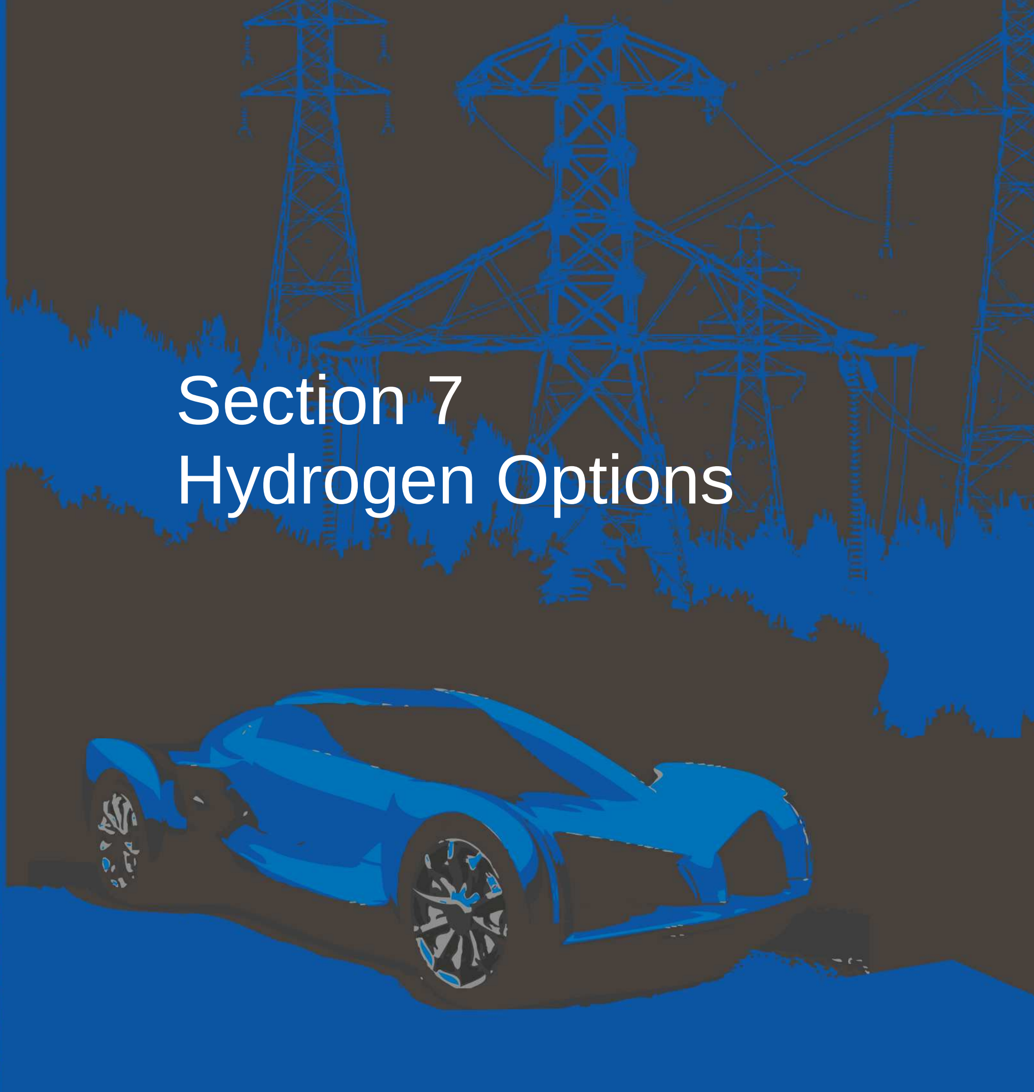
New Zealand's EnergyScape™

2000 2005 2030 2050

EnergyScape™ Basis Review

December 2009

Section 7
Hydrogen Options



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EnergyScape™ Basis Review

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Prepared for

Foundation for Research, Science and Technology (FRST)

Project:

NZES091- New Zealand's EnergyScape

Document number:

AKL-2009-034 (7)

Publisher:

NIWA, Auckland
December 2009

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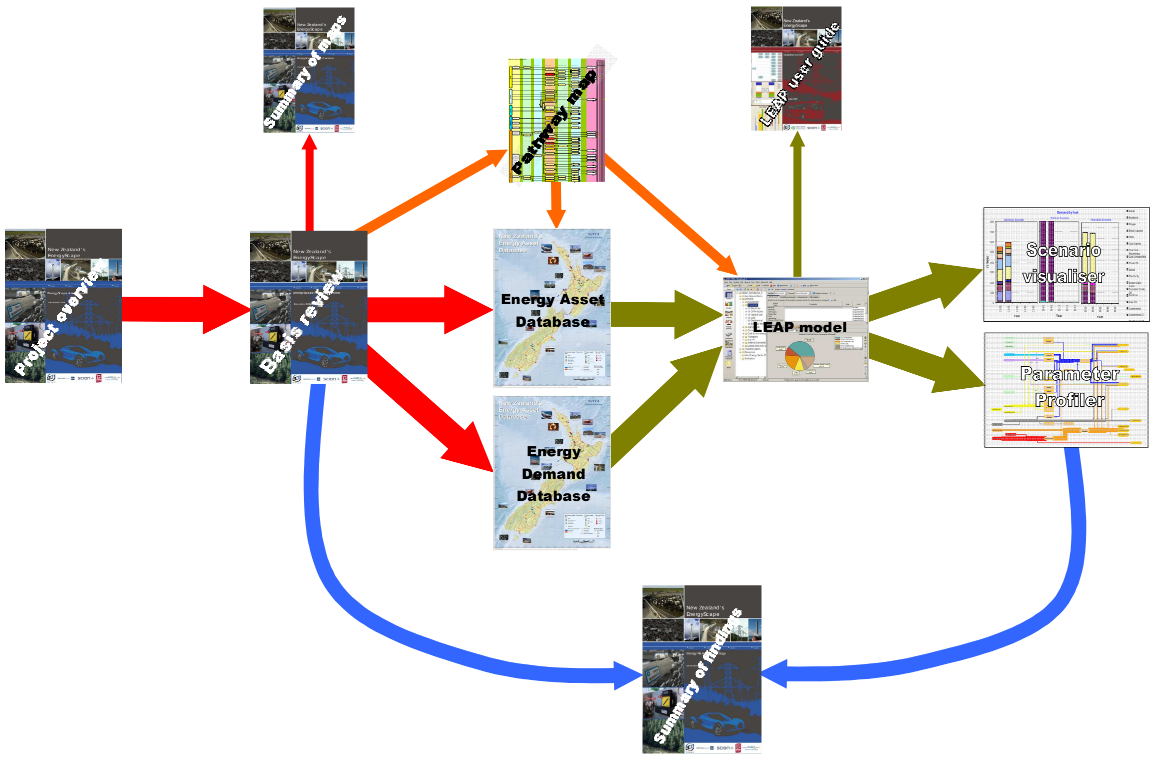
SUMMARY

The EnergyScape programme is a collaborative research initiative that seeks to develop tools that can support energy policy development by considering the impact of integrated solutions for the long-term time horizon, at a regional level on a broad range of social parameters. To achieve this aim, the programme has developed a series of linked tools (the EnergyScape framework) which can unify economic data, energy data, system assumptions and facilitate improved understanding of the complexities and dependencies of: resource depletion, energy substitution, transmission costs, conversion efficiencies, locality effects, scale, demand controls, environmental impact (on land, water and the atmosphere) and risk.

The linkages between some of the key deliverables of the programme are illustrated below:



The "EnergyScape Programme Overview" report provides the foundation for the research effort, by outlining the scope, purpose and methodology that would be utilised by the research programme. The "EnergyScape Basis Review" documents the status of energy infrastructure and flows for all energy pathways in New Zealand. Data pertaining to the pathways described in the "Basis Review" were captured in an "Energy Asset Database" and an "Energy Demand Database". These databases provide input to Long Range Energy Alternatives Planning (LEAP) models and subsequent analysis tools.

This “EnergyScape Basis Review” is intended to provide a broad introduction to New Zealand’s energy infrastructure. The seven (7) sections of the report cover the full spectrum of the energy system from resources, through generation, distribution, conversion and end-use:

Section 1 – Energy end-use

Section 2 – Renewable resources

Section 3 – Bioenergy resources

Section 4 – Earth resources

Section 5 – Distribution infrastructure

Section 6 – Secondary conversion

Section 7 – Hydrogen options

All energy sectors (e.g. industrial end-use, wind power, coal to liquids) are given separate chapters in the relevant section. Each chapter has been written so that if the reader only has interest for one particular area, an appreciation for how that area contributes to New Zealand’s energy portfolio, now and in future can be gained by reading that section in isolation. In addition to describing the current status of public domain knowledge pertaining to energy resources, each chapter also deals with the efficiencies, risks and research applicable to this energy sector. These chapters provide the philosophy for populating the New Zealand energy asset and end-use databases.

Section 7 summarises the work undertaken by CRL Energy Ltd in the “Hydrogen Options” program, which is interlinked with EnergyScape. Many analysts have touted that installation of hydrogen infrastructure could realise a paradigm shift in efficiency and carbon intensity of the economy. This portion of the research has selected and evaluated nine (9) hydrogen energy pathways that are most likely to assist in the transformation of the entire New Zealand energy sector to a low carbon emission system.

Significant conclusions drawn from Section 7 include:

- Hydrogen has potential to be a widespread “zero emission at point of use” fuel for transport applications in the medium to long term.
- New Zealand is well endowed with energy resources that can support the use of hydrogen as an energy carrier, with hydro and wind generated electricity, biomass, coal, and natural gas all being potential sources.
- Hydrocarbon sources such as natural gas and coal offer the most cost effective large scale production methods.
- Production of hydrogen by electrolysis offers an excellent energy storage means for balancing intermittent renewable electrical supply with variable demand.
- The high electrical conversion efficiency of fuel cells is the cornerstone of hydrogen fuel applications in transport. The price of fuel cells will define the acceptability of hydrogen fuelled light vehicles in an open market.

Section 7
Hydrogen options

7.1 HYDROGEN OPTIONS

7.1.1 General introduction

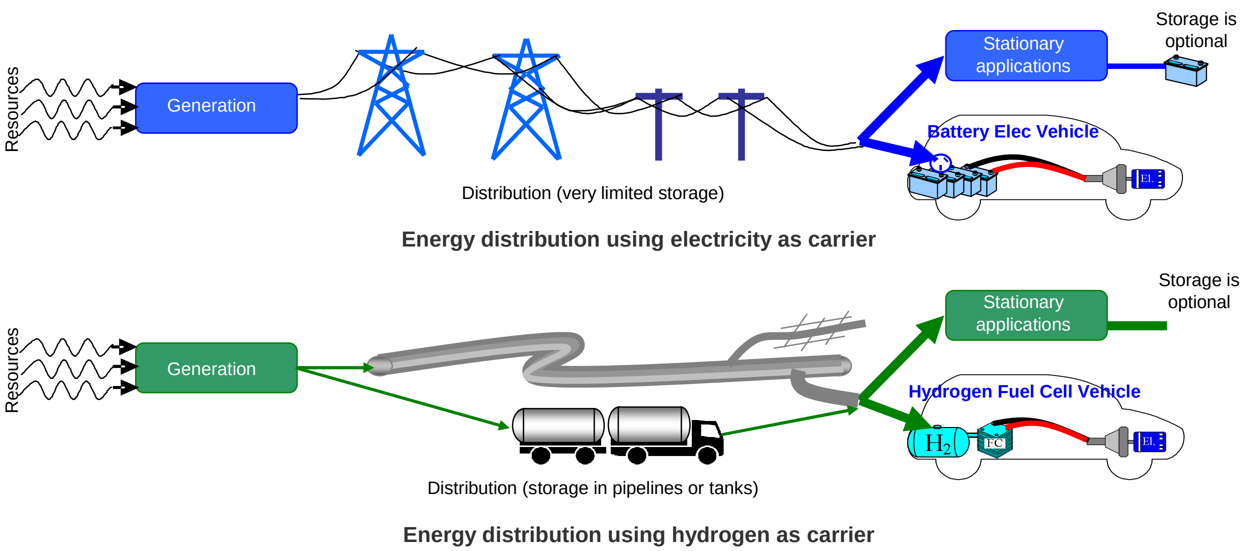
Hydrogen (H_2) is not an energy source like hydro, wind, coal or natural gas – it is an energy carrier like electricity. Hydrogen needs to be produced from other energy sources, such as solar, hydro, biomass or fossil fuel resources. These sources are then regarded as the original sources of the energy contained in hydrogen. The movement of energy in the form of hydrogen is achieved in much the same as natural gas is moved – conveyed though pipelines or trucked in storage vessels / bottles. The energy contained in hydrogen can either be released with fuel cells to produce electricity or burnt to produce heat and mechanical energy.

Interest in developing and distributing hydrogen and its associated fuel cell technologies arises from the potential to solve vehicle exhaust emission problems and security of energy supply issues. This is possible because hydrogen is a portable energy carrier that:

- Yields only heat and water-vapour emissions when used to generate power via a fuel cell, and;
- Can be generated from a variety of different primary sources using established technologies (wind, solar, coal, biomass etc.).

In order to better understand the role of hydrogen in a future energy economy it is useful to compare and contrast how hydrogen and electricity distribute energy, and deliver low emission transport solutions.

Figure 7.1.1 – Comparison of energy distribution by electricity and hydrogen pathways



Both energy carriers can efficiently convey large quantities of energy from sources of generation to sites of consumption, but use distinctly different infrastructure. Important distinguishing characteristics between the different energy carrier options pertain to: relative ease of storage; efficiency and cost of carrier generation; efficiency and cost of distribution; and, efficiency and cost of end-use.

The attraction of the hydrogen pathway is the inherently high conversion efficiencies of hydrogen generation and end-use. Hydrogen production efficiencies from fossil fuel sources are generally greater than electricity production efficiencies, and conversion efficiency back to electricity in fuel cell systems is comparable with batteries (up to 80%).

Although the hydrogen fuel cell system offers the hope of continuous, clean, low-noise, and highly efficient operation, the supporting technology still requires significant research and engineering before the entire pathway is commercially viable and efficient. Key areas still requiring development include: storage, transport and fuel cells. The enduring struggles to increase efficiency, durability and cost-effectiveness of these technologies has overshadowed the enthusiasm for adopting hydrogen as an energy carrier.

Hydrogen is already produced in large volumes in New Zealand - approximately 50,000 tonnes per year is used at the Marsden Point refinery for the processing of crude petroleum oil into standardised fuels and petrochemicals. This means that over 7 PJ per year of manufactured hydrogen is, in a sense, already contributing towards the energy demands of the transportation sector through the consumption of petrol and diesel fuels. If this hydrogen was used directly in fuel cell powered vehicles it could provide around 10% of the current land transport requirements.

In the above discussion, we have not considered the use of hydrogen as a fuel for nuclear fusion, since the technology required to support these reactions is considered to be too far away from commercialisation to be included in this report.

7.1.1.1 Pathways

Hydrogen pathways trace the energy processes involved in transferring the energy within a resource, via various intermediate processes, to the end-use application. Each pathway has its own set of energy conversion efficiencies, GHG emissions and economic costs and these can be compared for any particular end-use application. Generally, transport application pathways are called “well to wheel” pathways, and, stationary application pathways are called “source to use” pathways.

In the analysis of hydrogen pathways, nine have been generated that appear to be the most likely pathways of relevance for New Zealand energy resources and end-use applications. These nine pathways all feature proven hydrogen production routes, for which reasonable estimates of the associated process costs were available. Figure 7.1.2 and Figure 7.1.3 illustrate the typical energy transactions involved in these hydrogen pathways.

Hydrogen can be produced using a wide variety of mechanisms such as: electrolysis, steam methane reforming, coal gasification, thermo-chemical reforming, biological expression. The source of energy to create hydrogen provides an indication of the GHG emissions required to generate this energy carrier. The net GHG emissions associated with production from fossil fuels will be subject to the effectiveness of carbon capture and storage technologies (if applied).

Energy can be extracted from hydrogen either through combustion or through electrochemical conversion in a fuel cell, to produce motive power or electricity. The combustion pathway generally has low overall energy efficiency, which would not economically appropriate for this high cost energy carrier. Therefore, the predominant use of hydrogen would be as a feedstock to fuel cells.

Figure 7.1.2 – Hydrogen pathways (primary)

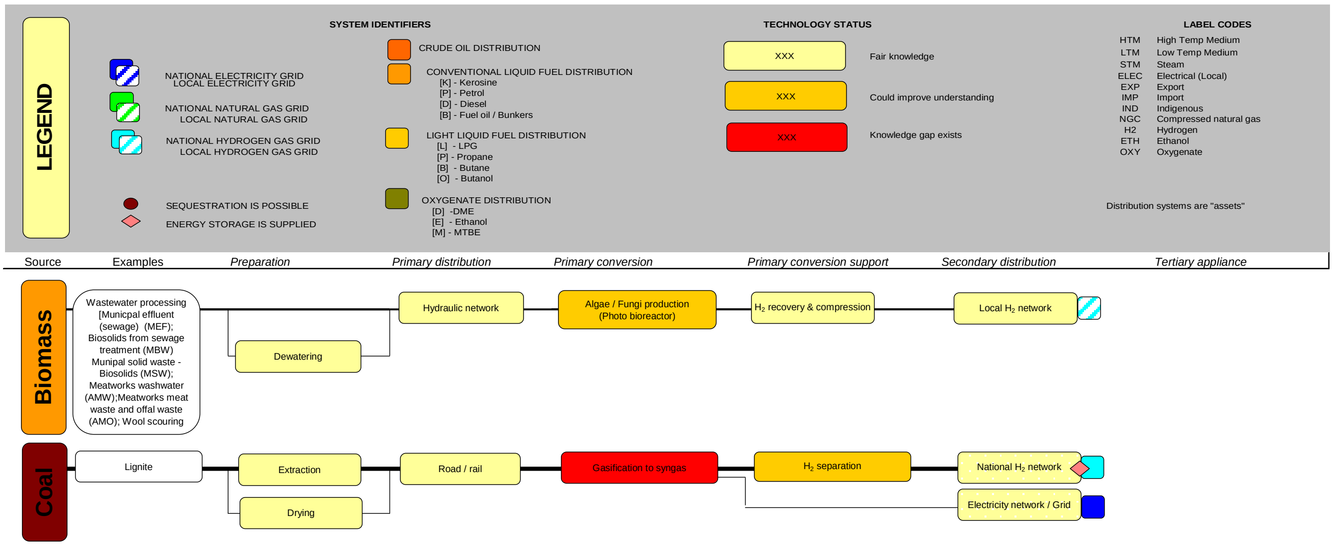
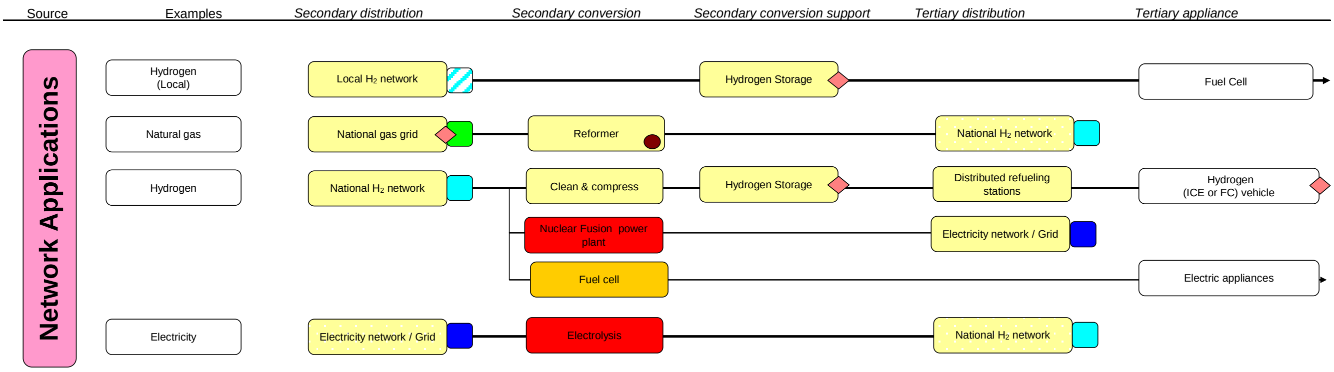


Figure 7.1.3 – Hydrogen pathways (secondary)



A full view of the pathway is presented in the Pathway Overview Map at the start of this document.

For stationary applications, hydrogen can be distributed to the end-users via a pressurised gas pipeline network. It should be noted that the required pipelines would have to be purpose-built in order to avoid hydrogen embrittlement issues, which affects the steel pipeline materials used for the distribution of natural gas. Alternatively, “tube trailers” can be used to truck compressed or liquefied hydrogen (at cryogenic temperatures) using the road network.

The transport sector could be supplied with hydrogen by a network of hydrogen-equipped filling stations that would receive their supplies by the pipeline network or by direct transfer of the cryogenic hydrogen supplied from tube trailers. On-site generation of hydrogen at these hydrogen filling stations, using other forms of easily transportable energy resources (e.g. natural gas or electricity), can be deployed during the infrastructure build-up phase. However, these on-site conversion processes may not be able to establish the same efficiencies of conversion and emissions mitigations as achieved in larger-scale, central processing facilities.

Further pathways for hydrogen are, of course, possible, but the remainder of those initially inspected were based upon hydrogen generation technologies that are still in their early stages of research and demonstration (e.g. photo-bio-organic reactors, algae production processes, and high-temperature electrolysis). These pathways have not been considered in this analysis because it is too early to make sensible predictions over their near-term commercial application.

7.1.1.2 Scale

Hydrogen production and distribution technologies are highly sensitive to scale. The typical minimum size of generation facilities are:

	Rated input (MW)	Output (ktH_2 / y)
Electrolysis	1.9	0.28
Forecourt SMR	36	4.19
Large SMR	265	36.5
Biomass	357	36.5
Coal cogen	452	39

Even the smallest units (i.e. electrolysis and forecourt SMR), require significant (i.e. industrial) scale.

Distribution is also very scale dependent. If large volumes of hydrogen are being distributed, then pipeline infrastructure becomes economic, but for small volumes, pressure vessels and cryogenic tanks are more cost effective.

7.1.1.3 Myth busting

Hydrogen is often talked about within public media as if it were an energy resource of the same standing as coal, oil, gas and renewable resources. There are no mineable sources of hydrogen in its molecular form, and all natural sources of the element require processing in order to produce free molecules. This processing always requires more energy than the energy content of the hydrogen gas produced. Hydrogen, like electricity, should always be referred to as an "energy carrier" and not an energy resource.

Hydrogen is considered to be a "clean" transport fuel because when used in a fuel cell to produce electricity, no harmful emissions are generated locally. If hydrogen was burnt in an internal combustion engine the intense heat of the hydrogen-oxygen combustion reaction forms nitrous-oxides (NO_x), but unlike conventional petrol and diesel fuels, it produces no smoke, unburnt hydrocarbons or sulphur-containing pollution. It is the primary energy source used to produce it that determines the overall 'cleanliness' of the energy carrier (just like electricity), and this aspect of the carrier's history must be included in all emissions analyses.

Hydrogen is the lightest element in nature, is highly flammable, and will burn at concentrations as low as 4% (volume basis) H_2 in air. There is a perception that hydrogen is a dangerous, explosive material. In practice, it is not any more or less dangerous than other forms of commonly used, flammable gases, such as natural gas, liquefied petroleum gas (LPG), propane, and butane. Being much less dense than air, it rapidly disperses from a spill area and can actually be easier to deal with than the denser fuel gases mentioned.

Despite hydrogen-powered and hydrogen-fuel-cell powered cars already being available for private ownership, the infrastructure required to support a major conversion to this form of transport technology (e.g. hydrogen production facilities, distribution networks, vehicle servicing stations) could take decades to implement unless there is a concerted public-private commitment to accelerating uptake.

7.1.2 Resource assessment

The most abundant source of hydrogen on earth is water, here it is chemically bound to oxygen. Elemental hydrogen is very rare in the atmosphere (1 ppm by volume) and relatively rare in the earth’s crust. Hydrogen is mainly produced at an industrial-scale from hydrocarbons resources such as natural gas. Interestingly, a significant portion of the hydrogen produced by these processes actually derive from the water that was introduced as steam part way through the process.

7.1.2.1 Resource uncertainty

Hydrogen can be produced from many primary energy resources and is, thus, relatively independent of any particular resource supply constraint. Through the diversification of resources, any hydrogen supply risks can be managed and its overall supply uncertainties reduced.

Hydrogen can be produced from water using electricity in the process of electrolysis, but due to the cost of electricity this is expensive to achieve at a commercial scale. Hydrogen can also be produced by some bacteria and algae and is frequently produced as a product of mammalian digestion, but this is difficult to capture.

Because of New Zealand’s substantial endowment of lignite coal reserves, the production of a “clean” fuel from this resource has gained much interest. While much of the energy in coal come from its carbon content, most of this can be captured by using it to strip hydrogen from steam during processing. In order to compare favourably with other fuels, the accompanying yield of carbon-dioxide and other waste products must be captured and stored. Whether or not, these resources will be developed will depend on how the production costs compared with the alternative uses of this resource e.g. electricity generation, coal gasification, or coal to liquids; and the cost of carbon emissions from the process.

7.1.3 Barriers and limitations

Reviewing the potential of a new energy carrier, particularly one with unconventional handling requirements, is difficult. The situation is made more complex by the inter-relationships that exist between hydrogen, its many possible sources, and competition from other, currently cheaper, energy carriers.

Barriers to the large-scale uptake of hydrogen as an energy carrier can be illustrated by uncertainties at each stage of a typical energy pathway:

- Supply-side: Which primary energy resource, and associated conversion processes, should be used and invested in?
- Distribution: How to distribute the hydrogen safely and economically in large enough quantities?
- Storage: How to store and retrieve sufficient hydrogen efficiently?
- Demand-side: End-use technologies are still under development and have greater complexity compared to conventional technologies.

On the supply-side, there are two methods for producing hydrogen that are well-proven at this time:

- Gasification or reformation of solid, liquid and gaseous hydrocarbons, such as, coal, wood and biomass, petroleum products, alcohols, natural gas, LPG etc.;
- Electrolysis of water using electricity.

A very large investment in production infrastructure is need to deliver the required quality of hydrogen or enough volume at the desired price to meet the possible commercial-scale hydrogen demand. It is unlikely that this investment will come from the private sector until it is clear that oil production is in terminal decline. Competition with conventional fuels and technologies will remain fierce whilst crude oil prices remain low.

The flexibility over how hydrogen can be generated does present an initial investment issue with regard to the future of the supply infrastructure. Hydrogen can be produced on a large-scale, centrally and distributed over an expansive pipeline network, or, it can be produced at moderate-scale, locally at numerous, distributed facilities. Early investors will want to ensure that the chosen distribution technology remains free from competition from the alternative scheme whilst a return on their investment is generated. As yet, there is no clear preference or barrier to either scheme being adopted.

There is limited agreement on standards and codes of practice for the regulation of hydrogen when used as an energy carrier. This can hamper and prevent the cooperative development of hydrogen generation technologies and end-user products. There is, however, still time to confront this issue and lead a globally unified development of hydrogen economies.

7.1.4 Introduction to conversion technologies – supply side

Extraction of hydrogen from biomass or coal is commonly performed using a gasification process. Large amounts of heat input are required to initiate the gasification process, which liberates carbon-monoxide (CO) as well as hydrogen (H_2) gases, and this is obtained from combustion of the primary resource itself for a relatively low cost. Commonly, the gasification process enters a "water gas shift" reaction phase in which catalysts are able to react steam with the CO to liberate more H_2 and a CO_2 by-product.

$$Coal / Biomass \xrightarrow{gaification} H_2O + CO \xleftrightarrow{Water\_shift} H_2 + CO_2$$

Hydrogen production from natural gas or low-grade crude oil is performed using steam reformation, and this is currently the lowest-cost and most proven method of high-volume hydrogen production. Conversion efficiencies range between 40 – 80%, depending on the scale, type of process used, and the primary resource type. Carbon capture and storage (CCS) is not currently implemented as standard with this process.

Electrolysis of water is commonly used for small scale production. It produces no by-product, other than a stream of pure oxygen, and is also well proven on a large-scale. Although efficiencies are in a similar range to the above (i.e. 40 – 80%, depending on the scale of operation), the process is not as cost-effective at large-scale due to the higher cost of energy source. If the electricity is supplied from a 100% renewable energy resource (e.g. wind, wave or solar), no CO_2 is associated with the production process and the hydrogen generated could be considered as truly "clean".

$$2H_2O \xrightarrow{Electrolysis} 2H_2 + O_2$$

The direct production of hydrogen using renewable electricity that is generated from intermittent resources, such as wind, wave or solar, is of increasing interest. However, the electrolysers used with this source of electricity must be capable of responding quickly to electricity supply changes and must be able to produce high-quality hydrogen (minimal oxygen, nitrogen, and water vapour content) over a range of input powers. Because electrolysers can operate very efficiently at the small-scale (< 1 kW), the on-site production of hydrogen at transport refuelling stations is seen as a likely first-step in the supply of hydrogen for fuel cell vehicles. Recent developments in high-pressure electrolysis (30 bar or more) mean that the first energy intensive stage of compression for storage is essentially eliminated.

7.1.4.1 Preferred hydrogen pathways for New Zealand

In the "Identification of Preferred Hydrogen Chains" report, CRL Energy Ltd undertook an assessment of New Zealand's preferred hydrogen energy pathways. Because the pathway analysis reviewed specific distribution systems, we considered this analysis to be assessing "chains" rather than just pathways. This first pass assessment adopted the European "HyWays" project methodology to identify 24 chains of interest to New Zealand (see Table 7.1.4). The exercise selected between hundreds of potential hydrogen chains by considering: sustainability, cost-effectiveness of feedstock, status of conversion technology and relevance to New Zealand. In order to compare the resulting parameters to those of conventional mechanisms of providing these services, reference chains were also analysed.

For transport application chains, both fuel cell powered vehicles (HFCV) and internal combustion engine vehicles (ICE) were considered. For the stationary applications, both fuel cell for combined heat and power generation (FC-CHP), and, fuel cells for distributed generation (FC-DG) were considered.

Table 7.1.4 – Preferred hydrogen chains

Chain	Feedstock	Conversion process	Distribution	End-use
1a - d	Natural gas	Central reformation	Pipeline	TRANSPORT: a) HFCV vehicle b) ICE vehicle STATIONARY: c) Small-scale FC-CHP d) FC-DG
2 a - d			Tanker	
3 a - d		Central reformation + CCS	Pipeline	
4 a - d			Tanker	
5 a - d	Coal	Central gasification	Pipeline	
6 a - d			Tanker	
7 a - d		Central gasification + CCS	Pipeline	
8 a - d			Tanker	
9 a - d	Biomass	Central gasification	Pipeline	
10 a - d			Tanker	
11 a - d		Central gasification + CCS	Pipeline	
12 a - d			Tanker	
13 a - d	Wind generated electricity	Central electrolysis	Pipeline	
14 a - d			Tanker	
15 a - d	Grid electricity mix		Pipeline	
16 a - d			Tanker	
17 a - b	Wind generated electricity	Refuelling site electrolysis	None	TRANSPORT: a) HFCV vehicle b) ICE vehicle
18 a - b	Grid electricity mix			
19 a - b	Natural gas	Refuelling site reformation	None	
20	Coal	Central IGCC + H_2 gas turbine + CCS	Direct-use	Electricity for grid
21	Biomass			
22 a - b	Natural gas (piped)	FC CHP with reformation	Direct-use	STATIONARY: a) Micro-scale FC-CHP b) FC-DG
23 a - b	LPG (by tanker)			
24 a - b	Ethanol (by tanker)			

Further analysis led to the selection of nine preferred hydrogen chains, again based on economic, emission and energy merits (see Table 7.1.5). These nine chains were selected for use in scenario modelling that explored how the use of hydrogen could benefit New Zealand.

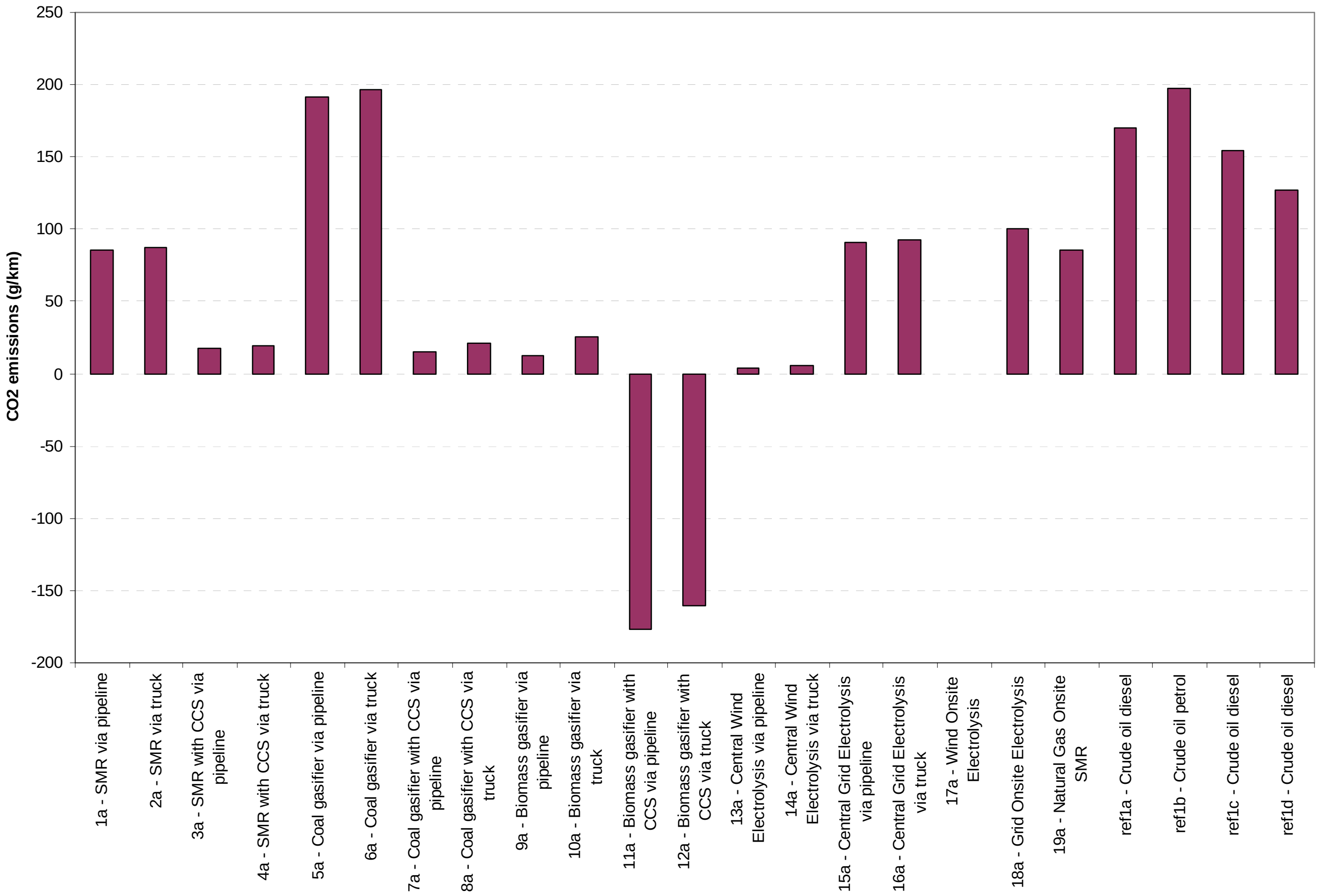
Table 7.1.5 – Nine selected transport and stationary application chains

Chain	Feedstock	Hydrogen production method	CCS	Distribution	End-use
2a	Natural gas	Central reformation	No	Tanker	Transport
3a			Yes	Pipeline	
7a	Coal	Central gasification	Yes	Pipeline	Transport
9c	Biomass	Central gasification	No	Pipeline	Stationary
10a				Tanker	Transport
13a	Wind electricity	Central electrolysis	-	Pipeline	Transport
16a	Grid electricity	Central electrolysis	-	Tanker	Transport
17a	Wind electricity	Refuelling site electrolysis	-	Direct-use	Transport
22c	Natural Gas	FC-CHP with reformation	No	Direct-use	Stationary

7.1.4.1.1. Transport applications

One of the outputs from the modelling process was CO_2 emissions for the whole hydrogen supply to end-user application pathway. Figure 7.1.6 shows the modelled emissions for each transport supply chain to an HFCV end-use application[1]. These chains are compared with four reference chains - diesel and petrol use in standard efficiency vehicles ("ref1a" and "ref1b") and diesel and petrol use in high-efficiency vehicles ("ref1c" and "ref1d").

Figure 7.1.6 - CO_2 emissions from transport chains: HFCVe end-use compared with conventional vehicle technology end-use for various fuel stocks



The CO_2 emissions are presented in units of equivalent grams of CO_2 per kilometer travelled. Some notable observations are:

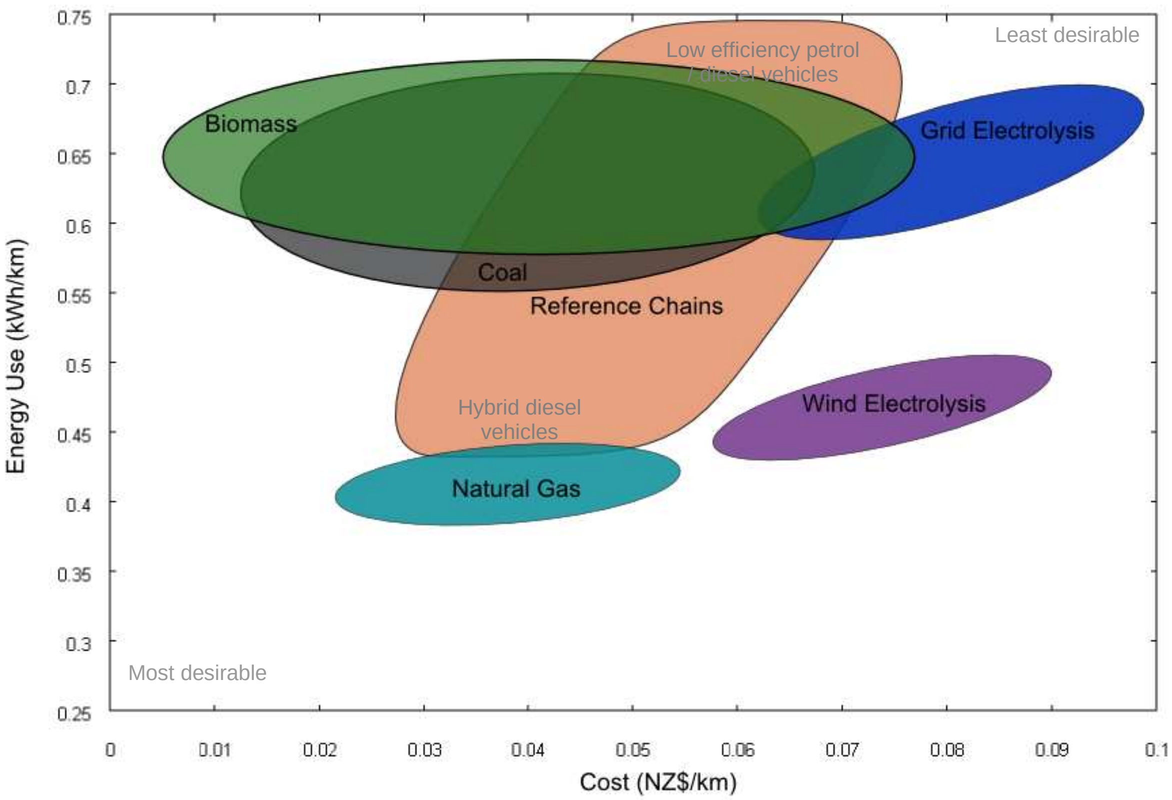
- Chains 5 and 6 (coal, no CCS) showed similar emission levels to the reference chains ref1b (conventional petrol vehicle).
- All other hydrogen chains (1 – 4, 7 – 19) showed reductions in emission levels, with natural gas reformation without CCS (1, 2 and 19) and grid electrolysis (15, 16 and 18) all reducing emissions to at least half that of the reference chain for existing vehicles (ref1a and ref1b).

[1] As discussed earlier, the use of hydrogen in ICE vehicles is a low value use of hydrogen and is not reviewed further.

- The central grid electricity electrolysis cases (15 and 16) were interesting in that the emission levels were not as low as expected, relative to the reference chains. This was mainly due to the degree of fossil fuel content of present grid electricity generation and the energy losses inherent in the production and transport of the hydrogen.
- On the other hand, if wind-generated electricity was used for central or refuelling site electrolysis (13, 14 and 17), the emissions were very low.
- As expected, the fossil-fuel sources with CCS and renewables (3, 4, 7, 8 and 9 – 14) all showed very low emission levels.
- The two chains with negative emissions both involve biomass coupled with CCS (11 and 12). This may appear to be an unlikely union of fuel resource with emissions-reduction technology at present, but a high carbon cost may make this pathway attractive in the future.

Further to the calculation of CO_2 emissions for these hydrogen chains, the per-kilometre-travelled values for the primary energy consumption and economic cost were also determined. These data were manipulated in order to allow them to be graphically represented on a two-dimensional chart. Essentially, the CO_2 emissions for each chain were converted into an economic cost figure by using the concept of a financial "carbon tax". This method for assessing emissions costs assigns a variable level of carbon taxation, of between 0 – 100 NZ$/tonne-$CO_2$ emitted, and adds this cost to the baseline fuel cost. The range of primary energy consumption values and fuel cost values associated with each hydrogen transport chain are then plotted and grouped by primary fuel resource, as displayed in Figure 7.1.7.

Figure 7.1.7 - Primary energy resource consumption and cost of various H_2 transport chains



The major conclusions drawn from the appearance of this chart are:

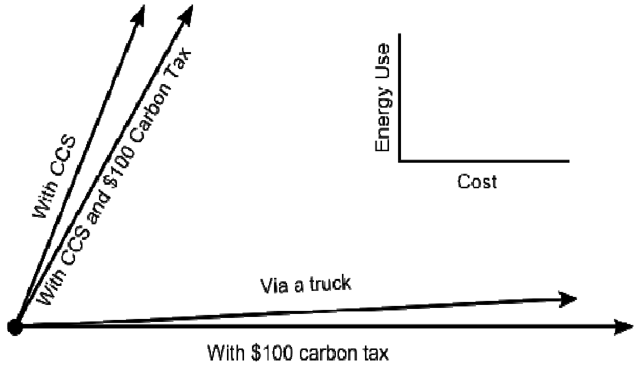
- The type of primary fuel resource has the most significant influence over the energy use associated with a chain. Details within the chain, including options relating to CCS, carbon taxation level, type of production plant and hydrogen transport options, were all of secondary significance.
- Coal and biomass based hydrogen pathways may become cost-competitive with conventional, fossil-fuel based, transport pathways in future, but they use more primary energy resource relative to natural gas reformation. This is mainly due to the energy use associated with gasifying the raw coal and biomass feedstock.
- The most expensive technology for generating hydrogen was electrolysis. The energy efficiency of hydrogen product was high when using wind to drive electrolysis, but was relatively low when using grid electricity to drive electrolysis.
- The reference chains region is extensive because it includes substantial energy efficiency improvements and cost reductions predicted for ICE and hybrid vehicle technologies. Data relating to conventional petrol-fuelled ICE vehicles appear at the top of the reference chain region, whilst hybrid-diesel vehicles appear towards the bottom.
- Natural gas based hydrogen pathways are highly competitive with the improved-efficiency versions of reference transport chains in terms of cost and efficient use of primary energy resource.
- All chains, except those involving electrolysis, were cost-competitive with the existing vehicle technologies within the reference chains. The electrolysis chains were competitive on an energy efficiency basis, but not on cost.

It must be noted that Figure 7.1.7 only includes the data for transport chains in which the end-use is in HFCV. If hydrogen-fuelled ICE vehicles were shown, the relative positions of the primary fuel resource regions would each be shifted up and to the right by a factor of, approximately, 1.8. This is due to the reduced drive-train efficiencies associated with the mechanical nature of this type of engine technology (HFCV have fewer moving mechanical parts). Hydrogen fuelled ICE vehicles may play a role in the transition from conventional fuels and vehicles over to hydrogen fuel cell vehicles, although the lower efficiency of these ICE vehicles makes the use of hydrogen costly.

The far right-hand-side of the natural gas and the two electrolysis group regions demarks the production of hydrogen at the site of the refuelling station plus maximum carbon taxation. Smaller-scale production is less efficient and uses more primary energy, and, more significantly, it is more expensive in terms of capital investment and fuel costs. However, overall, the horizontal spread is dominated by the range of carbon taxation from 0 – 100 NZ$/tonne.

The influence of the secondary effects (H_2 generation technology, transportation option, CCS etc.) on the energy consumption and costs for a particular primary fuel resource's set of chains is shown schematically in Figure 7.1.8.

Figure 7.1.8 – Influence of secondary effects on the cost and energy consumption of a hydrogen transport chain for a given primary fuel resource



For the case of coal as a primary fuel feedstock, the starting point (lower left corner) represents coal gasification with; no CCS, a carbon tax set to zero and, a pipeline to move the hydrogen 100 kilometer to the demand centre at Auckland. The arrows radiating from that point show the individual effects of: changing the delivery option from pipeline to truck; addition of a 100 NZ$/tonne carbon tax, and; the inclusion of CCS.

Clearly, transport by pipeline is cheaper and consumes less primary energy than the truck delivery option, but either option could be deployed if demand for hydrogen became high enough. Obviously, adding a carbon tax increases costs with no effect on the amount of primary energy consumed. Utilising CCS increases fuel consumption and the associated fuel costs per kilometre of end-user travel. However, when a high level of carbon taxation is enforced, the increase in fuel costs can be compensated by the reduction in costs associated with reduced carbon emissions.

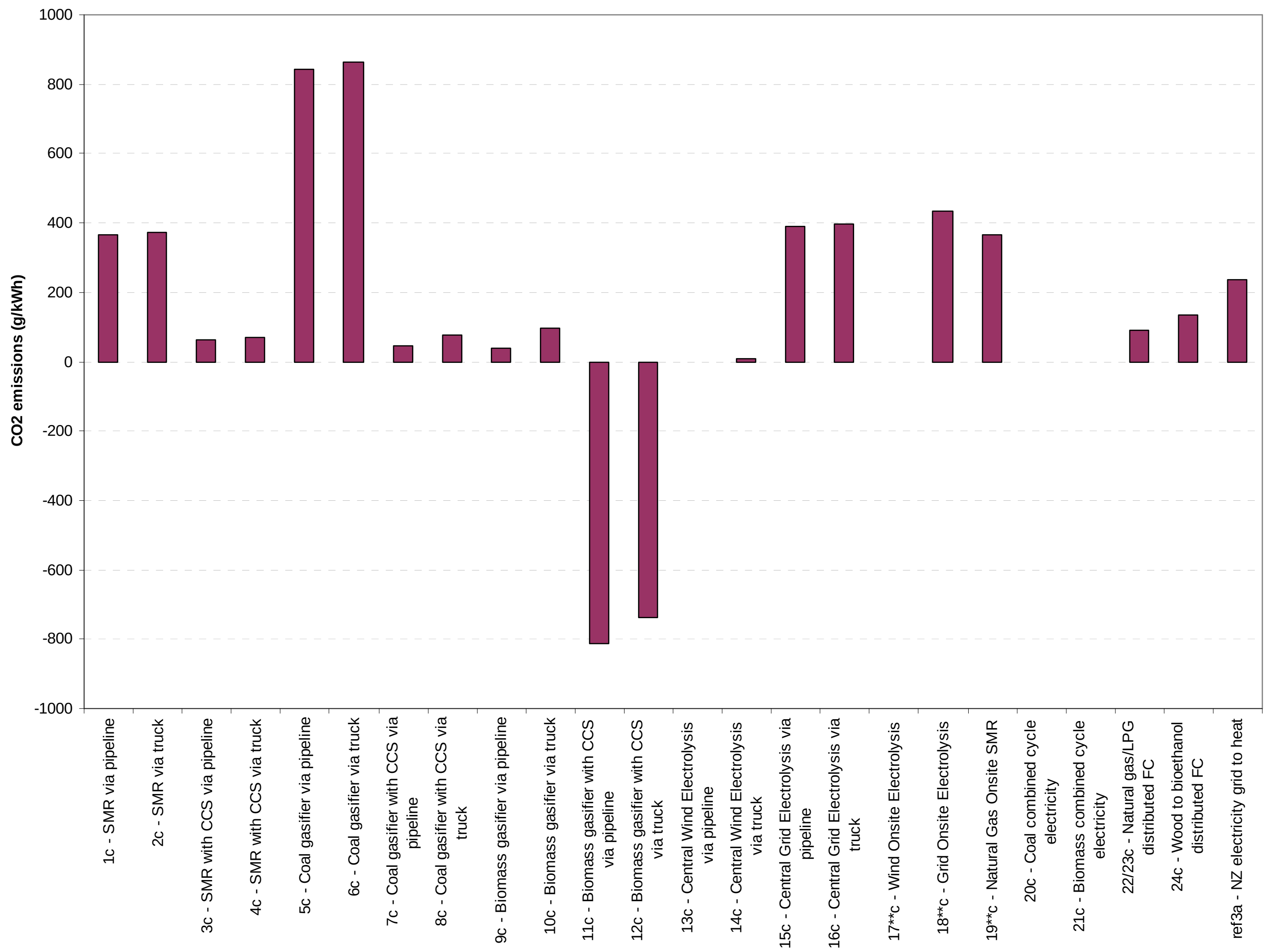
7.1.4.1.2. Stationary applications

For consistency, most of the central hydrogen production routes analysed for the transportation application were also considered for stationary application pathways. The use of hydrogen within stationary fuel cells is unlikely to have a major impact on global CO_2 emissions, but it is seen as a possible transition pathway to a fully-established, national hydrogen infrastructure by facilitating the early adoption of fuel cells.

In New Zealand, the emissions of CO_2 from stationary applications using hydrogen fuel pathways must be compared against an already low-emission, national electricity generation system. Only a minor proportion of the national electricity is generated by fossil-fuel burning thermal power plant, in the region of 30%; the majority is provided by renewable energy power plant. Thus, the conventional, reference chain used for comparison in this case ("ref3a") is based on the use of the national grid mix of electricity in an efficient, stationary end-use application. This provides a stationary application emissions reference level of 237 grams of CO_2 per kWh.

Figure 7.1.9 shows the modelled CO_2 emissions for the stationary chains that were listed in Table 7.1.4.

Figure 7.1.9 - CO_2 emissions from stationary chains: FC-DG and FC-CHP end-uses compared with conventional electricity end-uses for various fuel stocks



Observations made from this figure are:

- Chains 5 and 6 (coal, no CCS, DG-FC) showed emission levels significantly higher than the ref3a reference chain.
- At the centralised hydrogen production level (1 – 16), only fossil fuels with CCS (3, 4, 7, 8) showed improvement over the reference chain. Biomass chains (9 – 12) and wind-generated electricity (13, 14) were also an improvement upon the reference chain, with biomass with CCS chains (11, 12) showing substantial negative CO_2 emissions.
- The natural gas reformation without CCS chains (1, 2) showed higher emissions than the reference case, but to a lesser extent than the coal gasification without CCS (5, 6).
- Grid electricity electrolysis chains (15, 16 and 18) had higher emissions than the reference case due to the energy losses associated with the electrolysis and end-use fuel cell process. This strongly suggests that central electrolysis for stationary applications would only be useful if there was an urgent need to store grid electrical energy via hydrogen.
- The wind electrolysis chain (17) showed negligible carbon footprint and was representative of any renewable electricity source, in that it can be used to store electricity with a virtually zero carbon footprint.
- The micro-scale FC-CHP and DG-CHP systems make very efficient end-use appliances for use with conventional fossil fuels such as natural gas, LPG and ethanol (22 – 24). Even without CCS they demonstrate substantial reductions in CO_2 emissions (better than ~50%) over the reference chain.

The Government energy strategy goal of 90% renewable generation, if it is achieved, will progressively reduce the fossil fuel proportion of the grid electricity mix and, therefore, the emissions attributed to each kWh generated. Due to electricity demand growth, however, this may not actually reduce the total amount of CO_2 emissions. Should it become an imperative, the more costly generation of electricity via distributed fuel cells from clean hydrogen (and using CCS if necessary) could have a long-term role in addressing GHG emissions.

As in the case of the transportation pathway analyses, the range of costs and primary fuel resource consumption rates associated with the stationary application pathways have been generated in Figure 7.1.10. This figure is analogous to Figure 7.1.7, but with primary energy use and cost shown per kWh of combined heat and electricity used, instead of per kilometer travelled. Comparing these two figures, it can be seen that the regions for coal, biomass, natural gas and electrolysis remain similar, relative positions to each other.

Figure 7.1.10: Primary energy resource consumption and cost of various H_2 stationary CHP chains

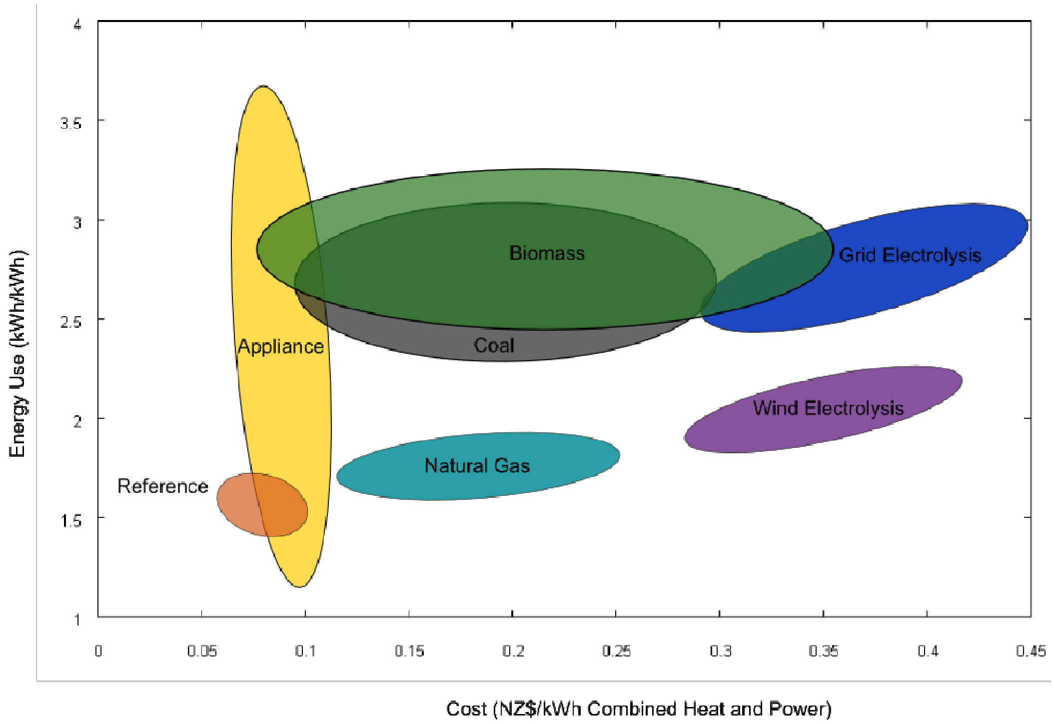


Figure 7.1.10 indicates that:

- The provision of distributed heat and electricity from hydrogen that is transported from centralised, hydrocarbon-based production processes and from grid electricity mix-based electrolysis was higher in cost and primary energy consumption than the reference chain. Along with the increased GHG emissions associated with these chains, this makes the use of centrally produced hydrogen unrealistic as a stationary power option at this stage.
- Coal and biomass chains (20 and 21) are special cases which involve centralised electricity production using a hydrogen gas turbine with CCS. As a result, these technologies are not competitive, at currently estimated costs, with the grid electricity mix reference case (ref3a).
- An exception to this general conclusion was observed for some "Appliance" based chains. These chains are based on distributed FC-CHP appliances that receive their primary fuel resource from local supply networks, such as natural gas pipelines and LPG bottled gas delivery networks. Their GHG emissions were also low. This assumed that the combination of high-efficiency heat and power offered by chains 22a / 23a were fully realised and consumed by the end-user.
- The upper extreme of the Appliance area represents the costs and high primary fuel consumption rate associated with the ethanol-based FC-CHP pathway of chain 24a. The high primary fuel consumption rate was primarily due to the inefficiencies associated with the "E3" ethanol refinement and production from wood residues processes. This E3 process was assumed to have an ethanol production efficiency of 30% and that the process energy used was primarily fossil-fuel based. This level of efficiency is a significant issue for hydrogen fuel cell applications, and even more so for applications involving conventional ICE vehicles. This suggests that the overall GHG emissions associated with either end-use technology will be high, unless more efficient and greener methods of ethanol production are developed.

Although the Appliance-related CHP options did not feature a significant degree of hydrogen infrastructure (the hydrogen being generated from the input energy resource and immediately consumed within the confines of the appliance), they may pave the way for later, direct use of hydrogen as a piped fuel to homes and businesses. It would be relatively simple to bypass the onboard fuel reforming component of these CHP appliances in order to supply the fuel cell component with hydrogen piped directly from a central production facility. This may occur in the longer-term if hydrogen becomes a dominant pipeline fuel.

7.1.4.1.3. Comparison of transport and stationary application results

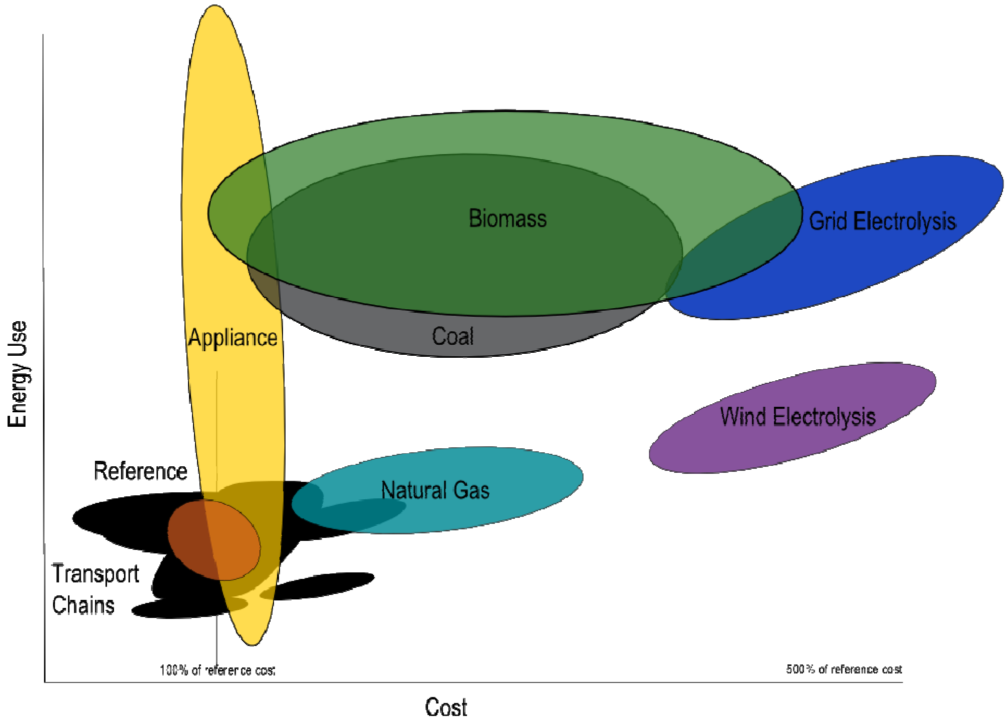
For both the transportation and stationary applications, the primary fuel resource type was of major importance in determining the overall costs and energy consumption rates for the various hydrogen pathways considered. The impacts of secondary variables, such as CCS, carbon taxation level and hydrogen transportation method, are less important.

A possible future advantage of using hydrogen produced from biomass combined with CCS is that, if carbon costs increase to a sufficiently high level, the cost of the energy delivered to the end-user may be reduced to levels comparable with the reference chain. This suggests that the capture of CO_2 generated from small-scale, biomass-based appliances, and subsequent transportation of this CO_2 to storage sites used by large-scale fossil fuel plants, may be worth researching.

The main message from the assessment of stationary applications is that natural gas consumption, along with its associated GHG emissions, could be reduced by using it directly in distributed CHP and FC-CHP appliances instead of using it for the central generation and distribution of electricity alone to the end-user (a proportion of the fuel's heat component being wasted at the central generating site). The direct use of the natural gas at the end-user's distributed generation CHP appliance is also preferable to its centralised conversion to hydrogen and subsequent transport to the end-user for CHP applications, again, due to the loss of a proportion of the fuel's heat back at the central plant.

Figure 7.1.11 compares the relative costs and primary energy resource consumption rates of the transport and stationary application chains – the transport applications appearing as the solid black areas. At this scale, several of the transport pathway areas appear to lie quite close to their reference pathways, whereas, the stationary application pathways (with the exception of the "Appliance" pathways), were considerably removed from their reference pathway.

Figure 7.1.11 – Relative cost and primary energy consumption rate for both the transport and the stationary application chains



7.1.4.2 Emerging trends

Fuel cells have now reached a level of development where their technical performance is acceptable when compared with conventional vehicles: in 2007, Toyota test drove their 90 kW HFCV for 560 kilometer without refuelling [Toyota (2007)]. Field trials of residential micro-CHP fuel cell systems, each with fuel cells rated at an electrical output of 1 kW, were reported as “successful" by at least 3 manufacturers in Japan [Panasonic (2008), Adamson (2008)]. These stationary applications were fuelled by natural gas or LPG.

In both transport and stationary applications, Japanese and other manufacturers are now planning initial market entry sales in 2010 – 2012 [Butler (2008), JapanCorp (2008)]. End-use technology costs are still very high and intensive research is continuing with the aim to reduce these. Mercedes expects that its B-Class FC vehicle could be ready for series production between 2012 and 2015 [DW-World (2008)]. However, the growth of the transport market will be naturally restricted by the availability of hydrogen filling stations. This restriction does not apply to micro-CHP applications, and, if they prove to be commercially cost-effective and reliable, can be expected to have rapid consumer uptake.

7.1.5 Introduction to conversion technology – demand side

Hydrogen has been considered for use in three particular end-user applications: transport, electricity generation, and high-temperature heating. The end-use conversion technologies associated with these applications can be categorised into:

- Fuel cell energy conversion devices
- Reciprocating engines
- Gas turbines
- Combined heat and power systems

Critical issues facing these end-use conversion technologies are:

- The high cost of efficient fuel cell devices
- The need for reliability and durability improvements in the materials and coatings used in high-temperature operating environments
- The design improvements required to increase system power output while maintaining high system efficiency.

7.1.5.1 Fuel cell energy conversion devices

The hydrogen fuel cell is an electrochemical device that produces electricity and heat from the combination of hydrogen fuel and oxygen (usually from the air) in a controlled reaction. Unlike combustion processes, the fuel and oxidant are not allowed to mix together with each other at any stage of the electrochemical reaction within the fuel cell. The fuel and oxidant remain separated by an electrolyte material within each cell of the fuel cell device. This allows only the migration of electrically charged components, from either the fuel or oxidant, to migrate across the cell. The internal migration of charged components across the electrolyte is accompanied by a flow of electrical current in an electrical circuit external to the cell, which is used for end-user power applications. There are several types of fuel cell technology available and these are classified by whether they operate at low-temperature (< 80°C), high-temperature (> 120°C) and on the type of electrolyte media used to divide the two halves of the electrochemical cell. The main types being developed at present are:

- Low-temperature, Proton Exchange Membrane Fuel Cells (PEMFC)
- Low-temperature, Direct Methanol Fuel Cells (DMFC)
- Low-temperature, Alkaline Fuel Cells (AFC)
- High-temperature, Solid Oxide Fuel Cells (SOFC)
- High-temperature, Molten Carbonate Fuel Cells (MCFC)

All have been demonstrated to function in the two main application areas: vehicle power, and; stationary distributed generation. Currently, the DMFC is seen as the best option for portable appliances; the PEMFC for transport, and; PEMFC and SOFC for micro-scale distributed power generation. The MCFC is best suited for industrial-scale distributed generation. No large-scale generation (> 1 MW) candidate has yet emerged at the commercial stage of development.

Hydrogen fuel cells offer a theoretical electrical efficiency of 83% at room temperature. At low power an efficiency of around 60% is easily achieved. A focus on high energy-density (more power from the same device) for automotive devices has reduced this to around 35 - 40% in the current generation of hydrogen fuel cell vehicles (HFCVs). This is up to twice the efficiency achieved with many conventional, petrol-engine vehicles, but comparable with existing petrol-electric-hybrid vehicle and diesel-engine vehicle technologies. The high end-use fuel efficiency of the fuel cell should compensate for the efficiency losses involved in production, storage and transport of its hydrogen fuel. Further development means that the well-to-wheel efficiency of fuel cell vehicles has the potential to be higher than many conventional internal combustion engine (ICE) vehicles.

Automotive fuel cells operating on hydrogen fuel face future competition from other novel technologies, such as bioethanol and biodiesel fuelled ICEs and, potentially, from battery-electric vehicles (BEVs). BEVs face the problem of having limited energy storage capacity and range, and, require lengthy battery recharging periods at their “refuelling” stations (although overnight recharging at the end-user’s home is an attractive refuelling option). Hybrid vehicles use conventional fuels as well as electrical energy storage / drive systems to overcome the objections associated with BEVs whilst maintaining compatibility with existing refuelling infrastructures. Whilst diesel fuel availability remains stable, efficient diesel ICE vehicles (with or without electrical hybridisation) will continue to outcompete HFCVs on a cost and fuel efficiency basis.

At present, the cost of fuel cell technology makes it uncompetitive with conventional and hybrid engine technologies (an equivalent power output fuel cell engine can be up to 100 times more expensive than its conventional counterpart). This cost issue is compounded by the lack of hydrogen refuelling infrastructure being available to support an early adoption of HFCVs. For these reasons, hybrid and battery-electric vehicles are the most likely forms of advanced vehicle technology to begin displacing conventionally-fuelled vehicles in the near term. Long-term transport technology solutions will be determined by the availability of conventional transport fuels and the environmental trade-offs of the succeeding technology options.

7.1.5.2 Reciprocating engines

Hydrogen can also be combusted with air in conventional, reciprocating, engine technologies for automotive or stationary power generation applications. These conventional technologies include the familiar “internal combustion” engine (ICE or “Otto-cycle” engine), and the “external combustion” engine (also known as the “Stirling-cycle” engine or just the “Stirling” engine).

ICEs operating on hydrogen, for automotive or stationary power generating applications, are, generally, slightly lower-powered than their petrol or diesel counterparts due to the lower volumetric density of the hydrogen fuel (although it is noted that BMW already operate a small number of hydrogen-fuelled ICE vehicles as a way of demonstrating the transitional use of hydrogen fuel within the automotive sector). When used in the Stirling or gas turbine engine, hydrogen fuel efficiency is similar to that of other fuels. However, since hydrogen is chemically purer and more expensive than conventional fuels, it is not currently cost-effective to use it with these engine technologies.

It should be noted that, under the high-pressure and high-temperature combustion conditions occurring within an ICE, air will naturally form nitrous-oxides (NO_x) as a by-product of the combustion process. The formation of NO_x increases with increasing pressures and reaction temperatures and is a recognised pollutant in automotive exhaust gases. In order to be used as a truly “clean” fuel technology, ICEs operating on hydrogen must use combustion-control technology or catalytic exhaust gas technology to mitigate the generation or emission of these NO_x gases.

7.1.5.3 Gas turbines

Large-scale gas turbine engines, used for stationary power generation in the range of 1 to 100 MW, can be fuelled directly on hydrogen gas or on “syngas”, which is a hydrogen-rich fuel gas derived from the gasification of coal. Conversion of existing turbine technologies for extended operation on hydrogen gas requires the development of turbine blade materials and coatings that are better able to withstand the increased operating temperatures, and system designs that increase efficiency when using a hydrogen based fuel.

7.1.5.4 Combined heat and power systems

Combined heat and power (CHP) systems provide heating and electricity supply services to the end-user and are located at, or close to, the end-user’s work site or application. Heat is generated as a by-product of the electrical power generation process, but, instead of being wasted through exhaust emissions directly to the atmosphere, it is utilised in a useful end-user application, such as space-heating or process heating (e.g. drying and heat-treatment of materials). The fuel efficiency of these combined end-user services can be in the order of 70 – 90%.

The majority of commercial CHP systems have been developed to operate on natural gas, land-fill gas, diesel oil and heating oil. Although these commercial systems could be adapted for operation on hydrogen gas, there is little commercial incentive for this whilst the fuel cost remains uncompetitive. Hydrogen is preferably used in high-temperature fuel cell based CHP systems, which are still undergoing research and development at this time. These CHP systems have the potential to convert a higher proportion of the fuel’s energy into electricity than is possible with conventional CHP systems.

Another unique feature of the fuel cell based CHP technology, particularly for residential distributed generation, is its potential lack of noise and vibration. Further, if a CHP system is based upon SOFC or MCFC technology, it can operate on natural gas as well as hydrogen. This is due to the high-temperature nature of these fuel cells’ operation, which allows the natural gas to be reformed into hydrogen and CO_2 within the fuel cell devices. This “dual fuel” capability may be attractive should a future transition from natural gas supply to hydrogen gas supply ever be envisaged for the commercial and domestic sectors.

If heat-only services are required from hydrogen fuel, a catalytic combustion processes can be employed to burn hydrogen in air over a platinum catalyst (this occurs at temperatures below those likely to result in nitrous-oxide formation). The heat generated by these catalytic processes is available for further end-user applications if it is extracted from both the exhaust gases and the catalyst support structure. Considering the cost of both the fuel and the catalyst employed within this scheme, it is unlikely that it would ever be adopted as a heating method on its own. As the catalytic combustion technique is sometimes used as a way of mitigating hazards associated with hydrogen gas leakages outside of a fuel cell system, the use of the combustor for a heat-only sub-service may be possible.

7.1.5.5 Storage

Hydrogen storage is a major issue for a future ‘hydrogen economy’, as practical storage options require significant inputs of energy in order to be realised. The issue lies with the relatively low energy-density associated with hydrogen, in gaseous or liquefied forms, when compared to conventional or alternative fuel options. The scale of energy densities for hydrogen in various forms is indicated in Table 7.1.12, below:

Table 7.1.12 - Energy density properties of hydrogen

*: Nominal Calorific or Lower Heating Values (NCV or LHV)

Fuel	Physical storage state	Volumetric energy density* (MJ/litre)	Gravimetric energy density* (MJ/kg)
Hydrogen	Gas - stored at room temperature and pressure	~ 0.010	120
Hydrogen	Gas - stored at a common automotive storage system pressure of 700 barg	~ 7	120
Hydrogen	Liquefied – cryogenic state	10.1	120
Petrol	Liquid	32.4	44.4
Ethanol	Liquid	26.8	21.3

The major technical issue hindering the uptake of hydrogen as a transport fuel is the storage of sufficient hydrogen energy in a vehicle in order to achieve an acceptable vehicle range, suggested to be at least 500 kilometer. Good progress in storing hydrogen at working pressures of 700 bar has been made using pressure vessels constructed using light-weight, non-metallic structures [SFOE (2006)]. Achieving these high storage pressures requires more external energy to be exerted during the compression stage, resulting in up to a 15% loss of the initial quantity of energy [Bossel (2006)]. Also, hydrogen gas molecules are physically very small when compared to the scale of other common fuel molecules, and they tend to be able to diffuse through the materials used to line the walls of conventional fuel storage tanks. The mass and the volume of the tanks needed to hold the desired amount of compressed hydrogen in a passenger vehicle can end up reducing its practical utility and its fuel economy.

Liquefied hydrogen storage may be used to gain a higher level of volumetric fuel energy density. However, the hydrogen needs to be stored at cryogenic temperatures below -250°C. Liquefied hydrogen storage cuts down on the weight of the storage tank because the liquid does not require pressurisation. However, the cryogenic liquefaction process, again, consumes a large fraction (nominally 40%) of the initial energy content of the fuel [Bossel (2006)]. There is also a daily loss of 3 – 4% of the stored fuel associated with cryogenic storage, and this is due to the natural boil-off rate of the hydrogen.

Another storage technology undergoing intensive research is solid-state chemical storage. Here, hydrogen is stored as a chemical hydride or hydrogen-containing compound within a chemically reactive host material. Hydrogen gas is reacted with the host material within a sealed vessel that can be transported relatively easily. At the point of use, the host material can be made to decompose and yield the hydrogen gas. Current barriers to the practical use of this technology relate to the high pressure and temperature conditions required for the hydride formation and hydrogen release.

An alternative solid-state storage technique is simply to adsorb molecular hydrogen onto the surfaces of a storage material structure. Unlike the hydride storage technology, the hydrogen does not chemically react or dissociate during the storage cycle and, hence, does not suffer from thermo-kinetic reaction rate limitations. Hydrogen storage densities similar to liquefied hydrogen can be achieved with appropriate absorption media. Some suggested absorbers include Metal-Organo-Frameworks (MOFs), nano-structured carbon (including Carbon Nano-Tubes - CNTs) and clathrate-hydrates. However, thermal and pressure related hydrogen transfer issues still persist within this technology too, and these place a practical limit on the overall hydrogen charge and discharge rates.

The most common method of on-board hydrogen storage in today's demonstration vehicles is compressed gas storage at pressures of roughly 700 bar (70 MPa). This has become an acceptable solution to the energy storage issue, with Honda, Toyota and GM each demonstrating that their fuel cell vehicles can achieve the target range (500 kilometer) with performances similar to conventional ICE vehicles.

7.1.6 Asset characterisation

The hydrogen supply assets were characterised using the data provided in “Regional Scenarios for the Development of a Hydrogen Economy in New Zealand” (Leaver et. al, 2008), supplemented with relevant estimates of asset life and risk profile – see Table 7.1.13.

Table 7.1.13 – Hydrogen supply asset characteristics

	Rated input (MW)	Electricity consumption (MJ/kg H_2)	Conversion efficiency (%)	Operating efficiency (%)	Manufacturing costs (NZD/kgH_2)	Life (years)	Risk profile
Electrolysis	1.9	151.20	79.2	70	3.28	10	0,0,2,4
Forecourt SMR	36	11.05	63.1	70	3.29	20	4,1,2,3
Large SMR	265	40.32	58.1	90	1.46	25	1,1,2,2
Biomass	357	60.16	45.7	85	3.08	25	0,2,1,1
Coal cogen	452	-87.19	45.4	90	5.19	25	3,3,3,2

Hydrogen compression and distribution systems were characterised assuming the use of compression for distribution with 75% efficiency.

End-use vehicle efficiency is discussed in “EnergyScape Basis Review – Section 1”.

7.1.7 Research status

Much of the key hydrogen research is being undertaken internationally. In order to be a fast adopter, New Zealand must actively follow / retain relationships with international research else there can be considerable delay in technology transfer. Supporting research into hydrogen manufacture from lignite / biomass via gasification and thermo-chemical technologies may have economic benefit to New Zealand. A more complete review of research needs and opportunities can be found in "Hydrogen Research Strategy for Facilitating the Uptake of Hydrogen as an Energy Carrier in New Zealand" [Clemens et al. (2009)].

Table 7.1.14 – Research status

(Green highlight indicates 'Fair knowledge', Amber indicates 'Could improve', Red indicates 'Knowledge gap exists')

	International	New Zealand	Comment
Systems / pathway studies	Evolving	Evolving Unitec, NIWA	Comparison of HFCVs, BEVs and PHEVs is required. Further analysis of market barriers.
Common costing and Life-Cycle Analysis databases	Advancing	Immature CRL Energy, NIWA, CAENZ	Access to common understanding of asset characteristics and costs aids, improves planning and allows accurate comparison of options.
Gasification of coal / biomass	Advancing	Immature CRL Energy, Solid Energy	Scale-up and commercialisation of this technology is still required, especially with lignite.
Syngas separation and clean-up	Advancing	Advancing CRL Energy	There is still potential for significant advances in water gas shit catalysts; hydrogen separation and syngas cleaning.
Carbon capture and storage (CCS)	-	-	See Section 6.
Pipeline transmission and distribution	Mature	Advancing	Investigate use of specific existing NZ infrastructure investment for NG-H2 mixing or eventual 100% hydrogen. Route preparation and RMA implications to be evaluated.
Tanker distribution of liquid hydrogen.	Mature	Immature	Well established overseas, but no NZ standards.
Vehicle storage	Advancing	Immature	Large international research effort into chemical and physical storage in solid materials. NZ is an observer.
Refuelling	Advancing	Immature	Pilot testing of alternative technologies is required. NZ is an observer.
HFCV technology	Advancing	Immature	Still much scope for FC reliability and efficiency improvements, as well as cost reduction.
FC CHP	Immature	Immature	CHP with gas is only now being commercialised effectively. Still much scope for FC reliability and efficiency improvements, as well as cost reduction. There is a need to increase domestic heat utilisation

	International	New Zealand	Comment
Education and training	Immature	Immature	Efforts to inform / debate policy makers and general public the benefits / challenges of hydrogen is required.
Future generation technology e.g. Solid oxide co-generation; biological; Thermo-chemical	Immature	None	These technologies have the potential to make huge advances
Policy planning	Advancing	Immature Various	Research input to planning is currently very limited by world standards.

7.1.8 Summary

The analysis of New Zealand's hydrogen energy carrier options indicates that New Zealand is as well placed as any other country to benefit from the introduction of hydrogen into the national energy system. The development of a hydrogen energy infrastructure would enhance the security of transport fuel supply, whilst providing GHG reduction benefits. If the oil price was sustained above 200 US$/barrel, then the cost to the economy of not adopting hydrogen as a transport fuel could be substantial – see the report "Transitioning to a Hydrogen Economy - Hydrogen Energy Options: Scenarios, Sensitivities and Pathways" [Clemens et al (2008)].

Analyses of the various hydrogen energy pathways for transport applications indicated that reductions in GHG emissions, over present-day vehicle pathways (including foreseeable improvements in diesel and diesel hybrid vehicle technologies), could be achieved. All chains chosen for scenario analyses showed greater than 50% reductions in GHG emissions. The source of primary energy for hydrogen production was the most important factor that defined resource usage efficiency and energy cost. Hydrogen production from natural gas offered the cheapest and most energy efficient hydrogen production, with modest attendant GHG emissions.

Facilitating the early adoption of hydrogen use within stationary fuel cells is unlikely to have a major impact on global GHG emissions, but it is seen as an important first-step towards developing a national hydrogen economy. Few of the large-scale hydrogen production pathways had advantages over the reference energy carrier pathway (i.e. grid electricity). The most promising stationary end-use pathways, were those involving distributed, small-scale "appliance level" fuel cell CHP systems operating on natural gas or LPG.

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Glossary

GLOSSARY OF COMMON TERMS

~	Approximately
Afforestation	To convert land into a forest by planting trees or their seeds.
ADCP	Acoustic Doppler Current Profiler – a measuring device that can be used for determining marine current flow speeds.
Assets	A physical item (or group of items) of infrastructure the either extract, convert or distribute energy e.g. wind farm, coal mine, electricity network.
AU	Ammonia Urea
Bar.g	Barometric gauge pressure – the pressure of a gas registered by a measurement gauge device, relative to the ambient pressure.
Bounded map	Land areas where activity is consider to be of low likelihood due to existing planning logistics e.g. Road in a National Park.
Bbl	"Esso" blue barrel – 42 US gallons, the international volumetric unit of oil.
Bpd	Barrels per day
BRANZ	Building Research Association of New Zealand - an independent consulting and information company providing resources for the building industry.
BTL	Biomass to liquids
CAPEX	Capital expenditure
CSS	Carbon Storage and Sequestration – The process of capturing greenhouse gas emissions can storing them for several hundreds of years
CCS	Carbon Capture and Storage (or Sequestration)
CCT	Carbon Capture and Trade
CGH_2	Compressed Gaseous Hydrogen
CHP	Combined Heat and Power. Electricity (power) production alone generates a lot of waste heat and is therefore doesn't recover maximum value from fuel. Heat generation achieves a fuel to energy output ratio, but doesn't produce high value electricity. A CHP operation combines the advantages of both.
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_{2EQV}	A common measure for greenhouse gas warming potential. This unit aggregates the emissions from CO2, CH4, SF6, N2Ox, HCF and PCF to Carbon Dioxide Equivalent.
CPI	Consumer Price Index
CTL	Coal to liquids
DME	Di-methyl Ether
DoC	Department of Conservation
DSM	Demand Side Management
E^3	A database used to assess Energy use, Economics and Emissions for processes
EDF	Energy Data File – Annual summary of New Zealand's energy demand. Maintained by MED.
EECA	Energy Efficiency and Conservation Authority
EERA	Energy Efficiency Resource Assessment
EEUD	Energy End-Use Database – Maintained by EECA
EEZ	Exclusive Economic Zone
EPRI	Electric Power Research Institute
EROEI	Energy Return on Energy Invested
EROFEI	Energy Return on Fossil Energy Invested
EtOH	Ethanol

F-T	Fischer-Tropsch process. A technology developed in Germany (1920s) which uses catalytic reactions to synthesise complex hydrocarbons from synthesis gas (carbon monoxide and hydrogen).
FC	Fuel Cell
FCV	Fuel Cell Vehicle
Firm capacity	A baseline (minimum) generation capacity that can be maintained on an inter-annual basis (e.g. dry year capacity of hydro power station).
FPSO	Floating Production, Storage and Offloading – a ship-based facility that accompanies off-shore oil and gas drilling platform operations.
FRST	Foundation for Research, Science and Technology
FTE	Full-Time Equivalent – the equivalent number of people employed in full-time positions within an industrial sector.
GBS	Gravity-Base Structure – a heavy-duty, off-shore, oil storage facility that is used to assist in off-shore oil drilling operations.
GDP	Gross Domestic Product
GHG	Greenhouse Gas – Emissions that add to radiative warming of earth eg. CO_2, CH_4, SF6, PFC, HFC.
GIS	Geographical Information System
GJ	Giga-Joule = 1,000,000,000 Joules = 10^9 Joules of energy
GTL	Gas to liquids
GWP	GHG warming potential
HRAP	High Rate Algal Pond – a type of waste-water treatment pond
HEEP	Heat Energy Efficiency Program
HERA	Heavy Engineering Research Association
ICDP	International Continental Drilling Programme – towards the study of the Earth's crust, natural mineral resources and interactions with surface ecological systems.
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IGCC	Integrated Gasification Combined Cycle
In-gate	All off-road transportation i.e. agriculture, forestry, mining, recreational and off-road vehicles.
IPCC	International Panel on Climate Change
Kt	kilo-tonne – equivalent to a million kilograms or a Giga-gram.
L/100 km	Litres per 100 kilometer – a measure of fuel consumption used for road transport vehicles
lde	Litre of Diesel equivalent – a unit of measure for comparing the energy content of alternative fuels with that of a litre of conventional Diesel fuel.
LEAP	Energy pathway visualisation software – Long-range Energy Alternatives Planning.
LEAP framework	The database, output files and visualisation tools that are associated with running LEAP.
lge	Litre of gasoline equivalent – a unit of measure for comparing the energy content of alternative fuels with that of a litre of conventional gasoline ("petrol") fuel.
LNG	Liquefied Natural Gas (mainly methane @ -160˚C)
LPG	Liquefied Petroleum Gas (mainly propane and butane)
mcfd	thousands of cubic foot per day
MED	Ministry of Economic Development
MEDF	Marine Energy Deployment Fund – administered by the EECA
MeOH	Methanol
MEPS	Minimum Energy Performance Standard
MJ	Mega-Joule = 1,000,000 Joules = 10^6 Joules of energy

mbbls	Thousand barrels – non-SI unit of volumetric measurement of oil
mmbbls	Million barrels – non-SI unit of volumetric measurement of oil (1mmbbl of crude oil contains approximately 6 PJ of energy)
MOT	Ministry of Transport
mmscf	millions of standard cubic feet
MT	Magneto-Tellurics – a technique used for mapping sub-surface rock features, relating to their natural, electrical conductivity.
Mt-km/kt$_{equivalent}$	Mega-tonne-kilometre travelled per kilo-tonne(equivalent) of various industrial stock moved.
MTG	Methanol-to-Gasoline plant
MW	Mega-Watt = million Watts – measurement of power output
NA and AN	Nitric Acid and Ammonium nitrate
NGL	Natural Gas Liquids
NZ	New Zealand / Aeotearoa
NZBCSD	New Zealand Business Council for Sustainable development
NZES	New Zealand Energy Strategy
NZEECS	New Zealand Energy Efficiency and Conservation Strategy
O & G	Oil and Gas
OPEX	Operational Expenditure
OWC	Oscillating Water Column – a form of wave energy conversion technology for marine applications.
Peak Oil	Defined as the maximum production (bpd) of a field, a province, or the world
Phase	The stage of development of an asset – eg. Research, Construction, Operating.
PHEV	Plug-in Hybrid Electric Vehicle
PJ	Peta-Joule = 10^{15} Joules = thousand, million, million Joules – measurement of energy.
PKT	Passenger Kilometres Travelled – used in the quantification of personal transportation
Risk score	An indication of the likelihood that a phase of asset development will fail (0 – Minimal to no risk; 5 – Extreme to almost total risk). When risk probabilities are applied to applied to Policy, research and financing costs an implementation risk ($000s) is calculated. When risk probabilities are applied to applied to operating capacity, an operational risk (MW) is calculated.
RMA	Resources Management Act
RON	Research Octane Number – a measure of the quality of a fuel, commonly seen at transport fuel filling stations to indicate the relative octane rating of petrol.
PWD	Public Works Directive
PV	Photo-Voltaic – relating to the conversion of solar energy, carried by photons, directly into electrical energy (via photo-voltaic cells that are built into panels or arrays).
RVP	Reid Vapour Pressure (The propensity of “light ends” to evaporate from crude oil).
SHW	Solar Hot Water
SI	le Systeme International d’unites – the international system for defining common units of measurement.
SMR	Steam Methane Reformation
SRF	Short Rotation Forest
StatsNZ	Statistics New Zealand
SUV	Sports-Utility Vehicle
Sweet gas	Well gas with low sulphur content (<4ppm H2S), as distinct from sour or “dirty”

TJ	Tera-Joule = 10^{12} Joules of energy
TE	Thermo-Electric – relating to the conversion of thermal radiation directly into electricity (via thermo-electric cells that are built into panels and arrays).
t-km	Tonne-kilomteres - used in the quantification of goods transportation
Tm^3	Tera-cubic metres – used as an SI alternative to “trillions of cubic feet” for measurement of natural gas reserves
tph	Tonnes per hour
TW	Tera-Watt = million-million Watts – measurement of large power output
US	United States of America
USDoE	United States Department of Energy
VFM	Vehicle Fleet Model – developed by the Ministry of Transport
VKT	Vehicle Kilometres Travelled – Generally associated wth passenger transportation.
WGIP	Wind Generation Investigation Project – set up by the Electricity Commission
WEC	Wave Energy Converters
WSP	Waste Stabilisation Pond – for waste-waster treatment