigate and determine the issues associated with hydrogen production in New Zealand	Waste Solutions Limited Industrial Research Limited
Hydrogen Storage	To develop new materials and process technologies for energy efficient and safe storage of hydrogen gas as chemical hydride materials	Industrial Research Limited
Hydrogen and Fuel Cell Demonstration	To build New Zealand's capabilities and knowledge in hydrogen energy and fuel cell technologies for stationary distributed energy applications	Industrial Research Limited Massey University
Supply Options for the PEM Demonstration at the US Antarctic Programme Facility	To consider a range of options to provide hydrogen to the US Department of Defence PEM Fuel Cell Trial at the Antarctic Centre, Christchurch, New Zealand	CRL Energy Limited Industrial Research Limited
Hydrogen – A Long Term Future for the Coal Industry	To provide a pathway of activities that the coal industry needs to undertake in order to ensure coal plays its role in the development of a hydrogen energy economy in New Zealand	CRL Energy Limited
Nanostructure Alumina Materials for Hydrogen Separation	Highly regular porous structures for hydrogen separation, both in coated and uncoated configurations	Industrial Research Limited
Ethanol Reforming Catalysts	Formulation and study of catalysts for ethanol reforming to produce fuel cell quality hydrogen	University of Auckland Industrial Research Limited
Bioelectronic Transformation	Replacement of platinum with biological alternatives for hydrogen production	Cawthron Institute
Transitioning to a Hydrogen Economy	Identifying scenarios for transitioning New Zealand to a hydrogen based energy system, the barriers to their realisation and a research plan for addressing these barriers	CRL Energy Industrial Research Limited
High performance electrocatalysts for proton exchange membrane water electrolysers producing hydrogen	Highly active electrocatalytic particles will be prepared and characterised for use in proton exchange membrane (PEM) water electrolysers	Massey University

More details of these research programmes are given in Appendix H.

6 Markets for Hydrogen

6.1 Current Market for Hydrogen in New Zealand

Currently, the only uses for hydrogen in New Zealand are in the industrial and scientific sectors and not in the transport or power generation sectors, unless one includes the production and use of hydrogen during oil refining which is not a direct use of hydrogen for transportation. The more common uses include: oil refining, food processing, the chemical industry (e.g. hydrogen as a raw material in synthesis of hydrogen peroxide or polymers and solvents; or used to purify gases that contain trace amounts of oxygen using catalytic combination of hydrogen and oxygen and later removal of water), pharmaceutical industry (vitamin manufacture), glass and ceramics (e.g. hydrogen is used in float glass manufacturing hydrogen to prevent oxidation of the tin bath), metal and alloy production (e.g. hydrogen is mixed with inert gases to obtain a reducing atmosphere which is required for many applications for example, in heat treating, welding, annealing, sintering and brazing), and cooling of large electrical generators.

Within New Zealand these markets are very small with the exception of oil refining, chemical and food industries.

- Degussa produces 1200 tonnes per year of hydrogen by reforming natural gas, 95% of which is used in hydrogen peroxide production. The remaining 5% (60 tonnes per year) is sold on in full to BOC [19].
- BOC produces 60 tonnes per year (by electrolysis) and buys 60 tonnes per year from Degussa giving a total of 120 tonnes per year for retail. At present they are developing a 100m^3/h facility at Glenbrook. The biggest clients for BOC are Goodman Fielder (non-dairy spreads) and BlueScope Steel [20].
- Fonterra do not consume large quantities and only use H_2 as a carrier gas for scientific instruments [21].
- BlueScope Steel use 40m^3/min. They rely on BOC for the hydrogen and BOC produce it on site via electrolysis [22].
- New Zealand has little commercial glass making industry and major suppliers of glass bring the glass in from Australia [23].
- The largest producer and consumer is the New Zealand Refining Company, with Marsden Point refinery producing and using 140 tonnes per day. This equates to 51,100 tonnes per year [24, 25].

The current aggregated annual hydrogen demand for New Zealand is approximately 55,000 tonnes, and as indicated earlier, none of this is as hydrogen for end use energy services.

6.2 New Zealand Market for a Hydrogen Energy System

How hydrogen demand develops within New Zealand will depend on technical, social, political and economic factors. The amount of hydrogen required in the long term for transportation and energy generation will be large compared to the current traded quantities. The best way to meet such an increase in demand will require careful planning and consideration of the supply chains options and external influences. For example, to supply 15% of the New Zealand light vehicle fleet with hydrogen (one of the IPHE critical objectives for a hydrogen economy) would require 44,700 tonnes of hydrogen per year for fuel cell vehicles (FCV) or 94,500 tonnes per year for hydrogen powered internal combustion engine vehicles (ICEV), compared to the 55,000 tonnes of hydrogen currently produced in New Zealand annually, the bulk of which is used on site[4]. Clearly, even powering such a small portion of the transport fleet will require significant investment in a distribution infrastructure for hydrogen in New Zealand.

Only a very limited amount of current production is sent through a distribution infrastructure and none of it is used for fuelling vehicles directly. As larger proportions of transportation fuel and a significant proportion of distributed and centralised power generation are met using hydrogen as a fuel, a radical rethink on hydrogen supply strategies will be required with far reaching consequences for the way energy is supplied and used in New Zealand. Proportionately larger quantities of hydrogen will need to be produced by existing and new hydrogen supply chains.

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[4] This assumes a light vehicle fleet of 3 million vehicles, 15,000km per year, 94MJ/100km for FCVs, 168MJ/100km for ICEs, hydrogen Higher Heating Value is 142MJ/kg relevant to FCVs and Lower Heating Value is 120MJ/kg relevant to ICEs [26]

7 Hydrogen Supply Chains

7.1 Energy Supply Chains

Energy supply chains were introduced in Section 3 as a description of the conversion processes and intermediate energy carriers required to take an energy resource and deliver a service to an end user. Hydrogen supply chains are simply energy supply chains where one of the intermediate energy carriers is hydrogen, which also enables chemical energy storage in the form of hydrogen. Energy supply chains are sometimes referred to in terms of Well-to-Wheels (WtW), and Source-to-Use (StU) [26, 27]. WtW relates to transport applications traditionally using petroleum products and Source-to-Use is a more generic term that also covers stationary applications such as electricity and heat services. For the rest of this document StU will be used to cover both transport and stationary applications.

Understanding and comparing all aspects of the full StU supply chains is the only way to assess the sustainability benefits of particular energy systems and technologies. It is vital to consider complete supply chains, from the source to the use, as comparing only parts of chains can be misleading. For example, for transport it might be argued that synthetic liquid fuels from coal are economically competitive with petrol, and have the advantage of being indigenous, therefore providing improved security of supply. The carbon dioxide footprint from the refuelling point onwards would indeed be very similar to petrol. However, a full StU supply chain analysis would uncover a larger carbon footprint for the processes up to the refuelling point, unless CCS was used[5].

An example for stationary applications is to compare the potential use of natural gas via emerging residential combined heat and power (CHP) fuel cell appliances with its use as a fuel in combined cycle gas turbine (CCGT) power stations. CHP technologies provide both heat and electricity at very high combined efficiency (to the order of 70–90%), because the heat generated is utilised rather than wasted. Simple generation using gas has much lower efficiency mainly due to the rejected heat energy. The transmission of gas via the pipeline network is also more efficient than the transmission of electricity by the transmission/distribution network, which also favours on-site CHP technology over centralised generation. The CHP appliance is effectively itself a hydrogen energy supply chain, because it requires on-site (internal) production of hydrogen for the fuel cell. An alternative supply chain scenario is to manufacture the hydrogen centrally in from a number of different sources, and then distribute it to end use sites via hydrogen pipelines. CHP appliances at these sites would then no longer require on-board reformation to produce the hydrogen and would therefore be much simpler. The hydrogen may then also be used to power other on-site appliances besides CHP.

Due to the flexibility of hydrogen as a fuel, storage medium and energy carrier, and the numerous feedstocks it can be made from, a multitude of hydrogen energy supply chains can be defined. Generically, these are covered by Figure 6, which includes feedstocks, transport methods, conversion technologies, distribution options and end uses. The transportation options include fuel cell powered vehicles, hydrogen fuelled internal combustion engine vehicles, and hybrid versions of both of these technologies. The stationary applications include portable use such as very small fuel cells for battery replacement, flame and catalytic type combustors for heat, gas turbines and reciprocating engines for electrical power, and fuel cell power units that may produce both heat and electrical power.

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[5] There is a significant release of carbon dioxide during the manufacture of synthetic petrol from coal which renders this option more carbon intensive than the production of refinery-derived petrol. The use of CCS, which is only practical for synthetic fuels production, would allow this option to then be of similar carbon intensity to the production of refinery-derived petrol.

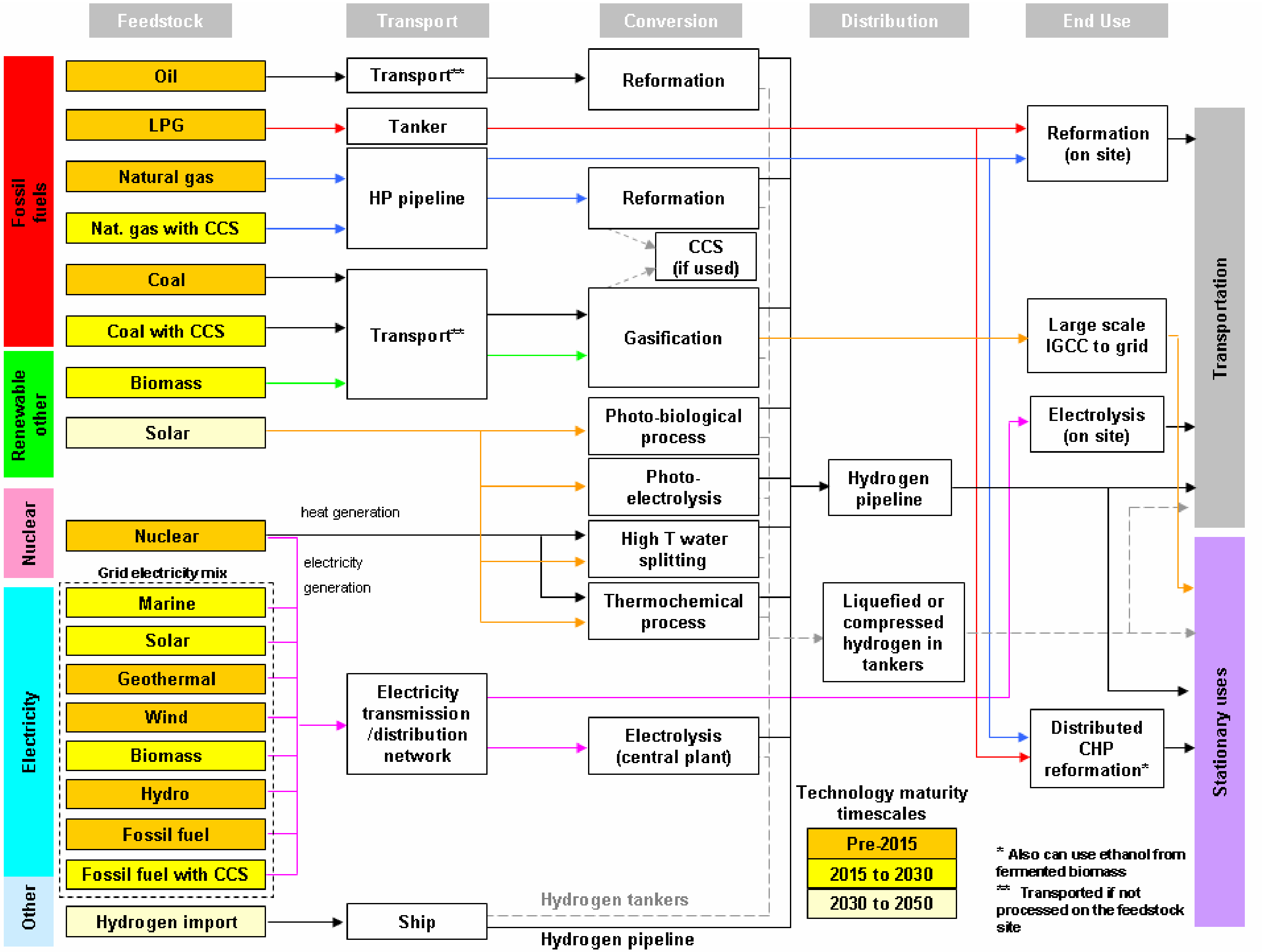

Figure 6: Generic Hydrogen Supply Chains

Figure 6 is a simplified diagram, but still includes more than 100 individual hydrogen supply chains. If the end uses were subdivided into the numerous possibilities detailed in Section 4.4 (e.g. FCV, hydrogen ICE, Hybrids, trains, planes, and delivery vans etc) the number of chains would be thousands. Similarly, some feedstocks may be subdivided into many completely separate sources (e.g. biomass from forestry wood, short-rotation coppice, specific agricultural crops, food processing wastes etc), which would increase the number of identifiable chains significantly. Combining this with the actual complexity of each supply chain (for example a chain for forestry wood gasified to produce hydrogen for transport use as shown in Figure 7) demonstrates that it would be impractical, if not virtually impossible, to model all the potential hydrogen supply chains in the detail needed to provide useful output for further analyses. In fact, it is not always possible to acquire all the necessary input data at sufficient accuracy to make the modelling meaningful, which may even preclude analysis of some chains.

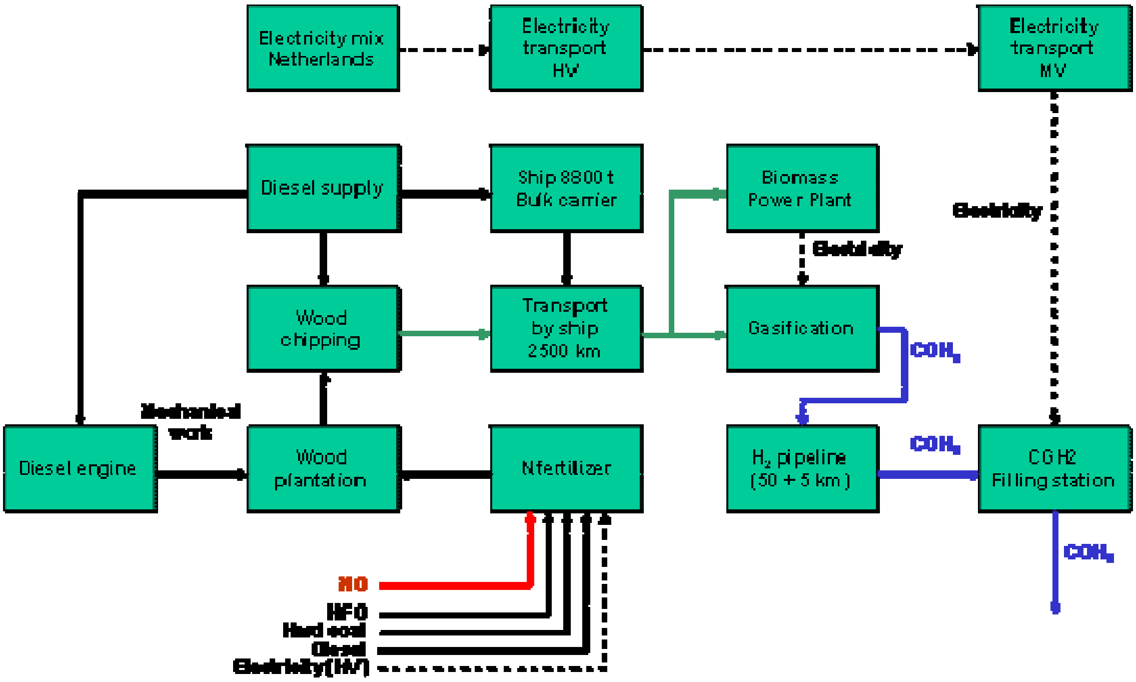

Figure 7: Example Hydrogen Supply Chain from the European HyWays Project – Gasified Forestry Wood used to Produce Hydrogen for Transportation in the Netherlands.

7.2 Initial Supply Chain Selection Criteria for New Zealand

It is necessary at this stage to reduce the number of chains for more detailed analysis to the twenty or so that are most likely to be relevant as potential hydrogen supply chains for New Zealand. Initial assessment of the hydrogen supply chains can be made using the information given in this document. The choice of chains will be based on the available natural resources in New Zealand to meet the goal of supply security, current hydrogen production sites and infrastructure (if available), characteristics of the current and future energy supply system, and the availability, efficiency and economic viability and anticipated developments for all of the current and possible future hydrogen technologies. There is also a time factor in the selection of chains as the transition to a full hydrogen economy will take many decades. It seems likely that the initial uptake of hydrogen technologies will be in stationary and distributed applications through niche uses of fuel cell systems. As demand for hydrogen energy develops, fixed infrastructure investments are likely to be made to enable large-scale centralised production with distribution by pipeline. This will most likely displace the earlier technologies that rely on distributed production or delivery by tanker. This should be taken into account when selecting supply chains which potentially span a time period of 50 years or more. A realistic approach is to select a few chains which appear to be near term options, a few which are medium term options, and one or two which are obviously much longer term options, but particularly relevant to New Zealand's energy resource base. One way of assessing the likely timeframe is to look at the extent and cost of infrastructure building required for a particular chain.

The starting point taken was to look at the feedstock and determine if this was a viable option, i.e. sustainable and cost effective. The timeframe aspect was then used as a filter. Oil was discarded because of the costs and likely increase in future price and because it would place New Zealand in a "dependent" situation for supply, unless a major commercially viable oilfield is discovered within the coastal waters of New Zealand. Hydrogen import was also discarded as an option for the same reason. Chains using large solar arrays for high-temperature applications were deemed to be of limited application as the solar resource of New Zealand is moderate compared to say, Africa or Central Australia. The nuclear option was not selected, as at present, and into the foreseeable future, it was deemed that there were too many political and socio-environmental barriers to its uptake. The other resources identified in Figure 6 are currently available within New Zealand in useful quantity and quality and so should be considered.

From the generic list of feedstocks the following 6 were selected as a starting point of a chain: natural gas, coal, LPG, ethanol, biomass and electricity either from wind farms or from the existing grid electricity mix. Taking into account government policy that new generation should be renewable energy based, the grid electricity mix will have an increasing contribution from renewables including marine, solar, geothermal, wind, biomass and hydro.

Coal and natural gas options have been considered twice, without CCS in the short/medium term and with CCS in the long term. Coal was selected due to its abundance. LPG was also selected because its use in the South Island is growing and there is no equivalent natural gas distribution network there. Natural gas was selected because the resource is available now and exploration for further resource continues. Even if no new large natural gas fields or sources of LPG are discovered the infrastructure developed could be maintained using imported gas/LPG, although at a higher cost and a lower security of supply.

Marine, solar, geothermal, wind, biomass and hydro have been considered together as part of a grid electricity mix in combination with existing fossil-fuelled generation. Wind generated electricity was also considered separately because the size of the unexploited resource and the relative maturity of the technology make it likely to be utilised significantly in the short to medium term. It is felt that the likelihood of building an electrolysis plant at any of these individual resource sites and having to transport the hydrogen from the individual sites was small, at least in the short to medium term, and that the more realistic path would be to feed the electricity produced directly into the national grid (with extension to the site) and transport it to electrolysis plants closer to the emerging demand centres. Biomass was also selected as a start of a chain due to the abundant and varied natural resources available which could aid security of supply coupled with technological advancements.

Conversion technologies were another consideration for selecting the above as feedstocks. The gasification (including large-scale integrated gasification and combined cycle gas turbine plant for electricity generation, IGCC), reformation and electrolysis technologies are relatively mature although significant research continues to improve these processes. High-temperature and photo-based technologies are currently a long way from commercialisation but were not ruled out on the grounds of the technology itself (by 2050 at least some of these could have become technologically mature) but the nuclear or solar resource to produce the required high temperatures are unlikely to be available in New Zealand. Solar Photovoltaic technology may be important in New Zealand well before 2030, but since this will primarily be a renewable electricity generating resource, it is covered in the grid electricity mix option.

End uses were divided into transportation and stationary. It is generally predicted that the future mass market for hydrogen will be in road transport but it was felt important to include stationary uses too as they may be instrumental in the transition to a hydrogen energy system and are likely to always be involved at some level. There are many options for road, rail and water transport but generic road use was selected because it is likely to form the bulk of the demand for New Zealand. Again there are many road transport applications that will benefit from hydrogen use such as local delivery vans and buses, which may form important small-scale steps in the transition to a hydrogen energy system, but eventually the bulk of road demand is likely to be based around private cars using hydrogen powered internal combustion engines (ICE) or fuel cell (FC) vehicles.

Stationary applications, including medium- to large-scale power generation and small-scale combined heat and power fuel cells (CHP), are seen as potentially important during the initial development phase of a hydrogen energy system, by providing a demand to drive the transition. Although a pipeline network might be the ultimate method of distributing hydrogen in a fully established large scale hydrogen energy system, during the transition phase when hydrogen volumes are smaller, both transportation by tanker and small-scale production on site could be essential in producing the demand necessary to justify major pipeline works.

Medium- to large-scale power generation may be based on large fuel cell or gas turbine technologies. Coal or biomass fuelled integrated gasification combined cycle (IGCC) gas turbines with CCS are often proposed for electricity production, where the hydrogen is produced and consumed on site. Effectively this makes them separate from a hydrogen energy system but long term the gas turbine could also accept hydrogen brought in from elsewhere, making them as much part of the hydrogen energy system as fuel cell power plants. Small-scale (domestic/small industrial) CHP plant may offset the higher costs of the technology by the greater overall efficiency gained by the utilisation of the heat generated.

7.3 Stakeholder Input towards National Hydrogen Supply Chain Selection

Selecting these specific supply chains is the first step in the definition of a roadmap for a future hydrogen economy and prompts thought about the viability and potential that hydrogen has in future energy systems. Limiting the number of chains will also focus the effort in the discussion of a hydrogen roadmap.

Based on the considerations in Section 7.2, the initial list of important chains was selected by the project team and is shown in Table 5. Chains are subdivided according to their end use e.g. chain 1a is central reformation of natural gas with the hydrogen delivered to a refuelling station via a pipeline for use with fuel cell vehicles, and chain 1b is identical except the end use is hydrogen powered internal combustion engine vehicles.

We now need your feedback on this initial selection. We are not asking you to prioritise the 24 chains but we do want you to:

- Identify chains that should be added.
- Identify chains that should be deleted.
- Give reasons for proposed changes.
- Identify chains you believe essential.
- Comment upon any other issues you feel are relevant.

Using your feedback we will select the chains that are to go forward to Stage 2 for economic, emissions and energy modelling technique. Reference chains and competitive chains will also be modelled and the selected chains will be assessed against these.

Please address all feedback to Tony Clemens at CRL Energy Ltd., PO Box 31-244, Lower Hutt (or t.clemens@crl.co.nz) by 22nd June 2007.

Chain Codes*	**Feedstock**	**Conversion Process**	**Distribution**	**End Use**
1 a - d[6]	Natural gas	Central reformation	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
2 a - d	Natural gas	Central reformation	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
3 a - d	Natural gas	Central reformation + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
4 a - d	Natural gas	Central reformation + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
5 a - d	Coal	Central gasification	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
6 a - d	Coal	Central gasification	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
7 a - d	Coal	Central gasification + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
8 a - d	Coal	Central gasification + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
9 a - d	Biomass	Central gasification	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
10 a - d	Biomass	Central gasification	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC

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[6] a, b, c and d refer to the end use of the hydrogen in each chain

11 a - d	Biomass	Central gasification + CCS	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
12 a - d	Biomass	Central gasification + CCS	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
13 a - d	Wind generated electricity	Central electrolysis	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
14 a - d	Wind generated electricity	Central electrolysis	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
15 a - d	Grid electricity mix	Central electrolysis	Pipeline	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
16 a - d	Grid electricity mix	Central electrolysis	Tanker	a) FC vehicle b) H_2 ICE vehicle c) Micro-scale FC CHP d) Distributed power FC
17 a - b	Wind generated electricity	Refuelling site electrolysis	None	a) FC vehicle b) H_2 ICE vehicle
18 a - b	Grid electricity mix	Refuelling site electrolysis	None	a) FC vehicle b) H_2 ICE vehicle
19 a - b	Natural gas	Refuelling site reformation	None	a) FC vehicle b) H_2 ICE vehicle
20	Coal	Central IGCC + H_2 gas turbine + CCS	Direct use	Electricity for grid
21	Biomass	Central IGCC + H_2 gas turbine	Direct use	Electricity for grid
22 a - b	Natural gas (piped)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC
23 a - b	LPG (by tanker)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC
24 a - b	Ethanol (tanker)	FC CHP with reformation	Direct use	a) Micro-scale FC CHP b) Distributed power FC

Table 5: Initial Selection of Hydrogen Energy Chains for Modelling

7.4 Modelling Hydrogen Supply Chains Using the E3-database

The E3-database is a tool developed by L-B-Systemtechnik (LBST) of Germany, for calculating the primary energy use, greenhouse gas (GHG) emissions and levelised costs associated with the processes in energy chains [2].

In Stage 2 of this project, selected hydrogen supply chains will be modelled using the E3-database tool. Energy use, GHG emissions and costs of the supply of transportation fuel, electricity and heat will be estimated from production to consumption of hydrogen. These data will be calculated for selected time frames out to 2050, so that trends resulting from energy price developments and technology learning can be determined. As well as being a tool for energy chain analysis, the E3-database collates the known techno-economical characteristics of all hydrogen technologies. The definitions and descriptions of the hydrogen production, distribution, and consumption technologies in the E3-database form the basis for the selection of the chains relevant to New Zealand.

7.5 Project Progression

The chains selected in Stage 2 will be used in the scenarios development and transition analysis processes of Stage 3 to identify a plausible future and a route for getting there. From this analysis the knowledge gaps and New Zealand specific barriers to transition will come into focus. Stage 4 looks at the identification of the gaps and barriers in understanding or resources in meeting the developed scenarios. The final stage of the process involves development of an action plan to address these barriers most efficiently.

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Appendix A - Hydrogen Production Technology Review

A.1 Introduction

Currently, the vast majority (96%) of the raw material used in the production of hydrogen is fossil fuel including natural gas, oil and coal; the remainder is produced from water. The energy for the processing is also dominated by fossil fuels but potentially much of this could be obtained from renewable or nuclear sources. The bulk (80%) of the hydrogen produced is for non-energy use in chemical processes and refineries and is usually produced on site. No existing technology can produce the required quality of hydrogen at a low enough price to make it commercially viable as an energy carrier at present. The range of issues that need addressing varies between the potential technologies.

A.2 Natural Gas Reforming

Hydrogen can be produced from natural gas by steam methane reformation (SMR), partial oxidation (POX) or auto-thermal reformation (ATR).

In SMR, methane is combined with water vapour endothermically at high pressure (3-25bar) and temperature (700-850°C), to give carbon monoxide and hydrogen following the equation:

$CH_4 + H_2O + \text{heat} = CO + 3H_2$

Usually, the heat is provided by combustion of some of the methane. The carbon monoxide is then reacted with more steam to give hydrogen and carbon dioxide using the water-gas shift reaction:

$CO + H_2O = CO_2 + H_2 + \text{heat}$

The POX process involves partial combustion of methane in oxygen following the equation:

$2CH_4 + O_2 = 2CO + 4H_2 + \text{heat}$

Again, the water-gas shift reaction is used to convert the carbon monoxide to hydrogen and carbon dioxide.

ATR is a combination of SMR and POX. The reaction is exothermic with high gas outlet temperature (950-1100°C) and pressure (up to 100bar). Again, the water-gas shift reaction is used to convert the carbon monoxide.

Large-scale natural gas reforming technologies are fully mature and are widely used in the chemical and refinery industries. Unlike electrolysis, the outlet gases require clean-up which reduces the overall efficiency and adds to plant costs. Development of new catalysts, adsorption materials and separation membranes will be needed to increase the process efficiency and the quality of gas to that required for fuel use.

Units can be produced on a small and large scale, with large-scale SMR plant able to convert methane to hydrogen at an efficiency of 75% (before compression) at relatively low cost. Conversion efficiencies for small-scale plants are 5 to 10 percentage points lower. ATR is a more complex process requiring advanced reactor design. The benefit of ATR is the potential for higher conversion efficiencies, particularly on the small scales suitable for distributed production. Capture and storage of the carbon dioxide produced to make the process carbon neutral may only be economic for large-scale plant. Despite this and the lower conversion efficiencies, small-scale plant may dominate the new infrastructure built during the transition to a hydrogen-based economy.

Within the next 5 years it is expected that the commercialization of decentralized stationary fuel cells in the range 10 to 250kW_e will occur. In order that these fuel cells can be used with natural gas, small natural gas reformers will be developed.

The first commercial application was the integration of such a reformer into a 200kW$_e$ fuel cell module, with phosphoric acid fuel cell (PAFC), produced by ONSI. Residential scale natural gas reformers at the 2 to 5 kW output level are now being evaluated in several hundred CHP fuel cell systems in Japan, USA, and Europe.

A.3 Electrolysis

Electrolysis is a well-established process in which electricity is used to split water into hydrogen and oxygen gases following this equation:

$2H_2O + \text{electricity} = 2H_2 + O_2$

The gases produced are of a very high purity compared to other techniques and no gas clean-up is required. The electricity used can be generated from fossil fuels (with CCS), nuclear reactors or renewable energy sources which give the possibility of carbon-free hydrogen generation. Electrolysers can be built on scales suitable for centralised or distributed production. Whilst centralised production on the large scale will give higher efficiency and lower capital costs ($/kW) because of the economies of scale, small-scale distributed units are likely to play an important role in the development of the infrastructure during a transition to a hydrogen-based economy. The two main types of electrolyser that are currently available at a commercial scale are the conventional alkaline electrolyser and the polymer electrolyte membrane electrolyser (PEM).

Alkaline electrolysers are a mature industrial technology for large-scale low-pressure (1-25bar) hydrogen generation. As a result of the large physical cell size they are only suitable for stationary applications. Electricity is passed through an electrolyte solution of potassium hydroxide via nickel electrodes. The electrolyte is usually circulated through a series of electrolytic cells which are arranged into a cell stack. The main issues to be overcome are the cost of the cells, the low efficiency of conversion and the length of the equipment lifetime, which currently makes the cost of the hydrogen produced too high for fuel use. A further issue is that the efficiency of the conversion drops significantly when the cell is operated at part load (low turn-down ratio). Efficiencies are currently in the range 40-69% (excluding the considerable energy required to compress the hydrogen to high-pressure for use) which is well below the theoretical maximum efficiency of 85%. To be cost-effective significant improvements in efficiency will be required. Advanced alkaline electrolysers for operation up to 120bar are under development with potentially high efficiencies (up to 77%). These will also require less energy to compress the hydrogen produced to the pressures required for storage and use (possibly 700bar).

In PEM electrolysis the electrolyte is a solid, acidic polymer membrane. There are several advantages over conventional alkaline electrolysers: No corrosive liquid is required in the process which makes them safer to operate; they are compact and so can be used for mobile as well as static applications; they can be designed to operate at high pressures (up to 400bar) so reducing the energy required to compress the hydrogen produced; and they operate closer to their maximum efficiency when under part load (higher turn-down ratios) and can use higher current densities. The current issues with PEM electrolysers are the cost of the cells, the low efficiency, and the limited lifetime of the membrane. The technology is less mature than conventional alkaline electrolysis and so it is expected that significant improvements can be made to overcome these issues with the development of new materials and new stack designs. Efficiencies close to the maximum theoretical value of 85% are predicted to be possible on a commercial scale for low current density operation.

There is significant interest in the development of electrolysers for operation at elevated temperatures (700-1000°C). High-temperature electrolysis uses considerably less electrical energy but the extra heat required increases the overall energy input. However, electrical efficiencies of 81-86% are possible. There are many potential heat sources including geothermal, solar, and waste heat from fossil-fuelled or nuclear power plant that could be utilised. One potential technology is the Solid Oxide Electrolyser Cells (SOEC) based on Solid

Oxide Fuel Cells (SOFC). The technology is not yet mature and the issues to be overcome include the thermal stress limits of the ceramic and other materials used in the cells.

A.4 Coal Gasification

Coal is a plentiful global resource and coal gasification is commercially mature (but not yet as a method for producing pure hydrogen). The carbon in coal is converted to carbon monoxide and hydrogen following the reaction:

$C + H_2O + \text{heat} = CO + H_2$

The water-gas shift reaction is subsequently used to react the carbon monoxide with more steam to produce carbon dioxide and more hydrogen. Frequently, a catalysed reaction is then used to reduce the carbon monoxide level further. The gas mixture is separated using physical absorption and further gas clean-up (including desulphurisation) is necessary for the hydrogen to be suitable for fuel cells.

In the future, gas prices are likely to increase relative to coal, and costs may then become competitive with SMR. High-temperature entrained-flow gasification gives the best conversion to hydrogen with the lowest amounts of char and tars. Other gasification technologies, such as fixed- and fluidised-bed gasifiers, are also well developed. Coal gasification is only economically viable for large-scale plant, which enables the benefits of carbon capture and storage (CCS) to be accessed. Hydrogen production efficiencies are typically 50-70%. Large-scale integrated gasification and combined cycle gas turbines (IGCC) with CCS, where hydrogen and electricity can be generated simultaneously, are considered the best opportunity to make hydrogen production from coal cost-effective. Efficiencies may be as high as 85%. To produce pure carbon dioxide for storage, oxygen would be used for gasification instead of air. At present, this is expensive but it is anticipated that methods of oxygen production currently under development will enable the costs to be significantly reduced. New membranes and catalysts for water-gas shift reactors, membranes for separation and membranes that combine both water gas shift and separation are in the early stages of development but could improve the conversion efficiency and reduce energy required for gas separation.

A.5 High-Temperature Water Splitting

At very high-temperatures (>2500°C) water will split into hydrogen and oxygen without the need for electrical energy and the associated losses during electricity production. Several techniques to reduce the water-splitting temperature to below 1000°C are being investigated including thermochemical cycles, hybrid thermal/electrolytic decomposition, direct catalytic decomposition with ceramic membrane separation and plasma/chemical decomposition with a carbon dioxide cycle. These processes are not yet commercially viable, with thermochemical cycling being the most advanced at present. The main issues to be addressed are the low efficiencies (much less than 50%) and the heat exchange and corrosion resistance properties of the materials used. Cheap sources of high-temperature are also required to make the processes cost effective. For example, to reach efficiencies of 50% for Sulphur-Iodine thermochemical cycling, temperatures over 1000°C would be required. These temperatures are only likely to become available economically from new generations of nuclear reactor or from concentrating solar collectors.

A.6 Biomass Gasification

There are numerous proposed biological and thermochemical pathways to convert biomass to hydrogen, but at present no commercial plant has been built. Biological processes, including anaerobic digestion, fermentation and metabolic processing, are slower and more costly than thermochemical processes, such as gasification and pyrolysis. Gasification, similar to that for coal, appears the most likely process to be adopted although probably on a smaller scale to reduce feedstock transport costs. Even so, the feedstock is likely to cost twice as much as coal per unit energy and so this technology is unlikely to be cost-competitive with coal gasification.

Several biomass gasifiers-IGCC projects for power generation have been successfully constructed but as yet no project to produce hydrogen has been demonstrated. The possibility of combining biomass use with carbon capture and storage could lead to a carbon negative process that may be economically and environmentally attractive. The main issues for biomass gasification are in the quality control, preparation (e.g. drying) and transport logistics for the feedstock. Competition for the biomass feedstock from other uses, such as biofuel production, may also be an issue.

A.7 Photo-electrolysis

As opposed to coupling a conventional photovoltaic panel with an electrolyser, photo-electrochemical cells (PEC) split water into hydrogen and oxygen by using semiconductor materials illuminated by sunlight and immersed in water. The semiconductor acts as both a solar absorber and an electrode, converting the light into chemical potential energy. Test-scale devices have produced conversion efficiencies up to 16%, which is significantly more efficient than using the photovoltaic panel-electrolyser combination. The techniques are divided into thin-film and powdered catalyst technologies. This area is technologically immature and advances in the semiconductor materials (to increase conversion efficiency and semiconductor lifetime) as well as the supporting engineering, will be required for it to reach commercialisation.

A.8 Photo-biological Production

Certain algae and cyanobacteria combine photosynthesis and hydrogenase-catalysed hydrogen production. Many biological materials, such as food waste, can be utilised by these organisms. Although the process has only been demonstrated at the laboratory scale, metabolic or genetic engineering of these organisms and use in large bio-reactors, could result in significant hydrogen production. Research into the genetics of hydrogen production and manipulation of the genes in these organisms are essential for progress of this technology. A further possibility is to use artificial photosynthesis and hydrogenase enzymes to mimic the processes occurring in these organisms. At present, the technology is not well enough established to be able to predict how far it might develop.

A.9 Liquid Fuel Reformation

Examples of liquid reformer processes are provided below

A.9.1 Partial Oxidation of Heavy Hydrocarbons

Partial oxidation or auto-thermal conversion is the reaction of heavy hydrocarbons (e.g. residual oil from the treatment of crude oil) with oxygen and steam. The quantities of oxygen and water vapour are controlled such that gasification continues without the need for external energy input and hence is auto-thermal. The following net reaction represents the process:

$CH_{1.4} + 0.3\ H_2O + 0.4\ O_2 = 0.9\ CO + 0.1\ CO_2 + H_2$.

The industrial scale production of hydrogen is carried out in partial oxidizers with usual capacities in the order of 100 000 Nm^3 H_2/h. The process is technically well-proven.

The investment costs alone for a partial oxidizer (including air separation, CO-conversion, sour gas separation, sulphur production, methanisation and exhaust gas usage) with a yearly capacity of 800 million Nm^3 H_2/h from 280,000t/a heavy fuel are approx. 150 - 175 million Euro. Taking into account all capital and operating costs gives a hydrogen production cost of about 0.125 Euro/Nm^3, whereby this price is strongly dominated by labour and primary energy related costs.

Partial oxidizers are manufactured by large plant engineering companies (e.g. Uhde, Linde, and KTI).

A.9.2 Small Reformers and Partial Oxidizers

Small reformers and partial oxidizers are being developed such that the use of hydrogen in systems with fuel cells is also possible in the near future. These systems are particularly intended for mobile applications in vehicles and for small stationary systems. Due to the chemical equation balance, natural gas reformers have to operate at considerably higher temperatures than partial oxidizers of diesel or methanol. Therefore, the inexpensive realization of the diesel or methanol process into a marketable process is probably simpler than that for a correspondingly small natural gas reformer particularly when the relative costs of storing liquid fuels as opposed to gaseous ones are taken into account.

In mobile applications, it is hoped to make profit of the high energy density and simple handling of a conventional liquid fuel for the supply of a fuel cell. In this respect, the reforming or partial oxidation of methanol and diesel plays an important role.

Presently there are still no series-produced small reformers on the market, as they are still all in the development phase. As there are still no small reformers on the market, there are also no price details available. In American investigations regarding possible costs for mass production, costs for small diesel or methanol reformers with 30 to 35 Nm^3 H_2/h capacities are quoted at around \$30 per Nm^3/h production capacity. It can be assumed that the costs in stationary reformers will be lower.

A.10 Separation of Hydrogen from Gas Mixtures

The main transport fuel cell contender (proton exchange membrane) requires very pure hydrogen. Hydrogen produced by electrolysis can contain small quantities of oxygen, which is easily eliminated by recombination. However all other practical production processes deliver hydrogen in combination with other gases which requires clean up and separation. A range of technologies are potentially available, including:

- metal hydride purification.
- pressure swing absorption.
- cryogenic separation.
- palladium / alloy membranes.
- ceramic membranes.
- polymer membranes.

The first two are absorption technologies which are characterised by the absorption of one gas into a medium and then by changing the conditions (normally temperature, pressure) so that the gas is desorbed. At least two beds are required to achieve a continuous process, which adds to the cost and complexity. The last three are filtering techniques which achieve continuous selective separation of the hydrogen from the other product gases according to filter pore size and differential pressure. The most common of each of the large scale and small scale technologies are briefly described below.

Pressure swing adsorption (PSA) – Various vendors offer systems, mostly in the very large scale. Latterly, it has been claimed that PSA is cost effective at 100kW or less. Its advantage is that it is a relatively mature technology, although improvements to the processes and materials are still being made. Its disadvantages are that high purity is difficult to obtain (>99.95%), it is energy intensive, and the purification rate is modest, i.e. as the partial pressure of the remaining gas drops, the extraction performance drops rapidly.

Metal (Palladium) separation filters – Hydrogen molecules can pass relatively easily through some metal structures (by transfer of electrons with the metal lattice). Palladium is particularly suited, and non porous Pd and Pd silver/copper alloyed membranes (to reduce embrittlement and add strength) are a means to lower the CO, CO_2, N_2 contents of a reformer product stream to less than 1 ppm by selective diffusion of the hydrogen gas through the metal under pressure and temperature. Because the Pd prices are high and the raw material resources are limited, current research efforts are aimed at reducing the palladium layer/content to a minimum. This has the dual benefit of reducing the pressure requirements and also the cost. Palladium alloy filters are expensive and hence are used for relatively small scale applications, where very high purity is required. They are also readily poisoned by some impurities often present in the syngas stream, such as sulphur, which means additional pre-separation gas clean-up is often required.

Appendix B - Hydrogen Storage

B.1 Storage Technology

There are several ways in which hydrogen can be stored. The most common are as a compressed gas or a liquid. However with advances in technology and significant R&D these methods may become less favoured. Below is a brief outline of some of the methods by which hydrogen in currently stored.

B.1.1 Compressed Gas.

Due to the low density of hydrogen gas (even highly compressed hydrogen) compressed storage is not as attractive an option as LPG for example. Compressing or liquefying the gas is expensive. Hydrogen can be compressed into various containment systems e.g. cylindrical aluminium or carbon/graphite tanks of up to 50 litres or high-pressure tanks where each additional cubic foot compressed into the same space requires another atmosphere of pressure of 14.7psi. High-pressure tanks achieve 6,000psi, and therefore must be periodically tested and inspected to ensure their safety. Compressing hydrogen requires energy to accomplish and the space that the compressed gas occupies is usually quite large resulting in a lower energy density when compared to a traditional gasoline tank. A hydrogen gas tank that contained a store of energy at atmospheric pressure equivalent to a gasoline tank would be more than 3,000 times bigger than the gasoline tank. A downside to compressing is that hydrogen has very small molecules it can escape from tanks and pipes more easily than conventional fuels and therefore needs better seals. Since other options for hydrogen storage are still at the research level, very high strength cylinders for increased pressures are being developed, with tank pressures of up to 700bar, or 10,000psi, now being certified. These tanks can store 2.4kWh/litre (occupied volume) of hydrogen compared with 11kWh/litre for petrol. Bearing in mind the higher efficiency of FC vehicles, this storage option is at least now viable, although not ideal.

B.1.2 Metal Hydrides: Solid State Hydrogen Storage Based on Reversible Metal Hydrides.

Many metals when exposed to hydrogen at certain temperatures and pressures will absorb large quantities of the gas and form hydrides. The reaction can be represented by: $M + H_2 \leftrightarrow MH_2$. Generally hydrides have a larger volumetric hydrogen storage capacity than compressed gas or liquid hydrogen. They work by distributing the hydrogen throughout the metal lattice and their ability to release the same quantity of hydrogen many times without deterioration. The hydrogen storage alloys in use appear in four common forms: AB_5 ($LaNi_5$), AB (FeTi), A_2B (Mg_2Ni) and AB_2 (ZrV_2). Reversible metal hydrides work at low pressure (c.f. compressed H_2) and do not require cryogenic temperatures (liquid H_2). Metal hydrides offer the advantages of safely delivering hydrogen at a constant pressure. The life of a metal hydride is directly related to the purity of the hydrogen it is storing. The alloys act as a sponge, absorbing not only hydrogen but also any impurities. The result is the hydrogen released is extremely pure but the impurities are left behind.

Liquid hydrides are substances such as methanol or cyclohexane. They are like liquid fuels in terms of ease of transportation, although, to release the hydrogen they must be reformed. Methanol has a high ratio of hydrogen to carbon atoms. Current prototypes extract hydrogen from Methanol in a reformer using the reaction with water. A benefit to using methanol is it is liquid at room temperature. Therefore, transport and distribution are possible within the existing networks. By using methanol, carbon dioxide emissions are reduced by 30 % with respect to regular gasoline.

Ammonia can be used to store hydrogen chemically and then release it in a catalytic reformer. It provides very high storage densities as a liquid with mild pressurization and cryogenic constraints. It can also be stored as a liquid at room temperature and pressure when mixed with water.

A factor in favour of using ammonia is that it is the second most commonly produced chemical in the world and a large infrastructure for making, transporting and distributing already exists. Ammonia can be reformed to produce hydrogen with no harmful waste, or can mix with existing fuels and burn efficiently.

B.1.3 Liquid Hydrogen

Hydrogen only exists in a liquid state at extremely low temperatures. Liquid hydrogen typically has to be stored at -253^{o}C. The requirements for liquid hydrogen storage necessitate expending energy to compress and chill the hydrogen into its liquid state. The storage tanks are insulated, to preserve temperature, and reinforced to store the liquid hydrogen under pressure. The margin of safety concerning liquid hydrogen storage is a function of maintaining tank integrity and preserving the temperatures that liquid hydrogen requires.

A negative factor for liquid hydrogen is that the compressing and chilling processes result in a net loss of about 30% of the energy that the liquid hydrogen is storing. If the cost for the energy required for hydrogen liquefaction is coupled with that for the tanks required to sustain the storage pressure and temperature, then liquid hydrogen storage becomes very expensive compared to other methods.

B.1.4 Nano-materials

Carbon nanotubes store hydrogen in microscopic pores or within the actual tubes. They are similar to metal hydrides in their storage and releasing mechanisms. They do however have one significant advantage and that is in the amount of hydrogen they can store, from 4.2% to 6.5% of their own weight in hydrogen (for metal hydrides it is generally between 2% and 3%).

B.1.5 Glass Spheres

Tiny hollow glass spheres can be used to safely store hydrogen. To increase wall permeability the glass spheres are warmed and then filled by being immersed in high-pressure hydrogen gas. Next, cooling locks the hydrogen inside. A subsequent increase in temperature will release the hydrogen trapped in the spheres. Microspheres have the potential to be safe, resist contamination, and contain hydrogen at a low pressure.

Appendix C - End Use Conversion Technologies

Hydrogen fuel will primarily be used for transport, electricity, and heat services and hydrogen fuel will be equally applicable for each of these services. In this sense it potentially transcends any other fuel types which usually have a primary market segment e.g. oil as in transport.

Because of its inherent electrical conversion efficiency of up to 80%, the most promising end use technology that is applicable to both transport use and stationary electricity production is the hydrogen fuel cell. The hydrogen fuel cell is an electrochemical cell that produces electricity and heat from the combination of hydrogen fuel and oxygen (from the air) in a controlled reaction rather than combustion. There are several contender technologies for the different application areas, generally classified by whether they are low temperature or high temperature. The main types being developed at present are Proton Exchange Membrane Fuel Cells (PEMFC), Direct Methanol Fuel Cells (DMFC), and Alkaline Fuel Cells (AFC) – all low temperature types, and Solid Oxide (SOFC) and Molten Carbonate Fuel Cells (MCFC) – both high temperature types. All have been demonstrated functionally within the two main application areas of vehicle power and stationary distributed generation. Currently the DMFC is seen as the best option for portable appliances, PEMFC for transport, SOFC for micro scale distributed generation and MCFC for small scale distributed generation. No large scale generation candidate has yet emerged.

Transport fuel cells operating on hydrogen fuel face competition from other low emission technologies such as bioethanol and biodiesel fuelled IC engines, and potentially from plug in electric vehicles, although it is unlikely that batteries will ever be able to be charged at high enough rates to satisfy all consumer refuelling time expectations.

A unique feature of fuel cell technology for residential distributed generation is its lack of noise and vibration, making it inherently suitable for appliance type applications in the home, meaning that a very high combined heat and power efficiency is possible (up to 90%). Due to their high temperature operation, both SOFC and MCFC can operate on natural gas, as they internally reform the natural gas into hydrogen. All technologies require advances in various areas to improve performance and reduce costs.

As previously mentioned there are additional hydrogen conversion technologies apart from fuel cells. These include hydrogen gas turbines and hydrogen reciprocating engines. Hydrogen turbines include 1 to 100 MW scale systems that can be fuelled either by hydrogen or coal derived syngas and large-frame turbines of similar scale to those currently used in gas and steam turbine power generation systems. The main issues here relate mainly to development of improved materials and coatings able to withstand increased operating temperatures and system designs that increase efficiency and power output.

Hydrogen reciprocating engines can be internal combustion or external combustion such as the Stirling engine. ICEs operating on hydrogen generally are slightly lower powered than their petrol or diesel counterparts due to the lower volumetric density of hydrogen. However, hydrogen can be successfully used in ICEs as is demonstrated by BMW in their new 7 series.

For delivery of heat services from hydrogen fuel, modified gas burners are available which can be effectively 100% efficient in some applications because the combustion product is entirely steam. Flameless catalytic converters are also possible, but the costs for this technology are currently high, due to the precious metals used (e.g. platinum).

Appendix D - Codes and Practices

D.1 Hydrogen and Fuel Cell Safety

Hydrogen is a common industrial gas and has been in use for over a century in a variety of work environments. In terms of handling and distribution these industries have developed safe and relatively straightforward techniques for dealing with hydrogen.

Having made the observation that hydrogen safety is well understood, it is important to address the specific areas where hazards may be present. For hydrogen the risk comes from the potential for the accidental release of gas and the subsequent formation of an explosive atmosphere. Hydrogen is explosive in air from 4% to 75% and this is a wider range than most hydrocarbons. The risk from this should be balanced however, by the rapid rate at which hydrogen will disperse upwards when given the freedom to do so. Hydrocarbons on the other hand (being heavier than air) tend to stay in low points such as sumps and drains and so remain an explosion hazard until they are actively displaced. Hydrogen, as a fuel, is certainly no more dangerous than the hydrocarbon alternatives in common use and in some aspects represents a significant step forward in safety.

The other main safety concerns that arise from fuel cell operation come from the presence of high DC current and the use of liquid electrolytes. Both electrical and chemical burns can be life threatening however, the risk is similar to that presented by the lead acid batteries already used in cars and remote area power supply scenarios. One advantage of fuel cell electrolytes is that they contain none of the environmentally damaging components of battery systems. If a spill were to occur then any clean up could be affected by containment followed by dilution with water rendering the electrolyte virtually harmless. Again, this represents a significant advance over the current best practice for energy systems in everyday use in household equipment.

D.2 Review of Standards

To integrate hydrogen fuel cells into New Zealand's energy supply infrastructure, it is important that appropriate local standards are developed or adopted that specifically address the special technical challenges that are introduced by this technology. This section discusses some of the existing standards and standards under development that are relevant to hydrogen gas, renewable energy and grid connection of distributed resources. These standards are compared with the operating requirements of hydrogen fuel cell systems and areas for improvement are identified. The main immediate problem is in the area of hydrogen safety for small-scale own use systems, as these will be the first to be introduced. Existing general hazardous gas regulations are designed for much larger installations or different gas properties. Additional safety standards will be required for transportation infrastructure prior to public access hydrogen fuelling stations being introduced.

D.3 Hydrogen Safety

New Zealand and Australian hazardous gas standards use a system of zones to classify areas where flammable liquids and gases are present, or could be present. Guidelines for classifying these areas are given in AS/NZS 2430 'Classification of hazardous areas'[7]. One interpretation of these guidelines for fuel cell applications is to consider the area immediately surrounding a fuel cell system as Zone 2 – i.e. explosive atmospheres are not expected to occur, with the area immediately above the hydrogen purge outlet Zone 1, due to the periodic releases of hydrogen gas during normal operation.

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[7] AS/NZS 2430:1997, *Classification of Hazardous Areas,* Wellington, Standards New Zealand.

AS/NZS 2381.1[8] outlines the explosion protection techniques required when dealing with electrical equipment in potentially explosive atmospheres. For Zone 1 and 2 areas, such as those identified as being present in fuel cell systems, one or more forms of protection are required. These protection types include amongst many options, the use of intrinsically safe or encapsulated equipment and forced or natural ventilation. For its fuel cell research and development program, IRL has presently adopted ventilation as the primary form of protection, implemented in accordance with guidelines in AS1482[9]. For increased safety, elements of special protection such as hydrogen detectors are also included for systems designed for use indoors.

Compliance with AS1482 requires interlocks to ensure air-flow is adequate and that the protected area is ventilated before operation for a time that will ensure the maximum flammable gas concentration is no higher than 50% of the lower explosion limit. To comply with the protection by ventilation prescribed in AS1482 requires substantial capital investment in extraction systems. Not only are extraction systems expensive, but they have a large energy consumption compared with the output power of the fuel cell system that they are designed to protect, creating real barriers to the economic viability of small scale fuel cell systems. This approach is not cost effective or convenient in commercial application of small-scale fuel cell products.

Being much lighter than air (approximately seven times), and having a very rapid free-air dispersion rate means that hydrogen has very different properties from other gases at which the hazardous gas safety standards are primarily targeted. It is important that hydrogen gas safety issues are re-examined to make the protections systems required for small-scale fuel cell installations more realistic, and bring them more in-line with regulations regarding other flammable gases used in small quantities in commercial or residential situations. For example, regulations are in place to allow LP Gas to be used and stored in unventilated residential homes without any form of leak detector or mandatory safety equipment. Small quantities of hydrogen for small-scale fuel cell systems could be considered in a similar light.

D.4 Fuel Cell Safety in Consumer Systems

Ultimately, from the user safety aspect, small own-generation fuel cell systems must be treated as a standard household appliance, somewhat akin to a gas fire or water heater. They should comply with general requirements of AS/NZS3000:2000, and specific requirements for generating systems.

D.5 Electrical Supply

In March 2002, AS 4509.2 “Stand-alone power systems, System design guidelines” was published as the final part of AS4509[10], complimenting the safety, installation and maintenance sections released in 1999. This standard is a huge step forward for the growing renewable energy and RAPS systems industry, as there is now a standardised framework for system design and safety requirements. The standard’s scope is wide reaching, and covers the design process, including needs assessment, economic evaluation, and techniques for evaluating the resources available at the installation location, component selection and civil and mechanical site-works to affect installation. The site-works discussion is kept quite general to allow adherence to local

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[8] AS/NZS 2381.1:1999, Electrical equipment for explosive atmospheres - Selection, installation and maintenance - General requirements, Wellington, Standards New Zealand

[9] AS 1482:1985, Electrical equipment for explosive atmospheres - Protection by ventilation – Type of protection v, Sydney, Standards Australia

[10] AS 4509:1999, *Stand-alone power systems* , Sydney, Standards Australia

statutory requirements. The standard is detailed enough that it could be used as a design handbook for a competent person to install a stand-alone power system.

AS4509.2 makes specific reference to sizing of equipment for photovoltaic, wind turbine, micro-hydro, genset and battery systems, and combinations of these. At this stage no reference is made to fuel cell systems. Work needs to begin to ensure that the first revision of this standard sees information specific to fuel cells introduced.

AS4777 "Grid connection of energy systems via inverters" has now been introduced[11]. Since fuel cells produce DC power and therefore require an inverter to allow connection to the ac distribution network or to power standard ac appliances, these two standards should form the basis of electrical technical requirements for small fuel cell generators.

D.6 Overseas Fuel Cell Standards Activities

The IEEE is developing a US standard in this area, under development as P1547 "Draft Standard for Interconnecting Distributed Resources with Electric Power Systems"[12] [13]. The standard will provide requirements relevant to the performance, operation, testing, safety considerations and maintenance of the interconnection.

The IEC has several standards under consideration by working group TC105, under the title IEC 62282 – Fuel Cell technologies[14]. These standards look set to cover issues related to safety, testing, installation procedures and performance requirements for fuel cells.

The National Fire Protection Association (NFPA) in the US released NFPA 853 in 2000[15]. This is particularly related to the fire safety aspects of fuel cell placement within or near buildings and is restricted to systems with power ratings not less than 50kW.

In 1998 the American National Standards Institute (ANSI) released ANSI Z21.83[16], specifically for a particular 1MW fuel cell. Its scope is limited only to a large-scale system that is fully pre-packaged and self-contained.

The Association of German Engineers (VDI) has also released VDI 6012.3 – "Local energy systems in buildings – Fuel cells"[17]. This technical standard covers the types and characteristics of fuel cells, installation of fuel cells for stand-alone power systems and grid connection, as well as hydrogen, electrical and thermal safety information.

Standards development required to cover the application of small-scale hydrogen fuel cells in New Zealand.

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[11] DR01212-01214:2001, *Grid connection of energy systems via inverters*, Draft Australian Standard for Comment, Sydney, Standards Australia.

[12] IEEE SCC21 - P1547 Home page (21 April 2002), http://grouper.ieee.org/groups/scc21/1547/index.html

[13] IEEE P1547/D07, Draft Standard for Interconnecting Distributed Resources with Electric Power Systems (21 April 2002), http://grouper.ieee.org/groups/scc21/1547/archives/P1547StdDraft07Contents.pdf

[14] Work Programme for TC 105 (21 April 2002), http://www.iec.ch

[15] NFPA853: 2000, Standard for the Installation of Stationary Fuel Cell Power Plants, Quincy, Massachusetts, National Fire Protection Association.

[16] ANSI Z21.83:1998, America National Standard for Fuel Cell Power Plants, Washington DC, American National Standards Institute.

[17] VDI6012.3:2001, Local energy systems in buildings – Fuel cells, Dusseldorf, Association of German Engineers.

Technical standards and safety guidelines are primarily required for fuel cells in two areas – hydrogen safety and electrical safety and interconnection. For hydrogen safety, new standards applicable to the relative hazard that small quantities of hydrogen represent are necessary. This is needed to simplify the handling of safety issues related to fuel cells, clearly defining the ventilation and explosion proofing required for hydrogen gas in a non-industrial setting. This new standard could be developed into a comprehensive fuel cell standard covering all aspects of fuel and chemical safety, system design, environmental issues and installation and maintenance procedures. None of the overseas standards surveyed above cover all these issues.

For the electrical issues, the framework is already in place for small (<10kW) systems, under the new standards mentioned above for stand-alone and grid connected inverter interfaced generation systems. Particular reference could be made to hydrogen fuel cells and their special requirements in an amendment to the AS4509 standard for stand-alone power systems.

Appendix E - IPHE Research Programmes

Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst (The NATURALHY Project)

The NATURALHY project involves a European consortium run out of the Netherlands and is comprised of 39 partners in the UK, Germany, France, Denmark, Belgium, Portugal, Greece, Norway, Sweden, Italy and Turkey. The project aims to use the existing gas infrastructure as a means for distribution of hydrogen through defining the conditions under which hydrogen can be mixed with natural gas in the existing gas infrastructure and subsequently withdrawn selectively from the pipeline system using advanced separation technologies. The programme also considers the socio-economic and life cycle consequences of this approach to hydrogen distribution will be mapped out.

Solar Driven High Temperature Thermochemical Production of Hydrogen (Production)

In this project, the most promising thermochemical cycles for hydrogen production will be identified, and one or two cycles will be down-selected for demonstration. Lower cost solar concentrating technology will be developed, as well as solar receiver and thermochemical reactor technology to demonstrate a fully integrated thermochemical process on-sun.

Reversible Solid State Hydrogen Storage for Fuel Cell Power Supply System (Storage)

The project develops reversible solid state hydrogen storage and purification systems and their integration with fuel cell power supplies. Integration results in appearance of new possibilities to increase the overall energy efficiency of the power supply systems together with identification and development of new technical challenges.

Advanced Membranes Conversion Technology – Fuel Cells

The technical goal of this project is to develop membranes for polymer electrolyte fuel cells to lower the cost and enhance the durability of hydrogen-air and direct methanol polymer electrolyte fuel cell systems. The objective of developing the IPHE program is substantially enhanced collaboration between parties to the project to ensure maximum leveraging of resources through researcher and material exchanges and joint meetings.

Fuel Cell Testing, Safety and Quality Assurance (FCTESQA) codes and Standards)

The project addresses pre-normative research, benchmarking, and validation through round robin testing of harmonised, industry-wide test protocols and testing methodologies. This activity will contribute to the early and market-oriented development of specifications and pre-standards. FCTESQA results will be discussed, debated and agreed in co-operative progress meetings and dedicated international workshops under the IPHE auspices.

Application of Gradient Porous Composite MEAs for Different Types of Fuel Cells Conversion Technology- Fuel Cells

This project develops a new design of thin monolithic multilayer more efficient and reliable MEA for different types of fuel cells (DMFC, Compact Mixed-Reactant Direct Methanol Fuel Cells (CMR-DMFC)) with the focus on small fuel cells for portable application, testing methodology for MEA as well as possible ways for FC miniaturization.

HyWays - The Development and Detailed Evaluation of a Harmonised "European Hydrogen Energy Roadmap" (assigned by IPHE to codes and Standards)

In spring 2004, the EU 6th Framework project HyWays was launched in order to develop a European hydrogen roadmap, to meet scientific, technical, strategic, and political concerns. The project partnership consists of 32 organisations from industry, institutes, governments and small and medium sized enterprises from 9 EU member states (B, D, E, F, GB, GR, I, NL, P) and one associated state (N).

HySafe – Safety of Hydrogen as an Energy Carrier (Regulations Codes and Standards)

HySafe will focus on safety issues relevant to improve and co-ordinate the knowledge and understanding of hydrogen safety and support the safe and efficient introduction and commercialisation of hydrogen as an energy carrier of the future, including the related hydrogen applications. To this end the project will prepare the foundation of the European Hydrogen Safety Centre.

Solar Hydrogen from Reforming of Methane (Production)

The project aims to design, test and demonstrate a unique, low temperature, steam reforming reactor using concentrated solar energy. A world-class solar facility for international collaboration in hydrogen production from solar sources will be constructed to integrate the system.

Clean Urban Transport for Europe - Ecological City Transport System – Sustainable Transport Energy for Perth (CUTE-ECTOS-STEP) (demonstration – education)

The CUTE – ECTOS – STEP project is an ambitious field trial of 33 fuel cell buses and hydrogen infrastructure in 10 participating European cities and Perth in Australia. Accompanying studies investigate the benefits of hydrogen and fuel cells in transport applications. Education, training, dissemination, quality and safety as well as permits & approvals are integral elements of the project.

Autobrane: Automotive High Temperature Fuel Cell Membranes

The objective is to develop innovative membrane-electrode assemblies (MEAs) for proton-exchange membrane fuel cells that are capable of operating at wider operating temperature range and have the ability to function at higher temperatures under at zero humidification. The project also seeks to adapt/ improve catalyst, electrode, and stack technology.

Hydrogen and Fuel Cell Bus Demonstration Program

The objectives of the project are to advance the commercial deployment of fuel cell transit buses; improve transit bus fuel efficiency and reduce petroleum consumption; reduce transit bus emissions; and increase public acceptance of hydrogen and fuel cell vehicles.

HYCHAIN MINI-TRANS : Deployment of Innovative Low Power Fuel Cell Vehicle Fleets to Initiate an Early Market for Hydrogen as an Alternative Fuel in Europe

The goal of this project is to deploy a fleet of small hydrogen fuel cell hybrid vehicles in a variety of application ranging from 250 watt power modules for tricycles to 3 kilowatt power modules for utility vehicles and up to 10 kilowatt power modules for hybrid mini-buses. The project also integrates the supply chain by addressing the hydrogen infrastructure which will be necessary for refuelling, storage, distribution and dispensing to final end users.

HyLights – A Coordination Action to Prepare European Hydrogen and Fuel Cell Demonstration Projects

The project will monitor concluded and ongoing demonstration projects and assist with the planning for future demonstration project phases. The project is a coordination action that will develop an assessment framework for concluded and ongoing demonstration projects; analyze individual projects and establish a project database; perform analysis to identify gaps and prepare a requirement profile for the next stage projects; assess and identify necessary financial and legal steps in preparation of the new projects; and establish a “European Initiative Group on Hydrogen for Transport”.

HyApproval- “Handbook for Approval of Hydrogen Refuelling Stations”

The goal of this project is to develop technical guidelines for the approval of public hydrogen refuelling stations. The handbook is targeted to assist companies and organizations in the implementation and operation of hydrogen refuelling stations. The handbook will also contribute to the International Standards Organization, Technical Committee 197 (ISO TC 197) on the development of international standards for hydrogen technology.

HYTHEC - HYdrogen THErmochemical Cycles

The project will investigate the potential for large hydrogen production through the Sulphur-Iodine cycle and compare it to Westinghouse cycle. The project aims to 1) conduct flow-sheeting, industrial scale-up, safety and cost modelling, 2) improve the fundamental knowledge and efficiency of the hydrogen production in the Sulphur-Iodine cycle and 3) investigate potential use of solar primary energy sources for decomposition of sulphuric acid.

Hydrogen for Clean Urban Transport in Europe (HyFLEET:CUTE)

The goal of the project is to advance the development of hydrogen powered public transport buses to the "pre-commercial" stage through continued operational testing of fuel cell drive train buses while also testing hydrogen powered internal combustion engine buses under similar conditions. The project also includes the design, construction and testing of advanced refuelling stations and associated infrastructure as well as socio-economic evaluation of current and predicted impacts of a developing hydrogen economy.

NESSHY- Novel Efficient Solid Storage for Hydrogen

The goal of this project is to identify the most promising hydrogen solid storage solutions for mobile applications complementary in stationary systems. The project covers porous storage systems, regenerative hydrogen stores and solid hydrides performing under reversible hydrogen storage and improved gravimetric storage.

Mechanical Synthesis and Rehydrogenation of Complex Hydrides and Nanocomposites in Hydrogen Ball Mills

The focus of the project is on assessment and discovery of novel nanomaterials and nanotechnologies for hydrogen storage. This project will perform research in an effort to discover materials that will specifically direct synthesis of new complex hydrides, hydride mixtures and nanocomposites conducted in specialized "hydrogen ball mills" under molecular hydrogen gas, hydrogen plasma and/or nitrogen plasma.

Hydrogen Pathways

This program is part of the University of California Transportation Studies and is focused on understanding the potential transition to a hydrogen-based transportation system. The project research is focused on four key areas: 1) Hydrogen Markets and Demand; 2) Hydrogen Infrastructure Modelling; 3) Policy and Business Strategy; and 4) Environmental Analysis.

Hydrogen Transportation Partnership and Demonstration Park (Beijing Hydrogen Park)

The objectives of this project are to demonstrate pre-market innovative hydrogen and fuel cell technologies to build a platform to promoting the international cooperation and to increase public awareness on new energy and high-efficiency power technologies, especially those related to hydrogen and fuel cell vehicles.

Combination of Amine Boranes with MgH2 & LiNH2 for High Capacity Reversible Hydrogen Storage

The purpose of this US led project, including IRL of New Zealand, is to synthesize and characterize hybrid materials that combine light element metal hydrides with the amine borane chemical based hydrogen storage through a coupled endothermic-exothermic approach for hydrogen storage.

Fundamental Safety Testing and Analysis of Hydrogen Storage Materials & Systems

The objectives of this project are to demonstrate technologies that minimize the risks of systems using solid-state hydrogen storage materials and to quantify physical risks associated with the synthesis, handling and utilization of these materials as hydrogen storage media. This project will also develop methods to mitigate the identified risks that would lead to commercially acceptable high density hydrogen storage system designs.

Appendix F - IEA Hydrogen Implementation Agreement Research Tasks

F.1 Completed Tasks

1) Thermochemical Production
2) High Temperature Reactors
3) Assessment of Potential Future Markets
4) Electrolytic production
5) Solid Oxide Water Electrolysis
6) Photocatalytic Water Electrolysis
7) Storage, Conversion and Safety
8) Technical and Economic Assessment of Hydrogen
9) Hydrogen Production
10) Photoproduction of Hydrogen
11) Integrated Systems
12) Metal Hydrides for Hydrogen Storage
13) Design and Optimisation
14) Photoelectrolytic Production
15) Photobiological Production
16) Hydrogen from Carbon Containing Materials
17) Solid and Liquid State Storage

F.2 Current Tasks

18) Integrated System Evaluation
19) Hydrogen Safety
20) Hydrogen from Waterphotolysis
21) Biohydrogen
22) Fundamental and Applied Hydrogen Storage Materials Development
23) Small-scale Reformers (SSR) for On-site Hydrogen Supply

F.3 Future Tasks (in definition)

24) Wind Energy and Hydrogen Integration
25) Near Term Routes to Hydrogen using Biomass as a Renewable Energy Source
26) High Temperature Production of Hydrogen

Appendix G - International Industrial Research Programme Examples

The sections in this appendix give a flavour of the hydrogen energy system research being undertaken by industrial companies. Naturally, much of the current work is confidential and so a complete picture is impossible.

G.1 Automotive Manufacturer – BMW

One of the most progressive car manufacturers in this area is BMW with their corporate CleanEnergy Strategy focussing the medium- and long-term development of their cars on hydrogen energy. Already, they have been researching and developing automotive hydrogen technology for nearly 30 years. The Chairman and CEO of BMW North America recently said that, "We at BMW believe that hydrogen will replace petroleum in the long-term. To accomplish this we must begin to take steps now, in order to ensure a smooth transition to a hydrogen-based economy in the future". Therefore, BMW work in partnerships to develop the production, storage and delivery technology for hydrogen as well as vehicle-based technology. This includes the German based CleanEnergy Partnership with Aral, BVG, DaimlerChrysler, Ford, GHW, Linde, Opel, and MAN. With Air Products they opened the first hydrogen fuelling station in the USA at the University of California in Irvine, and also have a partnership with Total Energy to run public filling stations in Germany for liquid hydrogen and conventional fossil fuels starting in Munich in 2007.

BMW have recently released a limited number of the BMW Hydrogen 7, the world's first hydrogen powered luxury saloon car, capable of running on hydrogen or petrol using a specially modified internal combustion engine [18]. Although, they are also developing fuel-cell powered vehicles, the BMW Hydrogen 7 uses an internal combustion engine for drive power and sophisticated engine management and valve control strategies to minimise emissions of NO_x. Because ICE technology is more mature than fuel cells, BMW see fuel cell technology as providing the auxiliary electrical power and not the drive power in the short term. They are currently working on turbochargers and fuel injection to reach the performance with petrol but at an increase in efficiency. They expect to have approximately a hundred of the current BMW Hydrogen 7 on the roads in Europe and the USA in the near future to promote hydrogen as an alternative fuel. In the area of safety BMW have also had not only the fuel tanks but also the full hydrogen vehicles tested under impact, pressure and fire conditions with the result that the inspectorate rated hydrogen fuel and hydrogen vehicles at least as safe as their petrol counterparts. BMW are researching moulded fuel tank designs to optimise the use of space in vehicles whilst not compromising the safety and insulation properties of the traditional cylindrical tanks. Research at BMW is also active in electric and hybrid drives.

G.2 Energy Company – BP

BP[19] has been researching the possibilities of using hydrogen as a power source for well over a decade. They are currently involved in the development of several major projects including the Barcelona hydrogen refuelling station and projects Peterhead and Carson.

BP's Hydrogen station in Barcelona provides hydrogen to fill three fuel cell buses as part of the CUTE Clean Urban Transport for Europe bus project. With a surface area of 1,100m^2 this is the first BP branded hydrogen filling station in the world.

The filling station is made up of the following components:

- Electrolyser, equipment that produces hydrogen from water and electricity using electrolysis, with zero emissions at the site.

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[18] BMW on line literature

[19] BP on line literature

- Compressor, equipment that compresses the hydrogen produced by the electrolyser to high pressure (250-400bar) to ensure that the hydrogen is dispensed within seven minutes and ensures a good vehicle range.
- Storage room, enclosure that provides storage for one day of backup hydrogen supply.

The BP Hydrogen station includes a plant to generate electricity using solar power. This electricity is used in the electrolysis process. The roof of the building holds a solar photovoltaic system that produces 7.200kWh/year, representing 5% of the total consumption of the station. The remainder of the electricity is obtained from the conventional electricity network. The BP Hydrogen Station incorporates innovative safety measures, including leak detectors and monitors to tack any pressure changes during the filling station.

The Peterhead Project is world's first industrial scale hydrogen power project. Clean burning hydrogen will be obtained from North Sea gas and the carbon dioxide will be stored in offshore oil reservoirs. The heart of the project is a reformation unit and a carbon capture facility. Daily, 70 million cubic feet of natural gas will be reformed into hydrogen and carbon dioxide. The hydrogen will be used as a fuel to generate 350 MW of electricity, enough to power 250,000 homes. The carbon dioxide will be transported 240 km off shore where it will be stored in oil reservoirs 4km underground. This process has the capacity to extract a further 40 million additional barrels and extend the life of fields "due for closure" by up to 20 years. January 2007 was the deadline for sanctioning the US$600 million and the completion date is set for January 2010.

In the BP Carson Hydrogen Power Project in California, several proven global technologies are united to make the largest project of its kind in the world. As with the Peterhead Project the heart of the project is a gasification unit and a carbon capture facility. Daily, 5000 tonnes of petroleum coke will be reformed into hydrogen and carbon dioxide. The hydrogen will be used to fuel a 500MW power station, enough to power 325,000 homes. The carbon dioxide will be transported to the California oil fields and stored in oil reservoirs thousands of meters below the surface where it will flush out oil that cannot be reached cost-effectively in any other way. The project will create about 1,000 new jobs during the construction phase and 150 permanent jobs at the power plant. The feasibility study was completed in July 2006. By December 2007 the front end engineering and design should be completed. The two other deadlines are 2009 – approval of US$1 billion capital investment and 2011 is the anticipated opening of the plant.

G.3 Energy Company – Shell Hydrogen

Shell's aim is to create a worldwide infrastructure for hydrogen and it has, over the last ten years, partnered a number of projects in Japan, Europe and America.

One of the most recent projects is a fuelling station located in northeast Washington, D.C. The station is part of a collaboration between Shell and General Motors (GM) to demonstrate hydrogen fuel cell vehicles and refuelling infrastructure technology. Both compressed and liquid hydrogen will be available. In a separate initiative, the United States Postal Service has been delivering mail using a GM fuel cell minivan, which GM refers to as the HydroGen3. The State of Maryland also has announced a similar lease with GM.

Other research being carried out by Shell[20] looks at CO_2-H_2 membrane separation. The research examines membrane separation technology used in production of hydrogen from fossil fuels. The benefits of this particular technology are that unlike conventional methods, this process allows separation of pure CO_2 at a lower cost. This is essential for economical carbon capture and storage, which allows for zero-emission production of hydrogen.

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[20] Shell on line literature

G.4 Fuel Cell Companies

In addition to automotive manufacturers there are numerous companies dedicated to the design, development and manufacture of fuel cells. Fuel cells are being developed for diverse applications including transport, distributed power generation, space, medical, military and battery power for items such as laptops and mobile phones. Currently, proton exchange membrane fuels cells (PEMFC) dominate both the transport and the small-scale power sectors with solid oxide fuel cells (SOFC) being the most significant alternative for small-scale power. For large-scale power applications production of phosphoric acid fuel cells has now been discontinued due to high cost, and in the future SOFCs and molten carbonate fuel cells (MCFC) will be important. Most development work is currently directed towards PEM and SOFC fuel cell development.

Much of the current research being undertaken is commercially-sensitive. Most of the work is directed towards developing new materials for fuel cells or improving the existing materials, and improving the cell stack design. The general aims are to improve fuel cell efficiency and durability in terms of lifetime and corrosion/poisoning resistance of the materials while reducing the size (particularly for transport applications) by increasing the energy density. There is also considerable interest in developing cells to operate at high pressures and temperatures for which improved materials and even new cell concepts are being developed. A recent trend has been for automotive companies to develop their own in–house designs. The fuel cell companies have in many cases turned to micro-scale distributed generation and standby markets which are predicted to offer the first commercial opportunities. ReliOn for instance has reportedly sold hundreds of 1kW units to telecom companies for standby applications in competition to battery-gensets. These systems currently operate from compressed hydrogen gas cylinders. For residential distributed generation applications, operation on conventional infrastructure fuels is initially necessary until a full hydrogen economy develops. This means that an integrated compact fuel reformer must be included to produce pure hydrogen on site for the PEMFC. Progress in this area by private companies has been impressive. Several hundreds if not thousands of systems are now in alpha and beta testing world wide. The most advanced countries are Japan and Germany. In Japan for example the current field assessment programmes are being funded by NEDO and the main gas utilities, Tokyo Gas, Osaka Gas and Toho Gas. The gas companies see this as an opportunity to extend their market through higher efficiency energy production. Limited commercial sales are expected in 2008 with full production ramping up from 2010 onwards. Depending on specific application electrical ratings are between 1kW and 3kW.

G.5 Other – Air Products

There are several international companies that have significant interest in the production/synthesis, transport and storage of hydrogen. Air Products[21] has numerous research projects underway, however, some of the more relevant for the current study are the membrane separation of gases which although already an established technique holds greater promise for future development. Air Products is interested in fundamental research into novel methods for synthesis, novel membrane materials and formulations (and their frequent synergistic interdependence), as well as more fully developed technologies with specifically identifiable gas separation applications. Another area examines possibilities in CO/H_2 Syngas Processing. Air Products produces CO, hydrogen and syngas mixtures to meet customer specifications via a variety of mature technologies. They are interested both in improving existing and developing new technologies. Most of these emerging technologies are proprietary and no information is in the public domain. Air Products has built a hydrogen refuelling station in the USA and has strong research interests in delivery and storage.

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[21] Air Products on line literature

G.6 Other – Linde

The Linde Group[22] has officially inaugurated the "Linde Hydrogen Centre" in Lohhof near Munich. The centre combines the functions of a hydrogen filling station with those of a technology test centre, a training centre and a presentation platform. The heart of the facility is a filling station, which supplies a test fleet of hydrogen fuelled cars and buses with both liquid hydrogen (LH2) and compressed gaseous hydrogen (CGH2). It is expected to fill around 10 hydrogen vehicles a day.

Linde is also involved in a large number of initiatives, such as ARGEMUC (Airport Munich), CEP (Clean Energy Partnership), CUTE (Clean Urban Transport for Europe) and Zero Regio. They also are a system supplier for mobile filling systems and are also looking at hydrogen production from a variety of renewable resources, especially biohydrogen, as the focus of current research and development activities.

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[22] Linde Group on line literature

Appendix H - New Zealand Research on Hydrogen Issues

New Zealand organisations are undertaking research and development into a number of hydrogen energy related technologies. Various projects are underway which span the spectrum of hydrogen energy related activities.

The Ministry of Economic Development (MED) has collated the research and development being undertaken into hydrogen energy in New Zealand

These projects are funded from government and private expenditure. The major government funding agency is the Foundation for Research Science and Technology which has committed in aggregate about NZ$8 million over a six year period to various projects.

The hydrogen research and development work that is being undertaken in New Zealand is consistent with and supports the Government's objective of achieving a sustainable energy future. New Zealand recognises that it is unlikely to be a leader of hydrogen related research and development, rather a taker and adopter of practices and technologies developed internationally. That said there are niche areas, supported by New Zealand's natural endowments where New Zealand can contribute. For example, the development and refinement of hydrogen production from wind powered electricity generation and the production of hydrogen from New Zealand's large lignite coal resources coupled with carbon storage are two areas where there is significant scope for progress.

Title:	**Hydrogen Energy for the Future of New Zealand**
Research Area:	**Hydrogen Production**
The overarching objective of this programme is to build the technology platform, knowledge and expertise necessary to underpin the introduction of a hydrogen energy economy into New Zealand. The programme has two main *themes*. The first is to generate economically viable high quality hydrogen from low rank coal and convert it to electricity using a fuel cell. The second theme is to generate hydrogen from distributed renewable energy sources via electrolysis, with particular emphasis on wind based generation. The programme also contains a modelling component to identify likely scenarios for the introduction of a hydrogen economy into the energy future of New Zealand. The modelling considers both stationary (distributed and large scale electricity production) and transport applications of hydrogen technologies.	

Title:	**Thermochemical Production from Renewable Resources**
Research Area:	**Hydrogen Production**
Investigation and determination of the issues associated with hydrogen production from renewable resources in New Zealand. Three projects have been undertaken in this general area of hydrogen production using renewable fuels: 1. Hydrogen production from small-scale steam reformation of biomethanol - this work was undertaken in 2002-2004 as a component of a project to investigate the production of biomethanol from biowaste feedstocks and its use for hydrogen production, under a project titled Renewable Fuels for Distributed Electricity Generation. A small tube reformer was constructed and its performance studied using biomethanol fuels. 2. Hydrogen production from small-scale steam reformation of bioethanol - this work carried on from the above project and investigated the yield and selectivity performance of some catalysts for low temperature steam reforming of ethanol. This project was completed in mid-2005. 3. Hydrogen production using a thermochemical cycle based on New Zealand ironsands – this work is ongoing and proposes a biomass based iron oxide reduction and steam oxidation cycle.	

Title:	**Chemical Storage of Hydrogen**
Research Area:	**Hydrogen Storage**

Develop new materials and process technologies for energy efficient and safe storage of hydrogen gas as chemical hydride materials. The programme currently addresses two different chemical storage systems:

1. Regeneration routes for sodium borohydride (where H_2 is released through hydrolytic processing)
    - Solvent-based chemical regeneration using aqueous and nonaqueous solvent systems
    - Electrochemical regeneration using nonaqueous solvent systems

2. Storage in amino-borane systems (where H_2 is released through pyrolytic processing)

Additionally, a new programme proposal is currently under development to design and synthesise new *hybrid* solid-state hydrogen storage materials that combine and take advantage of key features of several leading candidate storage systems.

Title:	**Hydrogen and Fuel Cell Demonstrations**
Research Area:	**Technology Demonstration**

The aim of this series of projects is to build New Zealand's capabilities and knowledge in hydrogen energy and fuel cell technologies for stationary distributed energy applications. This is being achieved through pilot scale technology development and demonstration, market evaluation of technologies and public education and outreach. A summary of the projects follows:
Completed: (i) 400W demonstration system based on Zetek AFC stacks modules – lab demonstrator and (ii) 6 kW experimental fuel cell system delivered to Australian Cooperative Research Centre for Renewable Energy (ACRE), Perth
In progress: (i) US Department of Defence (DoD) sponsored methanol PEM fuel cell yard lighting and grid connected demonstration installed at US Antarctic Programme (USAP) Facility, International Antarctic Centre, Christchurch, New Zealand and (ii) Powerco sponsored Ceramic Fuel cells Limited (CFCL) natural gas Solid Oxide Fuel Cell (SOFC) residential microCHP fuel cell grid connected demonstration, installed at IRL Gracefield, New Zealand
Planning and/or installing: (i) Remote rural wind-hydrogen power link and AFC fuel cell grid connected demonstration at Totara Valley, Kumeroa, New Zealand and (ii) NZ sponsored methanol AFC urban residential microCHP fuel cell grid connected demonstration, Christchurch, New Zealand.

Title:	**Supply Options for the Proton Exchange Membrane (PEM) Fuel Cell Demonstration at the US Antarctic Programme Facility, International Antarctic Centre, Christchurch, New Zealand.**
Research Area:	**Demonstration**

The objective was to consider a range of options for providing hydrogen to the US Department of Defence PEM Fuel Cell trial at the Antarctic Centre in Christchurch, New Zealand. The programme considered the issues of supplying the necessary 10,500 cubic meters per annum of hydrogen necessary to run the two 0.6 kW PEM cells used in the demonstration.
The options considered were:

- Bottled gas
- Water electrolysis – mains powered
- Water electrolysis – wind generated
- Wind electrolysis – solar PV
- Hydrocarbon reformation – methanol fuel
- Hydrocarbon reformation – ethanol fuel
- Hydrocarbon reformation – natural gas

Hydrocarbon reformation – liquefied petroleum gas.

Title:	**Hydrogen – A Long Term Future for the Coal Industry**
Research Area:	**Education**

This project aims to provide a pathway of activities that the coal industry needs to undertake in order to ensure coal plays its role in the development of a hydrogen energy economy in New Zealand. It is, in effect, a Hydrogen Roadmap for the coal industry going forward into a decarbonised, hydrogen based energy future. The project considered the following topics:

- global initiatives and investment towards making hydrogen based energy systems happen
- the issues facing a hydrogen economy
- the ability of coal (and other energy resources) to meet predicted hydrogen demand out to 2050
- coal gasification – the enabling technology
- carbon capture and sequestration – the partnering technology
- existing options for converting syngas into saleable products
- three applications of coal to hydrogen technology packages foreseen in the development of a hydrogen economy in New Zealand

and drew on the information in each of these topic areas to produce a series of coal specific and more generic activities that need to occur between now and 2050 in order for the hydrogen economy to happen and for coal to be an important part of the transition to a society based on a hydrogen energy system.

Title:	**Nanostructure Alumina Materials for Hydrogen Separation**
Research Area:	**Hydrogen Production**

This IRL project aims to develop new, more efficient and lower cost separation membranes for hydrogen purification, by the development of highly regular and porous alumina substrates through electrochemical etching processes. Highly regular porous structures consisting of long regular tubes have been produced with aspect ratios of better than 2000:1 and feature dimensions in the nanometer range. Both coated and uncoated membranes have been shown to exhibit very promising hydrogen selectivity characteristics. Research is continuing to characterize the materials options and processing techniques. Because of their good temperature stability these membranes could find application in new hydrogen fuel processing systems such as microreformers for fuel cells.

Title:	**Ethanol Reforming Catalysts**
Research Area:	**Hydrogen Production**

This University of Auckland project supported by IRL involves the formulation and study of catalysts for ethanol reforming, to produce fuel cell quality hydrogen. The aim is to optimize the production of hydrogen and minimise other energy carrying reformation products such as methane and carbon monoxide. The reaction of ethanol for the production of hydrogen is being studied over a series of Rh-Pd/CeO_2 catalysts. Reforming of ethanol to hydrogen using (3 moles of water per mole of ethanol) has been shown to be very efficient particularly above 650K. The research will include evaluating the effects of pressure and continuous extraction of hydrogen using separation membranes.

Title:	**Bioelectronic Transformation**
Research Area:	**Production**

The outcome of the research programme is to generate scientific and technical platforms through targeted application of cellular biotransformation pathways. Encompassed within the programme are two main objectives. The first is based on whole cells and cell fragments for use in novel electrochemical devices. The second is to identify micro-organisms from the New Zealand environment that possess novel biotransformation systems for use in the above.

The research carried out by the Cawthron Institute looks at ways to:

- express & purify micro-algal hydrogenase and deposit on a half-cell to develop a hydrogenase electrode
- determine the lowest level of purity that microalgal and microbial hydrogenase can be deposited on electrode surfaces to function as a hydrogen electrode. These outcomes are designed to lead to the development of hydrogenase half-cells that are much simpler to develop than by normal methods.

Title:	**Transitioning to a Hydrogen Economy**
Research Area:	**Education**
This programme aims to improve understanding of hydrogen energy systems among stakeholders, identify likely scenarios for the development of a national hydrogen economy and the research needed to facilitate the transition. An issues document is produced and disseminated to targeted end users and favoured hydrogen supply chains identified by a combination of E3 modelling and consultation. Scenarios for transitioning to a hydrogen based energy system in New Zealand are then developed from the favoured supply chains along with barriers to their realisation and research strategies for removing these barriers. The results of the analysis will be collated into an Action Plan.	

Title:	**High Performance Electrocatalysts for Proton Exchange Membrane Water Electrolysers Producing Hydrogen**
Research Area:	**Hydrogen Production**
Highly active electrocatalytic particles will be prepared and characterised for use in proton exchange membrane (PEM) water electrolysers. These particles will reduce the cost, improve the efficiency and increase the lifetime of the hydrogen producing electrolysers. The anode reaction limits the efficiency of these systems and therefore the work will concentrate on electrocatalysts for this reaction. It will be possible to improve of the performance of these cheaper materials by constructing electrocatalysts into core-shell particles using novel synthesis methods based on reverse micelle techniques. The particles are characterised using a range of techniques like cyclic voltammetry, X-ray diffraction, X-ray photoelectron spectroscopy and electron microscopy. Synchrotron based X-ray absorption spectroscopy will be used to determine the atomic fine structure of the particles. The performance and stability of the electrocatalytic particles will be measured in laboratory scale PEM water electrolysis cells operating under industrially relevant conditions. This work is funded through a FRST postdoctoral fellowship .	