Final Report

Hydrogen Production from Renewable Energy by Electrolysis

Centre for Research into Energy for Sustainable
Transport (CREST), Perth, Australia

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Title of the Study: Hydrogen Production from Renewable Energy by Electrolysis

Client: Centre for Research into Energy for Sustainable Transport (CREST), Perth, Australia

23rd March 2010

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Cover photograph: Andrew D Moore (Alinta Wind Farm, Geraldton, Western Australia)

Document Management

Date	Version	Author/editor	Description of Change
8/1/2010	v1	Andrew D Moore	Draft Document for comment created
12/1/2010	v2	Barbara Nebel	Review by Dr Barbara Nebel
12/1/2010	v2	Simon Whitehouse	Review by Simon Whitehouse
12/1/2010	v2	Dr Michael Faltenbacher	Review by Dr Michael Faltenbacher
15/1/2010	v2	Klaus Stolzenburg	Review by Klaus Stolzenburg
25/1/2010	v3	Andrew D Moore	Incorporated feedback by reviewers
12/3/2010	v4	Andrew D Moore	Incorporated feedback from CREST
23/3/2010	v5	Andrew D Moore	Minor changes. Document accepted and finalised

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Nomenclature

Abbreviation	Explanation
AC	Alternating current
AUD	Australian dollar (equal to EUR 0.6 or USD 0.88,for 6 month average between 1 July to 31 December 2009 (Exchange rates.org 2009)
bar	Unit of pressure equal to 100 kPa or 0.987 atmospheres
BEV	Battery electric vehicle
CGH_2	Compressed gas hydrogen
CNG	Compressed natural gas
CUTE	Clean urban transport in Europe
DC	Direct current
DPI	Department for Planning and Infrastructure, Western Australia
ECTOS	Ecological City TranspOrt System. Hydrogen bus trials in Reykjavik, Iceland.
EUR	Euro
FC	Fuel cell
GHG	Greenhouse gas
H_2	Hydrogen
H_2O	Water
HEV	Hybrid electric vehicle
HHV	Higher heating value or gross calorific value. For hydrogen the higher heating value is 3.54 kWh/Nm^3.
kg	Kilogram
KOH	potassium hydroxide
kWh	Kilowatt hour (3.6 MJ)
L	Litre
LH_2	Liquid hydrogen
LHV	Lower heating value or net calorific value. For hydrogen the LHV is 3.0 kWh/Nm^3.
MJ	Megajoule
MW	Megawatt

Abbreviation	**Explanation**
NG	Natural gas
Nm^3	Normal cubic metres (Nm^3). $1Nm^3$ of hydrogen contains 3.0 kWh/Nm^3 lower heating value and 3.54 kWh/Nm^3 higher heating value, and weights 0.09 kg (CUTE 2004).
O_2	Oxygen gas
PEM	Proton exchange membrane
PSA	Pressure swing adsorption
PV	Photovoltaic – technology for producing electricity from solar energy
SMR	Steam methane reformation
STEP	Sustainable transport energy for Perth
SWIS	South West Interconnected System
WA	Western Australia

Executive Summary

Hydrogen has been proposed as part of the solution to address issues such as peak oil and global warming. It can be produced from water using renewable energy and used to power vehicles. If the hydrogen is consumed in a fuel cell the only tailpipe emissions, during the use phase, are water vapour. Hydrogen can also be used for stationary applications, and has the potential to improve integration of intermittent renewable energy sources into the electricity networks.

This status report investigates the technology currently available for hydrogen production and reports on the results from hydrogen program trials including the CUTE trials[1].

The Clean Urban Transportation for Europe (CUTE) project was conducted from 2001 to 2006 with the aim to assess, in real world conditions, hydrogen technology in terms of availability, efficiency, cost, environmental benefits, safety, technology maturity, and stakeholder satisfaction. 27 buses were trialled in 9 cities including Amsterdam, Barcelona, Stuttgart, Stockholm, Madrid, London, and Hamburg. Associated projects were conducted with two other cities; STEP in Perth, Western Australia; and ECTOS in Reykjavik, Iceland.

This report follows the four steps outlined in the research plan as contained within the scope of works:

1. Undertake a review of the technology available for hydrogen production by electrolysis of water using renewable energy;
2. Obtain data on the CUTE trials of electrolysis from renewable energy;
3. Analyse the data to determine energy efficiency, costs of H_2 and any technical or environmental issues for the various technologies;
4. Attempt to identify the best option for producing "Renewable Hydrogen" in WA.

Review of hydrogen production technologies

Hydrogen can be produced from a range of technologies, the most mature of which are alkaline electrolysis, PEM electrolysis, and steam reformation of methane gas. Other methods currently being developed include; production of hydrogen from biomass such as biochemical conversion, thermochemical conversion, and fermentation; and methods to produce hydrogen from direct solar energy include thermolysis and photolysis. The most promising of these emerging technologies is thermochemical conversion of biomass.

Results of hydrogen program trials

Hydrogen production using onsite alkaline electrolysis was overall very successful during the CUTE trials with the units performing both reliably and within design specifications. Intermittent operation caused no problems for these units. Efficiency was good at 59% overall (lower heating value) which is likely to improve by up to 10% in the short term. The prototype onsite steam methane reformer units did not perform well under the conditions of intermittent hydrogen demand (hence requiring intermittent operation). This caused problems resulting in low overall efficiency and availability. Average efficiency was meas-

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[1] Final evaluation reports for the HyFLEET:CUTE trials have not been published but where information was available it has been included in this report

ured to be 36% overall although 53% production efficiency was achieved when units were operated continuously. The outlook is good with improved efficiencies forecast; although problems caused by intermittent operation are unlikely to be resolved due to the nature of the process. PEM electrolysers were not used during the CUTE trials. These types of units have, however, been installed in the first public hydrogen refuelling stations in the US and efficiencies are expected to be similar for alkaline electrolysers.

Cost estimates for hydrogen production in the CUTE project are higher than other studies because they are based on measured data from real life trials of the technology, much of which were prototypes. Cost for hydrogen production by alkaline electrolysis in the CUTE trials averaged at EUR 14 per kg (at EUR 0.10 /kWh for electricity). Half of the cost was associated with energy supply, the rest associated with initial investment, and maintenance. By 2015, as hydrogen production is increased to meet the European Commission 2% hydrogen fuel by 2015 goal, the cost is forecast to decrease to around 8 to 9 euros per kg. Cost for hydrogen production by steam methane reformer during the CUTE trials averaged EUR 14 per kg despite some problems. If the units operated at specification the cost would have been lower at EUR 12 per kg. Future cost (2015) is anticipated to be EUR 5 per kg by steam methane reformation of natural gas.

Bartholomy (2005) raised some interesting issues based on a study of hydrogen production from wind in California. He claimed the use of renewable energy to offset electricity generated from fossil fuels (such as coal) may have a better environmental outcome than using the renewable energy to produce hydrogen to offset the use of petrol or diesel in vehicles. The niche in which hydrogen vehicles will operate will be influenced by competing yet complementary technologies, such as battery electric vehicles, which share many components with hybrid hydrogen vehicles.

Renewable hydrogen in WA

Considering the large transport distances in WA, low volumetric density of trucked hydrogen fuels (compared to liquid fossil fuels), and the high capital cost of hydrogen pipelines-production of hydrogen in WA is likely to be local (on-site) rather than centralised. The exception would be the use of by-product hydrogen from the BP refinery, as used in the Perth STEP hydrogen bus trials, which could be used to kick-start the hydrogen vehicle use in Perth. For onsite production electrolysis seems the most likely scenario for WA given the success of the alkaline electrolysers during the CUTE trials for this application. Wind power capacity in WA is being expanded rapidly due to the maturity and cost competitiveness of this technology. It is therefore the most likely source of renewable electricity to be used to generate onsite hydrogen by electrolysis. Due to the limited extent of the WA electricity grid (compared to the size of the state) hydrogen production in regional areas for vehicle refuelling will also have to be considered.

The increase in intermittent renewable energy sources such as wind will potentially create a niche where hydrogen can be generated from off-peak capacity that may otherwise go unutilised. This potential opportunity needs further research. Biomass would be favourable for centralised production of hydrogen using steam methane reformer technology but due to the distribution issues of hydrogen as mentioned above onsite generation using electrolysis is more likely.

Further research should be conducted to model and simulate hydrogen production scenarios for WA to determine the conditions under which production of hydrogen by renewable energy would be most favourable from the perspective of cost, environmental impact, and energy security.

1 Introduction

1.1 Background

Climate change and peak oil are two major issues that human civilisation must address to have a sustainable and prosperous future. The question is how can hydrogen help to address these and other environmental and energy issues.

Hydrogen has been proposed as having a role in the solution given that it can be produced from water and can be used in a fuel cell where the only tailpipe emissions are water vapour. Hydrogen can be used as a transport fuel as well as for stationary applications, and has the potential to improve integration of intermittent renewable energy sources into the electricity networks. The use of hydrogen can reduce dependence on imported foreign oil which Australia is increasingly relying on since it is a net importer of crude oil and refinery products (ABARE 2009). The energy used to produce the hydrogen, however, must come from sustainable sources and, over the full life cycle, have lower emissions than the current technologies for there to be any net environmental benefit. The efficiencies in the production, storage, and consumption of hydrogen therefore are critical. Environmental impact is only one of the considerations that must be taken into account along side economics, and security of supply issues. This status report investigates the technology currently available for hydrogen production and reports on the results of hydrogen production from hydrogen program trials, including the CUTE trials.

This status report on hydrogen production was commissioned by CREST as part of a two stage project. This first stage of the project sets the foundation by reviewing current hydrogen production technology, focussing on the results of the CUTE hydrogen bus trials. This report follows the four steps outlined in the research plan contained within the scope of works:

1. Undertake a review of the technology currently available for hydrogen production by electrolysis of water using renewable energy;
2. Obtain data on the CUTE trials of electrolysis from renewable energy from the University of Stuttgart;
3. Analyse the data to determine energy efficiency, costs of H_2 and any technical or environmental issues for the various technologies;
4. Attempt to identify the best option for producing "Renewable Hydrogen" in WA.

1.2 CUTE project

The Clean Urban Transportation for Europe (CUTE) project was conducted from November 2001 to May 2006. The aim of the project was to test, in real world conditions, hydrogen bus technology including hydrogen production, transport, and dispensing technologies. 27 buses were trialled in 9 cities including Amsterdam, Barcelona, Stuttgart, Stockholm, Madrid, London, and Hamburg. Associated projects were conducted with two other cities, one of which was Perth, Western Australia. The trial in Perth was conducted under the name Sustainable Transport Energy for Perth (STEP). An associated trial called ECTOS was also conducted in Iceland. ECTOS produced the Hydrogen completely through renewable means using electrolysers and electricity from geothermal and hydro power.

In the first two years of the CUTE project the bus and hydrogen supply chain infrastructure was developed. The first bus operated early in 2003 with the project officially starting the operational trials in November 2003. All the buses that were operated within the CUTE, ECTOS, and STEP projects were powered by hydrogen fuel cells.

The CUTE project aimed to assess hydrogen technology in terms of availability, efficiency, cost, environmental benefits, safety, technology maturity, and stakeholder satisfaction.

The CUTE trials utilised two types of onsite hydrogen production; electrolysis (alkaline) and steam reforming of natural gas. Amsterdam, Barcelona, Hamburg and Stockholm used onsite alkaline electrolysers and Stuttgart and Madrid used onsite steam reformers of natural gas. London, Porto, and Luxembourg used external supply of hydrogen that was transported via truck to the bus refuelling depots. The hydrogen for these sites was produced in large scale commercial steam reformers. Hydrogen was produced for the ECTOS project using on-site electrolysis.

The findings of the CUTE project are used as the basis for this report as they represent real world trials rather than small scale test results which are often reported in other studies. Both actual results and forecasts will be presented.

The HyFLEET:CUTE project followed on from CUTE. The project was expanded to include 47 hydrogen buses in ten cities, and on three continents. Both hydrogen fuel cell and hydrogen internal combustion engines were included in this trial. Initial results of the HyFLEET:CUTE project will be presented where available as the final evaluation reports for this program are yet to be finalised.

1.3 Transport in Australia

The transport sector consumed 34% of Australia's final[2] energy or 24% of the total energy demand in 2006/2007 (ABARE 2009). The only two sectors with a greater share of energy consumption were manufacturing and the largest consumer- electricity generation. Transport also consumes the greatest share of liquid fuels in Australia at around 72% with three quarters of this for road transport (ABARE 2009). Of this road transport sector, 61% is consumed by passenger vehicles making it the single biggest consumer of liquid fuels in Australia. It is interesting to note that passenger cars are the least efficient mode of road transportation consuming almost double the energy per passenger kilometre of buses which are the most efficient mode of road transport (Apelbaum 2008).

1.4 Renewable energy in Australia

Renewable energy electricity generation accounts for 6.5% of electricity generated in Australia. The vast majority of this is generated by hydro power (6.1%), with wind and solar making up the remaining 0.4%. Wind and solar are rapidly increasing with a three fold increase up to 23 PJ between 2005/2006 to 2006/2007 alone. (ABARE 2009)

There is a distinct geographic trend in renewable energy capacity expansion which logically following the available resources. Hydro power is mainly limited to the eastern coast of Australia (NSW, QLD, TAS, VIC). Wind farms are generally installed in the southern

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[2] Final energy is the total primary energy consumption minus energy consumed or lost in conversion, transmission, and distribution (ABARE 2009)

areas (WA, VIC, SA) where coastal sites have higher average wind speeds. Biomass facilities are more evenly distributed around Australia with the exception of bagasse (from sugar cane plantations) which is limited to Queensland.

With the recent federal government commitment to a 20% renewable energy target by 2020 there is expected to be significant growth in the country’s renewable energy capacity. The renewable electricity generation type with the biggest growth is expected to be wind power- currently seven of the eleven major projects in advance stages of planning are wind projects. There are also an additional 42 major wind projects proposed for the near future. Other projects are planned using solar thermal (10MW in Cloncurry in 2010), wave, and geothermal energies.

1.5 Why hydrogen?

1.5.1 Hydrogen as a transport fuel

The main attraction to hydrogen as a fuel is that it can be produced from a variety of sources, can be consumed in a variety of engine types, and can have no emissions other than water vapour when it is consumed in a fuel cell vehicle. Because there are very low tailpipe emissions from hydrogen vehicles they are suitable for use in city locations where air pollution (particulates and smog) is often an issue.

Hydrogen is, however, often mistaken as being a source of energy when in fact it is an energy carrier, not a primary energy source. Electrolysis of water and steam reformation of natural gas were the main hydrogen production technologies used during the CUTE bus trials (these technologies are covered in more detail later in the report). Hydrogen can also be produced from fossil fuels, other than natural gas, including coal and oil (by partial oxidation). There are also new methods of hydrogen production being developed that use renewable energy or biological sources and methods (Gardner 2009).

Hydrogen consumption

Hydrogen can be consumed in modified internal combustion engines, gas turbines, or fuel cells to convert the stored chemical energy into motive power. Fuel cells are the most promising technology as they can have efficiencies two to three times higher than standard internal combustion engines (Ballard 2009). The efficiencies of each of these engine types may vary but the thing they have in common, when consuming hydrogen as a fuel, is that the exhaust emissions consist mainly of water vapour and contain no greenhouse gas emissions. When hydrogen is consumed in internal combustion engines there are some nitrous oxides, particulate matter, and hydrocarbons but they are all extremely low and fall well below the future EU emission limits (HyFLEET:CUTE 2010).

The environmental impacts associated with hydrogen are mainly in the production, rather than the use of the fuel- often described as “burden shifting”. These impacts can be minimised if the hydrogen is produced from sustainable energy sources such as solar, wind, wave, or biomass but the full life cycle of the fuel must be considered to ensure that burden shifting does not occur between life cycle stages.

Energy content and issues for transport applications

As shown in Figure 1, hydrogen has a very high energy density by mass; it is around 3 times greater than diesel fuel. The limiting factor, however, is that hydrogen has a low energy density by volume (Figure 2). Even when in liquid form the energy density by volume is 4 times less than diesel fuel. Commonly both gaseous and liquid hydrogen is measured in kilograms although gaseous hydrogen is often referred to in normal cubic metres (Nm^3). One Nm^3 of hydrogen contains 3.0 kWh of energy (lower heating value[3]) and weighs 0.09 kg (CUTE 2004).

When referring to the energy content of fuels, or the efficiencies of conversion processes, it is important to note whether the lower heating value (net calorific value) or higher heating value (gross calorific value) is being stated. The difference between the lower and higher heating values (HHV) is due to the latent heat value of water formed during combustion (IEA 2005). Throughout this study the lower heating value LHV) has been used for energy contents and conversion efficiencies.

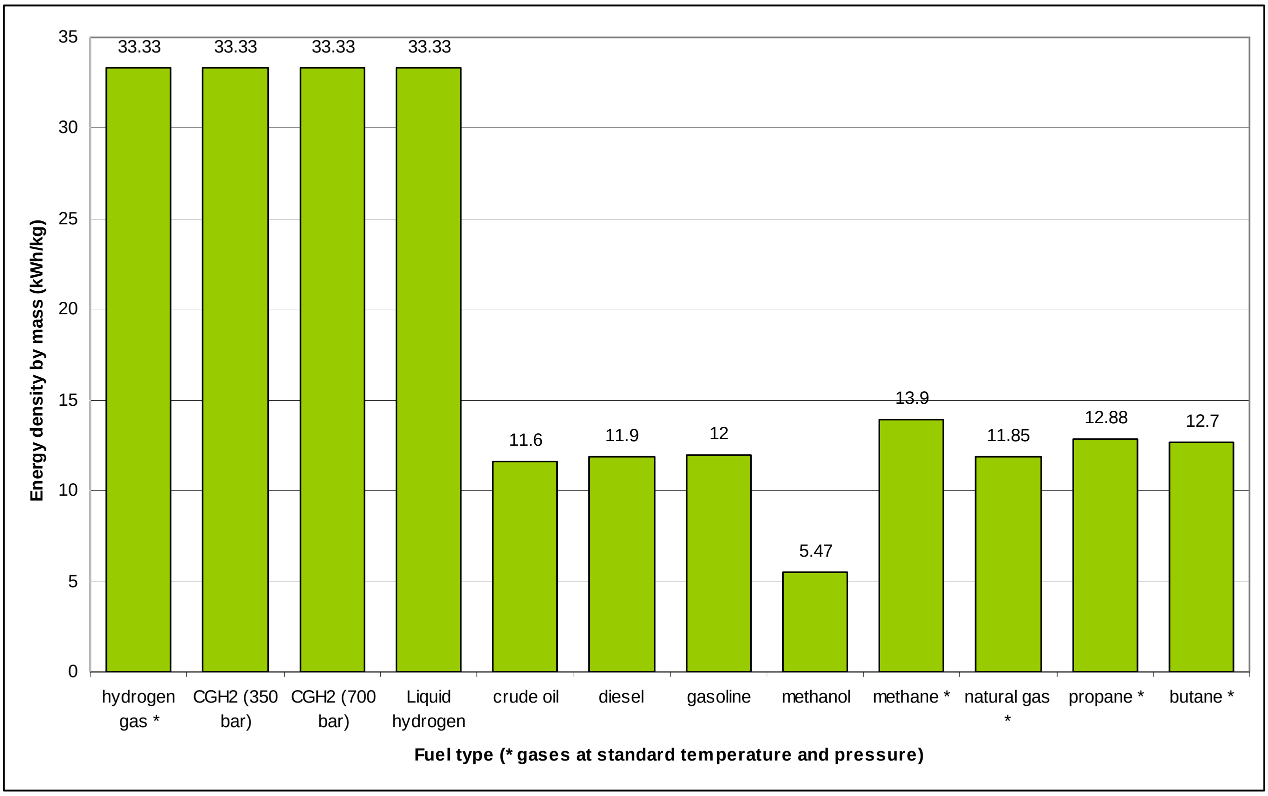

Figure 1 Energy density of fuels by mass (lower heating value) (based on data from HyWeb 2009 and Thomas and Keller 2003)

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[3] Higher heating value is 3.54 kWh/Nm^3

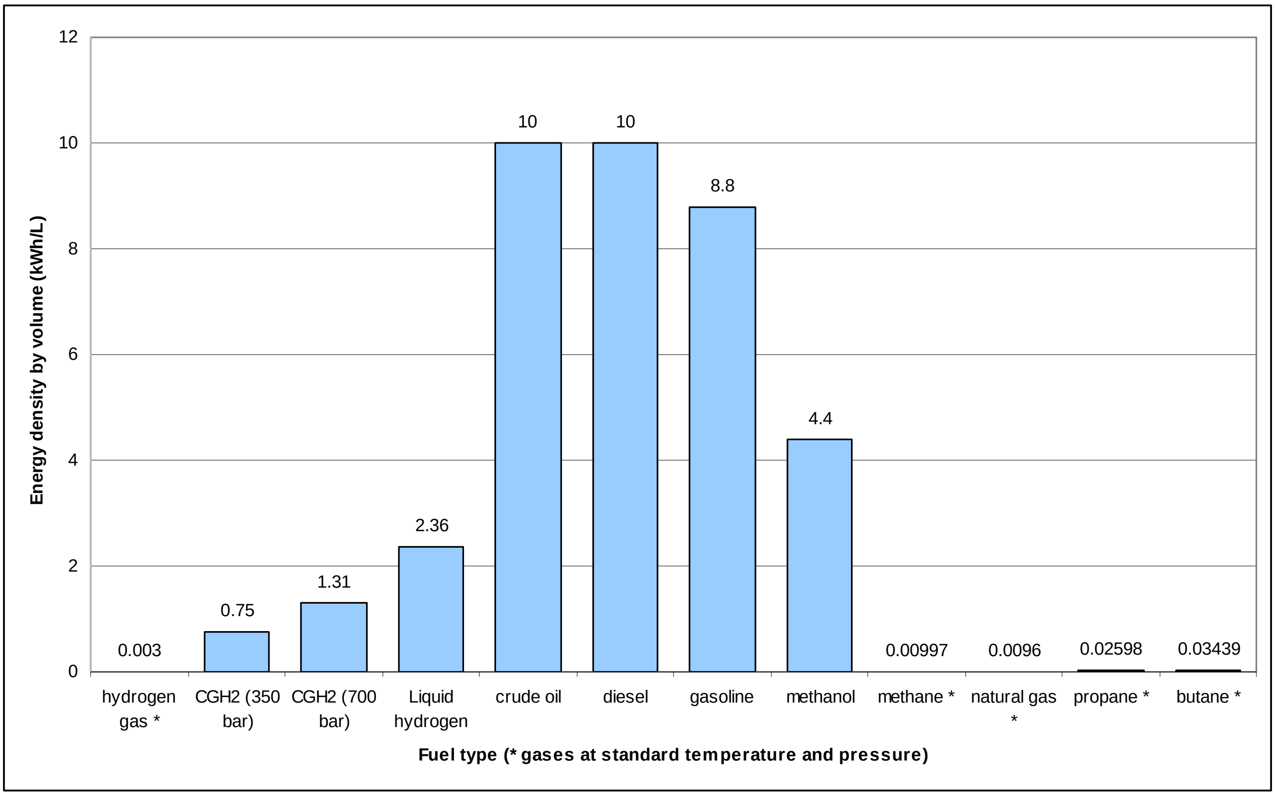

Figure 2 Energy density of fuels by volume (lower heating value) (based on data from Hy-Web 2009 and Thomas and Keller 2003)

Because hydrogen has a low volumetric energy density at standard temperature and pressure, it is commonly stored as either compressed gas hydrogen (CGH_2) or liquid hydrogen (LH_2).

Compressed gas hydrogen

Compressed gas hydrogen (CGH_2) is typically stored at pressures up to 200 bar for on-board vehicle storage. The CUTE hydrogen bus trials set a new benchmark for compressed gas hydrogen storage with 350 bar used for hydrogen stored in the refuelling station and bus fuel tanks (CUTE 2006a). Increasing the pressure of the stored gaseous hydrogen also increases the energy density by volume (see Figure 2) which gives vehicles a longer range between refuelling. CGH_2 is stable at these vessel pressures and therefore does not have boil-off loss issues that occur with liquid hydrogen.

The energy density of hydrogen is not such a major issue for vehicles such as buses where there is often sufficient space available to store the hydrogen as compressed gas. The additional storage vessels required to store the fuel do add to the total weight of the vehicle however and since they are often located on the roof, they can change the centre of gravity. There is also an additional penalty because hydrogen vehicles may have to refuel more often than traditional diesel buses depending on the daily distance travelled. This is less of an issue when refuelling stations can be located appropriately and rapid fill systems are used. It is also becoming less of a problem as fuel efficiency of the vehicles is rapidly increasing through the introduction of more efficient fuel cells, vehicle weight reduction through the use of composite materials, and power train hybridisation.

Liquid hydrogen

The production of liquid hydrogen (LH_2) is more energy intensive; the gas must be cooled below -253º for it to remain liquid. Above this temperature it begins to boil-off. To liquefy one Nm^3 of hydrogen gas consumes one kWh of energy, or 30% of the energy contained in the hydrogen (CUTE 2004). LH_2 is not stable at commonly used vessel temperatures and pressures so the hydrogen gas that 'boils off' has to be either vented or re-chilled and compressed. The boil-off or surplus hydrogen can also be used to fuel a stationary fuel cell to produce both electricity and heat (Whitehouse 2009). These losses can be considerable where the production and storage are not matched closely to demand. This can result in low overall system efficiencies. The benefit of LH_2 is that higher quantities of hydrogen can be transported in liquid state rather than as compressed gas. An example taken from the CUTE project is that a truck can transport ~3.3 tonnes of LH_2 (equivalent to 36,700 Nm^3) where as only 300 to 600kg can be transported as CGH_2 per trailer (CUTE 2004). This results in fewer trips to transport the same quantity of hydrogen so is beneficial where long transport distances are involved like, for example, in Western Australia.

1.5.2 Current sources of hydrogen

In 2000 worldwide production of hydrogen exceeded 500 billion cubic metres (~45 billion kg) (CUTE 2004), as shown in Figure 3, most of which was derived from fossil fuels natural gas, crude oil, and coal. The majority of the hydrogen is consumed for the production of ammonia, methanol, iron and steel, glass, edible oils, and the electronics industry.

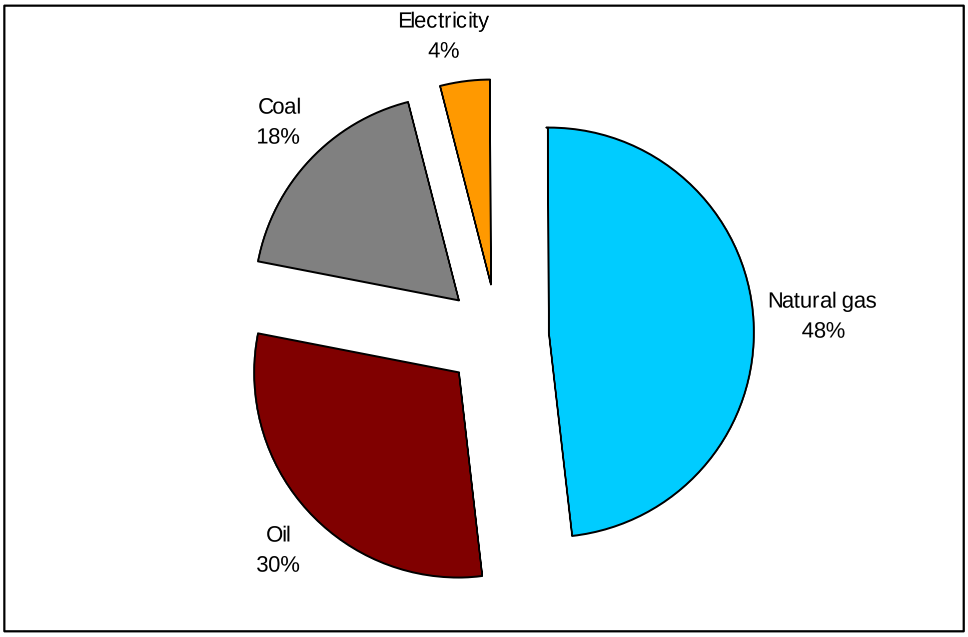

Figure 3 Global sources of hydrogen in 2006 (SRI 2007)

2 Review of Hydrogen Production Technologies

Hydrogen can be produced using a range of feed stocks and technologies. While there is a presumption that electrolysis may be the most appropriate option, there is a need to examine other renewably based possibilities. This section will review the methods of hydrogen production with an emphasis on those methods trialled in the CUTE project. Alternate methods will also be discussed. The following section investigates the efficiencies, costs, and technical issues from the CUTE trials.

The two methods of onsite hydrogen production within the CUTE project were alkaline electrolysis and steam reforming of natural gas. The electricity used for production of hydrogen by electrolysis was mainly from certified ‘green’ sources (Amsterdam, Hamburg, Stockholm) with only Barcelona using standard grid electricity although it was substituted with some onsite solar PV. Conventional (fossil) natural gas was used for the steam reformer units although methane rich biogas from renewable sources could be used as a potential feedstock in the future. For this reason steam methane reformer unit technology is also addressed.

2.1 Alkaline Electrolysis

Electrolysis is the process of electro-chemically splitting water molecules (H_2O) to produce hydrogen and oxygen. The electrolysers used in the CUTE trials were all alkaline type but there are also electrolysers that use Proton Exchange Membranes (PEM) as used in fuel cells. PEM electrolysers are discussed section 2.3 of the report.

In alkaline electrolysis, two electrodes are immersed into a liquid electrolyte and an electric current (DC) is applied to the electrodes. The process occurs in two partial reactions within an electrolysis cell, one reaction at the cathode and one at the anode:

Cathode: $2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-$

Anode: $2 H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Overall: $H_2O \rightarrow H_2 + \frac{1}{2} O_2$

To increase the conductivity of water an electrolyte is normally used, usually this is potassium hydroxide (KOH). Oxygen gas is produced at the cathode and hydrogen gas at the anode. To prevent the mixing of these gases, a gas impermeable but ion conducting membrane separates the cathode and the anode.

Several electrolysis cells are usually combined in series to produce an electrolysis module. Many modules may be combined to make larger systems with higher production capacities giving great flexibility.

Electrolysis modules are designed as either atmospheric pressure units or as pressurised units. Atmospheric units have lower energy requirements but have larger physical footprints than pressurised units- for this reason pressurised units were used during the CUTE trials. Pressurised units have slightly higher energy consumption but as the hydrogen is produced at up to 30 bar it reduces the energy required for compression. The electrolyser units used in the CUTE trials has delivery pressure of 10 to 12 bar (CUTE 2004). Pressurised units also have lower production rates than atmospheric units with 120 Nm^3/hour (maximum); atmospheric units can produce up to 500 Nm^3/hour (maximum) (CUTE 2004 and Norsk Hydro[4] 2009). As both of the electrolyser systems are modular, production capacities can be scaled as required by installing additional units. The specifications (energy consumption and efficiencies) of the different types of hydrogen production technologies are discussed in more detail in section 3.

Electrolysers can respond quickly with start-up and shutdown time of only a few minutes so are suited for applications with intermittent hydrogen demand or intermittent power supply (e.g. wind power or photovoltaic solar power).

2.1.1 Electrolyser components

Alkaline electrolyser units contain several component parts as shown in the system diagram below (Figure 4).

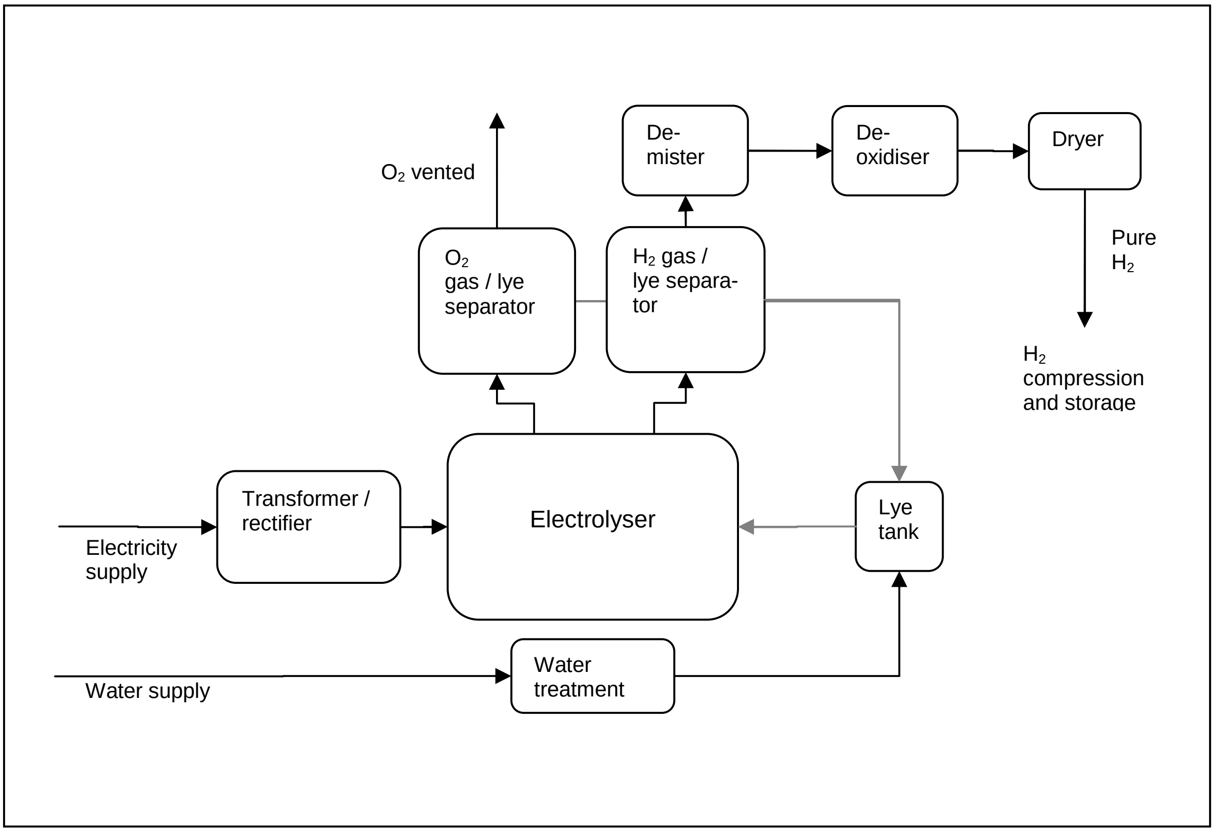

Figure 4 Flow chart of an Electrolyser unit (based on CUTE 2004)

Transformer and rectifier

Power is usually supplied to the electrolyser unit via the electricity grid as high voltage alternating current (AC). The transformer and rectifier reduce the voltage to the required system voltage and convert the AC to direct current (DC). Alternately DC power can be directly supplied to the unit from power sources (including wind or solar) which increases the efficiency of the unit as the rectifier is not needed.

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[4] Norsk Hydro is now Statoil

Water treatment

Water of high quality (low impurities) is required for the unit. Reverse osmosis and ion exchange resins demineralise the water and store it ready for use in the electrolyser module.

Electrolyte (lye) system

Potassium hydroxide is commonly used as the electrolyte. A concentration of 25-30% (by volume) is optimal. Solid KOH pellets are dissolved in a filter basket and the solution is stored in the lye tank for circulation to the electrolyser stack.

Electrolyser

The electrolysers consume water and electricity and produce hydrogen and oxygen gas. The gases and alkaline electrolyte pass through collection ducts to the separation units. The life of the electrolyser cells as used in the CUTE project is expected to be 7 to 10 years under continuous operation (CUTE 2004).

Separators

In the separators the hydrogen and oxygen gases are separated from the lye solution. The lye solution is then passed back into the electrolyte system and the gases proceed to the demister units.

Demisters

The demister units dry the gases by removing water.

Deoxidiser

The deoxidiser unit removes oxygen from the hydrogen gas by reacting the two gases together in a catalytic reaction to create water. This ensures that the resulting hydrogen gas does not contain any oxygen which could cause contamination and safety issues down stream (potential explosions). The temperatures of the reaction are controlled using pre-heater and after-cooler units.

Dryer

The dryer unit contains multiple chambers which alternately absorb moisture and regenerate themselves to ensure continuous operation. A percentage of the hydrogen gas (<5%) is consumed in the regeneration of the dryer columns which, although slightly decreasing the efficiency of the unit, is the most effective method of recharging the dryer units.

Gas analysers

The output gases are continuously monitored by gas analysers to ensure that there is no cross contamination between hydrogen and oxygen, and to ensure that neither gas contains water vapour.

2.2 Steam Methane Reformer

Steam reformers can be used to produce hydrogen from methane rich gas or other hydrocarbons. Methane can be sourced from fossil (natural gas or LPG) or renewable sources such as bio-methane. A system diagram of the process is shown in Figure 5 below.

The reaction process takes place in two stages:

Stage 1: $CH_4 + H_2O \rightarrow CO + 3H_2$

Stage 2: $CO + H_2O \rightarrow CO_2 + H_2$

The first reaction stage consumes natural gas and water to produce hydrogen rich gas (syngas) which also contains carbon monoxide (CO). This reaction occurs at 900º C, significantly hotter than the 80ºC operational temperature of the electrolyser modules (CUTE 2004). The heat required for the process comes from the partial combustion of the fuel gas and from heat recovered from the exiting gases using heat exchangers. The carbon monoxide is then consumed in a secondary reaction (stage 2), again in the presence of steam, to produce carbon dioxide and hydrogen. The gases pass through heat exchangers before entering the pressure swing adsorption (PSA) unit for purification. The PSA unit produces hydrogen that is greater than 99.999% pure[5] and less than 1ppm carbon monoxide. Delivery pressure of the hydrogen from steam methane reformer in the CUTE trials was 13 to 15 bar (CUTE 2004).

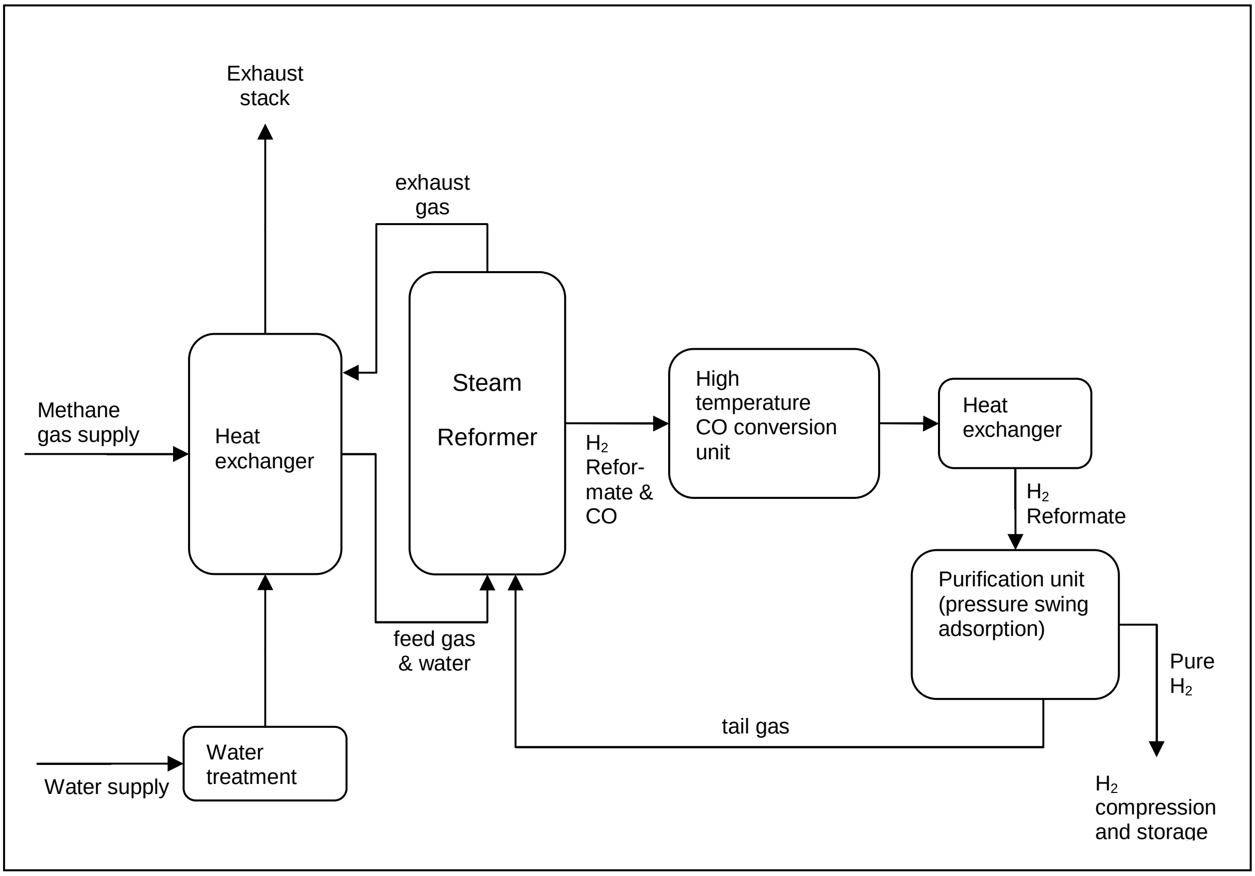

Figure 5 Flow chart of a steam methane reformer (based on CUTE 2004)

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[5] Electrolysers also produce hydrogen at this level of purity in order to meet bus manufacturer specifications.

2.3 PEM Electrolysis

Hydrogen can also be produced using proton exchange membrane (PEM) technology. In the last few years PEM electrolysis units have been developed with higher hydrogen production rates than previously achieved, making them suitable for some vehicle refuelling station applications[6]. PEM electrolysers were used to produce hydrogen in the first public hydrogen refuelling stations in the US (New York Times 2008).

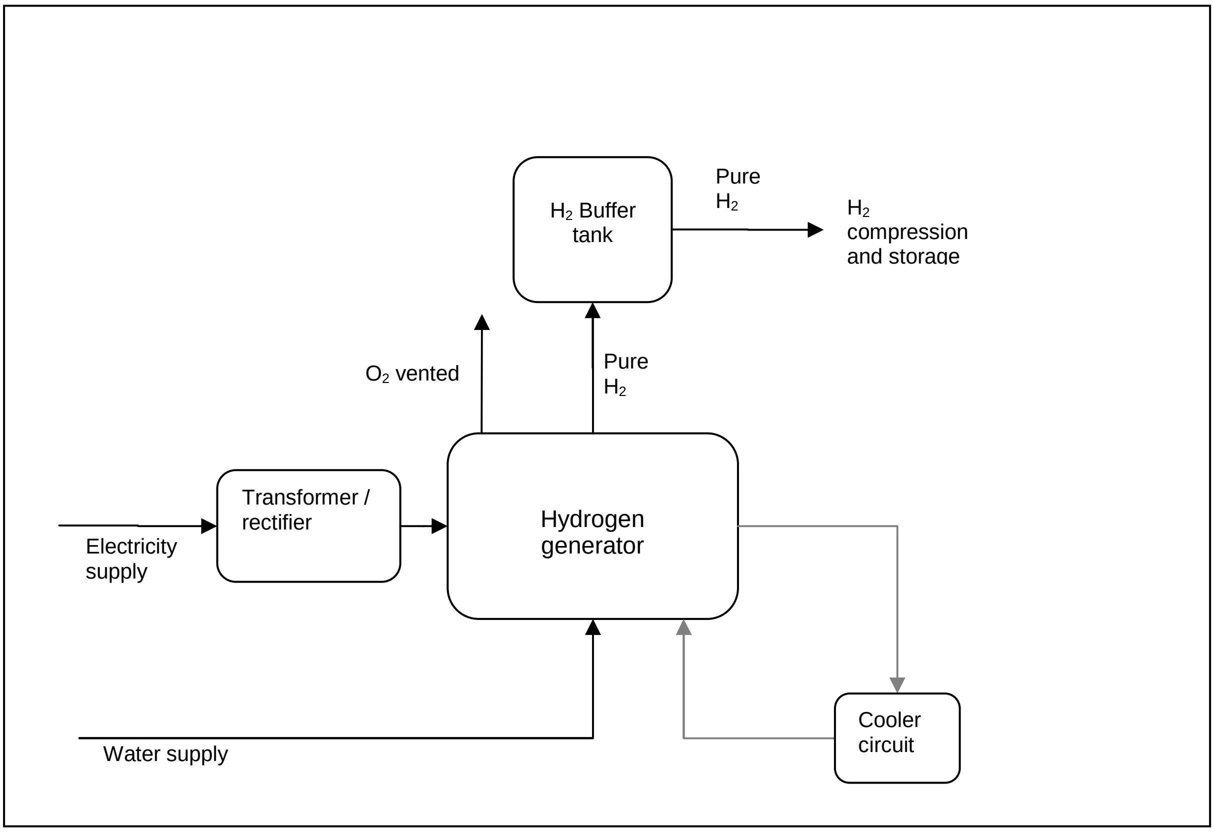

Figure 6 Flow chart of a PEM Electrolyser unit (Proton Energy Systems 2008)

Like alkaline electrolysers, PEM electrolysers produce hydrogen from water using electricity. The difference is that no liquid electrolyte is involved; instead solid polymer membrane is used. Water molecules are split into oxygen, protons, and electrons on the surface of the membrane. The protons are forced through the membrane by the applied voltage. The oxygen leaves as oxygen gas, and the electrons pass through the electric circuit combining with the protons to form hydrogen gas.

PEM electrolysis units can be simpler and smaller than alkaline units as they do not have alkaline electrolytes, circulation systems, and potential corrosion or leakage issues that can occur with alkaline electrolytes. PEM units are commonly used in laboratory and research applications where small volumes of pure hydrogen are required. As with pressurised alkaline electrolysers, PEM electrolysers are capable of producing pressurised hydrogen. Commercial units will produce hydrogen at up to 30 bar (Norsk Hydro 2006) but

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[6] Norsk Hydro's Inergon PEM electrolyser can produce 10 Nm^3 H_2/hour which is significantly less than the 60 Nm^3 H_2/hour for the pressurised alkaline units. Proton Energy Systems FuelGen system has a production rate of 6 Nm^3 H_2/hour (Proton Energy Systems 2009). Sized effectively the PEM units can still be suitable for certain vehicle refuelling applications.

demonstration units have been reported to generate pressurised hydrogen at over 138 bar with a minimal increase in cell voltage required thus operating at higher efficiencies (Proton Energy Systems 2008). Early this year Proton Energy Systems announced (Proton Energy Systems 2009) that they have been successfully producing hydrogen at 165 bar (2400 psi), for over 12 months, in test units that are being trialled by their strategic partners

2.4 Other methods of hydrogen production

2.4.1 Refinery by-product

Hydrogen gas is often a by-product from the oil refining process. Long hydrocarbon chains are ‘cracked’ to produce required grades of oils and hydrogen gas is the by-product. Traditionally this excess gas would be either used in the refining process for energy production, or de-sulphurisation of the final products, or flared. Increasingly by-product hydrogen is being viewed as a valuable product that can be used for other uses rather than being simply flared. By-product hydrogen has been estimated at over one billion normal cubic metres per annum for the EU15 alone (CUTE 2004) so it can be a valuable source that can be used to break the chicken-and-egg cycle[7] and kick start hydrogen projects. An example of this is where refinery by-product hydrogen was used for the Perth STEP project hydrogen bus trials (Ally and Pryor 2006). The BP refinery, from which by-product hydrogen was sourced for these trials, generated 60 tonnes per day of which the STEP program used 150kg/day (Ally and Pryor 2006).

Oil refineries are generally centralised plants so transport of hydrogen to refuelling stations also must be considered from practical, economic, and environmental perspectives.

2.4.2 Biomass

The biomass potential in WA is considerable. With its suitable climate and native tree species (oil mallee) WA has potential biomass yields per hectare nearly double those of the northern hemisphere where bio-energy production is more common (Diesendorf 2007). Agricultural crop residues and oil mallee could be used as sources of sustainable bio-energy with no adverse impact on food production (Diesendorf 2007). The oil mallee have also demonstrated environmental benefits in helping to regenerate degraded agricultural areas affected by issues associated with over clearing such as salinity, water logging, erosion, and habitat loss.

There are three pathways to produce hydrogen from biomass:

- biochemical conversion;
- thermochemical; and
- fermentation.

Biochemical production of hydrogen can be achieved by many methods; the most common of these is the reforming of ethanol. Ethanol can be produced by fermentation of grains or from lignocellulose material (e.g. wheat straw).

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[7] Hydrogen vehicles require a source of hydrogen for refuelling but hydrogen production infrastructure will often not be developed until there is demand for the hydrogen. By-product hydrogen can be used until there are sufficient hydrogen vehicles to create the demand for alternative hydrogen production infrastructure utilising sustainable energy sources.

There are several alternate pathways to thermo-chemically produce hydrogen and as the term suggests the commonality is the use of heat and chemical reactions to produce the hydrogen. Gasification is one method in which the biomass is heated to produce syngas which is refined and purified to produce pure hydrogen; a process not too dissimilar to steam reformation of methane as described previously. The U.S. National Research Council report 'Transitions to alternative transport technologies: a focus on hydrogen' picked this renewable hydrogen production method to be the most likely to become commercially viable within the next 5 to 25 years (Gardner 2009). It is expected that the hydrogen will be produced in large scale centralised facilities to improve conversion efficiencies. To improve the transport efficiencies the biomass can first be converted into energy dense bio-oil using fast pyrolysis and catalytic steam reforming.

Anaerobic bacteria have also been used to ferment glucose to directly produce hydrogen. The biomass feedstock has to be first processed to produce glucose on which the bacteria feed.

2.4.3 Solar hydrogen

The two main methods being developed to produce hydrogen directly from sunlight are thermolysis and photolysis. Production of hydrogen directly from solar energy is the least mature of the hydrogen production methods although it holds huge potential (Gardner 2009).

Thermolysis can either be achieved using high temperature concentrated solar energy along with chemical reactions to produce hydrogen or a combination of high temperatures and electrolysis. Using the latter method higher conversion efficiencies are possible compared to low temperature electrolysis alone (Gardner 2009).

Photolysis production methods of hydrogen can utilise chemical or biological processes to directly to produce hydrogen. Photochemical production of hydrogen uses semi conductor materials and catalysts along with light energy to split water directly. Research is currently being undertaken to further develop this method to improve efficiencies and decrease costs associated with the semiconductor materials. There are numerous technical challenges that need to be overcome to make it viable (Gardner 2009).

Another method that is gaining considerable research attention is bio-photolysis. Here algae and cyano-bacteria produce hydrogen by splitting water using photosynthetic reactions. As this method converts sunlight directly into hydrogen, theoretical efficiencies of 40% are possible which are significantly higher than those of other biomass methods which are around 1% (U.S. Department of Energy Office of Science 2009).

2.4.4 Conclusions for other methods of hydrogen production

There are alternative production methods for hydrogen, other than electrolysis and steam reformation of natural gas, although many of those mentioned are less mature technologies (except refinery by-product hydrogen). Renewable hydrogen is therefore likely to be produced by electrolysis using electricity from sustainable energy sources such as wind, hydro, biomass, and solar. Of the other renewable hydrogen production methods discussed, the one most likely to become viable in the near to medium term is thermochemical conversion of biomass. Direct production of hydrogen by solar technologies, although promising, still has technical challenges that need to be overcome before it becomes a viable source of renewable hydrogen.

3 Results of Hydrogen Program Trials

The CUTE trials were one of the first times that onsite hydrogen production infrastructure was tested and evaluated under real world operating conditions for transport applications (CUTE 2006a). Over the duration of the project 27 hydrogen buses travelled over 841,000 kilometres, carrying over 4 million passengers, and consumed greater than 192 tonnes of hydrogen. The onsite hydrogen production units produced 121 tonnes of hydrogen; 78t by electrolysis and 42t by steam reformation of natural gas (Stolzenburg et al 2009). In addition to onsite generation 153t of hydrogen were provided from external sources.

This section outlines the efficiency, cost, and technical issues identified during these and other hydrogen trials and studies.

3.1 Efficiency of hydrogen production

3.1.1 Electrolyser (alkaline) efficiency

The electrolysis process consumes both water and electricity. Manufacturers specifications state that around one litre of water and 4.1 to 4.8 kWh of electricity are consumed to produce 1 Nm^3 (0.09kg) of hydrogen (CUTE 2004). This represents an efficiency of 65% (LHV)[8] (CUTE 2004). To put this in context a 100% efficient electrolyser would still consume 3 kWh/Nm^3 (LHV).

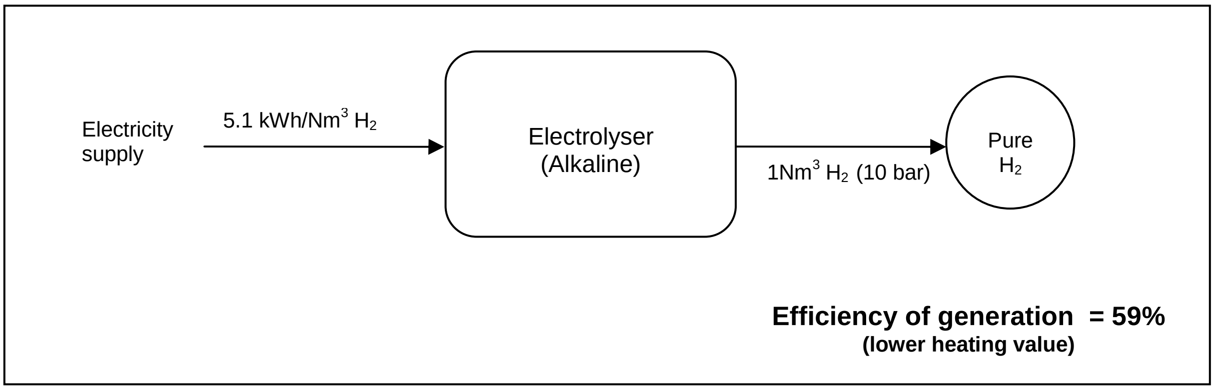

Figure 7 Average alkaline electrolyser efficiency for hydrogen generation as measured during the CUTE project (Stolzenburg et al 2009 and CUTE 2006b).

The results from the CUTE project have shown that the alkaline electrolysers performed close to specification with power consumption of 5.1 to 5.2 kWh/Nm^3 hydrogen generated and 5.8 kWh/Nm^3 for the entire onsite hydrogen supply chain including electrolysis, compression to >350 bar, and dispensing (CUTE 2006b). The availability of the electrolyser systems was very high for most of the trial sites with values around 95 to 99% (Stolzenburg et al 2009). The exception was the Hamburg unit with availability of 68% due to lye circuit issues (Stolzenburg et al 2009).

Water consumption was stated by the system manufacturers at 1L per Nm^3 of hydrogen produced although this was not monitored for the electrolyser units during the CUTE trials.

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[8] or 76% for the higher heating value.

The electrolysis units had no issues with “on demand” operation unlike the steam methane reformer units. Electrolysers have very rapid response times (few seconds) to changes in production rates and have start-up/shutdown times of only a few minutes. As such they are suitable for intermittent operation that was experienced at the bus refuelling depots.

The outlook for electrolysis units, from the manufacturer perspective, is excellent with efficiency increases of 10% likely in the short to medium term. Cost and physical size of units looks likely to decrease as they are produced in higher numbers and the units become more integrated. As operational costs depend mainly on the cost of electricity, these are unlikely to decrease significantly other than due to the efficiency improvements promised. Integration with renewable energy sources could avoid rectifier losses and lead to further increases in production efficiencies.

3.1.2 Steam methane reformer efficiency

Large scale steam methane reformer units produce most of the global hydrogen supply using efficient and proven technology. Small scale units (of up to 200Nm^3/hour) designed for on site generation, however, are only in the prototype stage. The design values for these small scale units are around 65% thermal efficiency (LHV) which is lower than 70% (and greater) efficiencies achieved by large scale commercial units (Stolzenburg et al 2009). The rated natural gas consumption of the units used in the CUTE trials (when operated at full capacity) was 4.65 (Stuttgart) and 4.86 (Madrid) kWh/Nm^3 hydrogen produced (CUTE 2004).

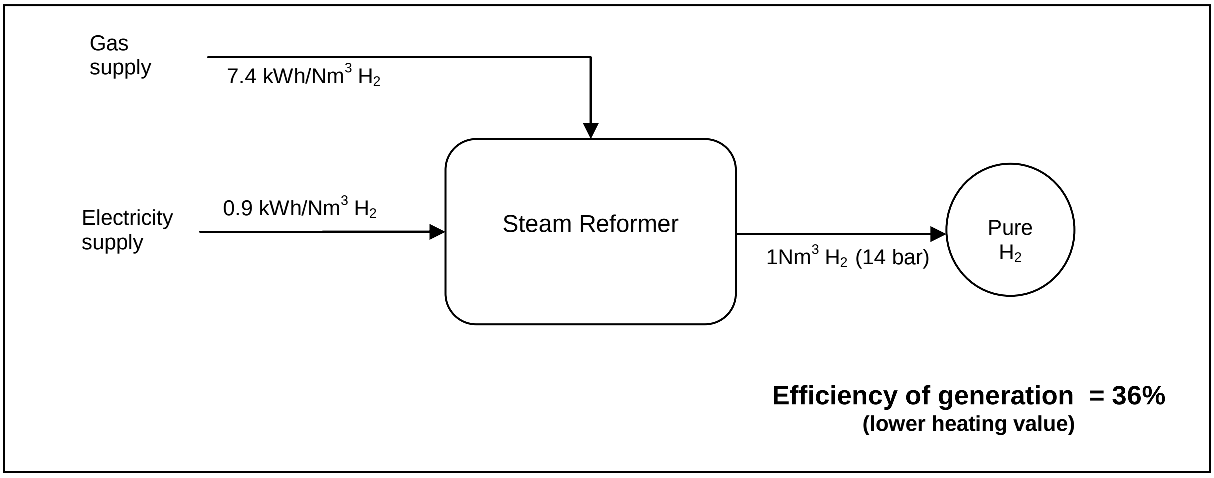

Figure 8 Average steam methane reformer efficiency as measured during the CUTE project (CUTE 2006b). Delivery pressure was 13 bar.

The average energy consumption measured for hydrogen production by steam methane reformer was 7.4 kWh of natural gas[9] and 0.9 kWh of electricity[10] per Nm^3 of hydrogen (CUTE 2006b). These values represent the real world measured values that were experienced when the units were not operating at full load capacity. This represents an average overall efficiency of 36% (LHV) (38% for Madrid and 35% for Stuttgart) (Stolzenburg et al 2009). Actual average thermal efficiency was measured at 40%, much lower than the de-

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[9] 7.0 kWh of natural gas per Nm3 of hydrogen produced for Madrid and 7.7 kWh of natural gas per Nm3 of hydrogen produced for Stuttgart (CUTE 2006b).

[10] 0.9 kWh electricity per Nm3 hydrogen for both Madrid and Stuttgart (CUTE 2006b).

sign specifications of 65% (CUTE 2006b). When the steam methane reformers used in the CUTE project were operated in accordance with the design specifications (continuous operation) the units performed considerably more efficiently at 4.7 kWh of natural gas and 1 kWh of electricity (per Nm^3 of hydrogen produced); an overall efficiency of 53% (CUTE 2006c). Measured water consumption of the steam methane reformer units was between 1.9 to 2.1 L/Nm^3 hydrogen produced (CUTE 2006b).

The outlook for these systems is that there could be improvements in thermal efficiency to achieve 75% in the short term and 80% in the long term leading to lower operational costs (CUTE 2004)[11]. Plant costs and physical size also should decrease significantly with a new smaller PSA unit design and as production volumes increase. The start-up and shut-down cycles may be improved however due to the nature of the process the response times are unlikely to challenge those of electrolysis units so they will be more suitable for continuous hydrogen production rather than "on-demand" production.

3.1.3 PEM electrolyser efficiency

PEM electrolysers were not used in the CUTE trials but their efficiencies have been included here for comparison to the other hydrogen generation technologies.

Very high efficiencies, of greater than 80% (reported as 94% based on higher heating value) or 3.75 kWh/Nm^3 have been reported for PEM electrolysers in laboratory trials utilising experimental catalysts (Marshall et al 2007). Norsk Hydro (2006) report energy consumption of 4.4 kWh/Nm^3 for their commercially available PEM electrolysers which is slightly higher than stated for their alkaline electrolysis units of 4.1 to 4.3 kWh/Nm^3.

Water requirements vary depending on the manufacturer but this may be down to the detail of the wording rather than the units themselves. Norsk Hydro (2006) quote $1L/Nm^3$ "feed water consumption" but this probably excludes the waste water that is not converted into hydrogen but sent down the drain as waste water from the water treatment process. Proton Energy Systems (2008b) quote 9 L/Nm^3 (54 L/hr for "feed water requirements" but also state that drain requirements are 8 L/Nm^3 (49L/hr) during production which gives 1 L/Nm^3 water that is actually converted into hydrogen.

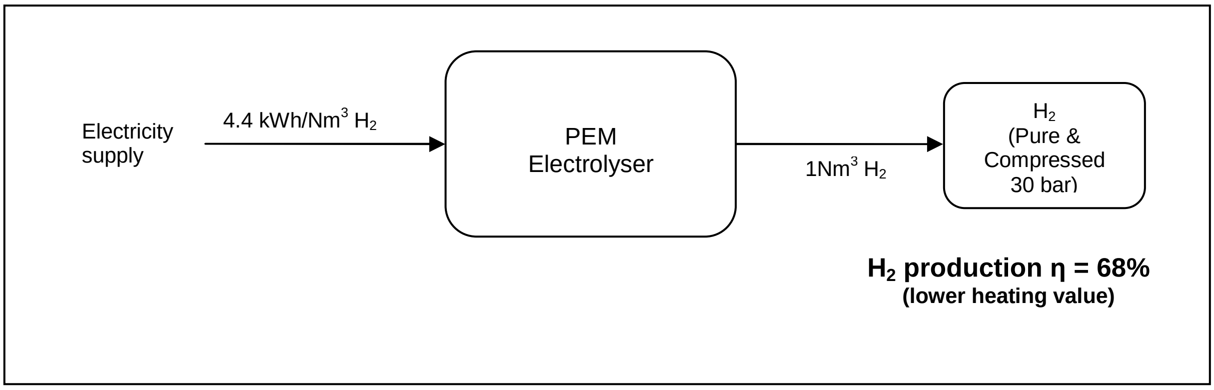

Figure 9 PEM electrolyser specified efficiency (Norsk Hydro 2006 and Proton Energy Systems 2008b)

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[11] Note that this outlook was stated at the beginning of the CUTE trials and these thermal efficiencies are yet to be achieved.

3.1.4 Summary of efficiencies

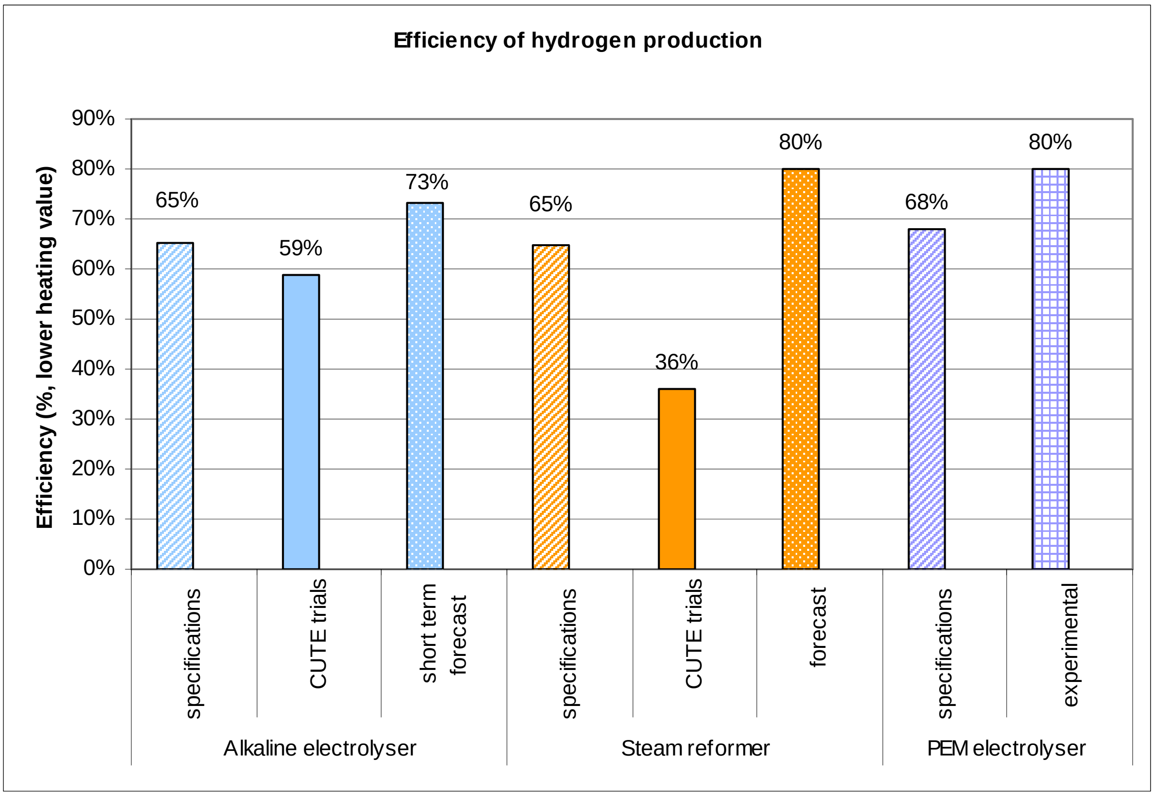

Figure 10 Efficiency of hydrogen production for alkaline electrolyser, steam methane reformer, and PEM electrolyser (LHV) (CUTE 2004, CUTE 2006b, CUTE 2006c, Norsk Hydro 2006, Marshall et al 2007)

Figure 10 above summarises the efficiencies of hydrogen production from the different production methods. Note that the figures quoted exclude compression to the pressure required for vehicle refuelling and all state efficiency values for the lower heating value of hydrogen. This latter point is critical as some references state the higher heating value. For all three production pathways improvements in efficiencies are expected. Alkaline electrolysis units performed close to specification during the CUTE trials but the prototype steam methane reformer units performed poorly under the stop/start conditions experienced during the trial which resulted in low overall efficiencies. This issue, and other lessons learnt from the CUTE trials, are discussed in more detail in Section 3.3 Technical or environmental issues of various hydrogen production technologies.

3.2 Cost of hydrogen

The costs of hydrogen production during the CUTE trials were analysed in the deliverable number 6 “Economic analysis of the hydrogen infrastructure” by Binder and Faltenbacher (2006c). These results and costs from additional studies are presented below.

3.2.1 CUTE results

The cost values from the CUTE project are based on actual costs from the project so accurately represent the real life cost of producing hydrogen. It is important to note that these costs include hydrogen production, compression, storage, and dispensing infrastructure- they include much more than just the cost of hydrogen production. The major finding from this project was that the final cost of hydrogen depends greatly on the cost of energy for both hydrogen from electrolysis and hydrogen from steam methane reformation. As there was considerable variation in the costs associated with the different production sites the data were presented as minimum, average, and maximum values. These minimum and maximum values do not represent individual sites, rather they represent a compilation of the minimum and maximum costs for each of the categories thereby more accurately representing the range in hydrogen production costs. The efficiency of operation used in the cost calculations was an average of consumption values measured during the CUTE project (as detailed in the previous section). The cost of electricity and gas varied depending on the country so to enable comparison of the different sites the costs were set at EUR 0.10 (AUD 0.17) per kWh of electricity and EUR 0.05 (AUD 0.08) per kWh of natural gas.

The cost of hydrogen represents the full cost of dispensed hydrogen and includes:

- Preparation cost

  This includes all relevant costs for planning, permits, foundations, additional heating, and connection of the units to utilities.

- Initial investment

  This represents the initial cost for equipment including the electrolyser/steam methane reformer, compressor, and the hydrogen dispenser.

- Operation cost

  Operation costs include all relevant costs for operating the hydrogen infrastructure unit such as cost of energy, nitrogen (purging), and staff costs.

- Storage cost

  The cost of equipment used to store the hydrogen.

- Maintenance cost

  This includes costs for maintaining the electrolyser/steam methane reformer, compressor, spare parts, replacement of the electrolyser stacks (10 year life), and insurance.

Electrolysis (alkaline)

The cost of producing hydrogen via electrolysis varied from EUR 12 to just over EUR 16 (AUD 20.00 to 26,70[12]), with an average cost of EUR 14 per kg of hydrogen produced (AUD 23.33).

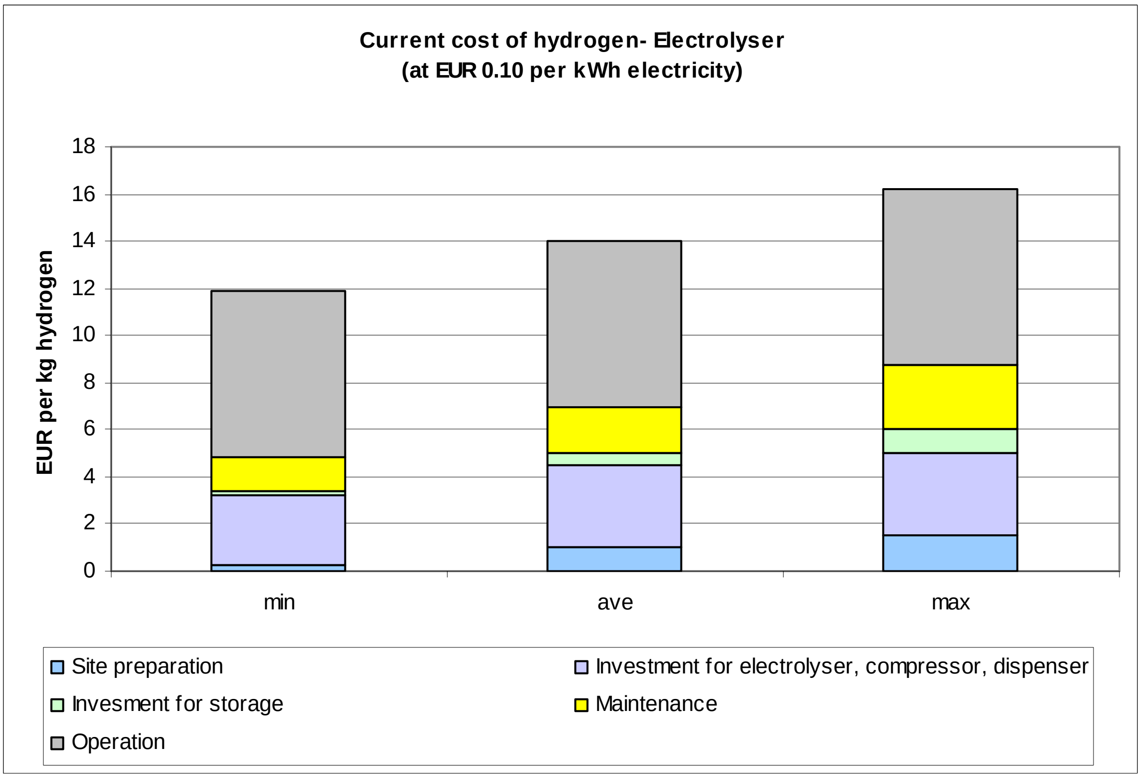

Figure 11 Cost of hydrogen produced by electrolysis (alkaline) from the CUTE project (CUTE 2006c)

Figure 11 presents the data for hydrogen produced by electrolysis. For hydrogen produced from electrolysis, between 45 to 60% of the cost was associated with the electricity used in the hydrogen infrastructure operation. Initial investment was the next major cost ranging from 22 to 25% of the total. Maintenance was also significant with between 13 to 17%. Cost for hydrogen storage was low but varied considerably at between 1 and 6% which is likely to reflect the variation in storage volumes and pressures at the different sites.

It is important to mention that the non operational cost of hydrogen varied between sites from 33% to 63% depending on the cost of electricity and the site specifics. The future scenarios investigated in the CUTE paper expect that these non operational costs will decrease significantly thereby making hydrogen a more viable transport fuel option.

Steam methane reformer

Figure 12 presents the cost of hydrogen produced by steam methane reformer as a comparison. There are some differences between this figure and the previous one that should be noted. Firstly the average cost of hydrogen was slightly higher for the steam methane reformer (~EUR 14.5 per kg or AUD 24.17) and secondly the operational cost was lower for steam methane reformer than for electrolysis. At most, the operational cost for the

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[12] Based on 6 month historic exchange rate 1 July to 31 December 2009 (Exchange rates.org 2009) of AUD 0.6 to EUR 1

steam methane reformer represented 45% of the cost of the hydrogen compared to 60% for electrolysis. This difference is due to the lower cost of the primary energy source, natural gas, compared to the cost of electricity. The share of the investment cost for steam methane reformer was higher than for electrolyser reflecting the higher cost for these units.

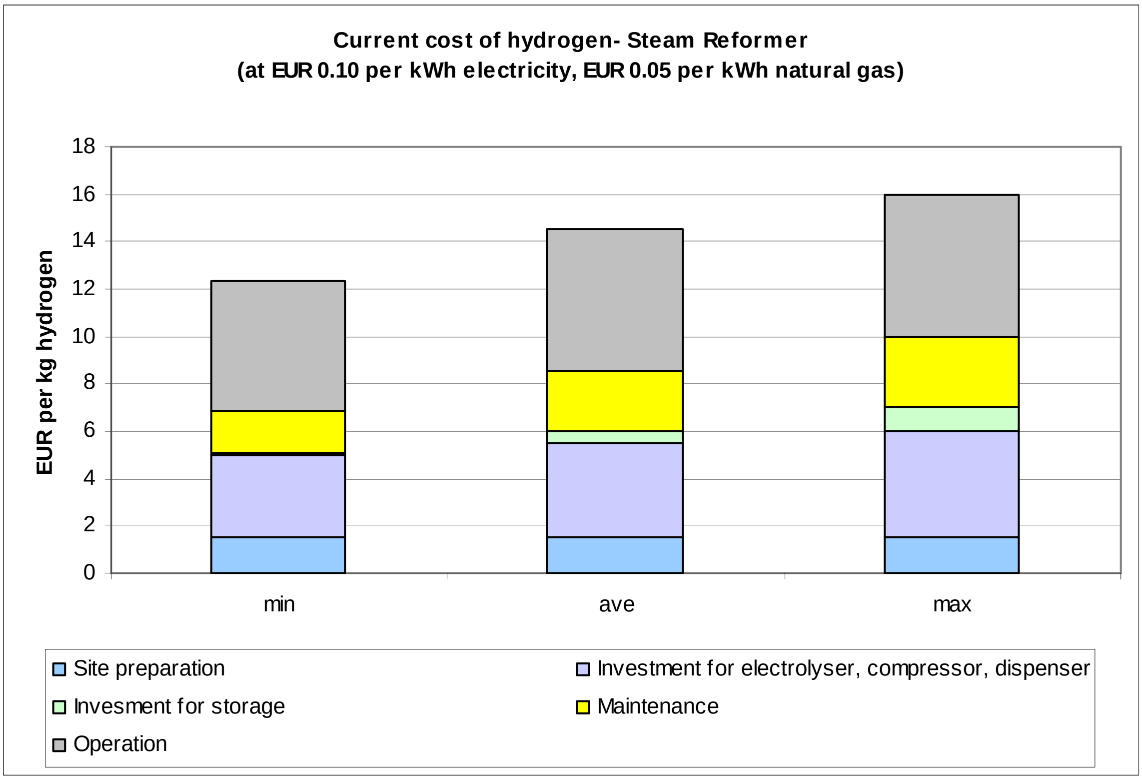

Figure 12 Cost of hydrogen produced by steam methane reformer from the CUTE project (CUTE 2006c)

If the steam methane reformers were able to operate closer to their design specifications the cost would be lower, averaging at EUR 12 per kg of hydrogen (AUD 20.00)

In 2006, the average cost of diesel within the EU was ~ EUR 0.50 per litre excluding taxes or ~EUR 1.01 including taxes (CUTE 2006c). To produce a quantity of hydrogen that has the same energy content of diesel it would cost EUR 3.8, approximately four times more than the taxed price of diesel.

CUTE Future scenarios

The future scenarios presented in the "Economic analysis of the hydrogen infrastructure" paper (CUTE 2006c) painted a more competitive picture for hydrogen. These scenarios were based on the assumption that hydrogen production would be scaled up to meet the political goal set by the European Commission where 2% of fuel[13] would be substituted with hydrogen by 2015 (CUTE 2006c). To supply the hydrogen for these scenario 170 plants with capacity of 600 Nm3 per hour would be needed[14]. The six tenths scaling factor

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[13] Based on energy content (lower heating value).

[14] The capacity of the onsite hydrogen production units used in the CUTE project were 60 Nm3/hour for the electrolysis units and up to 100 Nm3/hour (Stuttgart) for the natural gas reformer units.

rule[15] was applied to estimate the infrastructure costs. Slight improvements in the efficiency of hydrogen production, storage, and dispensing (5.8 kWh/Nm^3 hydrogen in the base case vs. 5.5 kWh/Nm^3 in the future scenarios) were also included. Efficiency improvements for steam methane reformer were expected to be higher than those for electrolysers with natural gas consumption decreasing from the CUTE measured average of 7 kWh/Nm^3 to 4.2 kWh/Nm^3 in the future scenarios (note that 4.7kWh/Nm^3 natural gas was experienced during CUTE when the plants were run optimally). The energy supply costs were assumed to remain constant for the future scenarios. (For further details of the analysis refer to CUTE 2006c.)

The cost for hydrogen under these future scenarios is expected to average between EUR 8 and EUR 9 (AUD 13.33 to AUD 15.00) per kg of hydrogen for electrolysis and EUR 5 (AUD 8.33) for steam methane reformation. As previously mentioned under these scenarios the non operational costs are expected to have the largest decrease. Steam methane reformer production had a higher non operational contribution to total cost. This fact, in addition to the expected improvements in efficiency, leads to a greater cost reduction that is expected for hydrogen produced by electrolysis.

In terms of diesel equivalent costs this equates to EUR 2.73 per litre for electrolysis and EUR 1.60 for hydrogen produced by steam methane reformer.

3.2.2 HyFLEET:CUTE

Wittstock (2008) presented a cost model based on the HyFLEET:CUTE results. The costs for hydrogen under this study were EUR 14.80 (AUD 24.67) for electrolyser and EUR 12.50 (AUD 20.83) for steam methane reformer per kg of hydrogen produced. Compared to the average results from the CUTE project, the HyFLEET:CUTE results are slightly higher for the electrolyser route and lower for the steam methane reformer route (although they are not outside of the minimum and maximum averages). He also presented a forecast cost of hydrogen under HyFLEET:CUTE with a cost of hydrogen produced by electrolysis of EUR 7.12 (AUD 11.87) per kg of hydrogen.

Wittstock also compared the future scenario costs for HyFLEET:CUTE with the hydrogen costs from electrolysis with other studies and found that despite different assumptions and boundary conditions the costs were quite close. The studies that were included in the comparison were U.S. Department of Energy H2A study and HyWays-IPHE (E3database). All of these studies forecast hydrogen production costs of between EUR 7.16 to EUR 7.30 per kg of hydrogen (Wittstock 2008). These are both lower than forecast under the CUTE future scenarios of EUR 8 to EUR 9 per kg hydrogen.

3.2.3 ECTOS

Cost details of the hydrogen infrastructure and production for the ECTOS project were considered by the ECTOS project team to not be representative of future systems so were not made available to the public.

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[15] The six tenths scaling factor rule of thumb has been used reliably in the chemical industry for the cost estimation of chemical processes and plants (CUTE 2006c). It is used to estimate cost reductions possible through economies of scale.

3.2.4 STEP

STEP hydrogen supply

The following description of the STEP hydrogen supply is base on DPI 2008: Hydrogen used in the STEP hydrogen bus trials in Perth was sourced from the BP Kwinana refinery. Raw hydrogen, a by-product from the oil refinery, was piped from the refinery 2km to the BOC site for purification to 99.999% using pressure swing adsorption (PSA). The purified hydrogen was compressed to 160 bar before being transported 66km in a tube trailer, by road, to the PATH Transit Morley bus depot. At the depot the hydrogen was further compressed to 295 bar and dispensed into the hydrogen buses. For the first two years of the trial, BP supplied purified compressed hydrogen at a fixed price per kilogram.

Cost of hydrogen for STEP

Cockroft (2006) stated that the price paid for hydrogen during the STEP trials was AUD 21.00/kg. Note that although this cost is simular to the results of the CUTE trials it is only based on a small scale trial and may not accurately reflect the cost of hydrogen for larger scale trial programs.

Due to the small scale of the STEP trial, the cost-benefit analysis conducted by Owen and Cockroft (2006) was based on literature values for the cost of hydrogen rather than the actual cost of hydrogen during the project. This and other assumptions were required to compensate for the economies of scale benefits which affected the bus purchase price and cost of fuel supply of the fossil fuel benefits. Based on literature sources available at the time of the study they determined that the price of hydrogen would be AUD 5.00 (AUD 4.16 net of tax) from electrolysis using wind power and AUD 3.80/kg (AUD 2.80 net of tax) from steam methane reforming (Owens and Cockroft 2006).

3.2.5 Summary of hydrogen cost from trials

Table 1 summarises the cost of hydrogen as presented from the various projects discussed in the sections above. Note that due to the range of assumptions made in each study the costs may not be directly comparable. Refer to the relevant sections above for further details.

Table 1 Summary of hydrogen cost from trials

Project	Hydrogen source	Hydrogen Cost	Cost AUD[16]	Comments
CUTE	Electrolysis (alkaline)	EUR 14.00 (EUR 12.00 to 16.00)	$23.33	Based on average results from CUTE trials
CUTE	Steam methane reformer	EUR 14.50	$24.17	Based on average results from CUTE trials
CUTE	Steam methane reformer	EUR 12.00	$20.00	Steam methane reformers when operating closer

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[16] Based on 6 month historic exchange rate 1 July to 31 December 2009 (Exchange rates.org 2009) of AUD 0.6 to EUR 1

				to design specifications
CUTE Future cost scenarios	Electrolysis (alkaline)	EUR 8.00 to 9.00	$14.16	Based on assumptions used for future scenarios
CUTE Future cost scenarios	Steam methane reformer	EUR 5.00	$8.33	Based on assumptions used for future scenarios
HyFLEET:CUTE	Electrolysis (alkaline)	EUR 14.80	$24.67	Based on initial results only
HyFLEET:CUTE	Steam methane reformer	EUR 12.50	$20.33	Based on initial results only
STEP	Oil refinery (BP Kwinana) by-product hydrogen	AUD 21.00	$21.00	Based on small scale trial

3.2.6 Costs of hydrogen produced from renewable electricity sources

Evans et al. (2008) conducted an extensive international review of the full life cycle cost of renewable electricity sources as presented in Table 2. They commented that the cost of photovoltaic electricity had the widest range in costs due to the variety of technologies (monocrystalline, amorphous etc) and variation of solar resources. Wind had the narrowest range which represents the maturity of the technology.

Table 2 Mean price[17] of electricity and greenhouse gas emissions for different generation technologies (Evans et al 2008)

Generation technology	AUD/kWh	g CO_2-e/kWh
Photovoltaic	$0.27	90
Wind	$0.08	25
Hydro	$0.06	41
Geothermal	$0.08	170
Coal	$0.05	1004
Gas	$0.05	543

The cost of electricity used in the CUTE economic analysis was EUR 0.10 or approximately AUD 0.17/kWh which is higher than for all electricity generation methods presented in Table 2, except for solar PV.

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[17] based on 6 month average (1 July to 31 December 2009) AUD-USD exchange rate of 0.88

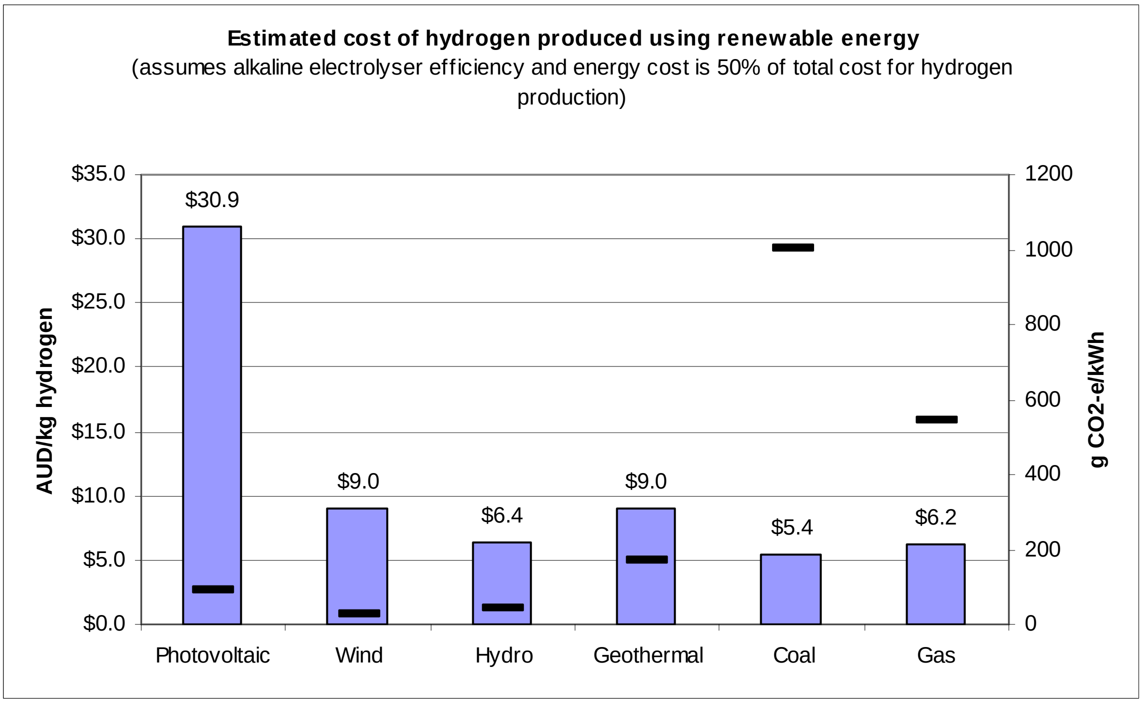

Figure 13 Estimated cost of hydrogen produced (and CO_2-equivalent emissions) using renewable energy, coal, and natural gas (Evans et al 2008, CUTE 2006c)[18]

Figure 13 estimates the cost of hydrogen production by electrolysis based on the average cost of renewable electricity generation as calculated by Evans et al. It also shows, using horizontal bars, the average greenhouse gas emissions produced by each generation method. The renewable source with the lowest cost is hydro but the GHG emissions are higher than those for wind power. Hydro is only marginally more expensive than generation by natural gas. Solar PV also has low GHG emissions but the average cost is over three times that of wind. Coal and gas have the lowest generation cost but also have the highest GHG emissions at 550 and 1000 g of CO_2-e per kWh produced.

3.3 Technical or environmental issues of various hydrogen production technologies

Stolzenburg et al (2009) conducted an extensive review of the lessons learnt from operation of the hydrogen infrastructure in the CUTE project. This report, along with the other CUTE deliverables, are unique in that they are based on results of real life trials of hydrogen production and bus technologies. These CUTE evaluation reports are the basis for the technical and environmental assessment.

3.3.1 Technical issues with alkaline electrolysis

In general the electrolysis hydrogen production units performed very well with good overall production efficiencies and high availabilities (>95%)[19]. The exception to this was the

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[18] Cost estimates for renewable energy generation based on Evans et al (2008). Assumes alkaline electrolyser used to produce hydrogen, that the energy cost is approx. 50% of the total cost of hydrogen production (from CUTE 2006c), and based on the 6 month average exchange rate (1 July to 31 December 2009) of 0.88 AUD-USD (Exchange rates.org 2009). Coal and gas are included for comparison purposes.

[19] Two of the four electrolysis units had high availabilities (Amsterdam and Stockholm), the other two units (Barcelona and Hamburg) had availabilities of 68% or lower.

Hamburg unit where there was a leak in the lye circuit due to corrosion of a pipe which caused extensive downtime and a low overall availability of 68% (Stolzenburg et al 2009). Once this issue was resolved there were no other significant issues.

There was insufficient data recorded for the Barcelona electrolyser to determine the efficiency and availability, although Stolzenburg et al (2009) commented that the availability should be similar to Stockholm which was 95%.

The Reykjavik electrolyser used in the ECTOS trials had the same issues as the Hamburg plant (the plants were identical) which resulted in three months down time while the issue was investigated and rectified (ECTOS 2006). Other than this issue the availability of the ECTOS hydrogen production unit was very high (ECTOS 2006).

3.3.2 Technical issues with steam methane reformers

As previously mentioned the steam methane reformers used in the CUTE trials were prototype small scale units. As expected with prototype units there were numerous problems during the trial. The main problem was the inability of the units to operate intermittently to match hydrogen demand. Intermittent operation was not feasible due to design, component, and material issues. The start-up times were very long - around 50 hours (compared with the minutes required to start the electrolyser units) as the units operate at very high temperatures. The Madrid unit had major design and operational issues resulting in only 18% availability. When the issues were resolved the unit did operate at 53% overall efficiency when operated continuously.

For onsite production, where intermittent operation is required, the steam methane reformer units did not prove to be suitable in comparison to the electrolysis units.

3.3.3 Hydrogen losses

One issue that is often not mentioned in hydrogen studies are the hydrogen losses. During the CUTE trials 274t of hydrogen were supplied but only 192t were consumed by the buses with the difference being accounted for by losses (Stolzenburg et al 2009). These losses can occur for many reasons including; component failure, maintenance, shutdowns, purging, and through normal system operation. Approximately 5% of hydrogen produced by alkaline electrolysers is normally used to regenerate the dryer units. For steam methane reformers the amount consumed to regenerate the PSA units is higher at around 15%. During the CUTE trials two sites had significant hydrogen loss issues; London and Stuttgart. At the other sites hydrogen losses ranged from 7% for Amsterdam (onsite production by electrolysis) to 29% for Luxembourg (external supply of compressed hydrogen) (Stolzenburg et al 2009).

The issues at the London site were due to the hydrogen being delivered in liquid form (LH_2) based on the expected consumption rate of 120 kg/day. The actual consumption rate was much lower at 60 kg/day. In order for the liquid hydrogen storage vessel to remain within safe operating pressure limits the hydrogen ‘boiling off’ was released. This boil-off accounted for 69% of hydrogen delivered.

The problems at Stuttgart were caused by the inability of the unit to operate intermittently (to produce hydrogen for refuelling only when required). Losses resulted when purging the system at start-up but the most significant losses occurred when the unit was run continuously at minimum production level to avoid start-up/shutdown issues. Any hydrogen that was produced when the storage vessels were full was simply vented.

3.3.4 Compressor issues

Hydrogen compression took place in the station units. Failure of the hydrogen compressors was a significant source of downtime of the station units. Membrane and seal failures caused leakage issues but more significant were the contamination issues caused by lubricant oils and graphite. Fuel cells require hydrogen of high purity, any contaminants can cause damage[20]. The graphite is thought to have entered the system when minor leaks upstream allowed air to enter. The air (containing O_2) then reacted with the hydrogen in the compressor causing micro explosions which damaged the graphite seals of the compressor resulting in contamination of the compressed hydrogen.

3.3.5 Hydrogen production from wind

Bartholomy (2005) raised some interesting points in a study into hydrogen production from wind power in California:

Many studies state that the electricity used to power the electrolysers was provided by ‘renewable energy’ which is true on a net basis but on an hour by hour perspective when the wind power isn’t available the power is often provided by fossil fuels. This creates a different environmental footprint to the scenario where hydrogen is only produced when the electricity from renewable energy sources is available. If hydrogen is only produced when renewable energy is available then sufficient storage is required. In his California study the wind resource varies dramatically with the worst month having only 10% of the energy output of the best month. To manage this variability large scale storage would be required (e.g. underground hydrogen storage) which would alter the efficiencies and potentially alter which of the scenarios is more environmentally beneficial.

The other question raised in this study is should renewable energy be used to produce hydrogen for transport or would it be of greater environmental benefit to use the renewable energy to displace electricity generated from fossil fuels. The Californian modelling showed that under most circumstances it was of greater benefit to the environment to offset the electricity rather than to offset use of gasoline or diesel for vehicles using renewable hydrogen. This is consistent with the findings of several other studies (Ally and Pryor 2006) although energy security and local air quality issues must also be considered.

One of the most interesting conclusions from this study was that in California the wind resource was often greatest during off-peak periods when additional electricity, above that provided by base load, wasn’t required. As the fossil fuelled base load plants take a long time to start-up and shut down the wind farm power output is ‘curtailed’ and the capacity factor of the wind farm decreases. Under these circumstances hydrogen could be produced from the excess electricity generated by the wind farms[21]. The amount of hydrogen that could be produced in this way is significant with the potential to produce enough hydrogen for 800,000 fuel cell vehicles (Bartholomy 2005). This is a critical point to be ad-

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[20] Hydrogen contamination is less critical for ICE hydrogen buses although impurities do increase tailpipe emissions.

[21] One issue is there may be low numbers of operating hours causing high costs per kWh.

dressed for the Western Australian context- how much hydrogen could be generated by ‘curtailed’ renewable energy?

3.3.6 Energy storage technologies

As hydrogen is an energy carrier, not an energy source, it has to compete with other energy storage technologies that are being developed which may have higher cycle efficiencies[22]. For transport applications this competition may come from battery technologies which also use high efficiency electric motors rather than inefficient internal combustion engines. The development of battery electric vehicles (BEV), however, is also complimentary to the development of hybrid hydrogen vehicles as they have many systems and components in common including batteries, electric drive motors, and control systems. Therefore advances in BEVs leads to advances in hybrid hydrogen vehicles (and vice versa). The environmental footprint of both BEVs and hydrogen vehicles is also dependant on their source of energy be it from fossil fuels or renewable sources.

Almost all of the major car manufacturers, including Audi, Renault, Peugeot, Citroen, Honda, Mazda, Mitsubishi, and Subaru, either currently have or will have, within the next two years, fully electric models or BEVs (battery electric vehicles) available. The BEV technology is not limited to cars either with Adelaide the first city in the world to trial a new bus powered by 100% solar energy (Adelaide City Council 2009).

A study conducted by the University of Queensland (Simpson 2005) found that BEVs have the potential to be twice as energy efficient compared with fuel cell vehicles due to the losses incurred in the conversion of energy to and from hydrogen. Both BEVs and hybrid hydrogen vehicles are benefiting greatly from the development of petrol hybrid electric vehicles (such as the Toyota Prius and the Honda Civic hybrid) where near identical battery and electric drive train technologies are used. The volume of sales of these petrol hybrid vehicles, which are rapidly increasing, will effectively finance the development of the next generation of battery electric vehicles.

New lithium battery technologies are expected to enable longer ranges and rapid recharge times[23] for BEVs although they are unlikely to match those of hydrogen vehicles, at least in the short term. Therefore BEVs look to find their niche in short range personal transport and hydrogen vehicles look to be used where extended vehicle range is required.

Battery electric vehicles may challenge the current paradigm of “refuelling stations”, provided by oil companies, as they can be simply recharged where ever there is a wall socket (although high speed recharging will require a more powerful three phase socket). Hydrogen production is likely to follow the current model where motorists go to a fuel station to ‘fill up’, at least until home electrolysis becomes a viable option[24].

As pointed out during the final HyFLEET:CUTE conference in Hamburg by Dr Hohmeyer (2009) Hydrogen would also have to compete with other technologies including the use of bio-fuels in conventional vehicles. It is anticipated that both hydrogen fuelled hybrid vehi-

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[22] Cycle efficiency is the efficiency of energy conversion from usable form to stored form and back again e.g. electricity to hydrogen and back to electricity.

[23] Subaru quote 5-15 minute charge times for their R1-e (fast charge) and Mitsubishi MIEV quote 25 minutes for 80% charge

[24] It is likely that it would still be cheaper to purchase hydrogen from a ‘gas’ station as; they would more than likely have contracts to purchase electricity at cheaper rates than residential tariffs; the smaller units would have a greater investment cost per kW capacity; and utilisation factor of home units would be lower.

cles, BEVs, and bio-fuel vehicles will be part of a suite of sustainable transport solutions available.

4 Renewable Hydrogen in Western Australian

4.1 Background

Western Australia is a massive state, covering 2.5 million square kilometres (ABARE 2008). To put this in context it is ten times larger than the entire United Kingdom, 30% of the size of the European Union, or 80% of India (ABARE 2008). The population is not evenly distributed with 80% of the population living on the coast. As such the electricity distribution infrastructure does not cover the entire state.

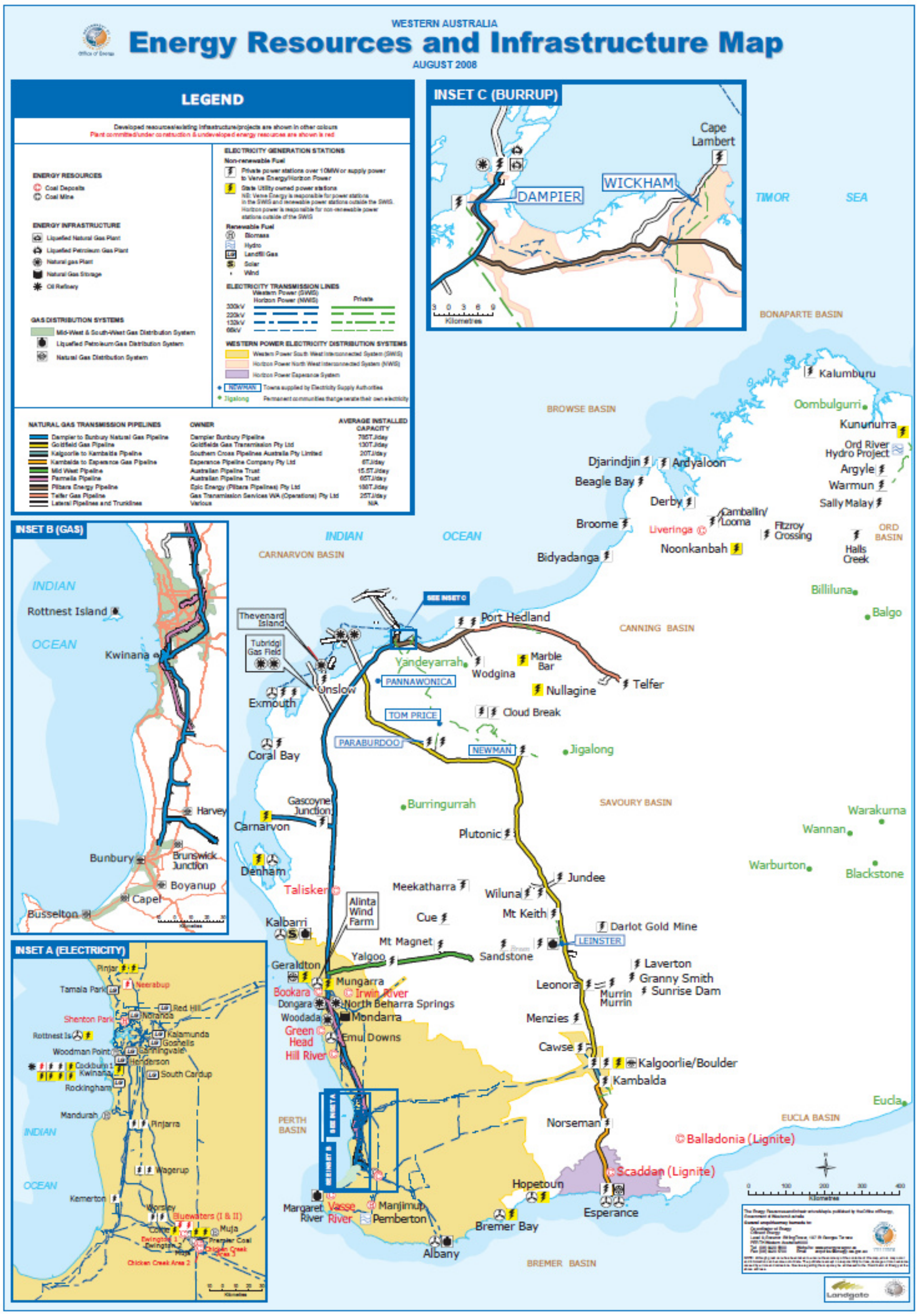

Figure 14 Western Australian energy resources and infrastructure (SEDO 2008a)

The South West Interconnected System (SWIS), as shown in Figure 14, delivers electricity to the majority of the population; it stretches from Geraldton in the north, east to Kalgoorlie, and south to Albany. The rest of the state is supplied by smaller scale discontinuous regional power supply systems.

The extent and coverage of the electricity network is important when considering renewable hydrogen production options. If the hydrogen is produced where the renewable energy resource is located then the problem is that this would not necessarily coincide with the location of the hydrogen demand. To bridge this gap either hydrogen pipelines or liquid hydrogen trucks would be required. Pipelines are currently the lowest cost option for delivering large volumes of hydrogen although high capital cost of construction, especially for long distances, would be a significant barrier (US DOE 2010. As noted in the CUTE assessment reports, the transport of hydrogen by truck in gaseous or liquid form is impractical due to the relatively low energy density by volume of (CH_2), high energy requirements for liquefaction of LH_2 and boil-off issues (see section 1.5 “Why hydrogen?”). The Department for Planning and Infrastructure report “Perth fuel cell bus trial summary of achievements 2004-2007” (2008) also commented that centralised production of hydrogen, distributed by tube trailer, would be impractical for bus fleets of greater than 10 vehicles and that a sustainable source of hydrogen was required for future hydrogen vehicle trials.

The logical solution is therefore to produce hydrogen on-site by electrolysis using renewable energy transmitted via the state electricity grid. Vehicles travelling between towns that are located off the SWIS will also require refuelling infrastructure. In this case on-site production using locally available renewable sources will be required.

Both the SWIS and the regional areas have renewable energy power sources; these are discussed below in the context of hydrogen production.

4.2 Renewable Energy in Western Australia

Western Australia has an installed electricity generation capacity of 6,951 MW (SEDO 2008b) which during 2006/2007 generated a total of 27,433 GWh (SEDO 2008c). Of this only 4% was generated by renewable sources (SEDO 2008c) as shown below in Figure 15. The majority of power was generated from fossil fuels natural gas (59%) and coal (35%).

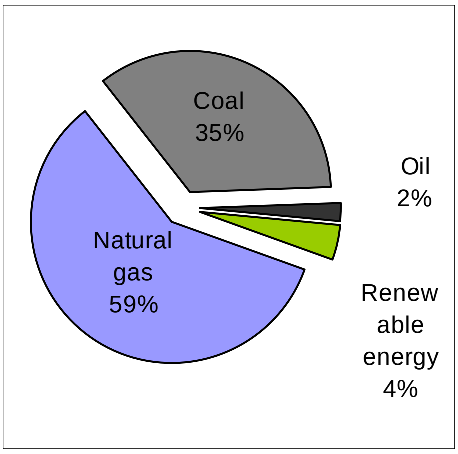

Figure 15 Western Australian electricity generation by source 2006/2007 (based on SEDO 2008c)

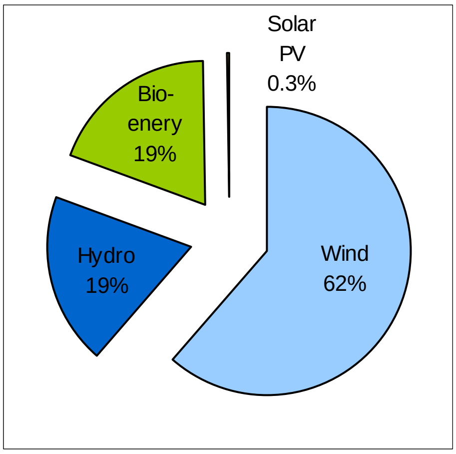

Figure 16 Renewable energy generation in Western Australia by source for 2006/2007 (based on SEDO 2008c)

Figure 16 shows the electricity generated from renewable sources of energy in Western Australia by source for 2006/2007. The majority of the power was generated by wind power followed by equal shares of bio-energy and hydro power (19% each). Solar PV contributed less than 0.3% for this period. Other sources of renewable energy are currently being developed (including wave and tidal power) but for the short to medium term wind, hydro, bio-energy, and solar look likely to dominate renewable energy generation in WA.

The majority of the renewable energy installed capacity is installed on the SWIS (87%) with only 13% installed in the regional areas (Figure 17).

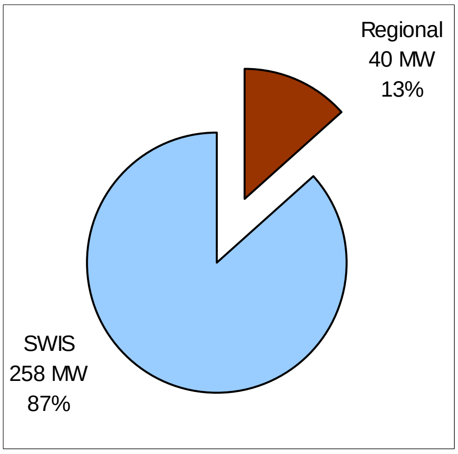

Figure 17 Renewable energy sources installed capacity 2008 (based on SEDO 2008d)

4.2.1 SWIS renewable sources

Renewable energy generation on the SWIS is rapidly expanding. Between 2002/2003 to 2006/2007 renewable electricity generated increased by over six times from 136 GWh to 840 GWh respectively (SEDO 2008c). Within the SWIS, the majority of the installed renewable energy capacity is wind power with over 192 MW installed capacity (Figure 18). Biomass accounts for 20% of the SWIS installed renewable energy capacity but it should be noted that this includes 8.5 MW of capacity at Muja power station[25]. Only a small amount is hydro power or solar PV.

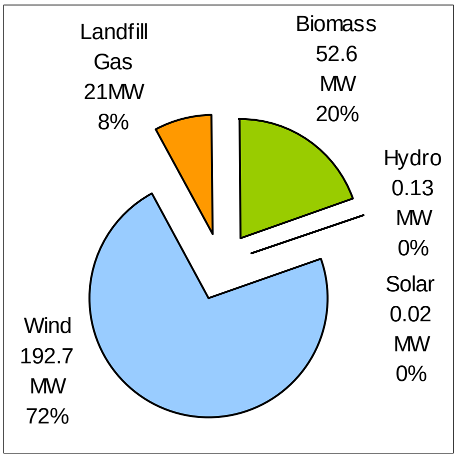

Figure 18 SWIS installed renewable electricity generation capacity for 2008 (based on SEDO 2008d).

There are plans for another three major wind farms at Grasmere (Albany, 14MW), Milyeannup (Augusta, 55MW)), and Mumbida (Geraldton, 90MW) which if approved will increase wind power on the SWIS grid by over 80% (Verve 2009a).

Wind power is one of the most mature and cost effective renewable energy technologies currently available. Wind power is now more cost competitive than diesel electricity generation although without an emission trading scheme it is not competitive with other forms of fossil fuel generation in WA on a purely economic basis (Verve 2009b). Therefore it would be the most likely source of renewable energy to produce hydrogen (both on and off the SWIS), at least in the short to medium term. For hydrogen production on the SWIS to become a reality it would have to be either economically viable at current electricity prices, or make better use of available renewable energy capacity during times when generation exceeds demand.

As electricity cannot be stored in the grid the electricity generated must be continuously managed to match demand. Failure to do so results in power quality issues (incorrect frequency or voltage[26]) or blackouts. As power produced by wind turbines can be governed more rapidly than base load fossil plants there may be times when the wind farms are shut off even though the wind may still be blowing. This results in unused generation capacity. This spare capacity could be used to produce hydrogen using electrolysis rather than ‘curtailing’ or governing the wind turbines. To meet the federal government target of 20% renewable energy by 2020 will require the installation of substantially more renewable energy generation capacity. If all of the proposed Verve wind farms mentioned previously are approved it will increase the installed renewable energy capacity on the SWIS to 7%; still 13% short of the government’s target[27]. In turn this will also increase the unuti-

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[25] 1% of the fuel for the Muja power station is provided from forestry waste biomass.

[26] Frequency of the WA grid is 50 hertz and voltage is 240 volts

[27] This includes retirement of 240MW of fossil plant due for retirement and 1067MW of new installed fossil capacity

lised generation capacity of these renewable sources. The question for future research is therefore; how often is (or would for proposed wind farms) the power output from these various wind farms governed to maintain grid power quality, and how much unutilized generation capacity does this represent? Following on from this the volume of hydrogen which could be produced could be calculated and used in cost modelling. Hydrogen production by electrolysis can respond very rapidly to intermittent power sources so can therefore make valuable use of this curtailed renewable energy capacity and may very well be the niche to make renewable hydrogen production a viable option in WA. This hydrogen could be used for transport applications or it could be "re-electrified" and used for grid stabilisation or at times when wind farm output is low.

4.2.2 Regional renewable sources

The picture is different for regional WA as power is generated for local use rather than wide distribution as it is with the SWIS. Outside of the SWIS renewable energy generation capacity is dominated by hydro power and wind power (Figure 19).

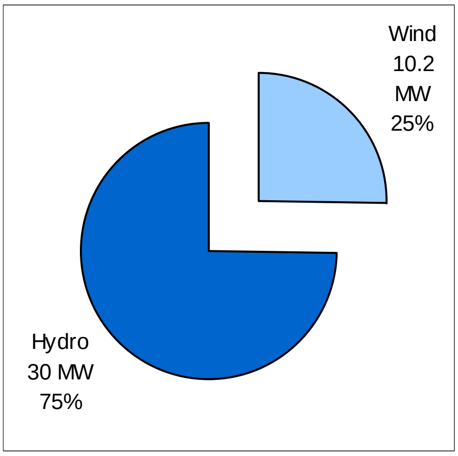

Figure 19 Regional installed renewable electricity generation capacity for 2008 (based on SEDO 2008d).

The installed renewable energy generation capacity is dominated by hydro power from one single installation- the 30 MW Pacific Hydro Ord River system. Hydro power has very rapid response times and can respond to changes in power demand so unutilized capacity for hydrogen generation would only occur in times when the storage dam is full to capacity and excess storage overflows down the raceway. And this is only one of over 60 large regional power stations installed in regional WA. For hydrogen vehicles to become a reality in WA hydrogen will have to be generated at many refuelling sites across the state.

Most of the renewable energy systems in the regional areas are wind power diesel hybrid systems located in coastal regions (Exmouth, Coral Bay, Denham, Bremer Bay, Hopetoun, Esperance, and Rottnest). Most of these systems[28] utilise world leading 'low load diesel' (LLD ®) and dynamic grid interface (DGI ®) technologies to maximise the capacity of the wind turbines and decrease diesel fuel consumption (DWS 2009). These systems do not store energy produced by the wind turbines but by running the diesel generators at low load they are able to increase penetration of the wind energy considerably. At many of

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[28] Esperance has a gas-wind hybrid system and does not utilize low load diesel generators.

the sites wind generates up to 44% of the power demand (Verve 2009a). Even though these systems are configured to maximise the capacity factor of the wind turbines there would still be periods when the wind turbine generates more than the power demand. The system at Rottnest Island is configured to utilise this excess energy to power the reverse osmosis desalination plant but other regional power stations do not have loads that can be switched on and off to maximise wind penetration.

5 Summary and Conclusions

5.1 Review of hydrogen production technologies

- Hydrogen can be produced from a range of technologies the most mature of which are alkaline electrolysis, PEM electrolysis, steam reformation of methane gas;
- Methods to produce hydrogen from biomass include biochemical conversion, thermochemical conversion, and fermentation. The most promising of these is thermochemical conversion although significant development is still required before it becomes commercially viable;
- Methods are being developed to produce hydrogen from direct solar energy including thermolysis and photolysis, however, these are the least developed of the hydrogen production methods;

5.2 Results of hydrogen program trials

Efficiency

- Hydrogen production using onsite alkaline electrolysis was overall very successful with the units performing reliably and within design specifications. Intermittent operation caused no problems for these units. Efficiency was good at 59% overall (LHV) which is predicted to improve by up to 10% in the short term;
- The prototype onsite steam methane reformer units did not perform well under the conditions of intermittent hydrogen demand. This caused problems resulting in low overall efficiency and availability. Average efficiency was measured to be 36% overall although 53% production efficiency was achieved when units were operated continuously. The outlook is good with improved efficiencies forecast, although problems caused by intermittent operation are unlikely to be resolved due to the nature of the process;
- PEM electrolysers were not used during the CUTE trials. These types of units have been installed in the first public hydrogen refuelling stations in the US. Efficiencies are expected to be similar to alkaline electrolysers;

Cost

- Cost estimates for hydrogen production and delivery in the CUTE project are higher than other studies because they are based on measured data from real life trials of technology, much of which were prototypes;
- Cost for hydrogen production by alkaline electrolysis in the CUTE trials averaged at EUR 14 per kg (at EUR 0.10 /kWh). Half of the cost was associated with energy supply, the rest associated with initial investment, and maintenance. By 2015, as hydrogen production is increased to meet the European Commission 2% hydrogen fuel by 2015 goal, the cost is forecast to decrease to around EUR 8 to EUR 9;
- Cost for hydrogen production by steam methane reformer during the CUTE trials averaged EUR 14 per kg despite the problems. If the units operated at specification the cost would have been lower at EUR 12 per kg. Future cost (2015) is anticipated to be EUR 5 per kg;

Technical and environmental issues of hydrogen production

- The alkaline electrolyser units used in the CUTE trials generally performed well and to specification;
- The prototype steam methane reformer units used in the CUTE trials did not perform as well as expected and had lower efficiencies than those stated in manufacturer specifications;
- Other technical issues in CUTE trials included hydrogen losses, compressor issues;
- Bartholomy (2005) raised some interesting issues based on a study of hydrogen production from wind in California. He claimed that the use of renewable energy to offset electricity generated from fossil fuels (such as coal) may have a better environmental outcome in the short term, rather than using the renewable energy to produce hydrogen to offset the use of petrol or diesel in vehicles. In the longer term however, the production of renewable hydrogen for use in transportation sector will help to address shortages of oil, increase energy security, and lead to lower environmental impacts.
- Hybrid hydrogen vehicles and battery electric vehicles share many components so they will both benefit from ongoing research. The niche for battery vehicles is likely to be short range personal transport and for hydrogen powered vehicles it is expected to be longer range.

5.3 Renewable hydrogen in WA

- Considering the large transport distances in WA, low volumetric density of trucked hydrogen fuels (compared to liquid fossil fuels), and the high capital cost of hydrogen pipelines- production of hydrogen in WA is likely to be local (on-site) rather than centralised. The exception would be the use of by-product hydrogen from the BP refinery, as used in the STEP hydrogen bus trials, which could be used to kick-start the hydrogen vehicle use in Perth.
- Hydrogen production by electrolysis seems the most likely scenario for WA given the success of the alkaline electrolysers during the CUTE trials for this application.
- Wind power capacity in WA is being expanded rapidly due to the maturity and cost competitiveness of this technology. It is therefore the most likely source of renewable electricity to be used to generate onsite hydrogen by electrolysis.
- The increase in intermittent renewable energy sources such as wind will potentially create a niche where hydrogen can be generated from off-peak capacity that may otherwise go unutilised. This opportunity needs further research to determine its potential in WA.
- Biomass would be favourable for centralised production of hydrogen using steam methane reformer technology but due to the distribution issues of hydrogen as mentioned above onsite electrolysis is more likely. This means that biomass may be better used to produce electricity that is fed into the grid where it can be used for onsite hydrogen generation although further research is required to investigate these scenarios.

- For hydrogen production to be competitive in regional WA (off SWIS), for stationary applications, it would have to be more efficient and practical than current methods of electricity network control or storage (e.g. low load diesel and use of off-peak electricity for other purposes such as reverse osmosis);

6 Recommendations

- There would be considerable benefit to run scenarios and simulations to optimise the production of hydrogen using renewable energy before conducting real life trials. There is potential to use hydrogen production facilities to increase the energy generated by renewable sources by utilising power when supply exceeds demand, especially during off-peak periods. These scenarios should include renewable energy plants both on the SWIS and in regional areas. With the federal government 20% renewable energy target this potential is set to increase substantially in WA;
- Simulations could be used to determine the hydrogen storage volume requirements for year round hydrogen vehicle operation in WA;
- Simulations could also be used to examine the use of battery electric vehicles and hydrogen fuel cell vehicles to determine the suitable applications of each technology within the WA context;
- To conduct research into the different production and transportation scenarios for large scale centrally produced hydrogen with transport vs. small scale local onsite production without transport for WA. Simulations could be used to determine the most cost and energy efficient production, storage, and hydrogen transportation options;
- Given the large potential for bio-energy in WA, from agricultural crop residue and oil mallee, hydrogen production from biomass is an area of that would benefit from further research. There are several scenarios for how the biomass can be transported (as a solid, electricity, or bio-oil), processed (central or distributed), and converted to hydrogen (central or on-site). These options could be investigated to determine the most suitable and efficient pathways for hydrogen production from biomass in the Western Australian context.
- Several renewable-to-hydrogen demonstration studies, similar to that proposed by CREST, are taking place around the world- these should be closely watched for results. One such study is the National Renewable Energy Laboratory (NREL) wind-to-hydrogen project which links wind turbines and a PV array to electrolysers. The hydrogen is either used to fuel a hydrogen vehicle, or used to produce electricity that is fed back into the grid during peak periods. The study aims to monitor all aspects of the system to identify any potential issues and opportunities for improvement.
- Initial results of the HyFLEET:CUTE project were presented where they were available. The final evaluation reports are yet to be completed, however, so these should be examined once they are published.

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