Ministry of Economic Development
Manatū Ōhanga

Stock-take of Hydrogen Energy Activity in New Zealand

December 2005

Contact details

Mr John Rampton
Ministry of Economic Development
Tel: (+64) 4 474 2971
E-mail: john.rampton@med.govt.nz

Disclaimer

ISBN [0478284624]
First published in December 2005 by:
Fuels and Crown Resources Group
Resources and Networks Branch
Ministry of Economic Development
P O Box 1473, Wellington
New Zealand
http://www.med.govt.nz

Stock-take of Hydrogen Energy Activity in New Zealand

A report prepared by the Ministry of Economic Development of New Zealand for the International Partnership for the Hydrogen Economy.

Contents Page

Foreword

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 and detailed it in this report. The production and release of this report meets our obligations as a member of the International Partnership for the Hydrogen Economy (IPHE).

The table below summarises the various projects underway or recently completed in New Zealand.

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
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

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. Further funding has been sought from the foundation for niche materials technologies.

New Zealand is a member of the IPHE and contributes to the hydrogen agenda of the International Energy Agency, through its membership of the Hydrogen Implementing Agreement.

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 as it relates to the transport sector, rather a taker and adopter of practices and technologies developed internationally. That said there are niche areas particularly in the stationary distributed energy sector, 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.

MED would like to thank CRL Energy Limited (CRL), Industrial Research Limited (IRL) and Massey University for their assistance in providing details of their projects.

Project 1: Hydrogen Energy for the Future of New Zealand

Title:	**Hydrogen Energy for the Future of New Zealand**
Research Area:	Hydrogen Production
Organisations conducting work:	Industrial Research Limited Alister Gardiner PO Box 2002 Christchurch, New Zealand Ph (+64) 3 358-6809 Fax (+64) 3 358-9506 a.gardiner@irl.cri.nz CRL Energy Limited Dr Tony Clemens PO Box 31-244 Lower Hutt, New Zealand Ph (+64) 4 570-3713 Fax: (+64) 4 570-3701 t.clemens@crl.co.nz
Funding Organisation:	New Zealand Foundation for Research Science and Technology BP New Zealand, Coal Association of New Zealand, Meridian Energy and Solid Energy New Zealand are providing extra support and/or governance to the programme.
Project Budget:	NZ$1,309,000 (inc GST) per annum
Project Duration:	6 years
Project Dates:	1 July 2002 to 30 June 2008

Objective of Project:

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 hydrogen from New Zealand's abundant reserves of low rank coal including the steps necessary to purify it to fuel cell grade quality and convert it to electricity through the use of a fuel cell. During the purification process, a waste stream comprised mainly of nitrogen and CO_2 is generated and the programme also considers options for the sequestration of this mixture.

The **second** theme is to generate hydrogen from distributed renewable energy sources via electrolysis, with particular emphasis on wind based generation. This research is aimed at understanding the systems sizing issues and technology application requirements, and to identify ways to reduce the current high costs associated with the potential use of hydrogen as a storable energy carrier in small scale and remote applications. The aim is to build local capability for production and use of hydrogen energy at a small scale community level, from renewable generation such as wind turbines and solar PV.

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.

Project work programme and timeline:

The programme is broken down into 10 objectives:

Objective 1, Production of Hydrogen from Carbon Based Fuels, is being carried out by CRL Energy. The objective aims to design, build, commission and demonstrate a 200 kW scale coal to syngas converter, to characterize the syngas and identify key factors for production of a constant syngas product.

This objective runs throughout the entire programme but the major activity in terms of design, construction and commissioning took place during 2002 to 2005.

Objective 2, Gas Cleanup to High Grade Hydrogen is being carried out by both CRL Energy Limited (CRL) and Industrial Research Limited (IRL). To date the majority of the work has focused on the earlier stages of the clean-up process and has been carried out by CRL Energy.

The objective aims to produce a technology package capable of removing all non-hydrogen components from the syngas stream generated by the 200 kW scale gasifier of Objective 1. In order to do so it must remove all particulates, condensable liquids and all non-hydrogen gaseous components from the syngas stream.

As an intermediate stage, a palladium membrane filter system has been set up to purify a small slipstream of hydrogen capable of delivering sufficient hydrogen for a 1 kW fuel cell prototype being developed under objective 5.

The entire clean-up line was designed during 2002 to 2004 and is being built and commissioned during 2005 to 2007.

Objective 3, Separation of Hydrogen from Syngas Streams investigates the development of ceramic membranes and other materials technologies that can contribute to the separation of hydrogen from the syngas stream to provide a feed suitable for fuel cells. Because of the complex materials science and processing techniques involved, this objective is scientifically challenging and high risk compared with the other objectives. It is not critical to a proof of concept demonstration of the package, but may contribute to improvements in gas separation technology needed for eventual commercialisation.

Objective 4, Sequestration Options for Carbon Dioxide Mixtures aims to develop an understanding on how to integrate CO_2 mitigation and abatement into a total distributed generation solution in an environmentally acceptable manner. CO_2 sequestration research is attracting increasing interest largely because it may make it possible to remove and store large quantities of greenhouse gases from the gasifier or the exhaust stream without requiring a major turnover of today's energy infrastructure.

If the technology can be made affordable, reliable, and environmentally safe, both industrialized and developing countries could use it to reduce and manage their carbon emissions.

Objective 5, Fuel Cell Peripherals and System Control aims to develop an alkaline fuel cell system that will operate reliably on high purity hydrogen produced from the coal gasifier and hydrogen purification system. It will deliver grid quality power via a grid connected inverter to the electricity network. The fuel cell controller and stack management systems are being developed under this objective.

Objective 6, Proof of Concept, aims to demonstrate the completely integrated coal to hydrogen to fuel cell to electricity package – the individual components of which are being produced within objectives 1,2 and 5 - and to identify possible scenarios for the introduction of a hydrogen economy into New Zealand. The first proof of concept demonstration – at the 5 kW scale - is scheduled for 2006.

During 2002 to 2004 a considerable amount of scenario development modelling was carried out by the Centre for Sustainable Energy Initiatives at Unitec New Zealand – a sub-contractor to this programme. This work focused on the transport sector. The model is being expanded to be inclusive of distributed generation applications on a regional basis.

Objectives 7, 8, 9 Electrolyser Technology Optimisation, Integration, and Scaleup, respectively, aim to develop an advanced small-scale electrolyser system specifically for producing low temperature fuel cell quality distributed hydrogen directly from small scale wind and solar energy sources. The knowledge gained through modelling and field experience in integration of small renewable energy generation technologies will be used to integrate and demonstrate a robust, stand-alone electrolyser system for producing hydrogen energy at the 5 kW hydrogen output level, from an intermittent renewable energy source.

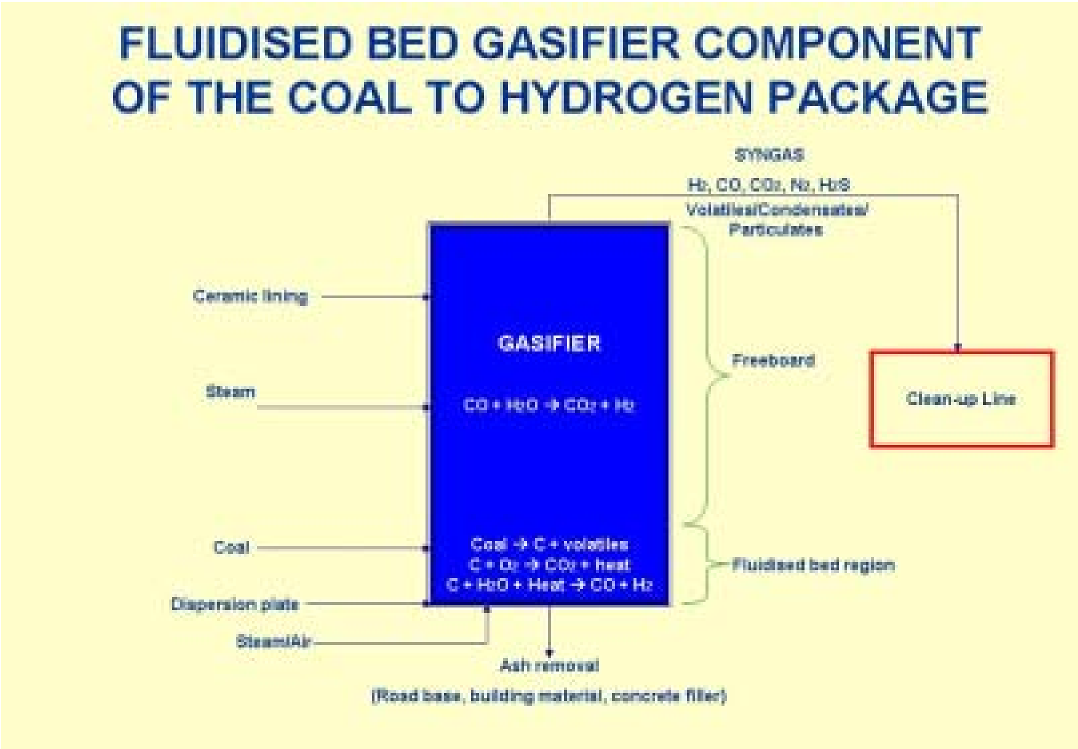
Objective 10, Solar Hydrogen Production aims to undertake initially a paper study and then experimental assessment of the status of and prospects for direct photoelectrochemical hydrogen production in the New Zealand context. This objective contributes to the programme outcome by maintaining a watching brief through scientific evaluation of progress in methods for hydrogen production from solar energy.

Detailed Explanation of Project:

Theme 1: Fuel cell quality hydrogen from coal

The 200 kW coal gasifier of Objective 1 is an atmospheric pressure, air blown fluidized bed gasifier. It is based on previous research carried out at CRL Energy which showed that New Zealand's low rank coals (lignite and sub-bituminous coals) are extremely well suited to fluidized bed gasification in terms of their high level of reactivity and low propensity towards ash melting.

A gasifier is basically a vessel inside which three events occur. First, the coal is heated and devolatilised to produce a char. Secondly, a portion of the char is burned (in air or pure oxygen) to generate heat and thirdly injected steam reacts on the surface of the char to produce hydrogen and carbon monoxide. The heat from the combustion process drives this reaction. In the freeboard region above the fluidized bed a number of subsequent reactions occur. The most significant of these is the water gas shift in which carbon monoxide reacts with excess steam to produce carbon dioxide plus more hydrogen.



In the fluidized bed gasifier, coal, ground to less than 6 mm top size, is fed into a bed of inert material (sand or ceramic) through which air is introduced from underneath through a dispersion plate. The flow is sufficient to lift the inert material off the plate and create a turbulent motion within the bed (fluidise it). This allows for good contact between the coal particles and the air and steam and allows the gasification process to take place at low temperatures (typically 900 to 950°C) compared to 1200°C or more required in other gasification processes. In order to undergo gasification at such low temperatures it is vital that the coal possesses sufficient reactivity and that the ash formed during conversion does not melt. If it were to do so and form large deposits of clinker in the bed, it would be very difficult to maintain fluidization behaviour.

The overall efficiency of the gasification process is 85 to 90% in terms of the calorific value in the product gas and the volume produced compared to the calorific value in the coal introduced to the gasifier.

The product gas contains a mixture of components in addition to hydrogen (15 to 17%), carbon monoxide (10 to 15%) and carbon dioxide (10 to 15%). There is methane, formed from the pyrolysis of the volatiles (usually less than 1%) released during the heating phase, hydrogen sulphide (in the ppm range), formed from the sulphur originally present in the coal and nitrogen (approximately 50%), which was introduced with the air and passes through the process unchanged. Trace amounts of other sulphides, ammonia and hydrogen cyanide may also form.

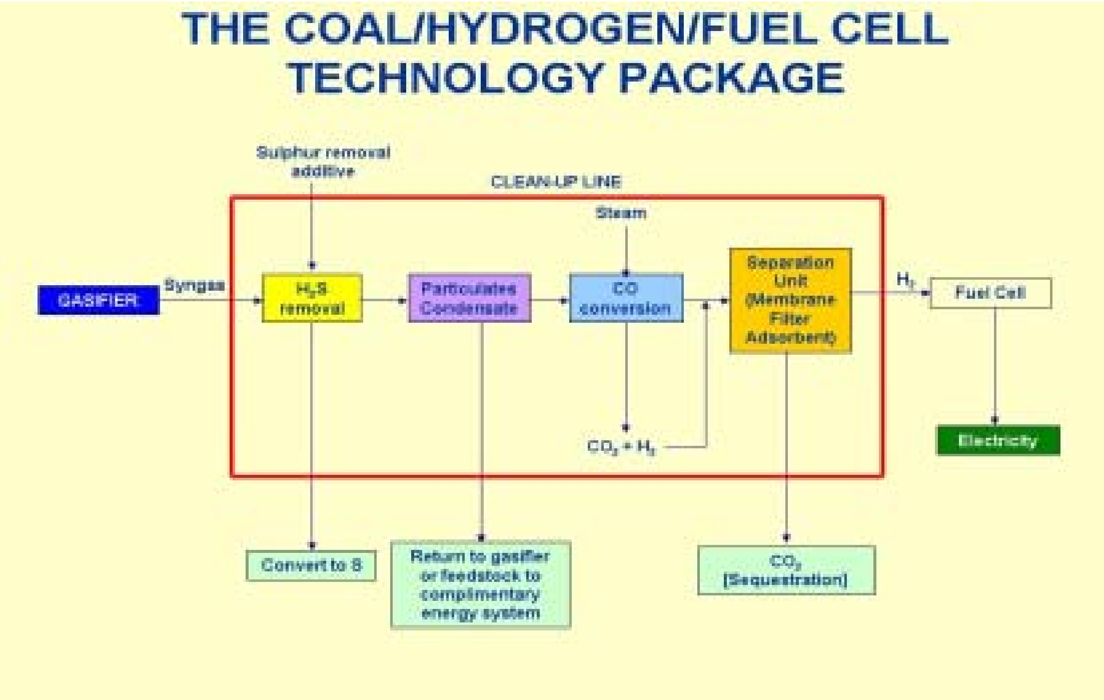
The product gas also contains entrained particulate material and uncracked volatiles which condense when the syngas is cooled. Large ash particles are retained within the bed and when the level of the bed increases to the point where the pressure drop across the bed is too great, an ash removal system automatically operates to return it to within the desired operating parameters.

The whole gasifier operation, and most of the downstream clean-up line is computer controlled and features a large number of thermocouples, flow meters and pressure transducers that continuously report data back to the control console throughout the gasification process. The product gas composition is measured on-line using gas chromatography.

The clean-up line is designed to remove all the non-hydrogen components from the syngas.

The first stage is an inertial cyclone assembly to remove the particulates. After exiting this device, the syngas is subject to a finely sprayed solution of sulphur scavenger material and then passes on to a Venturi scrubber system. These stages between them knock out the sulphide gases, any fine particulates that may have escaped the cyclone, ammonia, hydrogen cyanide and condensibles.

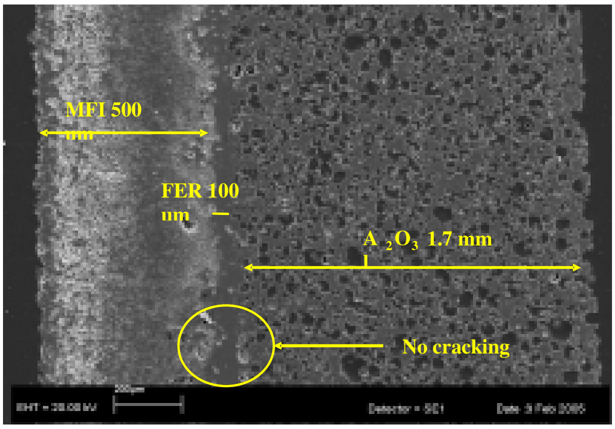
The cooled gas is passed through a water gas shift catalyst bed converting most of the carbon monoxide to CO_2 plus hydrogen. The syngas is comprised of hydrogen, carbon monoxide, carbon dioxide, nitrogen and small amounts of methane. For the initial demonstration of fuel cell based electricity production, a slipstream of the gas is passed through a palladium filter system producing hydrogen (99.9+%) and a waste stream of other gases. Some hydrogen is lost in the waste stream. Hydrogen production from the 200 kW demonstration will require the gas to be passed through a Pressure Swing Adsorption unit.



The 200 kW gasifier is shown below.

The picture clearly shows the feed hoppers and gasifier along with the ash removal system at the bottom of the gasifier. The silver coloured steam generator assembly sits on top of the gasifier and the air pre-heater can be seen suspended to the right of the gasifier. The cyclone is on the extreme right and the sample line heads out of the picture to the downstream clean-up line and the fuel cell.

Under *Objective 3*, a range of porous inorganic membranes have been fabricated and characterised. A cell for testing membrane efficacy was designed and constructed. Initial testing of membrane efficacy was undertaken.



The diagram opposite shows a SEM polished cross-section of a porous alumina/ Ferrierite/ Silicalite membrane showing a thin Ferrierite layer with the thicker Silicalite capping layer. NOTE: the thicknesses of each of the layers is not optimised in this sample. In an optimized membrane the Ferrierite layer will be 50-100 micron, the Silicalite layer 10-20 micron.

To date the project has been able to demonstrate membrane preparation and initial gas separation testing. Results do not yet indicate very high selectivity, but the research design and output matches that achieved in other laboratories. Future work within this objective will also investigate other materials options for the processing of syngas streams.

Research collaboration on this focus of work has been undertaken with Drs Chuah and Jaenicke at National University of Singapore. It involves materials design, characterisation and testing.

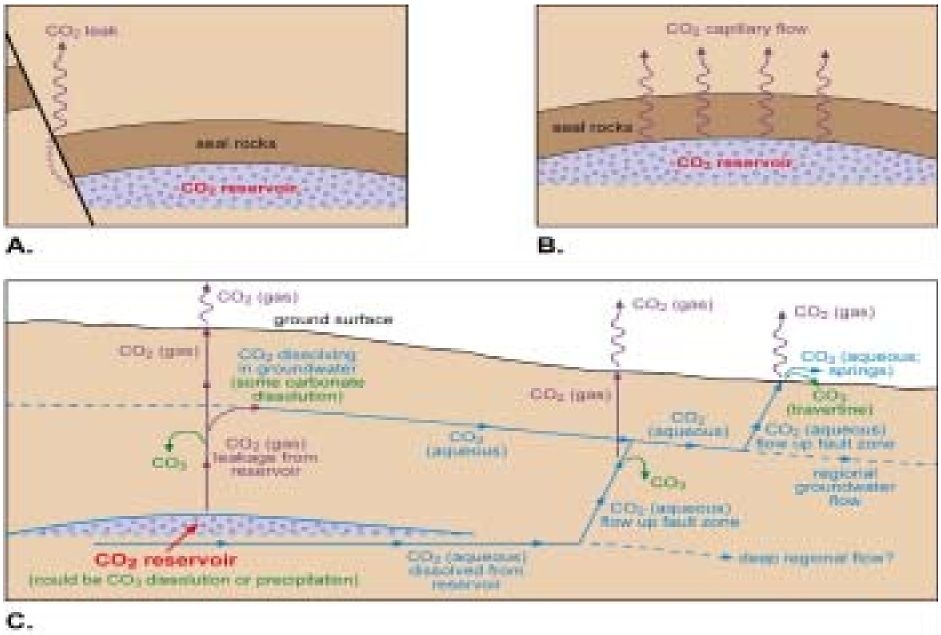
The specific goal of *Objective 4*, the CO_2 sequestration objective is to determine the feasibility of sequestering CO_2/N_2 mixtures with consideration of required gas post-processing, and degree to which the sequestration site may replace gas separation at source. This objective includes both physical and economic components and we are developing conceptual and numerical models of carbon sequestration in a New Zealand context.

To date we have developed a costing model of sequestration of CO_2-N_2 mixtures which shows an almost linear dependence on N_2 content to 30 % N_2 with significant increase in cost for N_2 content above this.

We have also modified standard reservoir modelling software to handle the injection of gas mixtures. Work is underway to investigate New Zealand sites suitable as geological sequestration sites.

There is a large international research effort in the area of geological carbon sequestration and we have links with groups in the United States and Japan and we have received funding from the Department of Energy in the US and Japan Petroleum Exploration Company Limited (JAPEX) and Research Institute of Innovative Technologies for the Earth (RITE) in Japan for work in this area.

The diagram below illustrates issues associated with CO_2 sequestration.
A – Spilling on faults
B – Leakage of gas through the seal when capillary pressures are exceeded
C - Hypothetical lateral flow paths when CO_2 gas is dissolved in the pool water, CO_2 (aqueous) is dissolved CO_2, CO_3 represents carbonate deposition.



Within *Objective 5*, a 1.2 kW alkaline fuel cell (AFC) system has been developed to a field ready testing capability. IRL has been actively researching and developing AFC technology over the last five years within this programme supported by the New Zealand Foundation for Research Science and Technology. This has resulted in the development of the balance of systems and technology and several demonstrations of alkaline fuel cell generators at the 400 W, 1.6 kW, 5 kW and 6.6 kW scale. Field trialling of a 1.2 kW grid connected system is now underway. The figure shows the Hydrogen Technology Facility at IRL in Christchurch.

The figure shows the current prototype 1.2 kW field ready system, which at present will run with hydrogen gas or methanol fuel via an add-on methanol reformer.

The technology goal for the programme is to produce a robust microCHP fuel cell system which will be suitable for a number of fuelling options and will be highly efficient in the conversion of fuel energy to electricity and heat.

Future research work in the fuel cell objective will be directed towards the development of long-life alkaline electrode systems and low cost regenerative CO2 scrubbing. Alkaline fuel cells offer potential advantages in stationary generation, due to their inherent high efficiency and low cost.

The energy modelling scenarios work in *Objective 6* has, to date, considered the introduction of a hydrogen-based transport fleet. It considers the New Zealand energy system as a whole and investigates seven different scenarios under which the hydrogen economy may develop within that system. Scenarios include cases with and without LNG imports, the effect of high carbon tax and the case where there is large scale centralized hydrogen production for the fuel cell fleet. It forecasts that by 2050, assuming 90% of the land transport fleet running on fuel cells, there will be a requirement to produce and distribute approximately 1.5 million tonnes of hydrogen per annum. This is approximately 10% of the amount currently produced and distributed (primarily for use as a chemical rather than an energy carrier) throughout the United States annually.

The IRL Hydrogen Technology Facility in Christchurch

DCI-1200 Alkaline Fuel Cell System Prototype

A highlight of the work to date was the official launch of the gasifier component of the technology package in February 2004. This event was attended by 150 high level representatives of government (national and local), industry and research organizations. The operation of the gasifier to near design expectations within a few months of initial start-up was also a considerable achievement. The degree of control and responsiveness of the gasifier to commands is also as good as, or exceeds, original expectations.

Future Work in Theme 1

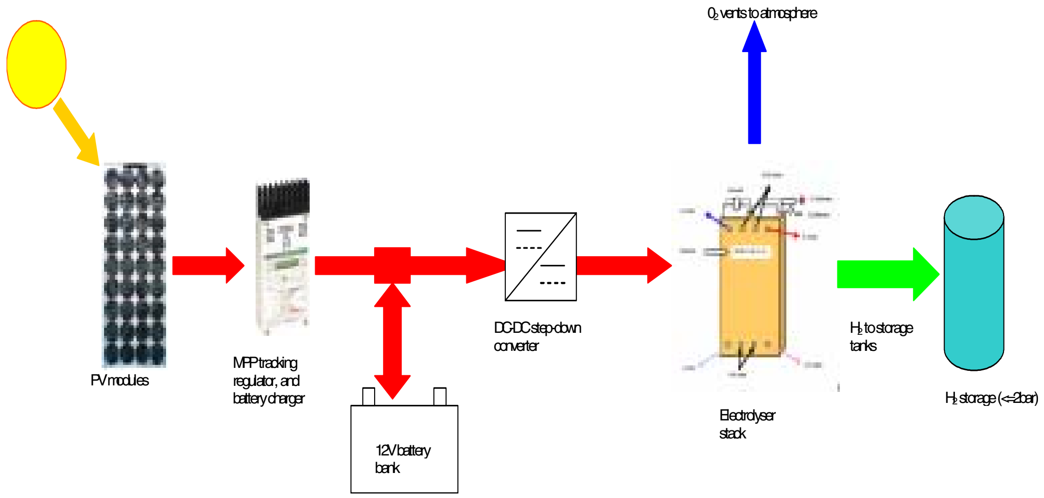
Future work within the existing programme will center on improving the running time of the gasifier, commissioning and running of the sulphur scavenger and water gas shift components of the clean-up line and their integration into the complete technology package. Work will also be undertaken to extend the scenario modelling capability to include stationary applications – in particular small scale distributed electricity production from either fuel cells or gas engines.

Beyond that it is also intended to use the gasifier as a means for trialling new separation membrane technologies being developed internationally and eventually expand the programme so as to demonstrate the wide range of products other than hydrogen that may be generated from syngas. These include electricity, chemicals, natural gas and Fischer Tropsch synthesized transport fuels.

Possible commercial applications of the coal to hydrogen component of this project are considered in Project 6: Hydrogen – A Long Term Future for the Coal Industry, considered below.

Theme 2: Distributed Production of Hydrogen from Renewable Electricity

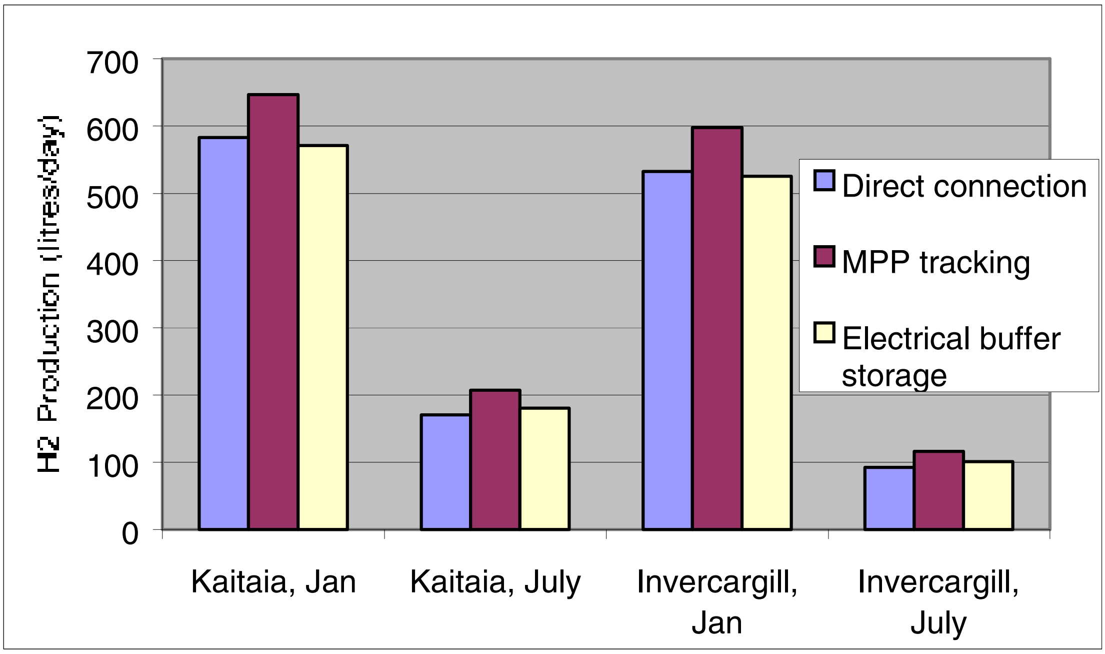
The group of *objectives 7, 8 and 9* contribute to the programme outcome by developing and demonstrating a pre-commercial integrated system for the distributed small-scale production of hydrogen by electrolysis from variable intensity supply of renewable electricity. The diagram below illustrates a typical solar source hydrogen production system using PV cells and an electrolyser.



Supply from PV array via charge controller and buffer battery

Electrolysis has been extensively used in the past as a means of producing large amounts of hydrogen for industrial applications. These plants in general use a liquid alkaline electrolyte, and operate at high capacity factor from a firm grid supply. The established electrolyser technology is not suited for small-scale applications due to a number of factors. New Proton Exchange Membrane (PEM) technology overcomes some of these problems, and offers the opportunity for small-scale distributed hydrogen production. In particular, PEM electrolysers can be easily pressurised, and because they have a solid electrolyte, they are relatively scaleable, and minimal gas clean-up is needed. Accordingly, they are suitable for small-scale, distributed applications. However, cost is a major issue at present.

Following analysis of the systems requirements for different configurations of solar PV and wind sourced electrolysis, the detailed experimental evaluation of two small electrolyser systems was undertaken. This analysis and experimental work identified that high cost was one of the key barriers to commercialisation of hydrogen storage technologies for remote energy systems. The relative hydrogen production from solar PV for two regions in New Zealand under differing technology configurations is shown in figure below.



Net H_2 production with PV power of 400W
(MPP = maximum power point)

The difficulty in obtaining a reliable and cost effective small scale electrolyser technology with appropriate specifications has prompted the internal development of a novel electrolyser stack specifically to address the cost and performance requirements of this type of application. Work is continuing on this, and on the balance of plant and control software for a demonstration system at the field site reported in Project 5. Currently, the most cost effective renewable electricity source is to utilize wind energy. Work has been carried out to evaluate the issues associated with managing and controlling the electrolyser stack under conditions of highly fluctuating wind energy input.

To practically evaluate the implementation of these systems, a small demonstration project is being developed for installation at a farming community field site in Totara Valley, near Woodville, in the North Island of New Zealand. The project involves an electrolyser producing hydrogen directly from a wind turbine, and the use of a small diameter polymer fuel pipeline to transmit the hydrogen at low pressure to the farmhouse for use. Key issues in the design are automatic stand-alone operation of the electrolyser stack, and evaluating the diffusion rate of hydrogen through the 2 km pipeline. The hydrogen is to be used at the farmhouse for both local heating and power generation via a fuel cell or hydrogen internal combustion engine.

Future Work in Theme 2

At the product development level, further work will be undertaken to establish if the in-house prototype electrolyser technology being developed within the programme has sufficient advantages to warrant further development for small scale pilot systems and possible commercialization. Future work at the application level involves completing the installation of the remote rural demonstration system and the evaluation of the performance of the various system components, as well as addressing safety issues. At the resource level, studies will be undertaken to evaluate the availability and economics of wind energy resources for distributed electrolytic production of hydrogen in New Zealand, and the impact that this could have on the supply of electricity for other applications.

This objective has research linkages with Massey University in New Zealand and the Research Institute for Sustainable Energy at Murdoch University, Perth, Australia.

Objective 10 aims at this stage to keep a watching brief on photoelectrochemical methods for hydrogen production. An exhaustive literature search has been undertaken, and an internal programme advisory report has been produced. A small capability building project is proposed, starting July 2005.

Project 2: Thermochemical Production from Renewable Resources

Title:	**Thermochemical Production from Renewable Resources**
Research Area:	Hydrogen Production
Organisation conducting work:	Industrial Research Limited Dr Ian Brown PO Box 31-310 Lower Hutt Wellington 6009 ph: (64) 4 931 3000 fx: (64) 4 566 6004 i.brown@irl.cri.nz
Funding Organisation:	New Zealand Foundation for Research Science and Technology and Ministry of Research, Science and Technology
Project Budget:	NZ$250,000 (inc GST) per annum
Project Duration:	3 years
Project Dates:	1 July 2004 to 30 June 2007

Objective of Project:

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.

Project work programme and timeline:

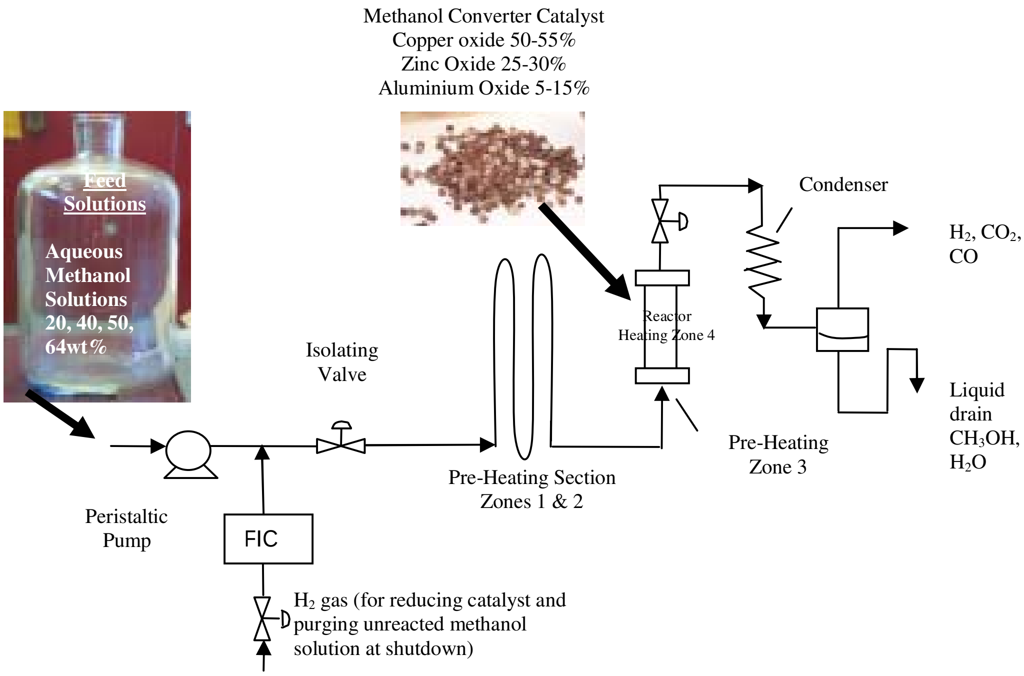
New Zealand has a good climate for biomass production. It is important to develop an understanding of the technological difficulties and costs associated with hydrogen production from biomass, particularly waste products such as animal and human effluent, or residues from valuable crops such as forestry and agriculture. New Zealand already produces substantial volumes of ethanol from dairy whey. This could be a suitable source of hydrogen for use in stationary and vehicle based fuel cells.

Detailed explanation of project:

1. Methanol reformation

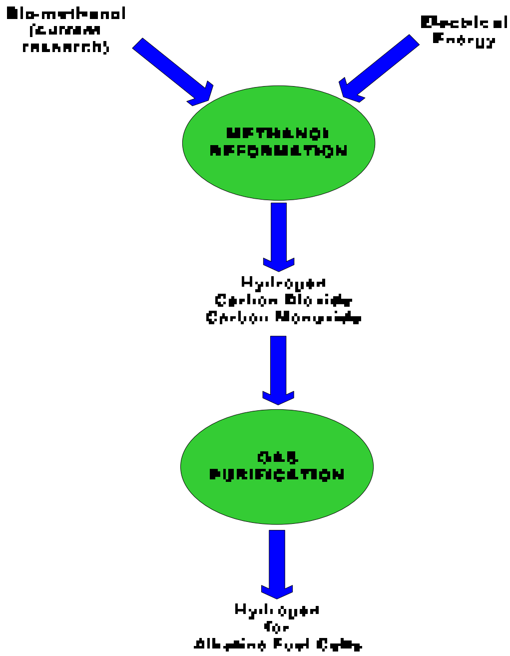
Tube reformer

A small tube reformer capable of producing approximately 2.4 litres/minute of hydrogen (0.5 kW) from aqueous methanol was constructed and tested. It was then used to evaluate a range of bio-methanol solutions obtained by distillation of the product developed under the main programme objective. The process used is best described as steam methanol reforming, where methanol and water are introduced into the reformer and heated together in the absence of oxygen, before passing across the catalyst bed.



Results

The objectives of this project were achieved. It was found that in this methanol reformation process hydrogen and CO_2 were the main components in the approximate ratio 74:25 by volume, and that traces of CO are also produced. The results have shown that if certain undesirable by-products are accounted for, it is possible to produce high purity hydrogen suitable for fuel cell applications from bio-methanol using relatively conventional reformation, purification and separation techniques. However, the output of this simple process is not suitable for direct use in either PEM or alkaline fuel cells for several reasons. First, CO_2 will contaminate alkaline systems, while CO even at ppm levels will poison PEM systems. Secondly, it is not possible to efficiently utilise the hydrogen when in a mixture with other gases, due to purge requirements. So an additional step of gas separation must be undertaken as shown in the diagram on the right. At small scale, palladium metal purification is the most convenient option, and this was also demonstrated in the project, producing hydrogen at adequate quality for operation of an alkaline fuel cell.



Plant scale-up

A preliminary analysis of the scale-up process was undertaken to identify the major costs in a commercial system. It was shown that the final cost of hydrogen was strongly dependent on both the cost of the feedstock and the distillation energy input for concentration of the culture broth. Technical issues relating to scale-up of these technologies were not addressed under the programme, but feedstock cost and process energy consumption are significant factors to be considered for commercialisation.

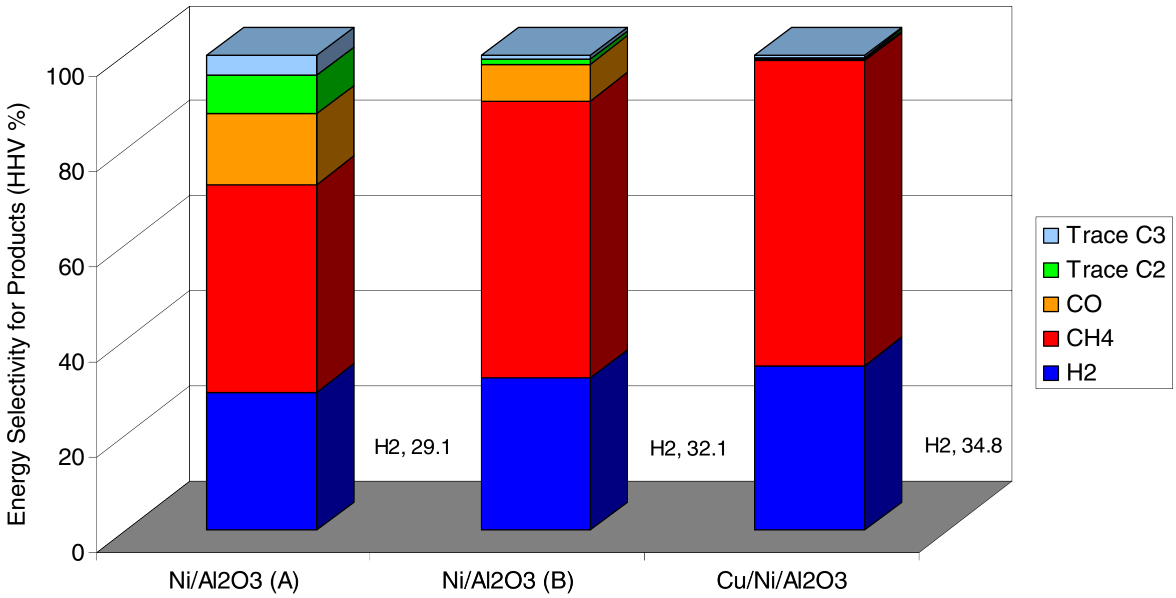
Two scales of operation were examined. The first was based on 1 MW of HHV methanol (small scale) and the second on 6 MW of methanol (medium scale). The study showed that at an aqueous 1.8 wt% biomethanol feedstock and cost of $50/tonne, a plant in case one would produce electricity at $1.96/kWh (worst case) and in case two if the biomethanol could be purchased at $5/tonne, the cost of producing electricity would be $0.34/kWh (best case). This is uneconomic at current electricity prices. GHG credits could reduce this cost in New Zealand by about 1.5c/kWh. Corresponding costs of hydrogen were calculated at $273/GJ and $47/GJ. The latter figure approaches that which it is estimated electrolysis based hydrogen could be produced for, so the process might have future application in supplying hydrogen for fuel cell vehicles.

At the present stage of fuel cell development, and with the current price for grid energy, the use of fuel cells to produce electricity from methanol at small-medium scale does not appear to be economic. However, fuel cells are predicted to play a major role in future energy systems due to their high efficiency and low point-of-use pollution. This research has demonstrated that it is technically feasible, and even relatively straightforward, to produce high quality hydrogen fuel for fuel cells at a distributed scale from aqueous methanol. This methanol can be produced from biological waste such as dairy shed effluent and other renewable sources by a number of means. The ability to produce refined hydrogen fuel from biological waste may be important in the future if New Zealand has to face the consequences of significant increases in the cost and reduced availability of imported oil supplies. Further work is necessary to define and implement a commercial process, and this will be very much dependent on the scale of the plant. Larger scale hydrogen separation technology would be different from the small-scale bench system developed under this objective. The most likely technique would be pressure swing absorption, although there is a great deal of research interest in the development of lower cost molecular sieve membrane technologies for this application. However, as yet no commercial products have appeared, and Pressure Swing Adsorption at present remains the only choice for industrial scale for high purity hydrogen production.

No further work on this project is planned at present.

2. Ethanol reformation

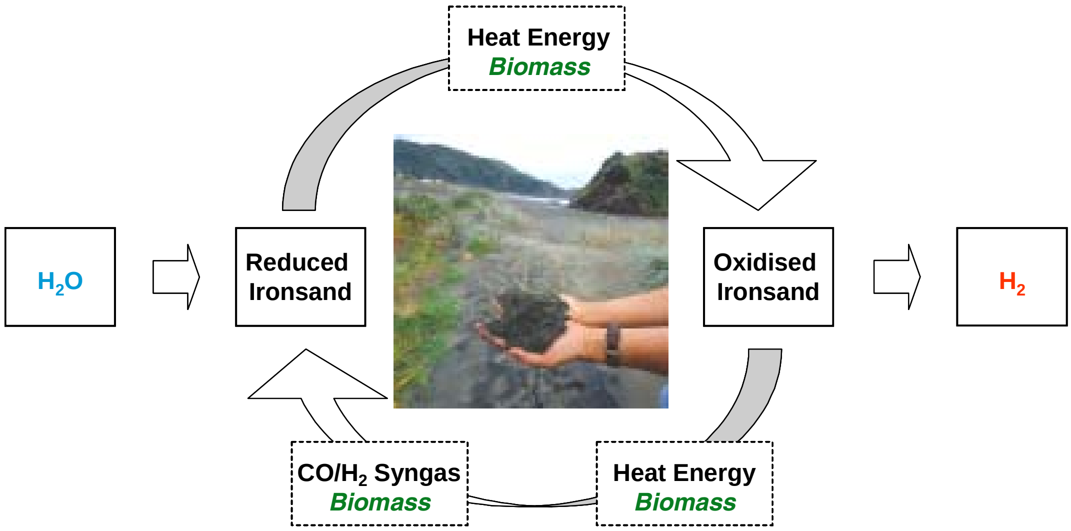
Ethanol was steam reformed over various supported metal catalysts at 300 °C and pressures up to 3 bar gauge in the tube reformer built for the previously described project. The catalysts trialled included a commercial methanol synthesis catalyst (Cu/ZnO/Al2O3) and catalysts with nickel and/or copper impregnated on gamma-alumina extrudates. The effect of the ethanol concentration in the feed was assessed in terms of ethanol conversion and hydrogen yield for each catalyst. It was found that a copper/nickel/alumina catalyst achieved the highest ethanol conversion (~100%) and hydrogen yield (1.3 moles hydrogen per mole ethanol reacted) at 300 °C and atmospheric pressure with excess water in the feed solution. While both the methanol synthesis catalyst and the Nickel/Alumina B catalyst achieved high selectivity for hydrogen, their relative performances were hindered by thermal instability and coking respectively. Tests at 300 °C and up to 3 bar gauge indicated that increasing the pressure decreases the hydrogen yield. The bar graph below shows the energy content of the various reformation products for 6:1 water:ethanol mix.



If project partners can be found, further work is being considered to develop an integrated low temperature fuel processor for a 1 kW microCHP fuel cell generator to run on partly concentrated ethanol fuel.

3. Ironsand Thermochemical cycle

Hydrogen can be generated from splitting water using a novel thermochemical cycle based on iron-rich New Zealand beach sands (ironsands). The ironsand is exposed to a sequential processing route involving reduction with syngas followed by steam oxidation of the reduced iron oxide to generate hydrogen. The re-oxidised ironsand is continuously recycled. The primary consumables are syngas and water. The process is shown schematically in following figure.



The iron oxide hydrogen production cycle

Raw Materials and Process Chemistry

New Zealand ironsand is a titanium-substituted magnetite (Fe,Ti)3O4 which is magnetically concentrated and purified on a large commercial scale as feedstock for steel production in New Zealand and for export. The reaction chemistry of major interest is the reduction of magnetite by syngas (CO/CO2/H2/CH4) as in reaction sequence (1) and its subsequent reformation by steam oxidation to evolve hydrogen.

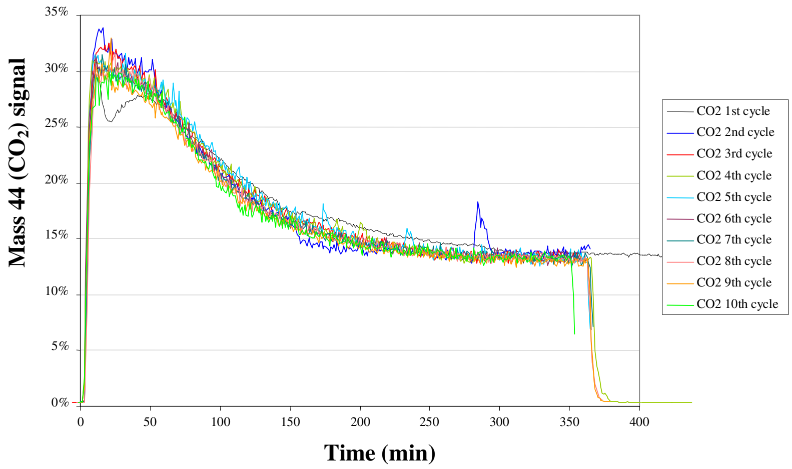
$[Fe_2O_3 \rightarrow]$ Fe_3O_4 $\leftrightarrow$ FeO $\leftrightarrow$ Fe (1)
[Hematite $\rightarrow]$ Magnetite $\leftrightarrow$ Wustite $\leftrightarrow$ Ferrite

Three of the syngas components can achieve the first stage of reduction to FeO:

$Fe_3O_4 + 0.25CH_4(g) = 3FeO + 0.25CO_2(g) + 0.5H_2O(g)$ (2)
$Fe_3O_4 + 4CO(g) = 3FeO + CO_2(g)$ (3)
$Fe_3O_4 + H_2(g) = 3FeO + H_2O(g)$ (4)

The CO_2 evolution measured over 10 syngas reduction cycles at 900ºC is shown in Fig 4. After 6 hours of reduction the measured CO_2 had declined close to the 12% level of the syngas mixture. This fixed minimum partial pressure of CO_2 acts as a thermodynamic barrier to further reduction.

Fluidised bed experiments have been undertaken using 350g ironsand powder in a 50 mm diameter reactor at NREL, with N2 as the carrier gas for a synthetic syngas composition, similar to that used in the fixed bed experiments at IRL. On-line gas analysis was undertaken using gas-specific IR sensors with quantitative X-Ray Diffraction (XRD) phase analysis undertaken off-line at IRL. The composition of the reducing gas and ratio of syngas to carrier gas were varied as required and monitored continuously. XRD of the reduced product showed high conversion of Fe3O4 with up to 76% Fe metal present following a reduction-oxidation-reduction cycle. The steam oxidation was undertaken using a nitrogen carrier gas. There was a good correlation between the on-line gas consumption data and off-line XRD phase analysis. Under the gas flow conditions used, it was demonstrated that CO_2 in the gas stream inhibited the reduction of magnetite through removal of H_2 via a shift reaction. Two subsequent experimental series confirmed successful reduction: CO/H2 mixtures at 850ºC and 30% CO in N2 carrier gas at 900ºC both demonstrated reduction to Fe metal with negligible FeO formation.



CO_2 evolution over 10 syngas reduction cycles.

In summary, the fluidised bed is more effective at reducing magnetite ironsand than the fixed bed reactor in terms of the extent and rate of conversion to iron metal. This is unsurprising given the ability of the fluidised bed geometry to transfer heat effectively to the reactants and flush waste gases rapidly from the product environment. However, the impact of other engineering factors needs to be more fully assessed in terms of process efficiency: for example the high gas flow rates necessary to sustain fluidity of the bed are some ten times those used in the fixed bed reactor.

Scope of Future Research and Opportunities for Partnership:

- Modify the thermochemical cycle, using different iron ores with different additives or impurities.
- Extend the options for syngas reduction, including use of different biomass sources; assessment of coal syngas as a transition technology; effect of stripping of CO_2 from the syngas stream.

Linkages/collaborations in these projects with other NZ projects:

Biomethanol production - Waste Solutions Ltd, University of Canterbury
Bioethanol production - University of Canterbury, HydrogeNZ

Linkages/collaborations in these projects with work in other countries:

Ironsand thermochemical production - US National Renewable Energy Lab

Project 3: Chemical Storage of Hydrogen

Title:	**Chemical Storage of Hydrogen**
Research Area:	Hydrogen Storage
Organisation conducting work:	Industrial Research Limited Dr Ian Brown PO Box 31-310 Lower Hutt Wellington 6009 ph: (+64) 4 931 3173 fx: (+64) 4 566 6004 i.brown@irl.cri.nz
Funding Organisation:	New Zealand Foundation for Research Science and Technology
Project Budget:	NZ$600,000 (inc GST) per annum
Project Duration:	3 years
Project Dates:	1 July 2004 to 30 June 2007

Objective of Project:

Develop new materials and process technologies for energy efficient and safe storage of hydrogen gas as chemical hydride materials.

Project work programme and context:

Cost effective storage and transport of hydrogen fuel is a key issue for the uptake of a hydrogen energy economy. Much international effort in hydrogen storage is focused on future transport applications. New Zealand has identified medium term opportunities and applications in stationary generation that will both complement and contribute to these longer-term transport goals. The supply of hydrogen for fuel cells for distributed and remote generation can potentially be solved with similar but less stringent storage requirements than those presently defined for transport solutions. To meet these intermediate and long-term targets Industrial Research Limited (IRL) has a strategy to work with international IPHE partner laboratories to develop new chemical hydride storage materials. The outcome will be Intellectual Property of international value that can be exploited through licensing or through business partnerships. Process integration with fuel cell developers/suppliers will enable early technology uptake in New Zealand as a springboard to larger international stationary energy markets. The programme outcome may also be the production of materials and the development of processes whose performance and economics approach the needs of a future transport market.

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 with international partners 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.

Detailed explanation of project:

Scientific explanation of project

Project 1. Regeneration of Sodium Borohydride

The release of hydrogen through the catalysed hydrolytic decomposition of $NaBH_4$ is well known. The technology-limiting factor is the efficiency reformation of $NaBH_4$ from the spent $NaBO_2$-rich reaction products. We have identified two approaches to solve this based on (i) chemical and (ii) electrochemical processing. The electrochemical pathway is currently subject to IP protection procedures.

The chemical processing route develops the strategy of weakening the very strong B-O bond in $NaBO_2$ through selected chemical substitutions, so that conventional hydrogenation technologies may be employed using lower energy pathways. Our strategy is to synthesise and then hydrogenate a series of sodium-boron-alkoxy compounds, prepared from sodium borate.

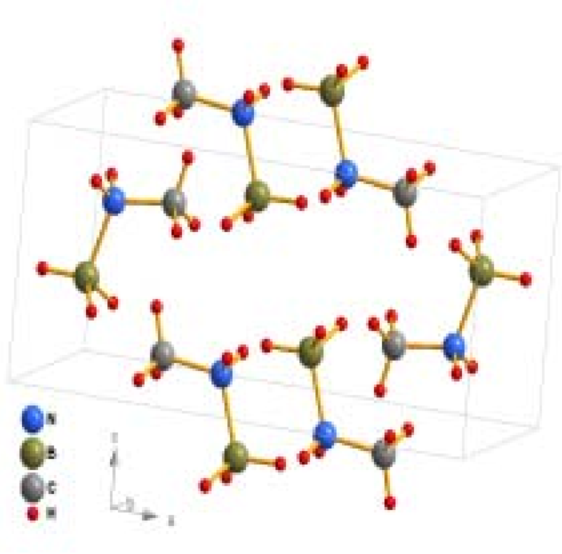
Project 2. Storage in amino-borane systems

The release of hydrogen through pyrolytic decomposition of NH_3BH_3 below 150ºC results in the formation of polymeric NHBH materials that cannot be rehydrogenated. Our strategy is to synthesise and characterise a series of substituted amino-borane materials (RNH_2BH_3 and NH_3BH_2R), measure their decomposition and hydrogen release characteristics and examine their capacity for rehydrogenation.

Research progress and outcomes

A multi-stage route to the reformation of $NaBH_4$ from $NaBO_2$ has been designed. The reaction conditions for the synthesis of a series of alkoxyborate derivatives of sodium borate have been determined and derivatives based on four primary alcohols, two secondary alcohols and a tertiary alcohol, produced via the 'methoxy' derivative, have been prepared and characterised. Some of these compounds are new to science and their synthesis and chemical structures have been accepted for publication. Future research in this area will involve catalysed rehydrogenation studies of these substituted sodium-boron-alkoxy compounds with the advice and support from our research partners at the US Los Alamos National Laboratory (LANL).

The synthesis and characterisation of amino-borane and new substituted amino-borane materials has been undertaken and the products characterised with respect to their structure and their hydrogen evolution as a function of temperature. The crystal structures of methyl- and propyl-amino-borane have been elaborated for the first time and are scheduled for publication. The structures show the existence of H---H dihydrogen bonds between adjacent molecular species which may prove to have a significant influence on the mechanisms of hydrogen release and re-adsorption. Figure 1 shows the crystal structure we have determined for $CH_3NH_2BH_3$ using single-crystal methods. The boron and nitrogen atoms on adjacent molecules are aligned head-to-tail, giving a 2.2Å dihydrogen bond (BьH ··· HьN).



Crystal structure of $CH_3NH_2BH_3$

The chemical structures have been further clarified through the use of a combination solution NMR and isotopic substitution strategies, in tandem with thermal analysis and on-line evolved gas analysis using mass spectrometry. Initial heating studies to understand the decomposition of these materials at elevated temperatures have revealed the unusual growth of ammonia borane needles, shown in figure 2.

Growth of ammonia borane needles at 80ºC

Future research on these materials will involve detailed mechanistic studies of hydrogen release from (substituted) ammonia-boranes in partnership with our colleagues at the US Pacific Northwest National Laboratory (PNNL), and will include high temperature X-ray diffraction studies.

This ammonia borane research has been presented as a poster paper (*Investigation of Substituted Ammonia Boranes for Chemical Hydrogen Storage*, M.E. Bowden. I.W.M. Brown and K.J.D. MacKenzie) at the June 2006 IPHE Hydrogen Storage Conference at Lucca, Italy.

Linkages & collaborations

The project has international partnerships with the US Los Alamos National Laboratory (LANL, Dr Bill Tumas & Dr Tony Burrell) and with the US Pacific Northwest National Laboratory (PNNL, Dr Tom Autrey & Dr Chris Aardahl). Within the past 15 months, Drs Mark Bowden, Tim Kemmitt and Ian Brown (IRL) have visited LANL and Dr Tony Burrell (LANL) has visited IRL in a series of visits funded through the US-NZ Climate Change Partnership (via MfE) and through BRAP/ISAT awards (via the NZ Royal Society).

The project has national linkages to the *"Hydrogen Energy for the Future of New Zealand"* programme (Project 1 in this report) funded by NZ FRST @ $1.3M p.a for 6 years. This facilitates links to CRL Energy Ltd, who have designed and built demonstration facilities for hydrogen production from coal and to projects within IRL that are designing and enabling new fuel cell technologies.

Our proposed *hybrid solid-state storage materials* programme is being developed for submission as a formally sanctioned IPHE research programme, with partners LANL, PNNL, National University of Singapore and the Inorganic Chemistry Laboratory, Oxford. Funding to cover New Zealand's contribution to this proposed programme is being sought through a parallel submission to the International Investment Opportunities Fund (IIOF) of the NZ Foundation for Research Science & Technology. If successful, this will enable commencement of a new 3-year programme at IRL from Jan 2006.

Project 4: Hydrogen and Fuel Cell Demonstrations

Title:	**Hydrogen and Fuel Cell Demonstrations**
Research Area:	Technology Demonstration
Organisations conducting work:	Industrial Research Limited Alister Gardiner PO Box 20028 Christchurch, New Zealand Ph (+64) 3 358-6809 Fax (+64) 3 358-9506 a.gardiner@irl.cri.nz Massey University Prof Ralph Sims Private Bag 11222 Palmerston North New Zealand Ph (+64) 6 350-5288 Fax (+64) 6 350-5604 R.E.Sims@massey.ac.nz Various other project partners
Funding Organisation:	New Zealand Foundation for Research Science and Technology plus various other project sponsors
Project Budget:	Variable around NZ$100,000 (inc GST) per annum
Project Duration:	6 years
Project Dates:	1 July 2001 to 30 June 2007

Objective of Project:

The aim of this ongoing 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.

Project work programme and timeline:

It is likely that hydrogen energy will initially make an impact in stationary power applications through the introduction of fuel cells. In the New Zealand context, the opportunities include fuel cell Combined Heat and Power (CHP) systems. A series of small fuel cell based demonstration projects is being undertaken under various funding mechanisms to develop and evaluate microscale integrated distributed energy systems involving fuel cells of various types. These demonstrations started at the laboratory/conference level several years ago and are moving to field demonstrations and pilot systems as fuel cell technology capability is improved and on-site fuel processing capability is developed. A summary of the projects which have been completed or are in progress follows.

Completed:

- 400W demonstration system based on Zetek AFC stacks modules – lab demonstrator
- 6 kW experimental fuel cell system delivered to Australian Cooperative Research Centre for Renewable Energy (ACRE), Perth

In progress:

- 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
- 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:

- Remote rural wind-hydrogen power link and AFC fuel cell grid connected demonstration at Totara Valley, Kumeroa, New Zealand

- NZ sponsored methanol AFC urban residential microCHP fuel cell grid connected demonstration, Christchurch, New Zealand

Project Description:

A brief description of three of these projects follows.

6 kW experimental fuel cell system for ACRE, Perth, Australia

A 6 kW experimental fuel cell system was delivered to ACRE at Murdoch University, Perth in 2002. This was the first operational fuel cell system in Australasia. It was designed as a fully instrumented research system to evaluate and demonstrate the use of fuel cells for remote area power systems (RAPS). The fuel cell currently runs on compressed hydrogen cylinders but there is a future option for the hydrogen to be produced from the electrolysis of water from electricity produced from wind energy. The wind energy would be sourced from the 20 kW wind generator at the research site. The system provides short term battery storage and a fully programmable load bank for defining various arbitrary load profiles.

The 6 kW alkaline fuel cell system installed and commissioned at Murdoch University, Western Australia

2 kW Residential PEM Demonstration Project installed at the US Antarctic Programme Facility, International Antarctic Centre, Christchurch, New Zealand

This is a project funded under a US DoD programme to demonstrate small domestic level PEM fuel cells (1 kW rating) at military sites (see DOD website http://www.dodfuelcell.com/res/).
Up until now, almost all of the installations have been in the continental USA. There is interest from the funding authority to get experience in overseas locations.

The PEM fuel cell system consists of two Independence 1000 units manufactured by ReliOn, Inc. The fuel cells are supplied by hydrogen produced on-site from a methanol reformer, manufactured by Genesis Fueltech, with back up supply available from standard industrial compressed hydrogen gas cylinders.

The housing at the US Antarctic Programme facility containing the methanol fuel tank, fuel cell system and monitoring equipment

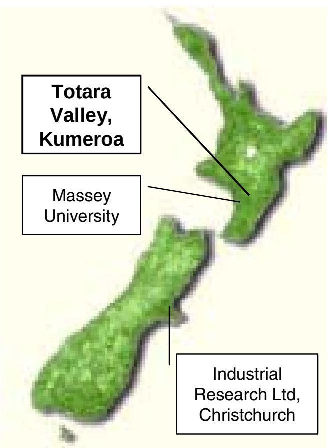
A photo of the completed installation is shown above. The fuel cell system is installed at the US National Science Foundation (NSF) facility at the International Antarctic Centre, Christchurch, New Zealand. This facility is the logistics base for air transport to and from Antarctica for the scientific research programmes operated by New Zealand, the United States and Italy. It hosts around 3500 researchers and other personnel per year, who will pass in close proximity to the demonstration site. Personnel en-route to and from the Antarctica directly pass the fuel cell system.

The fuel cell power is supplied at a standard 48 Vdc battery bus to demonstrate use in a range of portable applications associated with a field base, - eg, battery charging, instrumentation power, and yard lighting. To achieve a continuous operating environment as required under the contract, the fuel cell generator system also feeds energy into the local electricity network via a grid tied inverter.

The project requirement is for fuel cell power to be produced with at least 90% availability for a twelve month trial period. This period commenced on 11 April 2004. Since startup the system has achieved in excess of 96% availability.

0.5kW Remote Rural Wind-Hydrogen Project at Totara Valley, Woodville, New Zealand

Totara Valley is a typical New Zealand hill country community engaged in sheep and beef farming as the principal economic activity. In association with Massey University, IRL has installed various Distributed Energy Resources at three adjacent farms in the Valley, including solar thermal, PV and a bio-diesel generator. In particular, renewable energy resources are being monitored and harnessed to provide electricity and hot water supply to the community in parallel with the distribution network based electricity supply.



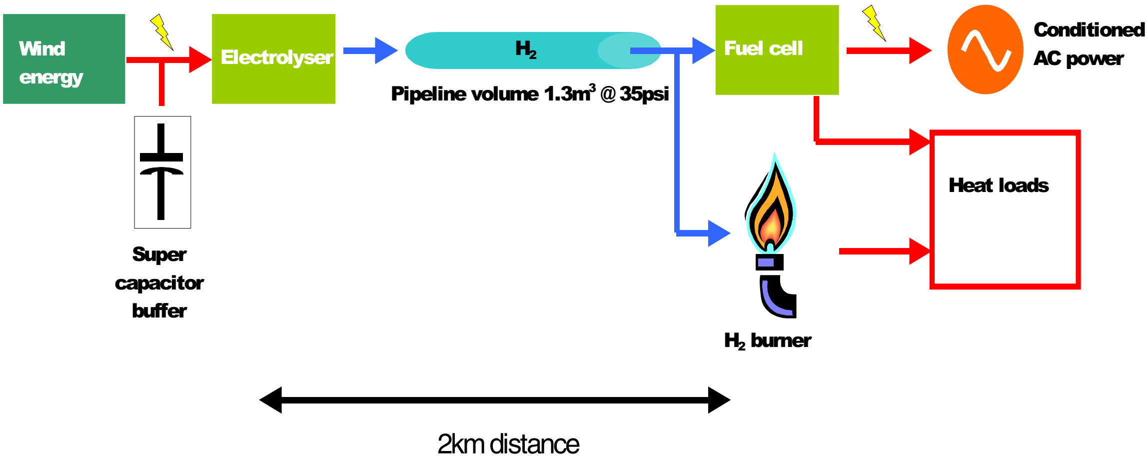
(a) Locality

(b) Looking down the valley

Totara Valley

The Hy-Link Concept - The next phase of research is to install a small hydrogen production, distribution and utilisation system. Based on the above analysis, this involves a hilltop wind turbine generator and electrolyser to produce hydrogen gas, connected to a fuel cell and hydrogen burner for water heating at the farmhouse in the valley below.

Because of the relatively long distance and low power it is not economical to run an overhead power line from the wind turbine. We have investigated the feasibility of a Hy-Link – a hydrogen pipeline to transport energy. The wind resource is used to power the electrolyser to produce hydrogen gas, which is then piped to the farmhouse, eliminating the need for an overhead power line.



The energy storage inherently included in the system due to the pipeline volume can be significant. If a 32 mm SDR11 pipeline is used over the full 2 km distance, this provides approximately 1.3 m3 of storage space. At 2.4 barg, the maximum pressure currently allowed for plastic fuel gas pipelines, this provides approximately 10 kWh of energy storage. Compressing hydrogen gas to high pressure for storage is both expensive and energy intensive. The Hy-Link option can provide an alternative by relying on large pipe volumes directly fed from a low pressure electrolyser, rather than high pressures for energy storage. To store more gas, the pipeline diameter can simply be increased, at relatively low cost (32 mm SDR11 Medium Density Polyethylene (MDPE) is priced at around $3/metre in small quantities).

From experimental work on polymer pipelines it was found that there would be less than 1% gas permeation over a 2 km pipeline length for a 32 mm SDR11 MDPE pipeline being run at 2.4 barg (the regulatory limit for low pressure gas pipelines) and with gas flow rate representing 1 kW of energy flow. Obviously as the flow rate increases the permeation as a percentage of energy transferred will reduce. Our example was based on a very low 1 kW of energy transfer for our proof of concept scale system, however with a 32 mm pipeline capable of carrying gas with a capacity of several hundred kW, the gas permeation will become almost negligible. These results have heightened our interest in further investigating such hydrogen pipeline systems.

Future Work

Future work in fuel cell applications is focused on microCHP technologies for remote, residential and small business applications. The rationale behind this is the potential large savings in fuel that can be achieved through the high efficiency delivery of combined heat and power directly to a site. This will improve sustainability from renewable fuels such as ethanol and reduce the greenhouse gas footprint from fossil fuels.

Linkages/collaborations in these projects with other NZ projects:

These fuel cell projects involve linkages and collaboration with other New Zealand projects and organizations, including:
Massey University – Prof Ralph Sims; Powerco; Tait Electronics; Energy Recyclers

Linkages/collaborations in these projects with work in other countries:

Linkages/collaborations and product supply arrangements with organizations in other countries include:

USA: DoD; ReliOn; Genesis Fueltech; Lynntech Industries
Europe: EVision; Gaskatel; Australia: CRC for Renewable Energy; Research Institute for Sustainable Energy, Murdoch University, Perth; Ceramic Fuel Cells Ltd, Melbourne.

Project 5: Supply Options for the Proton Exchange Membrane (PEM)

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

Organisation conducting work:

CRL Energy Ltd
Dr Tony Clemens
PO Box 31-244
Lower Hutt
(+64) 4 570-3713
t.clemens@crl.co.nz

Industrial Research Limited
Ben McQueen
5 Sheffield Crescent
(+64) 3 358- 6801
b.mcqueen@irl.cri.nz

Funding Organisation: Ministry of Foreign Affairs and Trade

This programme was included as one of a suite of programmes within the first round of the NZ/US Bilateral Climate Change Research Partnership 2003/04.

Project Budget: NZ$15,000 (inc GST)

Project Duration: 1 year

Project Dates: 1 July 2003 to 30 June 2004.

Objective of Project:

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.

Project Work Programme:

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.

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

Detailed Explanation of Project:

Bottled Gas:

It was estimated, on the basis of quotes from BOC, that the bottled gas option would require approximately 1650 cylinders at a cost of approximately $200,000 per annum delivered on an almost daily basis.

Water electrolysis – Mains Powered

Considered to be generally a rather expensive and "contrived" option in that if mains power is available at a site it could be used directly with an efficiency close to unity, making the fuel cell system somewhat redundant, unless its primary function was back up power.

However, it is considered to be a potential option for supply situations such as community level hydrogen reticulation from a large central electrolyser, or energy delivery via buried hydrogen pipeline in niche application where this could be competitive with overhead wires.

Water electrolysis – wind energy powered

Not practical for the demonstration site at the Antarctic Centre as it is located in a built-up environment and very close to the international airport. Furthermore the average wind speed at this site is too low. At only around 5 m/s at 10m it is not far above the cut-in speed of most conventional wind turbines.

Water electrolysis – solar PV powered

Solar PV systems are expensive – currently around $10,000/kW in New Zealand. At the project site it is estimated that 58 square meters of PV panel would be required at around $580,000 capital cost. This is considered unsustainable for the present application.

Hydrocarbon reformation – Methanol Fuel

While methanol is currently almost exclusively manufactured from natural gas, a number of renewable resource production routes are known. Therefore it is attractive as an easy fuel to reform, and having the potential for future renewable sources. Extensive investigation was done into companies who were able to supply methanol reformer systems at small scale. The company best positioned to provide a methanol reformer to the required specifications was Genesis Fueltech Inc. based in Spokane Washington.

Assessment criteria included:

- High quality hydrogen
- Compact reformer system
- Acceptable price to client

- Good technological understanding of this emerging technology

The fuel mix required for the Genesis reformer may be sourced through Australasian Solvents and Chemicals Company, ASCC in 2100 litre batches.

Hydrocarbon reformation – ethanol fuel

Ethanol is also a renewable fuel, which is produced in New Zealand from dairy whey. No proven micro-reformer for ethanol could be located at the time of this survey. Subsequent investigation of ethanol and its promotion as an octane enhancer suggests that when the technology is available this could be a very attractive fuel for remote and field fuel cell applications.

Hydrocarbon reformation – natural gas

Micro-scale natural gas reformers are available for purchase. However, since neither reticulated nor bottled natural gas is available within Christchurch, the fuel was not explored further.

Hydrocarbon reformation – Liquid Petroleum Gas

A supplier of microscale propane reformers was located but as New Zealand LPG is composed of varying ratios of propane, butane and other traces of higher hydrocarbons, it was considered as too risky an option. This is both because the reformer is unproven on these mixtures and any traces of any hydrocarbon compounds will damage the fuel cell electrodes.

After this initial screening, a more detailed economic analysis was carried out on the following options:

- Bottle gas supply
- Water Electrolysis – mains powered
- Hydrocarbon reformation – methanol fuel

The methanol reformer option was selected, augmented by back-up hydrogen tank storage. The hydrogen tank storage will automatically take up demand should the reformer supply shut down for any reason. This hydrogen is supplied by BOC Gases and is derived from natural gas as a by-product of hydrogen peroxide production.

Estimated overall electrical efficiency of the chosen system is 28.6% High Heating Value (HHV) when running on hydrogen gas and 25% HHV when running on methanol. The methanol reformer efficiency is around 86%.

The 2 kW PEM fuel cell system is now operating at the site and is briefly described under Project 4, which also identifies the main technology partners involved in the project.

Project 6: Hydrogen – A long term future for the Coal Industry

Title:	**Hydrogen – A Long Term Future for the Coal Industry**
Research Area:	Education
Organisation conducting work:	CRL Energy Limited Ramon Brown PO Box 31-244 Lower Hutt, New Zealand Phone: (64) 4 570-3714 ramon.brown@crl.co.nz
Funding Organisation:	Coal Association of New Zealand
Project Budget:	NZ$53,000 (including GST)
Project Duration:	1 year
Project Dates:	1 April 2003 to 31 March 2004

Objective of Project:

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.

Project Work Programme and Timeline:

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

The project 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.

The project is completed and it is planned to hold a formal launch of the document in the near future.

Detailed Explanation of Project

The main findings of the research, which drew on documents and discussion from a wide range of sources both nationally and internationally are that:

- Although the hydrogen economy may be as much as 20 years in the future, a great deal of activity needs to be undertaken prior to that time in order to ensure the transition is as smooth as possible. Those activities need to begin now.

- Each country must decide for itself the mix of indigenous energy resources it will need in order to produce sufficient hydrogen and benefit from moving towards a hydrogen energy economy.

- Many of the breakthroughs in issues relating to hydrogen storage, delivery and utilisation will come from international research and it is very important to be connected to the global community to be aware of these breakthroughs as they occur. There may, however, be niche applications for New Zealand research and development in the areas of storage and utilisation.

- Each country will also need to work out for itself the optimal way of building the infrastructure necessary to deliver the hydrogen from point of production to point of use.

It is generally accepted within the international community that while the ultimate aim is to base the hydrogen economy entirely on renewable energy sources there will be a transitional period of many decades during which hydrogen production will be mainly from fossil fuels. The reasons relate to resource availability and cost of production and are as valid in New Zealand as they are elsewhere.

It is also generally accepted that the really big demand for hydrogen will not occur until the purchase and operation of fuel cell vehicles becomes economically viable. For New Zealand a realistic scenario is that the growth in fuel cell vehicles will increase rapidly from 2025 onwards and that by 2050 over 90% of the fleet will be fuel cell vehicles. This fleet will consume between 1.2 and 1.75 million tonnes of hydrogen in the year 2050. This corresponds to 140 to 210 PJ of energy and approximately 10 to 15 million tonnes of coal would need to be consumed in order to produce it. Prior to then, other applications in small scale distributed generation and larger scale electricity generation will become established and will play an important role in raising public awareness and acceptance of hydrogen.

New Zealand has sufficient resources of coal to meet over 400 years supply at the proposed 2050 demand scenario level for transport hydrogen. Known natural gas resources are sufficient for approximately 7 years supply at 2050 levels and a Maui gas field sized find (ca 3700 PJ) of natural gas would give approximately 13 years security. If the hydrogen were to be generated by electrolysis using electricity produced from renewables an estimated 280 to 420 PJ of energy would be needed.

A key enabling technology in producing hydrogen from coal is gasification. Much of New Zealand's substantial coal resource – representing an energy equivalent to that of approximately 50 original Maui gasfields – appears to be well suited to one or more of the new high efficiency advanced coal gasification technologies developed and demonstrated over the past two decades.

The initial product of coal gasification is syngas - a mixture comprised mainly of hydrogen, carbon monoxide and carbon dioxide. Syngas is a versatile product. In addition to being cleaned up and used as a source of hydrogen for a fuel cell vehicle fleet of 2050 it can, with minimal clean-up, also be used to generate electricity in gas engines, microturbines, and gas and steam turbine combined cycles. It may also be used to produce hydrocarbons, fertiliser, synthetic natural gas and synthetic fuels.

The key partnering technology for hydrogen production from fossil fuels is CO_2 capture and sequestration (CCS). Concentrations of CO_2 are higher in syngas than conventional combustion flue gas making it easier to capture. It is also produced at pressure, which greatly reduces costs associated with geological sequestration. Globally, there are already three successful and well-established sites where CO_2 is removed from syngas and sequestered geologically. There are many other similar operations under development. Many international studies have confirmed that the widespread application of CCS is the most viable method for achieving deep reductions in anthropogenic CO_2 emissions.

US estimates of the costs of delivering hydrogen to the future hydrogen fuel cell transport fleet indicate that coal based hydrogen production and delivery systems, including allowance for carbon capture and sequestration (CCS), is likely to be significantly lower than those associated with renewable based production. Comparisons of the total supply chain costs of the gasoline and hydrogen needed to provide equal vehicle mileage when consumed in a gasoline hybrid electric vehicle or a fuel cell vehicle also suggest the coal based hydrogen generation option is a very competitive one. These studies are based on the assumption that the large international research and development programmes currently in progress, such as those within the IPHE, are successful in reaching certain well-established targets in terms of reduced costs of fuel cells and improved on-board hydrogen storage capability. New Zealand will benefit from being involved in these development programmes in some way. An active means of doing so is to be a testbed for the new technologies being developed within them.

From the above considerations, it appears extremely likely that the coal pathway to a hydrogen economy will initially involve the use of syngas for electricity or chemical production. Subsequently, as the transport fleet converts to fuel cells and demand grows, increasingly large portions of the syngas stream will be slip-streamed off and passed through a cleanup line capable of producing fuel cell grade hydrogen. Ultimately, predicted demand levels could require construction of several large plants dedicated primarily to hydrogen production. CCS capability will be integrated into these plants.

It is envisaged that there will be at least three types of coal powered application in a hydrogen based energy economy. One is to meet the energy demands of small remote communities – using a technology package similar to that being developed in Project 1 - one is to meet the demands of a large industrial complex and one is to produce the bulk of the hydrogen required by the transport fleet.

In the *small scale off-grid distributed generation application*, electricity is likely to be produced by a combination of fuel cell and gas engine/turbine technologies. Economic analysis suggests that the viability of such applications will depend heavily on recovery and utilisation of the low-grade heat produced. This could, for example, be used for heating a glasshouse, cleaning a dairy shed or heating a swimming pool. Although the coal consumption associated with this option may be small, this is viewed as an essential early step on the transition towards hydrogen and an invaluable tool in generating public acceptance of coal in a future hydrogen economy.

The energy *demands of a large industrial site* could be met by a tri-generation (electricity, heat and hydrogen) operation in which electricity is produced by a solid oxide fuel cell and heat recovered from the exhaust of the fuel cell is used to meet the thermal requirements of the plant. Hydrogen produced may also be used to run the plant's fuel cell transport fleet. A first pass assessment for a hypothetical plant generating 40 MW thermal, 20 MW electrical energy and sufficient hydrogen to power 200 light vehicles suggests this may well be a viable option in New Zealand.

The third application could be used to *produce the bulk of the hydrogen required by the transport fleet* using large-scale coal-powered centralised multiplexes. These plants may also simultaneously co-produce electricity. Ultimately, several of these plants could be required in New Zealand. The first plant of this type could conceivably arise in a modular fashion around an existing core gasification based facility – most probably a combined gas and steam turbine Integrated Gasification Combined Cycle (IGCC) facility.

For plants of this size, outlined in the above scenario it is important to consider issues around bulk hydrogen distribution and several different production/distribution configurations may be envisaged, as described below.

- The first is exemplified by a plant located in the Waikato/Auckland area, utilising local sub-bituminous coal and sending the hydrogen through 600 kms of large capacity pipelines to a series of 400 fuelling stations servicing 2 million vehicles. The plant is likely to utilise the sub-bituminous reserves of the Waikato region.

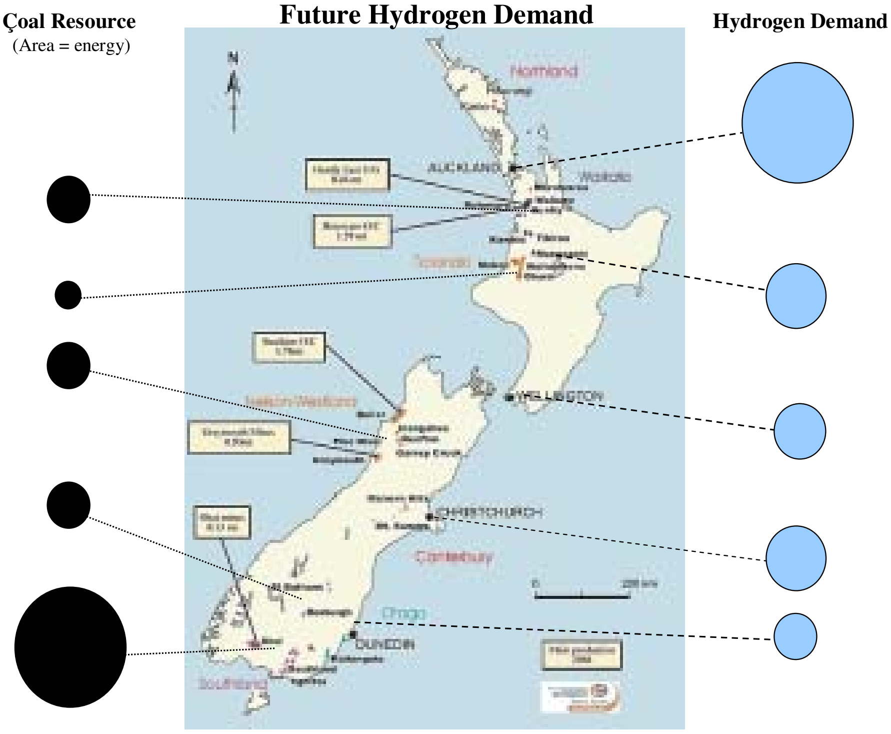
- Under a second scenario, a Southland/Otago gasification-based plant would produce hydrogen, and possibly also electricity. The hydrogen would be transported in a gaseous form to the high demand centres primarily in the North Island via a dedicated pipeline spanning the length of New Zealand.

- A third configuration has the gasification plant(s) based in the lignite fields of Southland and Otago. The plant would generate electricity only which would be transported through an upgraded national electricity grid to the refuelling stations or local facility where hydrogen production via electrolysis would occur. The use of gasification to produce the electricity has many advantages over traditional plant based on sub-critical or super-critical steam cycles. This includes increased efficiency, lower cost of CCS and the inherent flexibility offered by production of syngas.

- A fourth scenario would again utilise the large lignite reserves but in this case the syngas resulting from gasification would be converted to a hydrogen rich, low carbon synthetic liquid fuel. This would be shipped to the demand centres using conventional liquid fuel infrastructure at which point it would be further processed to release hydrogen. This is the least technologically developed option but is presently receiving a great deal of research investment, particularly in the US.

The above scenarios relating to large scale production highlight one of the major issues for coal utilisation as a source of hydrogen in New Zealand– the bulk of the resource is remote from the main demand centres.

New Zealand Coal Resources and Predicted Future Hydrogen Demand



In order for a hydrogen economy to develop, the delivered hydrogen cost must be competitive with other fuels. Initial estimates for the Waikato based centralised plant suggest a hydrogen fuel cost per kilometre driven as low as 0.66 times that of the equivalent figure current gasoline engine vehicle.

It is likely that a coal based hydrogen economy would utilise some combination of the above production/distribution pathways. Further New Zealand specific in-depth techno-economic studies are required in order to identify the most economically viable configuration.

All three application types – remote communities, industrial site and large scale hydrogen multiplex will produce CO_2 as a co-product. Large scale plants – each consuming 7,000 tonnes of coal per day and producing 1,200 tonnes per day of hydrogen - would be required to sequester approximately 6.5 million tonnes of CO_2 per annum. This highlights the importance of identifying and quantifying the available geological sequestration capacity in New Zealand. International studies have shown that worldwide there is sufficient geological sequestration capacity to sequester CO_2 for almost 400 years at current CO_2 production rates.

From all of the above, the following pathway to a hydrogen energy economy may be identified for the New Zealand coal industry.

Activities and milestones for 2005 to 2010: Laying the Foundation

- Small scale co-production plant installed
- Comprehensive carbon sequestration site survey completed
- Techno-economic assessment of a geological site for large scale CO_2 sequestration completed. Knowledge gaps relating to technical and economic aspects of coal to hydrogen production, distribution and utilisation identified and filled

- Link between coal and hydrogen production established with decision makers and the general public
- Alliances with international projects and technology providers for implementing near zero emissions coal based energy production established
- Promotion of New Zealand as a testbed for new coal and hydrogen technologies

Activities and Milestones for 2010 to 2015: Gasification Uptake

- First large scale gasification plant installed and operating (probably for electricity production via IGCC)
- First industrial tri-generation plant installed and operating
- Increase in small scale distributed generation plant
- First carbon sequestration verification trials conducted
- First large scale utilisation of carbon capture technologies

Activities and milestones for 2015 to 2025: Zero Emissions Power Plant

- Large scale syngas to hydrogen capability developed and demonstrated
- First large scale centralised co-production capable (electricity and hydrogen) plant installed (with CCS)
- Hydrogen infrastructure development plan in place (including production and distribution)

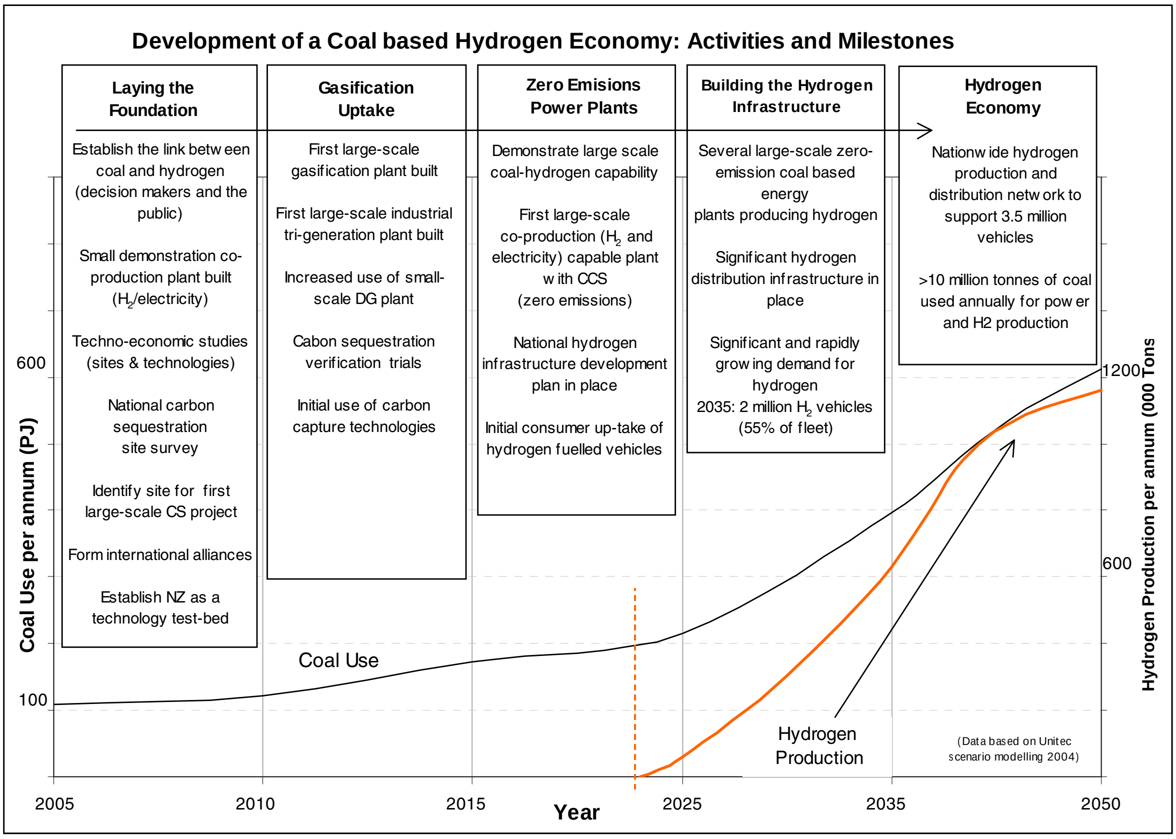
Activities and milestones for 2025 to 2035: Building the Hydrogen Infrastructure

- Several large-scale coal based energy plants installed in support of the rapidly expanding hydrogen energy economy
- Significant hydrogen distribution infrastructure in place

Activities and milestones for 2035 to 2050: The Hydrogen Economy

- Sufficient production and distribution capability to support a fleet of approximately 3.5 million (light and heavy) vehicles
- In excess of 10 million tonnes of coal used annually for hydrogen and electricity production

These milestones and activities are related to the state of the hydrogen economy development (and coal demand) in the following figure. It may be noted that there are a significant number of activities to be undertaken in the near term relating primarily to the planning for and promotion of the role of coal in a hydrogen economy. Unless these preliminary activities occur (laying the foundation) the sequence of development will be seriously delayed.



Cutting across all time periods are issues relating to public outreach, education of decision makers and other stakeholders and the development of standardised, internationally accepted codes and practices. It is particularly important that in order to create the enabling environment for a hydrogen economy, policy and decision makers are well-informed at an early stage.

In future it is planned to use a similar template to that used in developing the coal roadmap in order to produce a more comprehensive roadmap for New Zealand covering the contributions from renewables and natural gas over the period through to 2050.

It is also planned to further develop scenarios so that robust predictions relating to the cost to New Zealand of delays in implementing a hydrogen economy may be made and presented.