State Sustainability Strategy Background Paper
'The Hydrogen Economy'

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For Oil Vulnerability and Hydrogen Economy Reference Group

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Abstract

Oil reserves around the world are diminishing, prices are rising, and environmental concern surrounding the use of fossil fuels is increasing. In order for Western Australia to move towards sustainability, we need to reduce our reliance on fossil fuels and find renewable forms of energy to power our homes, businesses, industries and transportation. Hydrogen, the most abundant element in the universe, holds the potential to be the backbone of a clean and sustainable energy system for our future.

Hydrogen is an energy carrier that can be used in a myriad of different applications. Hydrogen may be used as a transport fuel for internal combustion engine vehicles and fuel cell powered vehicles. Hydrogen may also be used to power turbines or in fuel cells for stationary power generation. In the future, hydrogen fuel cells may power most modes of transportation as well as lighting, heating and everyday electrical appliances in our homes and businesses.

Today, Hydrogen is produced primarily from natural gas. However, Hydrogen can also be produced locally through entirely renewable means. Its use in fuel cells, an electrochemical energy conversion device, produces no harmful by-products (the only emission is pure water). In a world where national security is currently foremost in people's minds, and concern over environmental issues such as global warming and smog induced air pollution is increasing, hydrogen may present a bright future.

Oil companies, automobile industries, power utilities, and governments around the world are all starting to look towards hydrogen as the major energy carrier for the future. The United States of America (among most other countries) is starting to introduce significant initiatives to promote the use of hydrogen. For example, a new public-private partnership between the U.S. Department of Energy and major U.S. Automobile Manufacturers provides significant funds for the development of hydrogen as a primary fuel for cars and trucks. Billions of dollars are now being spent around the world to develop and harness the potential of hydrogen energy systems.

Most energy experts around the world believe that a transition from fossil fuels to a hydrogen economy is inevitable. Western Australia is in an enviable position (with a present abundance of natural gas and significant potential to harness renewable energy resources) to be able to lead the way in the transition to a hydrogen economy.

In order to move towards a sustainable hydrogen economy (an economy which relies on an energy system supported predominantly by the use of hydrogen), a future strategy must be outlined, followed, and continually revised. This background paper begins this process and suggests how Western Australia may be able to progress towards a hydrogen economy, and in doing so lead the Asia Pacific region and be at the forefront of world activity in this area.

Contents

Introduction

The hydrogen economy is a vision for the future in which our economic system is based around the use of hydrogen as an energy storage and transport medium. The need to find a sustainable alternative energy source (such as hydrogen produced from renewable energy) to replace fossil fuels is primarily threefold: oil vulnerability, global warming and air pollution.

Oil Vulnerability

Oil stocks are rapidly declining around the world. Expert estimations have put the timing of the 'big oil rollover' (when oil production will start to decline around the world) at between 2003 - 2020.[1] Australia has been consuming oil three times faster than it has been discovering it; Australian self-sufficiency in oil is expected to decline from 80-90% during the last decade to 40% by 2010.[2] Today, two thirds of the worlds known oil reserves lie within Middle Eastern countries such as Saudi Arabia, Iran and Iraq.[3] Reduced availability of this major energy source in the medium-term, coupled with short-term uncertainty due to political instability in the Middle East region, is resulting in an unprecedented urgency to pursue sustainable options that provide locally produced, renewable energy sources. Hydrogen can be the energy carrier that supports these renewable energy resources.

It is often advocated that Australia has abundant natural gas reserves that may be tapped to replace oil as our major energy source in the future. However, natural gas is also a finite resource and while cleaner than oil also produces greenhouse gas emissions when burnt. While natural gas reserves will still be able to meet the energy needs of Western Australia for decades to come, it would be wise to use this resource now to aid in the transition to a fully sustainable energy future.

The Executive Director of the Australian Petroleum Producers and Exploration Association, Barry Jones, has advocated an urgent shift from petrol and diesel land transport fuels to ones based on natural gas due to declining oil reserves.[4] Consumption of these petroleum products in Australia would be equivalent to 85% of current natural gas production.[5] Rising energy demand and the factors influencing the production and development costs of natural gas must also be acknowledged when looking to future use of alternatives to oil. While gas production currently comes from fields up to 110 km offshore and in water up to 120m deep, 40% of Australia's known reserves are up to 400 km offshore in depths between 800-1000m.[6]

Current trends in population growth, coupled with growth in energy demand could lead to almost a doubling of world energy demand by 2030.[7] "The Transport Energy Strategy, an industrial group of automotive manufacturers and fuel supply companies seems to have agreed upon hydrogen as the additional fuel to be introduced over

[1] Magoon, 2000.
[2] Akehurst, 2002.
[3] Akehurst, 2002.
[4] Jones, 2001.
[5] Fleay, 2001.
[6] Fleay, 2001.
[7] Wurster, 2001.

the next 20 years in Germany."[8] The U.S. Department of Energy has officially called for hydrogen-based energy to replace the equivalent amount of fossil-fuel energy to power 2 million to 4 million American households by the year 2010, and 10 million households by 2030.[9]

Air Pollution

Urban air pollution caused by the burning of fossil fuels is worsening to an extent where major cities around the world are being forced to restrict car use and introduce measures to encourage cleaner vehicles. Smog levels in cities are increasingly being blamed for a range of health problems such as asthma. The President of Italy's Lombardy region has declared that the sale of diesel and petrol cars will be banned from 2005 to mitigate air pollution in the area.[10]

In addition to health problems from air pollution, the burning of fossil fuels creates environmental problems such as acid rain from sulphur and nitrogen oxide emissions. The U.S. E.P.A. (Environmental Protection Authority) has estimated that vehicle use in the U.S. is responsible for 45 percent of nitrogen oxide emissions and 37 percent of volatile organic compounds nationwide.[11] Hydrogen fuel cell vehicles produce no emissions save pure water vapour, creating a solution to current urban air pollution problems.

Global Warming

Increasing fears over the effects of climate change are responsible for a number of measures being introduced around the world to reduce carbon emissions (for example the Kyoto Protocol http://www.unfccc.int/resource/convkp.html). The burning of fossil fuels is the major human induced cause of global warming.

Hydrogen produced from renewable energy provides an alternative fuel free of all carbon emissions. Even if hydrogen is produced from natural gas (which is the majority case today), substantial greenhouse gas emissions savings can be achieved. The large-scale production of hydrogen from natural gas also provides the opportunity for carbon dioxide sequestration. See Figure two for a comparison of lifecycle greenhouse gas emissions from various vehicle fuels and engine systems.

If cost competitive hydrogen fuel cell buses are introduced into the Australian public transport bus fleet as part of the existing replacement program, a reduction in greenhouse gas emissions amounting to 500 000 tonnes could be achieved by 2017.[12] (Hydrogen fuel cell buses are likely to be cost competitive with diesel and CNG (compressed natural gas) buses by 2008.[13])

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8 Wurster, 2001.
9 Scott Powers, *Orlando Sentinel*, April 2002
10 Philip Willan, The Guardian – United Kingdom, Feb 2, 2002.
11 Thomas and Zalbowitz, 1999.
12 Department of Infrastructure and Planning, 2000.
13 Department of Planning and Infrastructure, 2000.

Hydrogen Production

Although it is the most abundant element in the universe, hydrogen is not found in elemental form and must be produced or reformed from a primary source. Today, hydrogen is primarily produced through reformation of natural gas, electrolysis of water, or partial oxidation of heavy fossil fuels such as diesel. Close to 98% of hydrogen is presently generated from fossil fuels.[14] Steam reforming of natural gas is currently the most widely used and economical method of producing hydrogen.[15]

Steam reforming of natural gas involves the high temperature (769-925 degrees Celsius) catalytic conversion of methane and water to produce carbon dioxide and hydrogen.[16] A large-scale methane reformer can attain fuel conversion efficiencies of up to 83% (lower heating value of H_2 produced/lower heating value of fuel into the reformer).[17]

Methane steam reformation process to produce hydrogen:

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad (1)$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad (2)$$

Electrolysis involves passing an electric current through water to produce hydrogen and oxygen. (The use of hydrogen in a fuel cell effectively reverses this process by combining hydrogen and oxygen to produce an electric current and water.) Electrolysis is about 70-80% efficient in energy conversion and produces a highly purified form of hydrogen.[18] The cost of hydrogen production from electrolysis using fossil fuel generated electricity is generally three to five times higher than direct production from fossil fuels.[19] While the electrolysis process produces no greenhouse gas emissions, the use of fossil fuel generated electricity will involve emissions on a lifecycle basis. If electricity is produced from renewable resources (such as solar), then the process will be free of greenhouse gas emissions (neglecting emissions involved in plant production and construction).

Partial Oxidation of fossil fuels is similar to the process of steam reformation with an additional step of adding oxygen. The partial oxidation process is approximately 50% efficient.[20] The partial oxidation of coal is generally referred to as gasification.

Partial Oxidation of petrol:

$$H_3C(CH_2)6CH3 + 12H2O \Leftrightarrow 21H2 + 4CO + 4CO2$$

$$H3C(CH2)6CH3 + 7.5O2 \Leftrightarrow 6H2 + 4CO + 4CO2 + 3H2O \qquad (1)$$

$$CO + H2O \Leftrightarrow H2 + CO2 \qquad (2)$$

Other forms of production, such as thermochemical, photochemical or photobiological hydrogen production hold promise for highly efficient and cost effective production in the future. However, these technologies are still in their developmental phase and need more time and research to become viable.

[14] Connor, 2001.
[15] Gill, 1999.
[16] Levelton Engineering Ltd., 1999.
[17] Mitchell, 2000.
[18] NAVC, 2000.
[19] NAVC, 2000.
[20] NAVC, 2000.

Biomass or municipal waste gasification also holds potential for future hydrogen production. Hydrogen production from biomass would probably cost about 1/3 more than hydrogen production from natural gas,[21] with the delivered cost to customers being about 1/6 greater.[22] Hydrogen production from biomass provides a potentially sustainable future fuel supply with near-zero greenhouse gas emissions. However, it has often been touted that there is not enough arable land available for any significant production of biofuels. Alternatively, others such as Ogden et al. (2000) in the U.S. believe that investigations into the agricultural land situation in the context of producing biofuels for use in energy efficient vehicles suggest that there would be sufficient agricultural land to cater for a major proportion of transport energy requirements.

Efficiency

Over time, human use of energy resources has progressed from carbon rich fuels to more and more efficient and clean hydrogen rich fuels. This can be followed through the transition from wood, containing ten carbon atoms to each hydrogen atom (10C: 1H), to the use of coal (1 or 2 C: 1H), oil (1C: 2H), and natural gas (1C: 4H).[23] At each step, greater energy density has been achieved. The last major transition promises to be to pure hydrogen.

While renewable energies such as solar, wind, hydro, and geothermal energy are ideal energy sources; they have problems with intermittency and storage. An energy carrier such as hydrogen is often needed for storage and transport purposes. Hydrogen energy systems also allow production to be decentralised, creating more security.

Use

Hydrogen is currently used in a myriad of industry processes, such as the production of plastics, fertilizers and petroleum products. Hydrogen may be used to power steam turbines or as fuel in a vehicle internal combustion engine. However, the most interesting use for hydrogen in the future is in fuel cells. Fuel cells were first developed extensively during the 'space race' in the 1960's.[24]

> "We happen to believe that fuel cells are the wave of the future; that fuel cells offer incredible opportunity".
> *US President George Bush Feb 25, 2002*

Fuel cells are electrochemical energy conversion devices, which convert chemical energy in the form of hydrogen and oxygen into an electrical current and the by-product of water ($H_2 + 1/2O_2 \Rightarrow H_2O$). Fuel cells may be used in both transportation applications and stationary applications. Compared to electricity generation from coal or gas, hydrogen fuel cells are extremely efficient (see table 1).

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[21] Williams et al., 1995.
[22] Ogden et al., 2000.
[23] Ausubel, 2000.
[24] Thomas & Zalbowitz, 1999.

Table 1: Comparison of maximum electricity generation efficiencies achieved by coal, natural gas, and hydrogen fuel cell power stations.

	Max. Electricity Production Efficiency
Coal	<50%
Natural Gas CCGT (Combined Cycle Gas Turbine)	60%
Hydrogen Fuel Cell Cogeneration	85%

The fuel cell is also two to three times more efficient in converting fuel to power than an internal combustion engine vehicle.[25] Heat engines, such as internal combustion engines or gas turbines, use heat energy to produce mechanical energy. Therefore efficiencies are constrained by the Carnot Limit.

Carnot Efficiency = $(T_H – T_L) / T_H$

Where T_H = absolute high temperature (temperature of heat source)

T_L = absolute low temperature (temperature of sink to which waste heat is rejected)

The theoretical efficiency of the fuel cell is related to the ratio of the chemical free energy of Gibbs Free Energy ($\Delta G°$) and the total heat energy or Enthalpy ($\Delta H°$) of the fuel.[26]

Fuel Cell Efficiency = $\Delta G° / \Delta H°$

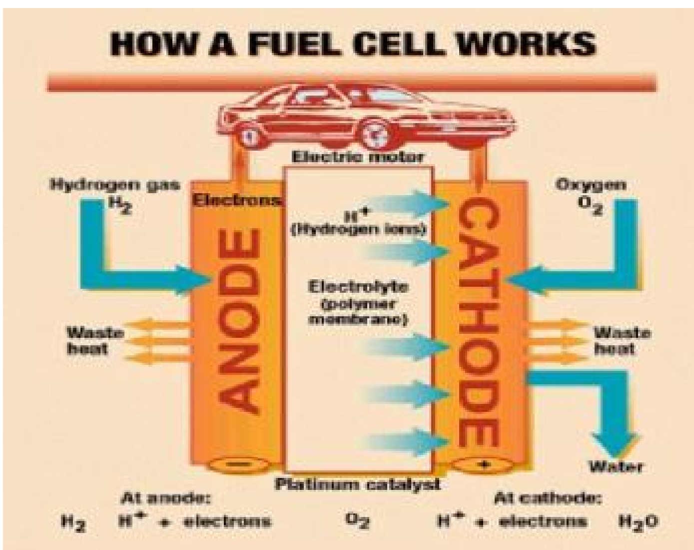

Figure 1. How a fuel cell works.[27]

To view an animation of the workings of a hydrogen fuel cell, see www.Ballard.com/pem_animation.asp

[25] Thomas & Zalbowitz, 1999.
[26] Brandon & Hart, 1999.
[27] Department of Planning and Infrastructure, 2001.

Types of fuel cells

There are a number of different types of fuel cells, including Polymer Electrolyte fuel cells, Phosphoric Acid fuel cells, Alkaline fuel cells, and Solid Oxide fuel cells. Classified by the electrolyte used, each has various advantages and disadvantages relating to cost, temperature, fuel purity, size and lifetime. All the above fuel cells can use hydrogen as a fuel; however, some of the high temperature fuel cells (Molten Carbonate and Solid Oxide fuel cells) may also run on other hydrogen-rich fuels such as methane.

Polymer electrolyte fuel cells are being trialed in a number of hydrogen fuel cell vehicles around the world. They also have the potential to be used for residential and small commercial distributed power generation, for premium power generation (applications where power supply must either be uninterruptible or particularly clean) and telecommunications.

Alkaline fuel cells are currently used for power generation during space flights and have potential to be used in utility vehicles (for example military applications) and small watercraft.

Phosphoric acid fuel cells may be used for baseload power and cogeneration. Cogeneration is where waste heat from the fuel cell is also utilised.

Molten carbonate fuel cells and solid oxide fuel cells generally use syngas and methane as primary fuels and are most suited to the production of baseload power, for cogeneration applications and hybrid power.

While hydrogen fuel cells are the most advanced, other types of fuel cells, such as direct methanol fuel cells and metal air fuel cells, are being developed. Direct methanol fuel cells may be used in electric motor vehicles or as portable power sources in lap top computers or mobile phones. Metal-air fuel cells, may be used in the future as portable power sources or in transportation. Metal-air fuel cells are yet to be developed to a commercial standard.[28]

For further information on fuel cells, the different types and their applications, visit http://www.fuelcells.org/.

History of the development of the fuel cell

The principle of the fuel cell was first discovered by William Grove in 1839.

> "I cannot but regard the experiment as an important one…"
> *William Grove writing to Michael Faraday, October 22, 1842*.[29]

However, it wasn't until over a century later that fuel cells began to be developed in earnest. The Alkaline Fuel Cell was developed by Francis Bacon in 1952, and subsequently used to provide power for the NASA Apollo and Space Shuttle missions in the 1960's.[30] One of the major benefits of using hydrogen fuel cells for power generation on space flights is the resultant production of pure water, which may be used by the crew. It wasn't until some time later that the cost of fuel cells

[28] Fuel Cells, 2000.
[29] Thomas & Zalbowitz, 1999.
[30] Zittel, W. & Wurster, R. 1996.

declined to a level which enabled use for everyday power supply. Fuel cells began to be used in stationary applications around the world in the 1990's; Ballard Power Systems demonstrated the first hydrogen-powered bus in 1992. Today stationary fuel cells are used in hundreds of specialist applications around the world.
To read a brief history of the development of fuel cells see http://americanhistory.si.edu.csr/fuelcells/sources.htm#articles

Benefits and Disadvantages of hydrogen fuel cells
Hydrogen fuel cells have a number of benefits including high efficiency; modularity (several fuel cells may be coupled together to increase capacity but can be mass produced keeping costs low); increasing efficiency at low loads; low maintenance (due to few moving parts); low noise level; and zero emissions except for water. The hydrogen fuel cell vehicle runs on an electric motor, this makes it very quiet compared to the conventional internal combustion engine and more than twice as efficient.[31]

The current disadvantages are mainly due to the infancy of the fuel cell market. They include high initial investment costs, poor availability, and lack of supporting infrastructure.

The environmental benefits associated with the use of hydrogen fuel cells depend to a large extent on the method of hydrogen production. Although hydrogen fuel cell vehicles are classified as 'zero emission', this only refers to tailpipe emissions and not those released during production of the hydrogen. Therefore, any comparison of fuel types must be made on a lifecycle basis (from well to wheels). Figure 1, adapted from a Pembina Institute for Appropriate Development Report (2000), presents a comparison of lifecycle greenhouse gas emissions from various fuel and engine systems.

[31] Thomas, S. & Zalbowitz, M. 1999.

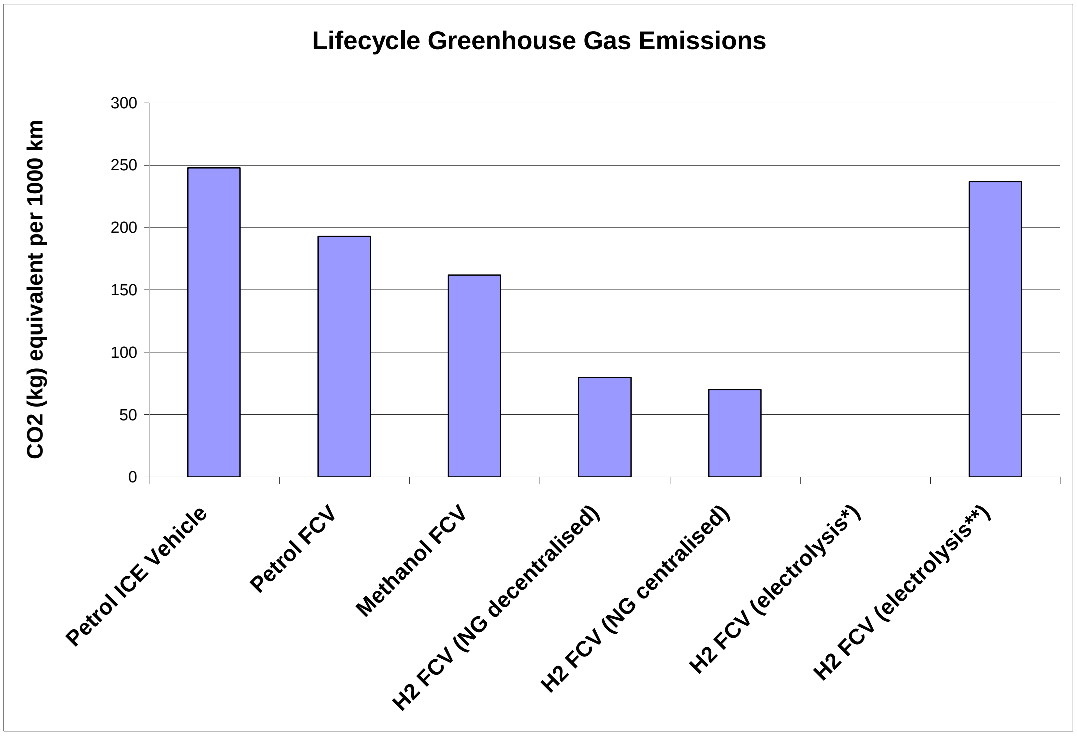

Figure 2. Comparison of lifecycle greenhouse gas emissions from various fuel and engine systems. Emissions include those in production of the fuel, storage, transport and end use.

Petrol ICE Vehicle: Mercedes-Benz A-class Internal Combustion Engine Vehicle fuelled with unleaded petrol.

Petrol FCV: Fuel Cell Vehicle with on-board fuel processor converting reformulated petrol to hydrogen for direct use.

Methanol FCV: Fuel Cell Vehicle with on-board fuel processor converting methanol to hydrogen for direct use.

H2 FCV (NG decentralised): Hydrogen Fuel Cell Vehicle using Hydrogen produced from methane reformers at small facilities (e.g. filling stations).

H2 FCV (NG centralised): Hydrogen Fuel Cell Vehicle using Hydrogen produced from large methane reformers and distributed to filling stations via pipeline.

H2 FCV (Electrolysis*): Hydrogen Fuel Cell Vehicle using Hydrogen produced via decentralised electrolysis using combined cycle natural gas electricity.

H2 FCV (Electrolysis**): Hydrogen Fuel Cell Vehicle using Hydrogen produced via electrolysis using non-emissive energy sources, such as solar, hydro, wind.

Greenhouse gas emission data from a fuel cell vehicle using hydrogen produced from renewable energy sources, has been included for purposes of comparison.[32] This was omitted from the Pembina study, as the authors believed that “it is uncertain if green power will meet the necessary demand under present renewable electricity production capacities.”[33] The future of a fully sustainable hydrogen economy in the future relies on increased efficiencies of renewable energy production and lower costs. Oil has been a very convenient and cost efficient

[32] As in NAVC, 2000.
[33] Pembina Institute for Appropriate Development, 2000.

(neglecting environmental costs) power source for decades. When pursuing alternative energy sources and fuels in the future, the energy profit ratio of the fuel must be scrutinised. That is to say, the energy costs of production, storage, transport and use must be calculated and seen to be less than the resulting energy content of the fuel.

Issue Analysis and Discussion

Barriers

Barriers to the development of the hydrogen economy

There are a number of barriers that must be overcome in the progression towards a fully sustainable hydrogen economy. Most of these arise from the infancy of the hydrogen industry for energy supply. While hydrogen has been used for many years in the production of a range of products, from glass to plastics and semiconductors to pharmaceuticals, it is only recently that hydrogen has become a potentially viable alternative to oil as a transport fuel, and coal and gas as a fuel for electricity generation. Major barriers include high cost, lack of infrastructure, lack of codes and standards, little existing training, lack of public acceptance and a lack of readily available insurance cover.

Infrastructure

Very little hydrogen infrastructure is in place throughout the world. This is not a big problem for stationary energy uses of hydrogen, as the necessary equipment can be developed as required at individual sites. However, the lack of available hydrogen infrastructure, in particular refuelling stations, is a problem for the vehicle market.

Before individual consumers will be willing to purchase a hydrogen fuel cell car, they will expect convenient refuelling stations to be in place. This creates the classic chicken and egg problem. Hydrogen providers will be unwilling to provide huge investments in refuelling infrastructure before the demand for hydrogen is already present and the cars are out on the road. Likewise, car manufacturers will be reticent to produce hydrogen fuel cell vehicles without the necessary infrastructure in place to cater for refuelling.

Storage and Transport

Onboard vehicle hydrogen storage is another area of infrastructure that will benefit from further research and development. A number of methods for the on-board storage of hydrogen are currently under development, such as metal hydrides and carbon nanotubes. These technologies hold potential for the future but are still in developmental phase and have various disadvantages associated with cost and weight. Alkali Hydrides also present a possible future safe method for carrying hydrogen. However, the process generally involves the use of dangerous or toxic chemicals and may also involve expensive recovery equipment.[34] Present onboard storage options of compressed gaseous hydrogen or liquefied hydrogen, while economically viable, have various problems of volume, cost and energy efficiency.

Currently, compressed hydrogen is the most cost effective method of onboard storage.[35] Compressed gaseous hydrogen storage systems generally have about 1/10 the volumetric energy storage density of petrol.[36] About 15 percent of the stored energy is needed for compression of hydrogen and about 30-40 percent for liquefaction.[37]

[34] Amos, 1998.
[35] Padro and Putsche, 1999.
[36] Ogden et al., 2000.
[37] Amos, 1998.

Off-board storage of hydrogen also presents problems of energy efficiency. Small amounts of hydrogen may be stored as a compressed gas in pressure tanks or as a liquid in cryogenic containers or dewars. As liquid hydrogen is stored as a cryogenic liquid (i.e. at its boiling point) it must be very well insulated, as any heat transfer will cause boil off (evaporation of hydrogen).[38]

Depending on the geology of an area, underground storage of gaseous hydrogen may be possible.[39] Old oil and gas fields, underground aquifers, and salt and rock caverns hold potential for bulk storage of hydrogen. However, as much as 50% of the working volume may be unrecoverable; solutions for this, such as displacing the hydrogen by pumping in brine, are costly.[40]

Hydrogen is currently transported by ship as a liquid or by truck as a liquid or gas. Transport of hydrogen in this way is highly inefficient. As use increases, it may be viable to create a hydrogen gas pipe network system analogous to the present natural gas pipeline system.

Public Acceptance

Public acceptance and consumer desire for hydrogen technologies is something that needs to be fostered for the hydrogen economy to progress smoothly. Fears of risk associated with the use of hydrogen are perpetuated by its unfamiliarity. Highly vivid and widely publicised accidents, such as the Hindenburg and Challenger disasters, have promoted concern over hydrogen use, even though hydrogen was not responsible for either tragedy.

The 1986 Challenger shuttle explosion was caused by the rupture of an O ring in the solid fuel booster rocket.[41] At the time of the Hindenburg disaster in 1937 it was thought that the hydrogen used to inflate the dirigible had caused the tragedy. However recently Addison Bain, a former manager of hydrogen programs for NASA, discovered that the covering of the Hindenburg had been treated with flammable compounds, which caused the dirigible to ignite in an electrical storm.[42] Almost all of the 35 passengers who lost their lives did so by jumping from the ship. See www.ch2bc.org/hindenburg.htm for the full story on the Hindenburg disaster.

If the general public and decision makers, such as government officials, are not provided with informed advice on safety issues concerning hydrogen fuel cell vehicles or the use of hydrogen as a distributed power source, then the introduction of hydrogen technologies could be delayed significantly.

Safety

Safety concerns may present a barrier to the early introduction of hydrogen technologies. While it is acknowledged that hydrogen is comparatively just as safe, if not safer than the use of other fuels such as petrol, its different properties present different concerns. "Hydrogen can be handled safely, if its unique properties –

[38] Hart, 1997.
[39] Zittel & Wurster, 1996.
[40] Amos, 1998.
[41] Cannon, 1995.
[42] Thomas & Zalbowitz, 1999.

sometimes better, sometimes worse, and sometimes just different from other fuels – are respected".[43]

Hydrogen will burn over a large range of concentrations in air and very little energy is needed for ignition. However, the lower limits for flame emissivity make it a safer fuel in confined spaces (which is particularly important for vehicle fuel use). Because of hydrogen's very low density it will disperse very quickly in unconfined spaces unlike petrol, which has a tendency to puddle. Hydrogen is also non-toxic, whereas petrol is poisonous to both humans and wildlife. See Table 2 for a comparison of safety related characteristics for gasoline, methane and hydrogen.

Hydrogen has been used in industry for many years; the technology to produce, transport and use hydrogen safely is well known. However, there are currently very few guidelines governing the use of hydrogen as a transport fuel. Codes and standards must be developed as soon as possible to ensure a safe and efficient widespread introduction of hydrogen technologies. Because there has not been wide use of hydrogen as a transport fuel, training programs are also scarce and must be increased.

Table 1. Comparison of safety properties between Gasoline, Methane and Hydrogen.[44]

Property	Gasoline	Methane	Hydrogen
Density (Kg/M3)	4.40	0.65	0.084
Diffusion Coefficient In Air (Cm2/Sec)	0.05	0.16	0.610
Specific Heat at Constant Pressure (J/Gk)	1.20	2.22	14.89
Ignition Limits In Air (vol %)	1.0-7.6	5.3-15.0	4.0-75.0
Ignition Energy In Air (Mj)	0.24	0.29	0.02
Ignition Temperature (^oC)	228-471	540	585
Flame Temperature In Air (^oC) Explosion	2197	1875	2045
Energy (G TNT/kj)	0.25	0.19	0.17
Flame Emissivity (%)	34-43	25 -33	17-25

[43] Conclusions from a major 1994 study of hydrogen safety carried out at the Sandia National Laboratory, USA.
[44] Veziroglu, 2002.

Figure 3. Simulation comparing severity of a hydrogen and gasoline fuel leak and ignition. (Dr Michael Swain, University of Miami.)

The simulation in Figure 2 demonstrates the safety advantage hydrogen's low density compared to petrol. When leaked in an unconfined space, hydrogen will rapidly dissipate, whereas petrol will tend to puddle.

Automobile manufactures developing hydrogen-fuelled cars have all conducted tests to determine the safety of hydrogen as a vehicle fuel. "BMW conducted numerous crash tests to see what would happen if the hydrogen tank was punctured or damaged. Their engineers report the liquid hydrogen dissipated harmlessly into the air."[45]

Cost

Cost is currently a major barrier to the introduction of a hydrogen economy. The initial investment required for hydrogen technologies is large, and because it is a fledgling industry, has uncertain returns. Hydrogen technologies, such as hydrogen fuel cell vehicles, are currently 'handmade' and therefore are yet to experience cost reduction through economy of scale.

Once mass markets for hydrogen vehicles begin, they should be an economically viable alternative to current vehicle technology on a lifecycle basis.[46] Significant investment from industry and government is needed in the meantime to get to a situation where large-scale production is possible. Costs will be further reduced as development proceeds through experience (learning by doing). While the internal combustion engine has had over 100 years of development, the hydrogen fuel cell is an immature technology, with significant opportunity for cost reduction and performance improvement.

The cost of building hydrogen infrastructure, such as hydrogen pipelines and refuelling stations will probably be in the billions of dollars. Shell Hydrogen have predicted that the cost of building Hydrogen fuel plants and stations in the U.S. would be US$19B; US$1.5B in Britain; and US$6B in Japan.[47] However, if the

[45] Marsha Walton, CNN Science and Technology, 2001.
[46] Ogden et al., 2001.
[47] Adam Piore, Newsweek International, April 8, 2002.

infrastructure is built up gradually – using small scale localised reformers, introducing fuel cell vehicles initially within fleets then linking up corridors of refuelling stations, demand may be catered for as it increases without initial costs being exorbitant.

Significant research and development is needed to further bring down the costs of hydrogen production, storage and use. Because many hydrogen applications include the use of immature technologies such as fuel cells, more time and money devoted to research and development should provide significant benefits.

Lifecycle Cost

Cost is one of the major barriers to the introduction of hydrogen fuel cell vehicles. This high cost arises primarily because hydrogen fuel cell vehicles and stationary power plants are radically new technologies that are trying to displace an entrenched technology that has had over 100 years of development and is supported by an extensive infrastructure system.

A study completed by Ogden et al. (2000) found that when environmental externalities are taken into account, the hydrogen fuel cell vehicle "costs no more on a lifecycle cost basis than other long term efficient, lower polluting vehicles such as gasoline or Diesel ICE/HEV"[48] (internal combustion engine/hybrid electric vehicles).

The results of the study depend on a number of assumptions, such as the mass produced cost of fuel cell and hybrid electric vehicle drive components. External environmental costs were derived from damage costs associated with air pollution (smog/particulates etc.) and greenhouse gas emissions. For the full study results and methods see Ogden et al., (2000).

In the same study, the buy-down cost of hydrogen fuel cell vehicles was calculated and estimated to be US$1.6 billion. About 1.3 million H_2FC cars would have to be produced (within the one fuel cell car factory) to reach lifecycle cost parity with gasoline ICE/HEVs (Internal combustion engine/hybrid electric vehicle).[49] The buy-down cost is the cumulative lifecycle cost expenditures in excess of the market clearing cost (the lifecycle cost at which the FC car is competitive with the gasoline ICE/HEV).

Stakeholders

Government

The Government has a mandate to look after the common good of the nation's people. This includes working to protect social and environmental ideals that may be jeopardised by purely commercial activities. Under this mandate it is the government's role to support the development of alternate fuels (such as hydrogen) to reduce dependence on fossil fuels and secure a healthy environment for present and future generations.

Governments are often notoriously slow and inefficient in supporting the development of new technologies. However, the Federal Government must, as far as

[48] Ogden et al., 2000.
[49] Ogden et al., 2001.

possible, reduce barriers to the implementation of the hydrogen economy. This will be done through working closely with industry, all other levels of government, academia and community organizations. In particular the Federal Government must provide seed money (especially where initial investment returns are unknown or uncertain) and ensure a sound regulatory environment for the introduction of various hydrogen technologies.

The main government barriers to developing hydrogen technologies include a lack of political awareness or support, budget constraints, and the absence of consensus commitment to reduce greenhouse gas emissions and move towards a sustainable hydrogen economy.

State Government

The role of the State Government follows on from that of the federal government in removing barriers and providing funding and incentives to encourage the transition to hydrogen. State government agencies also have a further role to play in the development of local codes and standards, and dealing with issues of siting of production facilities and refuelling stations etc.

Local Government

Local government has a role to play in zoning approval processes for the siting of hydrogen infrastructure and facilities. They also have a role to play in public awareness campaigns to educate the community about hydrogen technologies, such as the hydrogen fuel cell vehicle.

Industry

Industry has the means to define market place needs and shape the development of hydrogen technologies to cater for these needs in the most appropriate manner. Industries, while responsible to shareholders, have the expertise and resources to kick-start emerging technologies in the most efficient and cost-effective way.

Barriers facing the vehicle industry in the development of the hydrogen economy are cost, lack of refuelling infrastructure, inefficient onboard storage, large initial investments with as yet uncertain returns, and lack of hydrogen codes and standards.

Hydrogen energy providers face the challenge of a lack of hydrogen vehicles, difficulty in obtaining insurance (new technology), uncertain returns on investments, geographically dispersed investments, uncertain pay off time depending on market penetration, and a lack of regulations, codes and standards.

Academia

Academic institutions have an important role to play in research and development of hydrogen technologies. They also must play a part in educating students and the wider community about the state of fossil fuel reserves, their environmental impact and the properties of hydrogen as an alternative fuel.

Community

Community members in general have a role to play in the promotion and awareness of hydrogen as a fuel. It is also important for community members to set up organisations that bring together different parties and help with the progression towards a hydrogen economy.

The main barriers to the hydrogen economy from the point of view of the general public are lack of confidence in the safety of hydrogen, unfamiliarity, lack of hydrogen fuelling options, cost.

Existing Action

The development of the hydrogen economy is very much in the early stages. However, activity is increasing in the area of hydrogen energy technology at an almost unprecedented pace.

Few research and development projects are currently underway in Western Australia, or Australia. However, Western Australia has the opportunity to lead the Asia Pacific region in the development of hydrogen energy systems by acting now to start initiatives that encourage the research, development and adoption of hydrogen technologies.

Australia

DaimlerChrysler Hydrogen Fuel Cell Bus Trial

Figure 4. Example of the Daimler-Benz hydrogen fuel cell bus to be trialed.

Beginning in 2003, Perth will be host to one of the first commercial trials of hydrogen fuel cell buses in the world. This trial is part of a European Union project titled 'CUTE' (Cleaner Urban Transport for Europe). The CUTE project involves the trial of three DaimlerChrysler hydrogen fuel cell buses on normal service routes in each of 10 European cities (Perth will be the only city outside Europe). The European cities include Stuttgart, Hamburg, Luxemburg, Stockholm, London, Porto, Barcelona, Rekyavik, and Amsterdam. The trial will run for two years from mid 2003 to 2005.

Figure 5. The fuel cell system is housed at the rear of the bus. The compressed gaseous hydrogen is stored is stored in tanks on the roof of the bus.
Passenger capacity: 60-70 people (30 seats)
Net power of the fuel cell: >200 kW
Range: 200-300 km
Max speed: 80 km/hr

The purpose of the trial is to determine the critical technical, environmental, economic, and social factors that need consideration in the introduction of hydrogen fuel cell vehicles. The cities were chosen for their different topographic and climatic conditions to ensure the acquisition of performance data under a wide range of conditions. Perth was included because of the long distances and high speeds our buses travel at compared to those in Europe.

Different feedstocks, energy sources and methods will be used for the production of hydrogen in each of the cities. In Perth, B.P. will provide a purified form of hydrogen from their Kwinana refinery. In other cities a combination of electrolysis using renewable energies and steam reforming of natural gas will be used. The economic cost and environmental impact resulting from the different production methods and feedstocks will be analysed.

A number of work packages have been prepared and will be completed by various consortium members in each city. The consortium members include energy suppliers, transport companies, government bodies, universities, and consultants. The work packages are aimed at capturing knowledge of the technical, economic, environmental, and social factors surrounding the emerging technology. Variables such as breakdown rates, fuel efficiency, public acceptance etc. will be analysed in each of the cities. All learning from the trial will be shared amongst the participants. One bus in Perth will also be used to demonstrate its potential as a stationary power source.

The European Union is committing significant funds to the European trials; the Australian Federal Government's Alternative Fuels Programme has committed $2.5M to the Perth trial. The United Nations Environment Program and the United Nations Industrial Development Organisation have both endorsed the Perth trial. The Department of Planning and Infrastructure in Western Australia is responsible for the coordination of the trial (www.transport.wa.gov.au/fuelcells).

The price of the hydrogen fuel cell buses for the trial is significantly greater than the current purchase price of CNG and diesel buses. However, it has been predicted that the hydrogen fuel cell bus will be cost competitive with diesel and natural gas buses by 2006-8.[50] These views were supported at a recent United Nations Workshop held in New York, April 2000, "*Commercialisation of Fuel Cell Buses: Potential Roles for the GEF*".

CSIRO

The CSIRO and Ceramic Fuel Cells Ltd (Australia's leading fuel cell enterprise) are currently working on a project developing high temperature fuel cells for stationary applications. See http://www.csiro.com.au and http://www.cfcl.com.au/index.html.

Academic Institutions

Various universities around Australia are involved in fuel cell and hydrogen production research and development projects. In particular, the University of New South Wales (UNSW) and the Australian National University (ANU) are involved in significant projects. Murodch University (W.A.) is also involved in fuel cell and hydrogen research projects and will be actively involved in the Perth Hydrogen Fuel Cell Bus Trial.

Global Industry

Automobile manufacturers

Fuel cell vehicles have been trialed in a number of cities around the world, and an unprecedented research and development race is now on between automobile manufacturers to be first to market with fuel cell vehicles.

DaimlerChrysler, who have forecast a budget of US $1B on fuel cell research in the next 10 years are aiming to produce their first commercial fuel cell passenger vehicle by 2004.[51] By 2010, DaimlerChrysler hope to have fuel cell vehicles comprise between ten and twenty percent of their new car production.[52]

[50] Department of Planning and Infrastructure, 2000.
[51] DaimlerChrysler, 2002.
[52] Wurster, 2001.

Figure 6. DaimlerChrysler prototype fuel cell vehicles.

> "The fuel cell is the most promising option for the future. We are determined to be the first to bring it to market." *Juergen Hubbert, DaimlerChrysler*

Figure 7. Ford Focus fuel cell vehicle.

"The Focus FCV (fuel cell vehicle) is expected for fleet availability in 2004."[53] The Focus FCV combines high- pressure hydrogen gas storage with a Ballard Mark 900 fuel cell. The vehicle has a top speed of greater than 80 miles per hour and a range of 100 miles.[54]

> "In today's world, solving environmental problems is an investment, not an expense." *William Clay Ford, Jr. Chairman and CEO, Ford Motor Company, September 1998*

> "I believe fuel cells will finally end the 100 year reign of the Internal Combustion Engine."
> *William Ford   Chairman, Ford Motor Company.*

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[53] Ford Motor Company, 2002.
[54] U.S. Department of Energy's Energy Efficiency and Renewable Energy Network, 2002.

Figure 8. Toyota hydrogen fuel cell vehicle prototype.

Toyota are planing to release their first fuel cell passenger vehicle in 2003 in Tokyo, Japan.

General Motors have committed themselves towards being the first automobile company to have 1 million fuel cell vehicles on the road.[55] GM/Opel hope to have fuel cell vehicles comprise 10 percent of new vehicle production by 2010.[56]

> "Our long-term vision is of a hydrogen economy."
> *Robert Purcell Jr., Executive Director of General Motors.*

BMW are developing hydrogen fuelled ICE (internal combustion engine) passenger vehicles. Together with a fuel retailer, BMW intends to offer liquid hydrogen at refuelling stations in the vicinity of all BMW dealerships around Europe by 2005.[57]

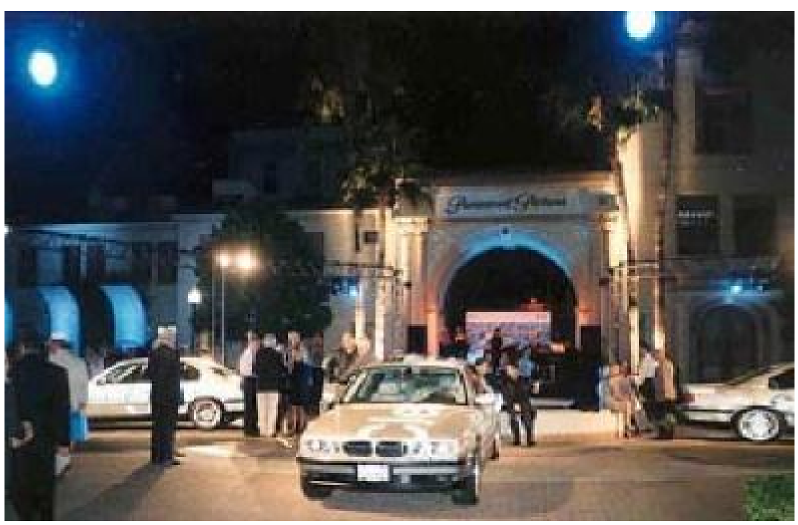

Figure 9. Unveiling of the BMW hydrogen ICE vehicle.

[55] General Motors, 2001.
[56] Wurster, 2001.
[57] Wurster, 2001.

"The hydrogen age has begun." (*BMW, 2002*)

BMW are undertaking a 'CleanEnergy World Tour' in 2002 to showcase hydrogen technology and the hydrogen internal combustion engine to leading decision makers from politics, industry and science. "The goal is to establish a hydrogen infrastructure through global partnerships in order to cause the breakthrough of the fuel of the future."[58] The tour will travel through five continents.

Energy Companies

All major energy companies around the world are starting to position themselves towards the emerging hydrogen economy.

Shell and B.P. both have major Hydrogen divisions within their companies. Exxon Mobile, working with General Motors and Toyota, claims to spend US $100M a year on research. Texaco is a major investor in hydrogen storage technology.

> "Just as hydrogen power may be the oil of tomorrow, that fine, so long as it's Shell Hydrogen that everyone's buying. For my part, if the world thinks that CO_2 emissions should be reduced, I see this as an opportunity. The Stone Age didn't end because they ran out of stones – but as a result of competition from the bronze tools, which better met people's needs. I feel there's something in the air – people are ready to say that this is something we should do."
> *Shell Oil Chief, Jeroen van der Veer speaking about hydrogen energy to the World Petroleum Congress, June 2000.*

A number of technology companies such as United Technologies, General Electric and Du Pont are also positioning themselves to take full advantage of the emerging hydrogen economy. On the 20th March, 2002 UTC Fuel Cells (United Technologies Corporation) announced the sale of seven PC25TM fuel cell power plants to be used as primary power for a critical call-routing center on Long Island, New york. Generating 1.4 MW of electricity, this will be the largest fuel cell installation to date in the world.

U.S.A.

In January 2002, U.S. Energy Secretary Spencer Abraham announced a US$150M initiative called FreedomCAR (Cooperative Automotive Research). FreedomCAR is a public-private partnership between U.S. Energy Department and U.S. automobile manufacturers to promote the development of hydrogen as a primary fuel for cars and trucks. FreedomCAR replaces the 'Partnership for a New Generation of Vehicles' that had been introduced by the previous Clinton administration, which focused on improving the fuel efficiency of petrol vehicles.

The announcement of this program led to the comment by a journalist, Dan Vergo of USA Today, that "Federal Officials may have staked our energy future on hydrogen."

[58] BMW, 2002.

The U.S. also currently has a program providing $3B over 11 years in Consumer Tax Credits for the purchase of hybrid or fuel cell vehicles.

The U.S. Department of Energy's Clean Cities Program supports public-private partnerships that deploy alternative fuel vehicles and build supporting alternative fuel infrastructure <<www.ccities.doe.gov>>.

The U.S. Department of Energy has also officially called for hydrogen-based energy to replace the equivalent amount of fossil-fuel energy to power 2 million to 4 million American households by 2010, and 10 million households by 2030.[59]

> "Hydrogen is getting major attention by the Bush administration. The administration has caught the vision of hydrogen and what it can do for our economy, our energy security and the environment." *John Turner, a principal scientist at the Department of Energy's National Renewable Energy Lab in Golden, Colorado, 2002.*

Other nations

Other nations, such as Canada, Iceland, and Japan, have significant hydrogen and fuel cell development programs. The Canadian Transportation Fuel Cell Alliance is a $23 million federal government initiative that will demonstrate and evaluate fuelling options for fuel cell vehicles in Canada. Iceland has made a commitment to be the first hydrogen based economy in the world. According to a joint World Wildlife Fund – Iceland Nature Conservation Association Report, Iceland could power up to 40% of its cars and fishing vessels with hydrogen by 2020, and have a 100% hydrogen based transport system within 35 years.[60]

Academia

A considerable amount of research and development work is being done in universities around the world in the area of hydrogen energy use and associated technologies. Two such universities are Princeton, New Jersey, USA http://web.princeton.edu/sites/PEI/ and Imperial College in London, UK http://www.env.ic.au.uk.

Murdoch University, Western Australia, will be closely involved in the Perth Hydrogen Fuel Cell Bus Trial and will be responsible for carrying out much of the analysis of the trial.

Communities

Collaboratives and partnerships, such as the International Association for Hydrogen Energy and the California Fuel Cell Partnership are promoting the use and development of hydrogen through disseminating information, coordinating trials and demonstrations and bringing together different stakeholders.

The International Association for Hydrogen Energy ‘strives to advance the day when hydrogen energy will become the principal means by which the world will achieve its

[59] Scott Powers, *Orlando Sentinel*, April 2002
[60] World Wildlife Fund, 2001.

long-sought goal of Abundant Clean Energy for Mankind. Toward this end, the Association stimulates the exchange of information in the Hydrogen Energy field through its publications and sponsorship of international workshops, short courses and conferences. In addition, the Association endeavours to inform the general public of the important role of Hydrogen Energy in the planning of an inexhaustible and clean energy system.' http://www.iahe.org

The California Fuel Cell Partnership is a collaboration of auto companies, fuel providers, fuel cell technology companies and government agencies working to demonstrate fuel cell vehicles and remove barriers to commercialisation. http://www.fuelcellpartnership.org

The California Hydrogen Business Council is a 'non-profit corporation dedicated to educating the public and public service sectors on the present developments and future uses of hydrogen and opening business partnership opportunities toward developing a non-polluting global energy economy' www.CH2BC.org.

Individuals are also capable of exerting considerable influence on the general public and government officials in promoting hydrogen use. An example of such an individual was a U.S. citizen, Dr. Zweig, who passed away in February 2002. Dr Zweig was renown for his work promoting hydrogen and policies that would reduce the impact of air pollution on his patients.

> "He fought so hard to educate the public, policy makers, and anyone else who would listen on the benefits of moving to a hydrogen energy economy, from the halls of Congress and the Offices of the President and Vice President of the United States to the schoolhouses."
> *James Provenzano,* Executive V.P. Clean Air Now, 25 Febrary, 2002.

Other individuals such as Dennis Weaver are promoting a hydrogen economy through setting up non-profit organizations such as the Institute of Ecolonomics.
Actor and community leader Dennis Weaver founded the institute (based in Colorado, U.S.) in 1993. The institute actively helps to identify, research, demonstrate and promote economically viable, environmentally friendly technologies and products. The Institute for Ecolonomics has organised such events as the 'drive for life, 2001' – a convoy of alternative fuelled vehicles (with an emphasis on hydrogen), which travelled from Los Angeles to Denver in the U.S. Another such event is planned for 2002. http://www.ecolonomics.org

Strategies for change

> "If we really decided that we wanted a clean hydrogen economy, we could have it by 2010".
> *Researcher from US National Renewable Energy Laboratory (2001).*

While most energy experts around the world now believe that a future hydrogen economy is inevitable, few are able to predict the timeframe of the transition away from oil. The vast majority of experts seem to agree that hydrogen fuel cells will be the ultimate power source for transportation.[61] If action is not taken soon, however, the transition will involve significant environmental and economic problems that may otherwise be avoided. For a sustainable future preserving or improving our present quality of life, it is imperative that we begin to move now towards a hydrogen economy.

> "In the long term we have to move to hydrogen. It's the only way to really divorce ourselves from fossil fuels."
> *Margaret Mann, an engineer at the U.S. National Renewable Energy Laboratory, 2001.*

Commercialisation Plan

With the technology of the hydrogen fuel cell for practical senses already proven, the challenge now facing Western Australia (and the rest of the world) is to reduce costs of the technology to competitive levels. Cost reduction will begin to occur naturally through economy of scale when the stage of mass production is reached. Hydrogen energy system technologies, such as the hydrogen fuel cell, are still immature and will benefit from the experience of 'learning by doing'. Therefore, costs will also reduce as learning is accumulated through the development process. Higher efficiencies and lower costs of renewable energy production will also help to reduce the cost of hydrogen production via electrolysis.

Transportation

> "We believe the most promising long-term approach is to employ hydrogen fuel cells combined with electric drive. Therefore, the first element of our strategic approach is to develop technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles and assure the hydrogen infrastructure to support them."
> *David Garman, Assistant Secretary EERN, 2001.*

The main barrier to the large-scale introduction of hydrogen-fuelled vehicles is a lack of supporting infrastructure. Therefore, early introduction should be through fleet vehicles, which can be refuelled centrally. The fleet market will include public transport bus fleets, government department fleets and also industry work place fleets. Industries that produce or use hydrogen on-site are particularly well suited to early adoption of fuel cell vehicle technology.

[61] NAVC, 2000.

> "The lack of refueling infrastructure is one of the major challenges facing commercialization of fuel cell vehicles. Initially, fuel cell vehicles will be marketed as fleets to organizations that have the ability to install hydrogen-refueling stations." *Ford Motor Company, March 2002.*

Centrally fuelled fleets, if large enough, may accomplish buy down for the hydrogen fuel cell vehicle market before introduction to the passenger vehicle market. Ogden et al. (2001) estimate that fleet markets in the U.S. are large enough to achieve significant cost buy down over a ten-year period.

Once a number of individual hydrogen refuelling stations are set up (catering to specific fleets) they may be linked up to form corridors along well-used routes to start catering for the passenger market.

In the long-term, hydrogen may be produced centrally either from the reformation of natural gas or from renewable energy via electrolysis and distributed through a pipeline network. In the short-term however (before demand is sufficiently large), it will be necessary to use small-scale reformers and transport the hydrogen as a liquid or compressed gas via road. A fuel cell vehicle density of about 200 cars per square km has been cited as sufficient to justify the construction of a local hydrogen pipeline system.[62]

It is generally assumed that natural gas will pave the transition from oil dependency to a totally renewable hydrogen energy economy. Currently, the reformation of natural gas is the most economical method of hydrogen production.[63] The present resource of natural gas in Western Australia's northwest provides a fantastic opportunity to launch a hydrogen industry in the state. Hydrogen could be produced on-site and shipped straight overseas to the Asian market. Old natural gas fields in the Pilbara may be suitable for storage of large quantities of gaseous hydrogen.[64]

The opportunity also exists for hydrogen production in Western Australia via electrolysis using renewable energies such as solar and wind power. The Pilbara region is acknowledged as one of the highest solar flux areas of the world.[65] Wind power is already being harnessed in the Southwest of the state and the Kimberly holds the potential of harnessing tidal power. The Ord River may provide a limited source of hydropower.

Fixed Power

The reliability of stationary fuel cells as a continuous power source will ensure early application as a premium power source for businesses, hospitals, call centres etc. which need to have guaranteed continuous power supply. The other area of application to which hydrogen fuel cells are ideally suited (due to their need for minimal maintenance and the ability to be produced from renewable energy) is in remote communities, such as mine sites or Aboriginal communities.

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[62] Ogden, 1999.
[63] Gill, 1999.
[64] Reed et al., 1992.
[65] Reed et al., 1992.

The long-term vision for stationary power is a distributed generation system based on renewable electricity generation and fuel cell power systems. In remote locations where there is no electricity grid, hydrogen can provide storage of energy produced from solar energy and electrolysis. Business and private residences could use hydrogen for electricity and heating. As hydrogen fuel cells begin to be used more extensively in commercial businesses, prices will decline, and they will then become a more viable option for use in private homes.

Hydrogen holds tremendous potential for remote power generation in Aboriginal communities, mining towns, or environmentally isolated places like Rottnest Island. In remote locations, fuel is often either imported at great expense or intermittent renewable energy sources are relied upon. Hydrogen can be produced locally from renewable resources and serve as a reliable energy storage medium and fuel. The modularity, reliability and low maintenance (due to few moving parts) of hydrogen fuel cells make them an especially promising energy provider for remote communities.

Government, industry, academia and the broader community all have a role to play in the transition to a sustainable hydrogen economy. Summarised below is a strategy for these stakeholders to deliver a sustainable hydrogen economy in Western Australia.

Government

The main role of the Government is to assist in removing barriers that stand in the way of the developing hydrogen economy. This will be accomplished most efficiently by consulting and working closely with industry, other levels of government and community organizations.

Hydrogen Economy Taskforce
One of the main initiatives that could be organised in the short term is the creation of a state Hydrogen Economy Taskforce. This body could be organised from within a particular agency such as the Office of Energy. However, it is crucial that it has the ability to work closely with other departments and should be well represented by industry, academia and community representatives. Hydrogen activities around the state should be coordinated in a systematic way such that full learning is captured from each trial or demonstration, and work is not replicated. This body would help in the dissemination of information to the necessary parties, it could organise appropriate funding measures for various projects and would generally focus activities towards a properly defined goal allowing Western Australia to lead other states in Australia and nations in the Asia Pacific region towards the goal of a fully sustainable hydrogen economy. An energy strategy should be developed for state with reference to the gas transition and progression towards a future hydrogen economy.

Research and Development
Because of the infancy of most hydrogen energy systems there is still a great need for research and development. Industry cannot be expected to invest heavily in research that will also benefit other parties (free-loaders) or invest in technologies

that only provide benefits external to market costs (i.e. environmental benefits). Therefore, the government must assist in providing inducements for research and innovation. This research should focus on onboard storage options and various hydrogen production methods, including production from fossil fuels, biomass, municipal solid wastes, and renewable electrical sources.

Initial Investment

The government has a role to play in providing initial investment in the hydrogen industry. Initially, investments in many hydrogen technologies will have unknown returns. Companies and industries, beholden to shareholders, can only invest so far in schemes that have uncertain returns. The government will also need to support technologies, which although commercially ready still have proportionally high costs.

Low interest loans could be provided for remote communities to set up renewably produced hydrogen systems. The government should also continue to support hydrogen technology trials such as the Hydrogen Fuel Cell Bus Trial (outlined above). Because of the infancy of the industry, participation in early development projects, will give Western Australia the opportunity to help shape the future industry in ways that best suit the state.

Policy Framework

It is the responsibility of the government to produce a policy framework for the introduction of hydrogen technologies. Codes and standards must be developed as soon as possible to enable early development projects to go ahead without unnecessary delay. It is vital to the development of the industry that accidents do not occur in early development projects. While regulations and standards are still being drawn up, there is a need for a clearly defined inspection or certification process for refuelling stations and other hydrogen infrastructure.

Policy measures should be introduced to internalise environmental damage costs from the use of fossil fuels and oil scarcity costs. Such policy measures could include regulations such as a zero emission vehicle mandate, fuel and vehicle taxes, and/or clean technology rebates.

The most efficient way to cope with externalities is to internalise them in market prices by adding the lifecycle environmental damage cost to the price of fuel. This initiative would however, be politically contentious. Another way to approach this would be to tax new vehicle purchases, an alternative that would probably be less contentious and cause fewer problems. A revenue neutral situation of taxing high emission vehicles and using this tax as a rebate for zero or low emission vehicle purchases could be introduced. Over time, the level of subsidies would slowly decline.

In order to accomplish widespread adoption of hydrogen fuel cell vehicles, it will be necessary for the government to introduce specific policy measures such as a 'zero emission vehicle' (ZEV) mandate. Initially, the mandate should start low, increasing to a 50+% ZEV mandate as cost buy down is achieved through the fleet market. The introduction of such mandates are vital to drive fuel cell vehicle production, which will in turn drive fuel providers to provide hydrogen fuel infrastructure to cater for the vehicles. Without aggressive policy measures, it will be easy for Western Australia to fall behind development in other areas of the world where greater levels of air pollution provide a greater immediate incentive for developing hydrogen technologies.

Government Vehicle Fleets

The Government has a responsibility to set an example for clean transportation in the state. Therefore, government department vehicle fleets should be converted to hydrogen as part of the normal replacement program as soon as this becomes viable. The opportunity for centralised refuelling will allow for early introduction of hydrogen vehicles in this sector. The initial higher vehicle costs compared to conventional ICE vehicles should be viewed as a necessary investment to kick-start the hydrogen economy in the state.

Industry

The primary role of industry is in the development of technology from research laboratories into the market place. Companies must define growth market sectors for hydrogen technologies and convey needs to government in terms of appropriate policy framework, regulations, codes and standards.

Partnerships between industries, such as the California Fuel Cell Partnership (though on a smaller scale in Perth) will help in the initial development phase of hydrogen technologies before commercialisation is reached.

Industries must be prepared to undertake development projects in the short to mid term and invest in hydrogen technologies with uncertain investment returns. It may be beneficial to forward price products, providing the opportunity to capture a greater market share in a few years time when the technology has developed further, and demand is higher.

Industries with company vehicle fleets, particularly those that either produce or use hydrogen on-site, should lead the way in turning over their vehicle fleet to hydrogen fuel cell vehicles. Even if the costs of the hydrogen fuel cell vehicles are high compared to present day competing technologies, the industries will receive in-kind benefits from the initiative. Not only will it promote hydrogen fuel cell vehicles (and other hydrogen technologies), but it will also positively influence the public image of the company.

Academia

Academic institutions should direct increased resources to hydrogen energy research. Hydrogen energy systems could become an area of strength for a particular university, attracting extra government funding. Particular areas that would benefit from research (as mentioned above) are hydrogen production methods and hydrogen storage techniques. Universities should collaborate with government, industry and national bodies such as the CSIRO to undertake research and development projects.

Considering the potentially large market for stationary fuel cell technology in remote areas of Western Australia, this could become an area of strength for the state.

Therefore, extra resources should be earmarked for research and development in this area.

Classes in hydrogen and fuel cell technologies should be included to a larger extent in appropriate university courses. Knowledge of hydrogen and fuel cell technologies should also be included in school curricular.

If Western Australia is to develop its potential to be at the forefront of the hydrogen industry throughout the world (and certainly the Asia-Pacific region), specific measures must be undertaken now so that early progress is achieved and a slow drawn-out (and ultimately more costly) development process is avoided. A summary of short to long-term actions is set out below.

Timeline

Short Term (1 year)

- Set up an interagency Hydrogen Economy task force.
- Plan future research and development projects, in the area of both transport and stationary applications.
- Design government grants to specifically cater for research and development in the area of hydrogen energy.
- Begin first hydrogen fuel cell bus trial.
- Promote the use of hydrogen as an energy carrier throughout the community.
- Begin use of stationary fuel cells as backup power sources.
- Develop codes and standards for hydrogen production, storage, transport and use in Western Australia.

Mid Term (4 years)

- Begin introduction of hydrogen fuel cell vehicles into government and industry fleets.
- Begin to introduce specific policy measures such as a zero emission vehicle mandate for vehicle fleets.
- Expand trials of hydrogen fuel cells as power generation in remote locations of Western Australia. Begin stationary fuel cell demonstration projects in remote mining communities.
- Expand use of stationary fuel cells as back-up power sources for critical power supply to replace emergency generators.
- Expand hydrogen fuel cell demonstration projects to include various hydrogen production methods including reformation of natural gas, gasification of biomass, solar energy based electrolysis.
- Increase government and industry funding to research and development projects.

Long Term (20 years)

- Expand zero emission vehicle mandates to include the passenger vehicle market (for example 20%).
- As demand for hydrogen fuel grows, further develop hydrogen production capacity and expand hydrogen export markets to the Asia Pacific region.
- Invest in hydrogen infrastructure to cater for hydrogen vehicles.

- Introduce hydrogen fuel cell vehicles as part of the normal replacement program for public transport bus fleets and require the same for government department fleets.
- Introduce specific policy measures for stationary power sources (for example, a requirement of 10% new electrical generation to be from hydrogen).

Measuring Progress

Western Australia's progress will probably be best measured through comparison with other countries and states around the world. Target goals will be very tentative because development progress of various technologies is uncertain. Goals should continue to be revised as technological progress is achieved.

Expert estimates of the timeframe for fuel cell transit vehicles to comprise 5% of the market range from 2005 – 2010, with most predicting between 2008 – 2010.[66] It should be Western Australia's goal to achieve such targets within the earliest possible timeframe and to remain at the forefront of world activity.

Progress such as the mass production of hydrogen fuel cell vehicles is largely dependent on global car manufacturers and the will of countries, such as America, with the largest car markets. However, in terms of local hydrogen production, or the development of stationary fuel cells for application in remote communities, progress in Western Australia should have fewer constraints from outside forces. It is in these areas that Western Australia should have clearly defined goals. An export market for hydrogen gas/liquid should be developed and Western Australia should be regarded as the leading provider in the Asia-Pacific region.

As viable development paths to energy independence in Western Australia are more clearly defined, and as hydrogen energy systems begin to compete on a commercial basis with conventional fossil fuel use, we will know that we are on the path to a clean and sustainable energy future in Western Australia.

[66] NAVC, 2000.

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For a glossary of hydrogen and fuel cell terms see http://www.hydrogen.org/index-e.html