Key Factors in the Introduction of Hydrogen as the Sustainable Fuel of the Future

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1. BACKGROUND

This paper considers the future potential of hydrogen fuel for large scale use in New Zealand, especially in fuel cell applications. The most likely uses of hydrogen are as *fuel for motor vehicles,* as a *source of distributed generation in electricity networks* and for *remote area electricity supplies.*

Factors which will impact on the likely rate of uptake of hydrogen over the next 50 years are considered together with the likely economic and environmental considerations in the large scale use of hydrogen, bearing in mind hydrogen is an energy carrier and not an energy source. The energy source used to create the hydrogen will be an important economic and environmental factor.

A possible future use of hydrogen is as an *energy storage medium* (e.g. using excess wind power to electrolyse water to produce hydrogen, which can later be converted back to electricity using a fuel cell). Use of hydrogen in this way will have to be evaluated, technically and economically, against other options such as conventional batteries or pumped storage schemes.

The paper is divided into two parts. The first part examines a number of key factors to be considered and the second examines possible rates of uptake of hydrogen as a transportation fuel, which is likely to be the principal application in the development of a hydrogen economy.

2. PART A – KEY FACTORS IN DEVELOPING A "HYDROGEN ECONOMY"

2.1 INTRODUCTION

In the 1990s it was thought that battery-powered electric vehicles could be the solution to motor vehicle pollution problems in cities, but the long awaited breakthrough in battery technology has not eventuated. As a result, these cars remain uncompetitive with internal combustion engined (ICE) cars because of their limited range before requiring recharging, the cost and limited life of the batteries and the weight of the batteries required for a reasonable range. Gradually during the late 1990's, the focus of attention shifted towards hydrogen fuel cell vehicles as being the eventual solution.

Several key factors need to be considered in the development of a hydrogen economy. These include :– the future availability and price of oil as a transportation fuel given that New Zealand is becoming increasingly dependent on importing most of its oil; the potential use of natural gas as a source of hydrogen, or coal, with its associated environmental impacts, noting the very large reserves of coal in New Zealand; and the economics of large scale production of hydrogen by steam methane reduction (SMR), coal gasification and electrolysis, including costs and environmental effects.

Rates of uptake of hydrogen for widespread use will initially be facilitated by cost-effective small plants near the point of use. Later infrastructure will require high capital investment to assist the likely rate of uptake of the fuel cell motor vehicle (FCV) powered by hydrogen, and that uptake rate will be greatly influenced by the relative capital and running cost of such motor vehicles in comparison with other increasingly fuel efficient motor vehicles currently under development.

From an environmental and human health point of view, the benefit of the widespread use in major cities of motor vehicles with water vapour as the main emission, and with negligible other emissions, is very attractive.

On the other hand, the widespread use of fossil fuel to produce hydrogen will have considerable environmental implications, and especially in the case of coal unless adequate measures can be taken to remove emissions produced from the atmosphere.

In the particular case of New Zealand's 8.5 billion tonnes (NZERDC 1982), of economically recoverable lignite resources in the South Island, Goldthorpe (2004) has pointed out that even with carbon dioxide sequestration, the challenge of reducing greenhouse gas emissions would be daunting. The lignite-to-hydrogen process would deliver carbon dioxide at a rate of about 400kg/GJ of delivered fuel on a full fuel-cycle basis compared with about 80kg/GJ for conventional transport fuels. This means that at least 80% of the carbon dioxide would have to be captured and stored just to maintain the status quo.

During 2001/2003 several students at Unitec considered some of the key factors and their findings are summarised below.

2.2 INFRASTRUCTURAL ISSUES
Adapted from Tokelove and Clapham (2002)

2.2.1 Summary

Before a changeover to hydrogen fuel can take place in New Zealand, many new systems must be designed and built. There must be production and storage facilities and a distribution system in place. The process of setting up this kind of infrastructure is a large and costly task and there needs to be a gradual transition from a fossil fuel-powered motor vehicle fleet to a hydrogen-powered fleet. The process will eventually involve hundreds of filling stations across the country as well as the distribution systems to serve them.

2.2.2 Production of Hydrogen

There are a number of alternatives to produce hydrogen on a commercial scale as follows:

- **Steam Reforming of Natural Gas.** This is a two stage process. This first step is to expose natural gas to high temperature steam which produces hydrogen, carbon monoxide and carbon dioxide. The second step is to convert the carbon monoxide with steam to produce additional hydrogen and carbon dioxide. Most hydrogen is produced by this process as it is currently the most cost effective way. SMR is very similar and is already used on a large scale in the production of ammonia urea fertilisers and can be duplicated on a medium scale by reformers or on a small scale with a reformer on the vehicle itself. Methane is a major constituent of CNG and there is considerable experience in handling CNG in New Zealand.

- **Electrolysis.** This process uses electricity to split water into its basic elements, hydrogen and oxygen. Manufacturing hydrogen using electrolysis is at present very expensive but water is an abundant and renewable resource and technological advances in renewable electricity generation could make electrolysis a more attractive and viable option to produce hydrogen in the future.

- **Biomass Gasification.** Feed stocks such as wood chips and agricultural wastes are superheated until they turn into hydrogen and other gases.

- **Reformation of Methanol.** Hydrogen can be stored in methanol than can be produced from natural gas, coal or fermentation of biomatter or processing of wood chips. Methanol can be directly fed into some fuel cells which have a reformer attached or methanol can be converted to hydrogen at an earlier stage. Therefore hydrogen can be obtained from methanol in large production facilities, at the service station or on board the vehicle. Methanol is a fuel which is reasonably easy to handle and storage and filling are long established technologies with considerable overseas experience available.

- **Coal Gasification.** Manufacture of coal gas from steam and superheated coal is a well tried and used technology. Coal gas is a mixture of carbon monoxide and hydrogen which can be further reduced to hydrogen and carbon dioxide.

- **Future Possibilities.** Those include *photo-electrolysis*, using sunlight to split a water molecule into its components of hydrogen and oxygen and *biological production* as scientists have discovered that some algae and bacteria may produce hydrogen under certain conditions using sunlight as their energy source.

2.2.3 On Board Vehicle Storage of Hydrogen

There are three main future options for doing this.

- **Compressed gas storage tanks.** New materials are becoming available enabling vehicle storage tanks to be made which can hold hydrogen at very high pressure. At present the costs of such tanks and compression are high but the technology is available. Relatively low pressure storage of hydrogen gas on the vehicle either requires a large volume tank or the vehicle will have a limited range of operation.

- **Liquid hydrogen.** Condensing hydrogen gas into its more dense liquid form enables a larger quantity of hydrogen to be stored and transported. However, converting hydrogen gas to liquid hydrogen is costly and requires a large input of energy.

- **Chemical Hydrides.** Various pure or alloyed metals can combine with hydrogen producing stable metal hydrides which decompose when heated, releasing the hydrogen. (This is likely to be a considerably more expensive option for motor vehicles for the foreseeable future, and may not be feasible because of the large weight of metal hydride banks required).

2.2.4 Future Hydrogen Production and Distribution

There are two main scenarios to be considered in delivering hydrogen at the vehicle filling station.

- **Hydrogen Produced Off Site on a Large Scale.** Hydrogen is produced in bulk using one of the processes described above and then has to be moved to the place of consumption, entailing ships/tankers and/or pipelines. Very large economic investments will be required in provision of such facilities.

- **Distributed Production.** Large investments can be avoided, at least initially, by allowing service stations to produce hydrogen on-site either by reforming or by electrolysis. The technology required for steam reforming of natural gas is presently available for medium scale production. Technology for reforming methanol and natural gas is becoming available for small-scale production. If electrolysis becomes widely used, then local electricity distribution networks would need to be substantially upgraded to service the electricity requirement and many new electricity generation plants would eventually need to be constructed as the hydrogen demand grows.

2.3 ENVIRONMENTAL IMPACT ISSUES
Adapted from Stratton and Levet (2002)

2.3.1 Summary

The environmentally friendly fuel cell vehicle (in comparison to a petrol powered vehicle) is more efficient, has near-zero emissions apart from water vapour, and hence the ability to eliminate the pollutants currently emitted by petrol vehicles.

At present, the pollutants emitted from petrol and diesel vehicles include smoke, particulates, sulphur dioxide, carbon monoxide, oxides of nitrogen and hydrocarbons. These pollutants affect ambient air quality and human, animal and plant health while carbon dioxide emissions contribute to the enhanced greenhouse effect.

Hydrogen fuel cell technology has the advantage of being able to significantly reduce vehicle pollutants, as the only emission from a vehicle powered by a fuel cell running on hydrogen is water vapour. Water vapour emissions of the already existing fossil fuel-based energy economy are estimated at less than 0.005% of the world's annual evaporation.

For overall efficiency and zero emissions, if the advantage is to be gained, the energy source used to generate the hydrogen should not decrease the efficiency or increase emissions. New Zealand's non-renewable energy sources include coal and natural gas, while actual and potential renewable energy sources include hydropower, wind power, geothermal, biomass and solar energy.

2.3.2 Hydrogen from Renewable Energy

If renewable energy sources such as wind, hydro or solar are used to produce the hydrogen by electrolysis to power the fuel cell, then leaving aside issues of carbon dioxide emissions (or other pollution) created by the construction of the renewable energy source, the FCV is truly a near-zero emission vehicle.

2.3.3 Hydrogen from Methanol or Natural Gas

If methanol or natural gas is used as a source of hydrogen for the fuel cell, then the carbon dioxide emissions can be reduced substantially compared with an ICE, but this percentage saving will reduce by the amount of carbon dioxide emissions which are generated during conversion to hydrogen and there also may be significant energy losses in this conversion. Local pollution within cities, however, will be almost completely eliminated for the fuel cell vehicle in comparison with the ICE provided that the hydrogen production plants are not located close to the city.

2.3.4 Hydrogen by Electrolysis from Thermal Electricity Generation

If hydrogen is produced by electrolysis using electricity generated using natural gas in a combined-cycle power station operating at an efficiency of about 55%, then assuming the energy conversion efficiency of the fuel cell is around 50% compared with 20% for a modern internal combustion engine (i.e. 2.5 times) the overall gain in efficiency is 37.5%.

However, if the electricity comes from an older power station fuelled by natural gas or coal at an efficiency of about 30%, there is an overall efficiency loss of 25%.

Greenhouse gas emissions from the electricity generation must also be taken into account and will be a significant factor, especially in the case of coal-fired generation.

2.4 MOTOR VEHICLE DEVELOPMENT
Adapted from Norfolk (2002)

Development of infrastructure for a hydrogen powered motor vehicle fleet will present severe logistical challenges at least in the short term. Hence demonstration projects are the most likely way in which hydrogen powered fleets of motor vehicles will first be brought into use.

Although most of the world's major automobile manufacturers are now claiming that they will have hydrogen powered FCVs available for demonstration by around 2005, FCVs will not be competitive on a cost basis with ICE vehicles for at least 10 years, and neither will sufficient infrastructure be established to support large scale hydrogen production within the same time frame.

A transition of the motor vehicle fleet towards hydrogen powered fuel cell motor vehicles instead of petrol-diesel or other vehicle types will not happen quickly and these new technology vehicles will have to compete in the market place with other types of motor vehicles on both cost and performance (as well as on the efficient use of energy and being relatively pollution free) before they will be accepted.

In particular, fuel cell vehicles may face strong competition from hybrid electric vehicles, at least over the next 20 years, and also from much more fuel efficient petrol and diesel engines, some using purer fuels, in the worldwide quest for less environmental pollution and much greater efficiency of fuel use.

In recent years, some demonstration fuel cell cars have been produced using methanol or natural gas as a fuel in conjunction with an on-board reformer to convert that fuel to hydrogen. However, difficulties associated with slow start up for these vehicles is such that it is unlikely that they will be produced in the future. Research continues on producing a viable direct methanol fuel cell which can convert methanol directly to electricity without the need for a reforming sub-system. If this goal can be achieved, it will be a major advance.

2.5 REDUCING MOTOR VEHICLE POLLUTION IN CITIES

The quest for more fuel-efficient motor cars with lower exhaust emissions began in earnest about 1990 when the State of California (and the City of Los Angeles in particular) became very concerned about smog problems in major urban areas caused by increasing use and concentration of motor vehicles and the impact of vehicle exhaust emissions on human health.

The near zero noxious emissions from FCVs is the primary feature that has led Californian Governor Schwarzenegger to promote the technology.

Disley (2003) notes that air pollution particularly affects human hearts and lungs and can cause cancer. He reports on the work of Fisher et al (2002) who estimate that air pollution causes at least 486 premature deaths each year in the Auckland Region. Of these, 58% or 253 premature deaths are estimated to be due to motor vehicle emissions. The focus of this study was on fine particulates which were shown to have a dominant effect and can be considered as a good "indicator" of the combined exposure to a range of pollutants from motor vehicles. The report concludes that the overseas results are applicable and the methodologies valid for making such an assessment in New Zealand.

The 253 estimated premature death figure for the Auckland Region due to motor vehicle emissions is 64% of the New Zealand estimated total. Wellington and Christchurch experience much lesser rates of 56 and 41 premature deaths respectively, or 14% and 10% of the total. The other cities and towns larger than 5000 people throughout New Zealand experience the remainder (46 premature deaths, and 12% of the total).

The widespread use of motor vehicles powered by hydrogen fuel cells, therefore, has the potential to significantly reduce the environmental impact and consequential effects of vehicle exhaust emissions within cities, provided that a fast enough rate of uptake can be achieved to eventually displace most other motor vehicles.

3. PART B – KEY FACTORS AFFECTING THE RATE OF UPTAKE OF HYDROGEN AS A TRANSPORTATION FUEL

3.1 SOME INITIAL CONSTRAINTS

Yeaman (2004) has pointed out that to try and change people's behaviour to move simultaneously from ICEs using petrol or diesel to FCVs using hydrogen will be very difficult and may require a great deal of incentivisation and encouragement. She also notes that only 2% of the 230,000 vehicles in New Zealand under three years old (which is 10% of the total vehicle fleet) are in private ownership, so the vehicle purchasing decisions of companies and public sector organisations will be all important.

Yeaman also notes that in New Zealand in the early 1980's, people were actively encouraged towards LPG or CNG (but still using the same engines and moving to a cheaper fuel) with limited success. She suggests that moving to hydrogen with different engines and a probably more expensive fuel will be much harder.

Hydrogen distribution presents significant challenges. For cryogenic hydrogen distribution Eliasson et al (2003) note that 30% of the higher heating value (HHV) of hydrogen is used in liquefaction. The volumetric energy density of liquid hydrogen is still less than a third that of petrol. Hence at least 3 times as many tankers are required to deliver the same amount of energy. If we assume that FCVs are twice as efficient as ICEs then the number of actual hydrogen delivery vehicles on the road may be 50% more than the number at present.

For compression of gaseous hydrogen to pressures of between 20 MPa and 80 Mpa, 7-10% of HHV is required. However transport of gaseous hydrogen by anything but pipeline is impractical except for small applications such as demonstration projects.

On board storage of hydrogen using metal hydrides is unlikely at present except for military applications such as submarines, as the storage potential, currently at about 1% by weight (but improving) means that the storage of 30 kg of hydrogen that has the same calorific value as 27 Imperial gallons of petrol, requires 3 tonnes of hydride carrier.

Fuel cell costs that were about US$2000/kW in 2000 will need to be reduced by a factor of 40 to US$50/kW in order to compete with the ICE. Shell (2001) estimate that this will occur at about 2020.

Modelling at Unitec (Baglino and Leaver, 2004) indicates that the development of the hydrogen economy in New Zealand will be constrained by the availability of fossil fuel feedstock if oil prices remain static. The competition for this feedstock with the electricity generation sector combined with the shortage of natural gas and the imperative to sequester large volumes of greenhouse gas emissions if coal is used, may restrict the market share of FCVs in the vehicle fleet to less than 50%. Volatility in the oil price along with the prospect of improved security of supply from indigenous generation of hydrogen and financial incentives from automobile companies could easily see the major portion of the fleet converted. The model of Baglino and Leaver assumes initial generation of hydrogen in the North Island of New Zealand on the service station forecourt by SMR of natural gas distributed via existing infrastructure. In the South Island initial generation is by forecourt electrolysis, due to the lack of gas pipeline infrastructure.

3.2 DEMONSTRATION PROJECTS

Because of problems in financing delivery infrastructure until sufficient demand is established, demonstration projects are the most likely way in which hydrogen powered fleets of motor vehicles will be brought into use. This is also because for the first few years of the uptake of the new vehicle technology, private individuals are unlikely to be able to afford them. Also these vehicles would generally need to be fuelled from a central filling station, so would be mainly confined within a city. Fleets of delivery or service vehicles would be an obvious first target.

Demonstration bus projects are now frequently proposed as a means of raising the profile of hydrogen as a transport fuel and encouraging confidence in its use. There are now probably over 100 demonstration buses around the world running on fuel cells, but there are high costs attached. The cost of the buses themselves is still several times the cost of a conventional modern diesel bus. Also Vasisht (2003) investigated the estimated cost of setting up a filling station in Auckland for a demonstration bus project. Using a package electrolysis plant similar to one supplied recently to Reykjavik in Iceland, the installed cost in Auckland would be around NZ$5 million to service three demonstration buses. It is therefore not surprising that for a demonstration bus project now under way in Perth, a decision was made to supply hydrogen from an existing plant, compressed in cylinders delivered daily to be fitted in the roof of each bus.

3.3 POSSIBLE RATES OF UPTAKE

In some initial work, Yardley (2002) proposed and modelled three scenarios for the uptake of hydrogen FCVs in New Zealand up to 2050.

Kruger et al (2002) then investigated three scenarios for hydrogen fuel and electricity demand in New Zealand from 2010 to 2050. Two classes of vehicle with 5000 vehicles each were assumed to exist in 2010 with growth rates of either 10% p.a., 20% p.a. or 30% p.a. through to 2050.

The study showed that for the assumed starting point of 10,000 FCVs in 2010, the contribution to reducing dependence on fossil fuels will be small at any of these growth rates until about 2030.

Beyond 2030, at a growth rate of 30% p.a., almost the entire remaining fleet of fossil-fuel vehicles could be retired by 2050; at a growth rate of 20%, about 60% of the fleet would be FCVs by 2050; and at a growth rate of 10%, less than 5% of the fleet would be FCVs by 2050.

A growth rate of 30% per annum between 2010 and 2050 would be very difficult to achieve in practice unless and until hydrogen fuel cell vehicles have become very economically competitive with fossil-fuel vehicles, the necessary servicing infrastructure is all in place and/or severe limitations occur in the international availability of fossil fuels for transport purposes.

3.4 POSSIBLE FUTURE ENERGY DEMAND

Kruger et al (2002) also made a preliminary assessment of future energy demand to provide the hydrogen for FCVs through to 2050 looking at both a business-as-usual scenario and a conservation scenario.

If the required energy to produce the hydrogen all comes from electricity generation, at a 30% per annum growth rate for fuel cell vehicles, then 40 – 70 TWh per year of extra electricity generation would be required in 2050, depending on which scenario was chosen.

This would be in addition to the growth in electricity demand in other sectors of the economy which could by 2050 have increased demand to 86 TWh per year from the present 40 TWh per year (in 2003).

The result would be anywhere between a threefold or fourfold increase in present electricity demand by 2050. This however would only apply with the maximum (30%) annual growth rate studied, and if the source of all the energy required to produce the hydrogen came from electricity generation rather than from other sources.

Kruger et al (2003) have since presented a much more detailed study of the energy resources required for developing large-scale hydrogen fuel production in New Zealand. The above figures are somewhat revised. The business-as-usual growth in electricity generation load could more than double to 92.5 TWh per annum in 2050 but the additional load for hydrogen fuel production would be 34 TWh per annum in 2050 for the 30% annual growth figure, which would give a combined total of 3.2 times the present electricity demand figure, again assuming that all the energy required to produce the hydrogen comes from electricity generation rather than from other sources.

4. CONCLUSION

The vision of hydrogen as a clean, sustainable fuel securing New Zealand's energy future is a very attractive one. Hydrogen can be produced by a number of processes ranging from on board vehicle installations to small scale forecourt and large scale centralised production. The acceptance of hydrogen as the preferred fuel will require heavy capital investment in centralised hydrogen production plants using natural gas or coal if nuclear power remains off the agenda. In addition the cost of fuel cells will need to be reduced by a factor about 40 if they are to be competitive with the ICE.

While FCVs will reduce noxious vehicle emissions in urban areas to near zero, greenhouse gas emissions produced from the production of hydrogen will require extensive mitigation measures if New Zealand is to meet its international commitment to limit greenhouse gas emissions under the Kyoto Protocol.

If New Zealand can meet these technological challenges it will be well on the way to achieving a hydrogen economy by 2050.

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