Sustainable Hydrogen in Wales as a Clean Fuel for Urban Transport

D L Hawkes*, J Maddy*, S Cherryman*, F R Hawkes, R M Dinsdale**, A J Guwy**, G C Premier*, S Cole***
*School of Technology University of Glamorgan, Pontypridd, Wales, UK CF37 1DL

** School of Applied Sciences University of Glamorgan, Pontypridd, Wales, UK CF37 1DL

dlhawkes@glam.ac.uk

Abstract: **The paper examines the drivers towards using hydrogen as a Clean, Efficient & Safe Urban Transport fuel in the future. It briefly reviews the major hydrogen production routes at present and examines some possibilities for sustainable production in the future together with costs of production either actual or estimated. Problems of storage and distribution are discussed and research into promising developments are examined at. Examples of some modern demonstration transport projects are given**

Introduction

Wales is a Principality within the United Kingdom of approximately 3 million people and an area of 20,640 km^2. It has a devolved government, the National Assembly for Wales (NAfW), which is mandated to implement sustainable development. The vast majority of our existing energy needs are met from carbon sources. Of the 33.5TWh electricity produced in Wales last year, some 79% came from carbon based sources and a further 18% from nuclear. Only 2.6% is currently produced from renewable sources. The UK as a whole is a poor performer when compared to our European neighbours. Part of the reason for this is the long history of coal production especially in Wales and the convenience of carbon-based fuels. This convenience brings a penalty that we should be increasingly unwilling to pay a penalty in terms of climate change, a penalty in terms of local pollution and a penalty in terms of security of supply, each an unwanted legacy for future generations. To achieve a sustainable society it is imperative to prevent these legacies of environmental problems and of tensions created through securing supplies.

The evidence is becoming overwhelming that the release of greenhouse gases, most notably CO_2 from the burning of fossil fuels has contributed to a global temperature rise of approximately $1^{o}C$ over the last 150 years. The scientific consensus is that this trend will continue and may accelerate if we fail to act. The consequence will be increased sea levels, increased precipitation and an increase in storms. All these phenomena will have an effect on human health and economic prosperity.

Whilst this is a global phenomenon, Wales currently contributes some 14 million tonnes per year of greenhouse CO_2 from its consumption of carbon-based fuels. As we now face floods on an annual basis, there is a growing perception among the Welsh public of climate change, whether or not one is aware of the scientific evidence. Thankfully, hydrogen as an energy carrier can reduce the dependency on fossil fuels and in turn reduce greenhouse CO_2.

The second factor taking us from a carbon economy towards a hydrogen economy is urban air pollution. The evidence is that air quality has improved in Europe over the last decade, mostly through an effective legislative framework. However, there is little room for complacency as road transport and industry are still the most significant contributors to air pollution. The main pollutants are particulates from diesel engines and industry, CO_2, CO, sulphur dioxide and nitrogen oxides from transport. Hydrogen can be used as a vehicle fuel greatly reducing these pollutants. Hydrogen fuel cells, when used in transport or in stationary combined heat and power systems are free of these pollutants and represent a significant step forward in improving the air that we and future generations have to breathe. Hydrogen when used in an internal combustion (IC) engine produces very low NOx and no CO_2.

In addition to the environmental need to shift to a hydrogen economy, there is an increasing need in terms of security of supply. A large proportion of Europe's diesel fuel and petrol for vehicles comes from the Middle East oilfields that are finite. The reliance on oil and the uneven distribution of the reserves with the consequent potential economic and social instability means that Western governments are urgently looking at alternatives. Whilst precise figures vary, most experts predict that the global demand for energy will rise significantly over the next 50 or 60 years. This prediction from Shell shows a trebling of energy demand between now and 2060. At the same time reserves of oil are being depleted. It is likely that the majority of existing sources of oil will run out by 2040. Between now and then, there will be increased competition for the diminishing amounts of oil to be found. Gas supply will last somewhat longer, but gas is anticipated to run out no more than 20 years after oil. Again the major reserves will be in the Middle East and Russia. These drivers mean that hydrogen is a 'hot topic' and subject of increasing research and development efforts.

Hydrogen production

Current production technologies mean that hydrogen has been relatively expensive to produce. Over 90% of the 5 billion Nm^3 hydrogen currently produced each year currently comes from fossil fuel sources, mostly by steam methane reforming, but also by partial oxidation. With a steam methane reforming plant, around 10 tonnes of CO_2 is produced per tonne of hydrogen product. Capture of the CO_2 is uncommon, although this technology could be modified to sequester the CO_2 if required.

Partial oxidation of heavier hydrocarbons such as petroleum and petroleum-derived fuels is a technology that is gaining ground. Currently most applications are refinery scale, but there is potential to scale this technology down to individual vehicles to allow on-board conversion to hydrogen for the vehicle's fuel cell.

Integrated gasification combined cycle plants are now becoming more common, using heavier oil or coal as the primary feedstock. In general these are used to produce hydrogen rich streams for power recovery using gas turbines. The proposed Valleys Energy project for the Dulais Valley in South Wales is an example (Patterson 2003).

The challenge with hydrogen produced from all fossil fuel is to prevent the release of CO_2 to the atmosphere. Sequestration or capture of the CO_2 can be achieved by a number of means, trees and soils, carbonate materials, in the ocean, or in geological formations (Hart et al., 1999). Research activity is increasing in this area, particularly as this enables a realistic bridge between the carbon producing technologies of today and the emerging carbon free technologies.

Sustainable methods of hydrogen production (Figure 1) are required if hydrogen is to replace fossil fuels as we move towards the hydrogen economy. Hydrogen may be produced renewably by:

- electrolysis using electricity from renewable sources
- photo processes
- generation from biomass by;
    - gasification or pyrolysis
    - reforming methane from biogas
    - photo-biological processes
    - hydrogen-yielding fermentations

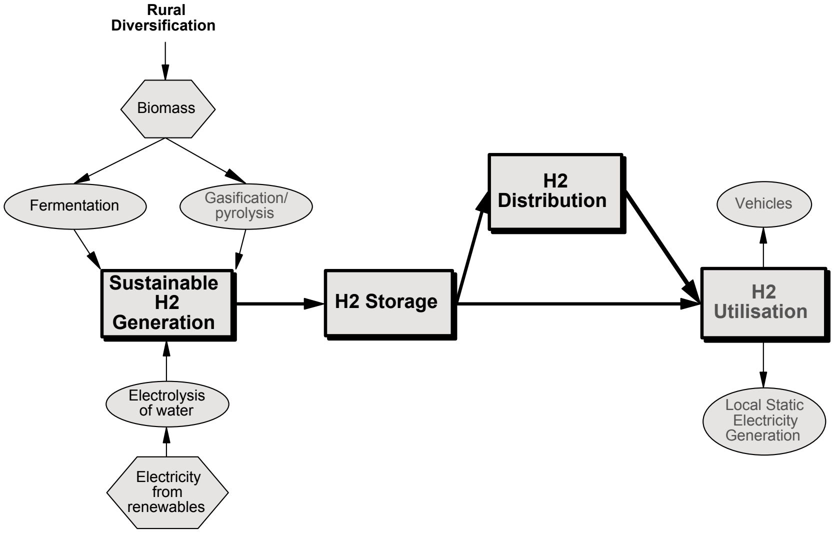

Figure 1 Sustainable routes to the hydrogen economy

Electrolysis

Electrolysis is a tried and tested method of producing hydrogen (and oxygen) from water. It would seem that this is the ideal technology to be used in conjunction with renewable energy to produce hydrogen, effectively producing no CO_2 in the manufacture of the hydrogen product. However, electrolysis is much more expensive than reforming natural gas and accounts for less than 4% of current world hydrogen production.

In addition, the vast majority of the current hydrogen electrolysis plants are powered by non-renewable electricity to provide a merchant hydrogen product. To realise the potential beneficial effect of this technology, the electrical energy must come from renewable sources. Photovoltaics are to be used in the UK's USHER project to produce 'green' electricity for electrolysis producing hydrogen to fuel a local bus in the city of Cambridge (Slater 2002). There are also a number of variations on this theme of splitting water currently being researched, plasmolysis, magnetolysis, thermal and photo-electrolysis, all trying to achieve more efficient and cost effective ways of splitting water.

Photo processes

The best known of these is the Tandem Cell marketed by the Hydrogen Solar Production Company (H2SPC) which uses light to split water and produce hydrogen. The device was developed in the EPFL's Laboratory in Switzerland and claims to have a 10% light conversion efficiency through the ability to more effeciently capture the different spectral emissions of sunlight (H2SPC, 2003)

Hydrogen from biomass

Hydrogen from biomass is another emerging technology and an area of expertise at the University of Glamorgan. The benefit is that as the plant source consumes CO_2 in its growth, the overall cycle is CO_2 neutral. There are two main routes to produce hydrogen from biomass, the thermo chemical route, including gasification, pyrolysis and super critical gasification or a biological route, including fermentation.

Woody biomass can be gasified to produce hydrogen (as with coal) indeed there is the possibility to use biomass and coal as duel feedstock to a gasification plant. This can include dry biomass wastes, partially avoiding any competition for land use. Although there have been some commercial false starts, this route will increasingly provide sustainable hydrogen in the future.

Biologically, hydrogen can be produced either photosynthetically or from dark fermentative processes. Bio-hydrogen production from biomass is, again, CO_2 neutral and sustainable. This technology is at the stage of moving from R&D lab to pilot scale. One of the research focuses at the University of Glamorgan is to optimise the sustainable fermentative bio-hydrogen process. The ability of pure cultures of bacteria to produce H_2 from sterilised carbohydrates by batch fermentation is well known. However, from an economic viewpoint an easily obtainable, mixed bacterial population operating continuously on non-sterile feedstock to yield hydrogen is required. The bacteria used should be naturally occurring, and the University of Glamorgan team have investigated start-up of the fermentation process using sewage sludge to select for hydrogen-producing fermentative bacteria (Hawkes et al., 2002). There are reports in the literature of hydrogen production from some food industry wastes in batch culture, but there is little information on H_2 yields expected from a continuous process operating on a complex starch feedstock. The process gives fermentation end-products which are easily converted to methane by conventional high-rate anaerobic digestion.

Many species of bacteria can produce hydrogen. The challenges for the process are:

i. to find the best organic materials for use as substrate
ii. to maximise the yield and rate of hydrogen production be maximised
iii. To determine the overall process economics & how costs can be reduced

A comparison table of the current costs of hydrogen production (Table 1) indicates how far we have to go with the more sustainable production routes. There is some debate on the detailed costs of renewable routes to hydrogen. For example, the fermentative process should be capable of producing hydrogen at a unit cost comparable to that of methane produced by anaerobic digestion which would be near to the cost of present steam reforming. With all of the renewable routes, the economies of scale that could come with increased implementation will inevitably bring down the unit costs.

Distribution

Hydrogen is transported around the country as either by pipeline or by road or rail as a compressed gas or as a liquid. There are already hydrogen pipelines in the UK based around production plants and heavy industry and there are large distribution network pipelines in Teesside and in Wales. The hydrogen pipeline is similar to natural gas pipelines although due to the physical properties of hydrogen natural gas pipelines cannot be used directly to transport pure hydrogen (Eliasson and Bossel, 2000) but would need to be upgraded to accommodate hydrogen. A compressed hydrogen tube trailer holds one load equal to approximately 460kg at pressures of 20.60mPa (Howes, 2002 and Amos, 1998). The maximum amount of liquid hydrogen transported in one container is normally 360-430kg (Howes, 2002 and Amos, 1998) Liquid hydrogen has a higher gravimetric density than compressed gas cylinders and therefore can be transported more economically over longer distances. Today all of the UK liquid hydrogen is imported, much of it from The Netherlands.

Vehicle on-board storage

Standard compressed gas cylinders do not hold very much hydrogen in comparison with the overall weight of the cylinder. High pressure cylinders at a pressure of 40MPa hold an approximate 1.8kg (Howes, 2002). Vehicle manufactures are however looking at very high pressure storage around 70 MPa with the new challenges that brings to safety and public acceptance.

Even with the very efficient insulation that is now possible boil off will occur with liquid hydrogen transportation and is estimated to be around 0.3% per day on long hauls (Dutton, 2002). The BMW 7 Series car uses this to advantage as it powers a 5kW fuel cell to maintain the electrical power in the vehicle even when it is not running.

Table 1 Comparative Cost of Hydrogen Production

Fuel / Energy Carrier	Price (2001-2003)	£/GJ
Petrol	77p/litre (UK pump price)	£24.06/GJ
	16.6p/litre (pre-tax estimate)	£5.19/GJ
LPG	36p/litre (forecourt price)	£14.10/GJ
	29p/litre (pre-duty)	£11.36/GJ
Natural Gas	$6.50/MMBtu (Mar 2003 Peak)	£3.92/GJ
Hydrogen (typical production cost values)	Reforming Natural Gas	£3.2/GJ
	Partial Oxidation of Oil	£5.73/GJ
	Coal Gasification	£7.01/GJ
	Biomass Gasification	£8.28/GJ
	Hydroelectric Electrolysis	£7.64/GJ
	Wind Electrolysis	£20.38/GJ
	Solar Thermal Electrolysis	£24.84/GJ
	Solar Photovoltaic Electrolysis	£28.66/GJ

The storage of hydrogen using metal hydrides would be an advantage over compressed or liquefied hydrogen as solid storage allows a high storage density without the high pressure or dangers of a liquid hydrogen spill. Metal hydrides are however heavy and expensive, precluding this as a viable large-scale storage method at present. Research work is ongoing into other storage materials such as light metal hydrides, polymers and micro-, meso- and nano-porous carbons. The UK's EPSRC is funding a project (£3.5 million) on hydrogen, SUPERGEN. A large part of this work is on storage methods as this is seen to be crucial to the future widespread use of hydrogen.

Safety is an important aspect and all fuels are potentially unsafe in certain circumstances. Hydrogen being lighter than air has advantages over many fuels in the event of a vehicle accident. Test have shown that a petrol fuel tank fire resulted in the total destruction of the vehicle whereas a hydrogen tank fire left the vehicle hardly damaged due to the rapid escape of the low density gas (Swain, 2001)

Hydrogen cars

Most of the major motor manufacturers are working on hydrogen-powered vehicles and a number of demonstration trials are going on around the world with both cars and buses in operation. The vehicles either have fuel cells producing electricity for electric motors or use hydrogen directly in an IC engines. With fuel cells the emission are only water vapour but with IC engines there is some NOx as the nitrogen in the air remains. The estimates vary as to when such vehicles will be in mass production rather than as the few demonstration models that currently exist but some manufactures have declared that by as early as 2004 there will be models available to the public. Of course by that time there will need to be an infrastructure capable of supporting them.

Typical fuel cell vehicles

The main advantages of a fuel cell operating on hydrogen over IC engines are; greater energy efficiency, zero emissions (apart from water vapour) and low noise levels. Ford, in 2000, brought out a hydrogen version of the Ford Focus which had a 75kW fuel cell stack and used compressed hydrogen. The 2 kg of hydrogen that it carried gave it a range of 160km and a top speed of 130km/h (Birch 2003)). This was further development of their work on hydrogen powered vehicles which began with the Ford P2000 in 1998.

Also in 2000 General Motors launched their HydroGen 1 based on the Opel Zafra station wagon which had an 80kW fuel cell stack and used hydrogen stored as a liquid. The 75 litres (about 5kg) gave it a range of 400km (Kruse *et al.,* 2002)

The DaimlerChrysler Necar 5 was launched in 2000 and utilsed hydrogen from a methanol reformer system. The methanol fuel is the only major difference between the Necar 5 and the Necar 4 which had 5 kg hydrogen stored in liquid form. The fuel cell stack was 70kW and had a range of 450km and a top speed of 145km/h.

Toyota started road tests on a fleet of hydrogen cars in Japan in 2001 after years of research. The hydrogen is stored as pressurised gas and gives a range of 250km using a 90kW fuel cell stack. The top speed is 150km/h and the car has a reputed efficiency of 48% compared to the equivalent petrol version.

Internal Combustion Engine (ICE) vehicles

Although most of the major vehicle manufacturers have fuel cell powered prototypes the relatively high price of fuel cells is a significant barrier for current mass production. To overcome this a number of manufacturers have converted conventional ICEs to be fuelled with hydrogen. BMW is one of the best known manufacturers to produce a hydrogen car with liquid hydrogen storage and an ICE as the power unit. The BMW 750 hi modelled on their 7-Series has a super insulated tank and has a range of 350km. The vehicle is dual fuel with a petrol tank giving an extra 500km range. A demonstration programme of hydrogen powered vehicles at Munich Airport is currently operating with both fuel cell and ICE powered buses (Figure 2).

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Figure 2 Robot liquid hydrogen refuelling at Munich airport

Hydrogen in Wales

Hydrogen Distribution: Passenger Vehicles in Wales

Fossil Fuel Basis **-** There were 1.2 million passenger cars registered to owners in Wales at the end of 2001. Each vehicle travelled an average of 9230 miles per year and consumed 250 gallons in doing so (1136 litres or 36.35 GJ). So the total fuel usage of these passenger cars alone was some 1.36×10^9 litres (= 43.5 PJ or 4.35×10^{16} J). Assuming unleaded fuel at a current average of 77p/litre (£24.06/GJ). Total passenger vehicle fuel expenditure in Wales was £1.047 billion.

Hydrogen Equivalent - Consider by comparison the hypothetical case of all of these vehicles being powered by fuel cells rather than internal combustion engines. Assume a fuel cell vehicle efficiency of 45% compared to the internal combustion engine efficiency of 25%. This equates to an individual fuel requirement of 20.19 GJ to travel same distance, equivalent to 159kg hydrogen. For a total passenger vehicle fleet, this equals 191,000 tonnes hydrogen per year or 523 tonnes per day.

Hydrogen Distribution - To satisfy this demand, there would have to be an equivalent of 174 liquid H2 tanker deliveries per day in Wales, or 1867 compressed hydrogen trailer deliveries per day, based on existing hydrogen transport capacities.

Forecourt Price - For the Welsh consumer to pay the same total amount (i.e total annual expenditure should be £1.047 billion) the price per kg of hydrogen at the forecourt would be £5.49/kg (£43.23/GJ)

Hydrogen Research in Wales

There are a number of research projects on hydrogen being carried out in Wales at the present time. One of these is the ERDF Objective 1 Priority/Measure: 2.5. Project, Title: A Sustainable Energy Supply for Wales: Towards the Hydrogen Economy. The project will identify and bring together the main players in the Objective 1 area/Wales with a stake in the development of the hydrogen economy to work together strategically. Hydrogen generation by fermentation of biomass, by electrolysis from wind energy, or by gasification/pyrolysis from biomass, together with H_2 storage and utilisation technologies need to progress simultaneously, informed by data on economic and social issues. Advances made by each stakeholder will have a synergistic effect on others. The project will identify the most viable demonstration projects for a second stage, including possible sources of funding. These demonstration projects should be able to be implemented rapidly, because the necessary technical, economic and social information will have been put in place by the project. The project will also provide a framework of information to support decision-making by those responsible for developing a sustainable energy policy in Wales, notably NAfW. Appropriate fiscal measures and support structures can then be put in place to allow the Objective 1 region/Wales to be at the forefront of this technological revolution and benefit economically.

Conclusions

The future fuel for vehicles is likely to be hydrogen. It is not certain how long it will be before such vehicles are common on Europe’s roads but a start has begun with several EU funded projects at both research and demonstration scale. Research into methods of production, transportation, storage and final use are all being undertaken and demonstrations of both cars and buses are taking place already or in the near future.

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