Tyndall°Centre
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# The role of hydrogen in powering road transport

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# The Role of Hydrogen in Powering Road Transport

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# 1 INTRODUCTION

In the United Kingdom, at present, transport is the third largest source of carbon dioxide emissions and the UK Climate Change programme (Department of the Environment, Transport and the Regions (DETR), 2000a) do-minimum forecast is for carbon dioxide ($CO_2$) emissions from the transport sector to increase from 40.0 MtC (million tonnes carbon) in 2000 to 45.4 MtC in 2010. The chapter on transport focused on increasing the efficiency of road vehicles and reducing their use to move towards the commitment to cut greenhouse gas emissions by 12.5% below 1990 levels by 2008-12 and the goal of achieving a 20% reduction in $CO_2$ emissions below 1990 levels by 2010. Policy measures include those in the Ten Year Plan for Transport (DETR, 2000b) and the voluntary agreement between the European Commission (EC) and the Association des Constructeurs Européens d'Automobiles (ACEA) (ACEA/EC, 1998) which aims to reduce average carbon dioxide emissions from new cars to 25% below 1995 levels by 2008. In combination these measures could lead to a 5.6 MtC reduction in greenhouse gas emissions. This corresponds with data from Auto Oil II as reported by ACEA (2000), which suggests a stabilisation of carbon dioxide emissions from the transport sector at the European level. In the longer run to 2020 further increases are expected in UK transport emissions (DETR, 2000a).

At best then it appears that emissions from transport may be stabilised or exhibiting slowed growth by 2010. This will not be sufficient if transport is to contribute to more ambitious targets such as the Royal Commission on Environmental Pollution (RCEP) target of 60% reduction by 2050 and 80% by 2100 aiming for stabilisation of $CO_2$ at 550ppm (RCEP, 2000). Hydrogen, especially if ultimately produced from renewable sources offers a means of achieving substantial reductions in $CO_2$ emissions without significantly altering our current levels of personal mobility. In this respect the step change in technology is very attractive as achieving behavioural shifts in the use of motorised vehicles poses major political and practical difficulties.

This paper examines issues relating to the use of hydrogen in the road transport sector. While the air transport sector is extremely important as it is the fastest growing source of $CO_2$ emissions within transport, we have focused on the road sector as it is the main source of emissions and the sector where the technology is developing most quickly. This work was carried out during Phase 1 of the Tyndall Centre Project: The Hydrogen Energy Economy: its long-term role in greenhouse gas reductions. The overall aim of the project is an assessment of the long-term viability of the hydrogen energy economy as a way of reducing carbon dioxide emissions. While the main driver towards a hydrogen based economy is climate change, there are a range of other possible benefits in the transport sector, reviewed below.

### *Air pollution*

Air quality has historically been the principal driving force behind moves to encourage cleaner fuels and technologies in the UK and elsewhere. Transport emissions include nitrogen oxides, benzene, carbon monoxide, particulates, and sulphur dioxide. Nitrogen dioxide, particulates and carbon monoxide are associated with respiratory problems, while there is potentially a risk of cancer from exposure to benzene. Sulphur dioxide and Nitrogen oxides contribute to acid rain. In the UK in 1999 road transport produced 68% of benzene emissions, 68% of carbon monoxide emissions, 19% of particulates, 17% of nitrogen oxide and sulphur dioxide emissions combined (National Statistics, 2001). The use of hydrogen in vehicles can if through fuel cells reduce tailpipe emissions to water vapour, if in an internal combustion engine, pollutants are significantly reduced.

***Noise***
For the majority of people in the UK transport is the main source of noise in the environment (RCEP, 1994). While tyre/road interaction is the dominant noise source at speeds above 50kph (light vehicles) and above 80kph (heavy vehicles) (Organisation for Economic Co-operation and Development (OECD), 1995) at slower speeds engine noise is more significant. The use of hydrogen in fuel cells eliminates engine noise, which would be particularly beneficial at lower speeds in urban areas.

***Accidents and spillage***
The production and transport of oil can have severe environmental impacts. Drilling for oil can disrupt already vulnerable ecosystems. While accidental spills at sea can cause devastation to marine habitats. A spill of liquid hydrogen would boil-off in gaseous form. As hydrogen is lighter than air any spill would disperse rapidly, with no adverse environmental impact. The remaining risk is that of ignition which is a risk with any flammable fuel.

***Energy Security***
In 2000, transport accounted for 74% of the total oil consumption in the UK (Department of Trade and Industry (DTI), 2001), with road transport relying on oil to power 99.8% of its vehicles (Department of Transport, Local Government and the Regions (DTLR), 2001). The UK fuel crisis of September 2000 and the oil crises of the 1970's illustrate some of the problems that reliance on one source of fuel may create. Hydrogen is an 'energy carrier' and it may be produced from a number of different sources and methods including: steam methane reforming; electrolysis of water; dissociation of methanol, partial oxidation of hydrocarbons, biomass gasification, and reversible fuel cells (Dutton, 2002). Production is not tied to specific locations and may be dispersed. Thus hydrogen has the potential to meet the Governments desire for security of supply: one of the considerations in the recent energy policy review (Cabinet Office press release, 25 June 2001).

Hydrogen has the potential to reduce various environmental impacts of transport and enhance energy security as well as reducing $CO_2$ emissions. In this paper we explore some of the key aspects to be addressed in considering the use of hydrogen in road based transport. Section 2 addresses the technical issues and considers the costs of different options. Section 3 examines the evidence on $CO_2$ emissions from different vehicle technologies and energy supply mechanisms. Section 4 explores the potential for the widespread use of renewables to produce hydrogen. Section 5 looks at measures, which might be taken in the short and medium term to encourage technological progression towards hydrogen based road transport. Section 6 contains our conclusions and suggestions for further work.

# 2 HYDROGEN IN ROAD TRANSPORT

In this section we consider some of the key technical factors influencing the potential role of hydrogen in the road transport sector namely:

- options for energy supply and use in the vehicle
- vehicle characteristics and efficiency
- hydrogen production and distribution

We also examine cost estimates for the different technologies where available. We do not examine the technical aspects of hydrogen production in great detail as these are addressed in the paper by Dutton (2002).

## 2.1 Options for Energy Supply and Use in the Vehicle

Hydrogen may be used to power a vehicle in two key ways:

- fuel cell
- internal combustion engine.

There are five main types of fuel cells: Alkaline (AFC), Phosphoric acid (PAFC), Solid Oxide (SOFCs), Molton Carbonate (MC) and Solid Polymer (SPFC), which are also known as Proton Exchange Membrane (PEM). For private vehicles most car manufacturers are concentrating on Solid Polymer fuel cells, these offer high power density, rapid start-up and low temperature operation, though Alkaline fuel cells could also be used. In trucks and other large vehicles there is the potential for Solid Oxide fuel cell use. At present, fuel cell costs are high: a SPFC for transport purposes is estimated to cost $550/KW; however if mass produced costs could fall to $30/kW (transport SPFC) (Brandon and Hart, 1999). One potential drawback is the catalyst for SPFC is platinum, but the quantity required is decreasing (Dutton, 2002).

Conventional Internal Combustion Engines (ICE) require only minor modifications in order to use hydrogen.

Vehicle manufacturers are pursuing both types of technology. There is a wide range of options for producing the hydrogen, mostly off-vehicle, although on-board reforming of petrol and methanol is possible. Figure 2.1 shows the main options.

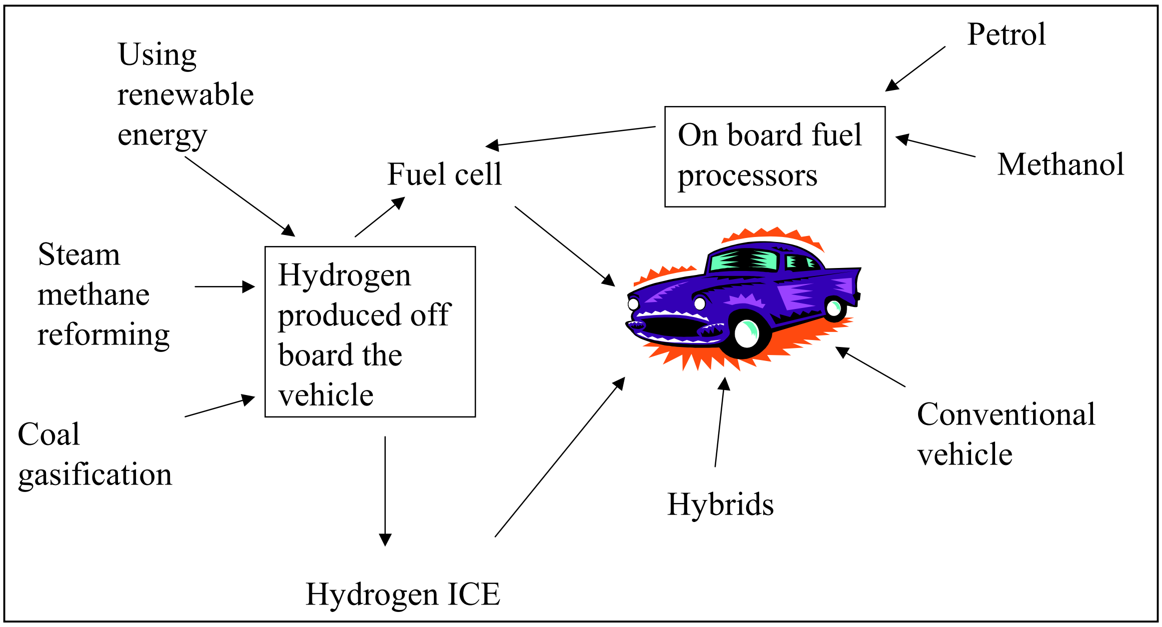
***Off Board Production of Hydrogen***

Hydrogen may be produced off vehicle by a variety of means including: steam methane reforming (approximately 50% of the current production for industrial use); coal gasification; pyrolysis; reversible fuel cells; dissociation of methanol; partial oxidation of hydrocarbons, biomass gasification and electrolysis of water (Dutton, 2002). The long-term aim would be the use of renewable energy, since this would bring the largest benefits in greenhouse gas reduction, air pollution reduction and energy security. Renewable energy sources for hydrogen production through electrolysis include solar power, wind power and hydropower. Hydrogen may also be generated directly from solar photoelectrolysis, or biomass.

### *Production of hydrogen on board*

Hydrogen could be produced on board the vehicle. In this case an interim fuel such as petrol or methanol would be used in on board fuel processors to produce hydrogen, which would then be used in a fuel cell.

**Figure 2.1 Hydrogen Use in Transport**



## 2.2 Costs

A range of studies have been undertaken to determine the costs of using hydrogen in transport. The studies cover price of the fuel, the cost of the vehicle and the cost of introducing a hydrogen infrastructure. The costs of a present day internal combustion engine have been included for comparison. The studies are based on US data and may not be representative of the situation in the UK or Europe.

### *Vehicle Costs*

The vehicle cost estimates are based on an assumption of mass production of the vehicles and may be seen in Table 2.1. However, the likely differences in timescales for development of the different technologies are not examined. At present it is not clear which technologies will reach target cost levels first. Though hydrogen internal combustion engine development will benefit from previous internal combustion engine experience.

Even with mass production of the vehicles, the cost estimates are higher than for a present day internal combustion engine. These additional costs can be attributed to storage with off board production of hydrogen, and the fuel processors when hydrogen is produced on board the vehicle.

**Table 2.1 Cost of Hydrogen Powered Vehicle**

| Route taken | Cost of Vehicle ($)<br>(mass production) |
|---|---|
| Present Day Internal Combustion Engine | \$18,000 (a) - \$19,255(b) |
| Fuel cell with Hydrogen produced off board the vehicle | \$19,900 (a) - \$26,876 (b) |
| Internal Combustion Engine with Hydrogen produced off board the vehicle | \$21,765 $H_2$ Internal Combustion Engine with liquid hydrogen (b)<br>\$26,296 $H_2$ Internal Combustion Engine with gaseous hydrogen (b) |
| On board production using methanol | \$20,100 - \$21,500 (a) depends if best case / probable scenario |
| On board production using petrol | \$20,550 - \$24,300 (a) depends if best case / probable scenario |

Source Thomas *et al* 2000 (a), Padro and Putsche 1999 (b)

***Infrastructure Cost***

Reforming of natural gas, electrolysis of water and partial oxidation of heavy oil have all been examined as means of producing hydrogen for transport purposes (Ogden 1999, Thomas *et al* 2000, Berry *et al* 1996, Thomas *et al* 1998). Cost estimates in these studies also take account of the various means of transporting the hydrogen to the fuelling site, truck delivery, pipeline delivery, cryogenic tanker truck delivery and on site location. Again as these studies are based in the US, which has different energy supply structures to the UK, it is not clear how the infrastructure or costs suggested would translate to UK use, but they do provide an indication of the range of methods available and an indication of cost relativities. The costs shown for different methods in Table 2.2 are taken from two sources: Ogden 1999 and Thomas 2000. Ogden *et al* (1996) in Ogden (1999) assume existing hydrogen production capacity is utilised, with the costs of the infrastructure spread over a fleet of 18,400 fuel cell cars. Thomas *et al* 2000 assume that the cost of providing hydrogen via one on site steam reformer would be spread over 1000 Fuel cell vehicles.

The cost of producing methanol for use in the on board production of hydrogen is included in Table 2.2. Thomas *et al* (2000) provide two examples 1) Assumes no new production capacity is required and the cost of converting a gasoline tank and dispenser to methanol is spread over 1000 vehicles 2) New production capacity is required, the plant costs \$1 billion and the cost is spread over 2.2 million vehicles. For the use of petrol it is acknowledged that the cleaning of the petrol, to make it suitable for use in a fuel cell, may be necessary, and that this new petrol may require separate tanks and dispensers. However no cost estimates were found.

Natural gas appears to offer the cheapest solution for off board production. The most expensive is electrolysis, which could be seen as a proxy for renewable energy use in electricity production. We do not have costs for the direct use of renewables.

**Table 2.2 Infrastructure costs**

| | Costs per vehicle | Assumptions |
|---|---|---|
| Present day Internal Combustion Engine | No new costs involved | |
| Off board production of hydrogen | $230 | One on site steam methane reformer to supply 1000 FCV would cost $230,000 (a) |
| | $76 | Centralized production via steam reforming of natural gas w/LH2 delivery. Assumes 2 stations combined cost $1.4 million, existing hydrogen production capacity and trucks used, 18,400 vehicles would be served (b) |
| | $370 | On site steam reforming of natural gas: fuel cell steam methane reformer. Assumes two stations combined cost of $6.8 million, existing hydrogen production capacity used, 18,400 vehicles would be served. (b) |
| | $522 | Centralized production via steam reforming of natural gas w/pipeline delivery. Assumes 2 stations combined cost of $3.4 million, plus 10 km of pipeline at $6.2 million, 18,400 vehicles would be served (b) |
| | $587 | On site steam reforming of natural gas: conventional steam methane reformer. Assumes 2 stations combined cost of $10.8 million, 18,400 vehicles would be served (b) |
| | $620 | On site advanced electrolysis using off peak power. Assumes 2 stations combined cost of $11.4 million, 18,400 vehicles served (b) |
| Methanol for use in on board fuel processors | $50 | For conversion of gasoline tank and dispenser to methanol. Assumes cost of conversion $50,000 and that 1000 fuel cell vehicles would be served (a) |
| | $450 | If new production capacity is required. Assumes Methanol Plant would cost $1 billion and would serve 2.2 million methanol fuel cell vehicles (a) |
| Petrol for use in on board fuel processors | No costings available but companies may have to supply a separate fuel cell grade of gasoline. This new gasoline may require separate tanks, dispensers etc. | |

(a) Thomas *et al* 2000 cites American Methanol Institute (1998) as the source of the $50,000 conversion cost
(b) Ogden *et al* (1996) in Ogden (1999)

These papers acknowledge the chicken and egg problem that the development of a hydrogen infrastructure faces. Energy companies will not want to invest large sums of money developing a complex hydrogen infrastructure until they are sure that the demand will be there. However in order for people to want to drive a hydrogen car and so create this demand they need to be able to access a hydrogen filling station easily. The Cleaner Vehicles Task Force acknowledged that the low number of publicly accessible refuelling points can act as a barrier to the take up of alternative fuelled vehicles using Liquid Petroleum Gas (LPG) and Compressed Natural Gas CNG) (DTI, 2000).

One possible means of overcoming this dilemma is by the use of small scale on site production of hydrogen from natural gas (Berry *et al* 1996, Thomas *et al* 2000, Foley, 2001). Here the UK benefits because it already has a natural gas infrastructure in place, with between 80 and 85% of the population having access to a natural gas connection (Foley, 2001). The sites could initially be, existing petrol stations and fleet re-fuelling depots. In the longer term however they could feasibly be located anywhere with access to a natural gas supply (Foley, 2001). In addition natural gas is at present one of the cheapest means of producing hydrogen (Hart *et al* 2000). However, energy security issues would remain due to reliance on natural gas. It also limits the means of storing the hydrogen since liquid hydrogen cannot currently be produced on-site efficiently. The use of natural gas continues the dependency on carbon based fuels. A limited hydrogen infrastructure is less of a problem if a bi-fuelled internal combustion engine were to be used, since petrol could also be utilised.

***Operating Costs and Efficiency***
Identifying an estimate of the likely cost of the hydrogen in use as a transport fuel has not been straightforward, instead costs of hydrogen by different production methods are provided in Table 2.3, these do not include transport or storage costs for the hydrogen.

**Table 2.3 Costs of hydrogen by different production methods**

| Method | Cost Pence per kWh | Cost ($/GJ) |
|---|---|---|
| Reformation of Natural Gas | 1.23-2.00 | 5-8 |
| Other Fossil (Oil pox, coal gas) | 2.50-3.00 | 10-12 |
| Biomass Gasification | 2.25-3.25 | 9-13 |
| Hydroelectric Electrolysis | 2.50-5.00 | 10-20 |
| Wind Electrolysis | 5.00-10.00 | 20-40 |
| Solar Thermal Electrolysis | 10.00-15.00 | 40-60 |
| Solar Photovoltaic Electrolysis | 12.50-25.00 | 50-100 |

Source: Bauen (2001)

Fuel cell vehicles are more efficient than internal combustion engines in urban conditions so on a per kilometre basis operating costs could be lower. The maintenance costs are also expected to be lower as there are fewer moving parts. However it is not clear at this stage what the life span of a fuel cell is.

Thomas *et al* (2000) suggest that the cost of producing methanol for use in a fuel cell would be slightly higher than the cost of gasoline.

## 2.3 Vehicle Characteristics

The characteristics of current demonstration vehicles are:

- BMW hydrogen ICE is a 750 hl sedan car is capable of 141 mph. It is a bi-fuel vehicle and can operate on petrol or hydrogen. It has a range of 220 miles on hydrogen and 430 miles on petrol. Hydrogen is stored in liquid form

- DaimlerChrysler NECAR 4 is a liquid hydrogen fuel cell car is capable of 90 mph and has a 280 mile range. Hydrogen is stored in liquid form.
- DaimlerChrysler NECAR 5 fuel cell car powered by on board reformation of methanol is capable of 90 mph and has a range of 125 miles.

One key issue is the range of the vehicle. Here the BMW hydrogen ICE has an advantage in that it can be powered by both petrol and hydrogen so distance from a refuelling point will not be an issue. Moreover the current range is greater than for many petrol vehicles. Other means of limiting this problem could include ensuring a wide network of hydrogen refuelling points, though it is appreciated that this could be difficult, and/or increasing the vehicle range.

On performance a top speed of 90mph may be perceived as reflecting a poor performance on other characteristics such as acceleration, which may dissuade take-up. The move from a petrol powered internal combustion engine to a hydrogen powered fuel cell vehicle is a significant change that people may be reluctant to consider. There is the possibility that a hydrogen powered internal combustion engine or the use of petrol in a fuel processor to power a fuel cell vehicle could be considered a more acceptable step towards change. There may be safety issues regarding the use of very quiet vehicles, with the potential for road transport accidents if a vehicle cannot be heard approaching. This problem has been recognised by Oxford City Council who operate a fleet of electric vehicles, and has been partially rectified by the use of reversing bleepers (Powershift, 2001a).

A fuel cell car offers many advantages. It has far fewer moving parts than a modern internal combustion engine and requires less maintenance. Fuel cells are also more efficient than conventional internal combustion engines, especially in urban conditions, where energy consumption could be halved (Fergusson, 2001). Furthermore demographic changes will lead to an increase in the proportion of female and elderly drivers who may favour the use of quieter, slower cars (Fergusson, 2001).

Once people get used to low noise vehicles large benefits could be felt, especially in urban and residential areas, particularly at night. A fuel cell car would also be able to incorporate technological options such as digital communications, and advanced in-car entertainment (Shell, 2001). Though this would also be possible in an internal combustion engine, if additional electrical power was supplied or if a fuel cell (small) was utilised.

Hydrogen stored on board vehicles in liquid form will require much larger tanks for the same range, with gaseous hydrogen requiring even larger tanks unless very high pressures are used. It is not clear at this stage when the technology for metal hydrides and carbon nanotubes will become available or how suitable it will be for transport applications.

The major motor manufacturers are predicting that hydrogen fuel cell vehicles will be made available on a limited basis by 2004, and hydrogen powered internal combustion engines in the next 5-7 years. For the cars to be available on a commercial basis is expected to take longer, for fuel cell cars estimates are in the range 10-15 years (DTLR *et al* 2001).

# 3 GREENHOUSE GAS EMISSIONS

The key consideration is the level of emissions from the different means of using hydrogen. This section concentrates on greenhouse gas emissions and private vehicles.

A fuel cell vehicle would produce only hydrogen and oxygen from the tailpipe and these would dissipate harmlessly. However a hydrogen powered internal combustion engine would produce some $NO_X$, the amount emitted dependent on operating conditions, although the amount would be lower than that of conventional vehicles and could be controlled by the use of a catalyst. It would also produce a small amount of CO and non-methane organic gases, and a very small amount of particulates (Lipman and DeLucchi, 1996).

However, tail-pipe emissions are only part of the story, a life cycle analysis also takes into account the greenhouse gases and air pollutants that are produced in the manufacture and delivery of hydrogen. A hydrogen powered fuel cell vehicle and a hydrogen powered internal combustion engine are examined below, and compared with conventional vehicles.

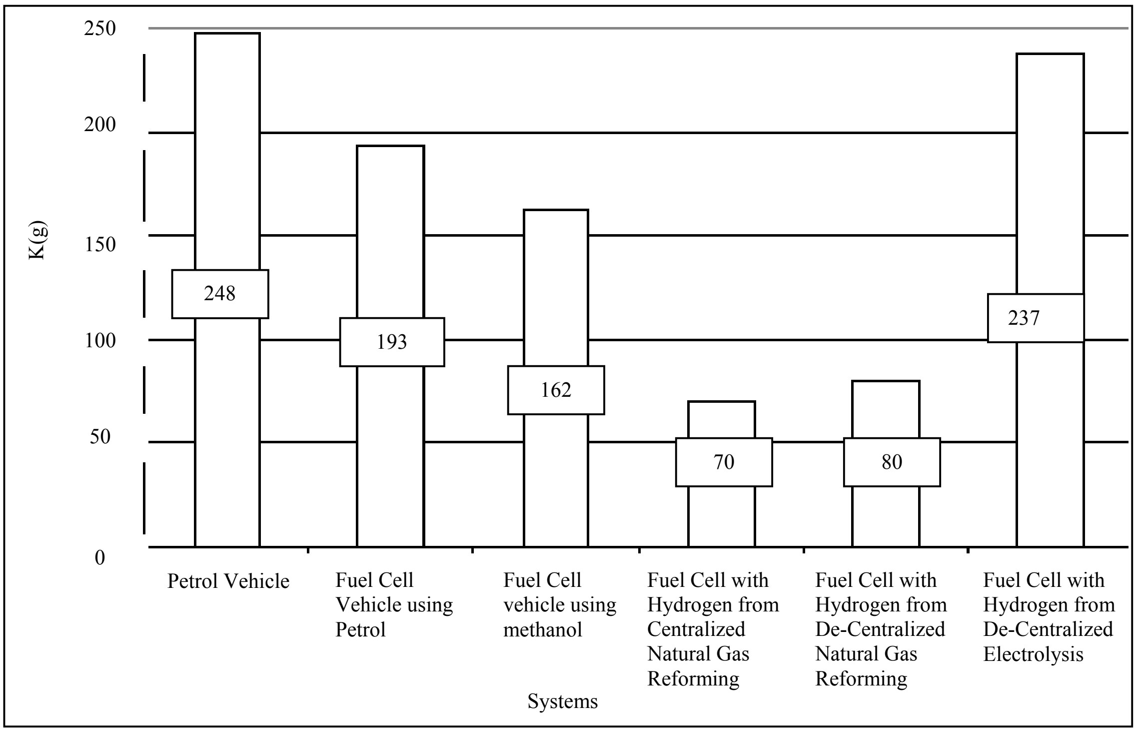
## 3.1 Greenhouse Gas Emissions From Hydrogen Powered Fuel Cell Vehicles

When a life cycle analysis is undertaken a hydrogen powered fuel cell vehicle is still less ‘polluting’ than a conventional internal combustion engine. However, the extent to which emissions are reduced is dependent on the method used to produce the hydrogen.

The Pembina Institute (2000) undertook a life cycle examination of a typical petrol vehicle, a Mercedes A class and compared it with a fuel cell, with hydrogen produced by five different means for Canadian conditions. The results are illustrated in Figure 3.1.

It is apparent that the greenhouse gas reduction offered by the use of a hydrogen fuel varies depending on the means of hydrogen production. Centralized natural gas reforming produced the greatest reductions. However de-centralized production has only slightly greater emissions, poses fewer technical challenges and is expected to be the most cost effective hydrogen system, since it can be expanded as fuel cell vehicles increase in numbers. The Pembina Institute (2000) analysis does not include emissions from the construction, maintenance and operation of the natural gas reformer.

**Figure 3.1 Total Greenhouse Gas Emissions for Each System (per 1000km travelled)**



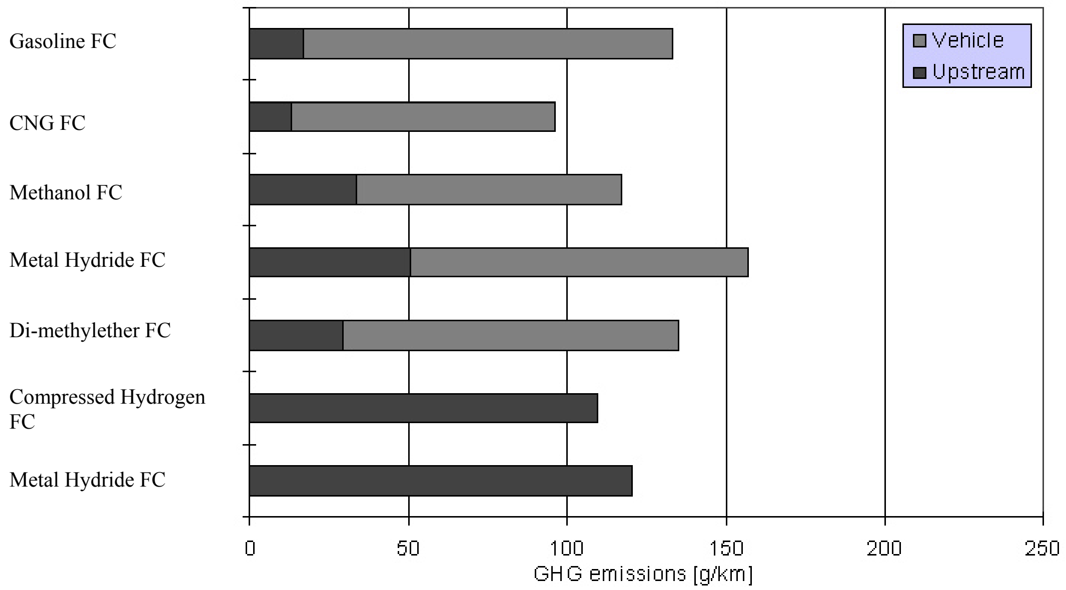
Source: The Pembina Institute 2000

The high emissions that result when the hydrogen is produced from de-centralized electrolysis are due to the use of a fossil fuel (natural gas) to produce the electricity. If the electricity were generated from renewables the $CO_2$ emissions would be under 70kg per 1000 kms (using the Pembina figures).

The study concludes that decentralised natural gas reforming and electrolysis systems are the most feasible options as they utilise existing power grids and can be expanded incrementally allowing organic growth. In the long run electrolysis could be undertaken using electricity generated from renewables. From an environmental point of view this would be the most attractive option.

Another life cycle analysis undertaken by Shell for UK conditions again based on a Mercedes A Class (Louis, 2001) shows similar results (Figure 3.2), though the magnitude of the reduction is not as large. It is thought that this could be attributed at least in part to the Pembina Institute analysis (2000) not including the emissions from the operation of the natural gas reformers, and the different electricity supply mix in the UK.

**Figure 3.2 Greenhouse Gas Emissions from Fuel Cells**



Source: Louis 2001

## 3.2 Greenhouse Gas Emissions from Hydrogen Powered Internal Combustion Engines

As with fuel cells greenhouse gas emissions from hydrogen powered internal combustion engines depend on the means of producing the hydrogen and how the hydrogen is stored. Lipman and DeLucchi (1996), undertook life cycle analysis for hydrogen powered internal combustion engines with the hydrogen coming from different sources. The results are shown in Table 3.1.

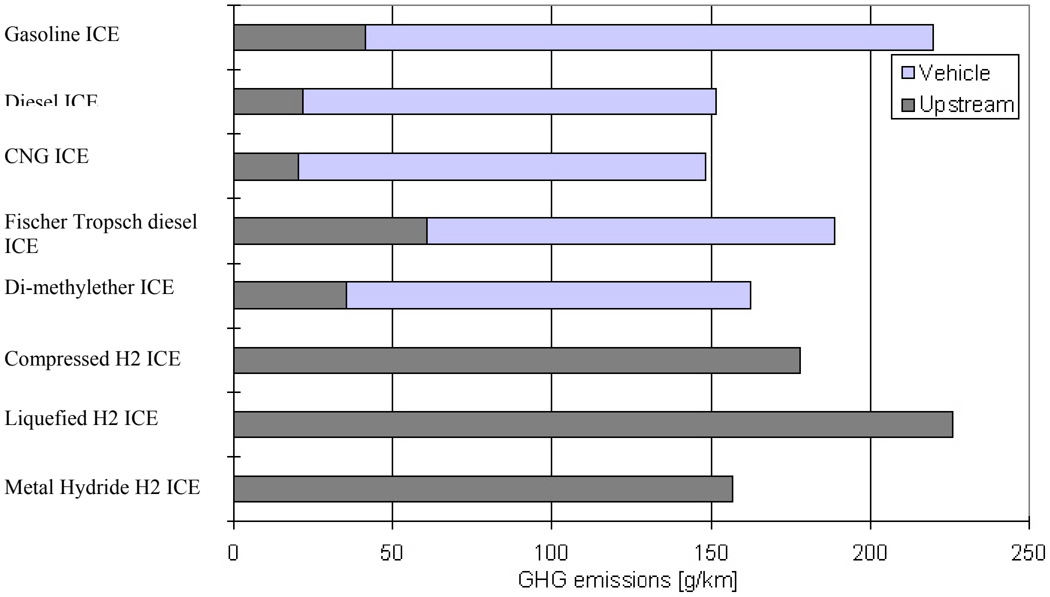
**Table 3.1 Fuel Cycle Carbon Dioxide Emissions**

| Feedstock/fuel/vehicle | Fuel cycle $CO_2$ – equivalent emissions (change with respect to reformulated gasoline) |
|---|---|
| Coal/compressed hydrogen/ICEV | 52% |
| Natural gas /compressed hydrogen/ICEV | -25% |
| Biomass/compressed hydrogen/ICEV | -75% |
| Solar electrolysis/compressed hydrogen/ICEV | -82% |

Source: adapted from Lipman and DeLucchi (1996)

The more recent work by Louis (2001) showed similar results, see Figure 3.3, with hydrogen produced from natural gas and stored as compressed hydrogen leading to 22% less emissions than a petrol powered internal combustion engine.

**Figure 3.3 Well-to-Wheel greenhouse gas emissions from alternatively fuelled internal combustion engine vehicles**



Source: Louis 2001

In terms of storage issues if liquid hydrogen is used then the greenhouse gas emissions are comparable with a conventional gasoline internal combustion engine. This is because the low liquefaction temperature of hydrogen means that large amounts of energy are required to covert it to liquid form. The largest reductions are achieved when the hydrogen is stored in metal hydrides.

The Louis (2001) study assumes a conventional electricity generation mix. Were the electricity to be produced from renewable sources $CO_2$ emissions would be much lower.

# 4 CARBON FREE HYDROGEN PRODUCTION

In order for the maximum environmental benefits to be secured then the hydrogen used should be carbon free. There are several ways of producing the hydrogen:

- Fossil fuels and carbon sequestration
- Electrolysis of water using carbon neutral electricity, the electricity being produced either from fossil fuels with carbon sequestration; or by renewable energy or nuclear power
- Biomass, either by the chemical or thermal reformation of biomass feedstocks or the biological reformation of biomass using micro-organisms
- Solar photoelectrolysis, the direct splitting of water using light with special catalysts or extreme heat

## 4.1 Use of Renewable Energy

At present the UK has the potential to use wind, landfill gas, wave, solar, geothermal, waste and energy crops as means of producing energy. Of these onshore wind and landfill gas are nearing competitive pricing. A major barrier at present is that renewables only produce 3% of the UK's electricity. However the Government has a target of 10% of all electricity being generated by renewable energy by 2010. The key intervention measure to help achieve this target is the introduction of the Renewables Obligation, which from April 2002 will require electricity suppliers to provide an increasing proportion of electricity from renewable resources, the proposed level of obligation is 3% in the period 2002-2003 rising to 10.4% in 2010-2011. In addition electricity produced by renewable forms will be exempted from the Climate Change Levy, and an expanded programme of capital grants will be made available.

In the UK landfill gas and onshore wind with prices in the range of 2.5–3.0p/kWh are close to being competitive (Performance and Innovation Unit (PIU), 2002), as wholesale electricity prices are currently well below 2p/kwh. Other renewable technologies are more expensive: Offshore wind is 4-5p/kWh and energy crops are 6-8p/kWh with higher prices for tidal stream, wave and photovoltaics (PIU, 2002). At present the use of renewables in the UK is limited, consisting of only 1% of the UK primary fuel mix compared to 43% for gas and 32% for oil.

There are doubts over whether the 10% target can be achieved (RCEP, 2000, Foley, 2001, Parliamentary Office of Science and Technology (POST), 2001), the main concern being that growth in renewables is not occurring at a fast enough rate. This is attributed to several factors, the difficulty in obtaining planning permission for wind farms due to concerns over noise and visual intrusion; the costs of connecting embedded generators to the network; and the effect of the introduction of the New Electricity Trading Arrangements (NETA). The small scale of some renewable generators means that they cannot take part in the trading directly, furthermore NETA penalises generators who fail to meet their contract requirements, which because the output of electricity from renewables tends to be more variable means that renewable energy is particularly susceptible to these penalties. The PIU (2002) energy review acknowledges these problems, but sees them as surmountable advocating a target of 20% of electricity coming from renewables by 2020.

It is probably too early to say whether the 10% will be achieved or if a 20% target will be introduced. The potential for the use of this electricity to produce hydrogen is very limited at this stage for several reasons:

- The electricity produced by renewables might be better utilised meeting future demand, and replacing the electricity that would have come from more carbon intensive sources
- Substantial investments are needed
- Electrical output would have to double for there to be sufficient energy for the road transport sector, if most vehicles were run on hydrogen (PIU, 2002)

Small scale on site use of renewables may be a way forward. Renewable energy is being assessed alongside a number of other options in the CUTE project and is the sole means of hydrogen supply with the USHER project (see section 5.5). Though these are demonstration projects, at present, in the longer term, when renewable costs fall, this is perhaps a feasible suggestion for fleet vehicles.

Hydrogen can also be generated directly from solar photoelectrolysis and biomass. However for the UK the costs of solar photolectrolysis are likely to be too high and fuels derived from biomass are likely to be constrained by limits on available land (PIU, 2002). Though these sources could be used for smaller scale projects.

It is recognised that transport, because of the pollution and efficiency benefits offered, will be one of the main means of utilising hydrogen (PIU, 2002). Hydrogen also acts as means of storing energy, and could help overcome one of the barriers to the use of some renewables e.g. wind and solar, which is their intermittent nature. If hydrogen was to be used as an energy store, then its use in transport may happen more quickly than initially anticipated.

### 4.2 Nuclear Power

The PIU (2002) acknowledges that the nuclear option should be kept open as it offers an established means of providing very low carbon electricity, with its role being strengthened if other existing means of producing low carbon electricity generation and energy security are difficult to provide cheaply. However, there are public concerns over the disposal of nuclear waste and the perception of vulnerability of nuclear power plants to accidents and attack.

### 4.3 Carbon Sequestration

Carbon sequestration involves the capture of carbon, and its storage or reuse. The carbon could be stored in oceans and geological formations. However there are several issues that need to be considered. Firstly are the risks of leakage. Secondly the economics; it is estimated that sequestration would add 25-30% to the costs of producing hydrogen from natural gas (Hart *et al* 1999). Sequestration is likely to make more economic sense on a large scale, whereas small scale on site production of hydrogen using natural gas may be most appropriate for initial transport applications. Thirdly, there is a range of other environmental costs associated with the use of oil, as shown in Section 1. Finally if this were seen as an environmentally friendly solution to the use of fossil fuels the development of renewable energy could be slowed. The PIU Energy Review (2002) acknowledges the potential role of carbon capture and sequestration in allowing the use of fossil fuels in a low carbon world, but also acknowledges that at present there are uncertainties surrounding costs, safety, environmental impacts, and public and investor acceptability, and that these uncertainties need to be resolved.

### 4.4 Conclusion

To conclude, in the short or medium term low carbon hydrogen use in transport will be limited because of a number of issues, which have been covered briefly in this section. In the longer term for the UK the electrolysis of water is probably the most viable option for the wide scale production of low carbon hydrogen. The carbon free electricity for this process can be made by several means: fossil fuels with the carbon being sequestrated; renewable energy; and nuclear power. It is too early to say which route is likely to be followed, although the renewable route is ultimately the most attractive.

# 5 MEASURES IN THE SHORT TO MEDIUM TERM

The widescale implementation of hydrogen in transport is a long run outcome. It is necessary to consider both pathways toward that end and ways of reducing emissions in the shorter term. The problems faced in the transport sector of congestion, environmental pollution, social exclusion and increasing demand cannot be resolved by any measure in isolation; integrated strategies are required. In the transport sector it is likely that demand management strategies will play an important role in moving toward a more sustainable transport system. There is a large body of evidence on the effectiveness of individual policy measures in influencing transport technology and behaviour (Grant-Muller, 2000; May & Matthews, 2001) and ways in which policy measures may be combined for maximum effectiveness (May *et al*, 2000; May *et al* 2001). Studies have sought to identify sustainability in transport (for example Banister *et al* 2000) and very recent work has explored the best potential measures for decoupling transport and economic growth (SPRITE, 2002). Here we do not attempt to address a very wide range of policy measures nor do we consider in detail issues relating to take up and diffusion in the market. We focus on the options and measures that could aid in reducing carbon emissions through technology, research and development and supportive policies.

## 5.1 Hybrid Electric Vehicles

Hybrid Electric vehicles use two types of power source together for example an internal combustion engine and electric motor. This increases fuel efficiency and reduces emissions. In normal conditions the engine will provide most of the power and charges up the battery. In the stop start driving conditions typical in many cities the electric motor will provide the power. Environmental benefits arise from the greater fuel efficiency, around twice that of a conventional vehicle resulting in a halving of carbon dioxide emissions, and air pollution reductions. There is a price premium but this is partly offset by increased energy efficiency (PIU, 2002).

The relevance to a hydrogen future is that some of the technology, which will be developed for advanced hybrids will also be necessary for or desirable for advanced fuel cell vehicles. This includes improvements to: electronic control systems; electric drive trains and the development of super capacitors all of which are vital components of the progressive electrification of the motor vehicle from which fuel cell technology will benefit (Fergusson, 2001). The hybrid could be seen as a ‘bridge’ from pure internal combustion engines to fuel cells (DTLR *et al* 2001).

## 5.2 Compressed Natural Gas (CNG) and Liquefied Petroleum Gas (LPG)

LPG consists predominantly of propane, which is a by-product of oil refining. LPG vehicles can run on solely LPG and these are spark ignited, alternatively they can operate as dual-fuel vehicles, which switch over from petrol to LPG at the flick of a switch. At present there are around 40,000 LPG vehicles in the UK (Powershift, 2001b) and 1020 refuelling sites (Lees, 2002). The main market is light goods or private vehicles, it is estimated that LPG could replace up to 5% of the petrol and diesel market.

CNG is natural gas, which is predominantly methane. Again vehicles can be set up to run solely on natural gas and are spark ignited or as dual-fuel vehicles, which switch easily between CNG and petrol. There are a limited number of public refuelling points and typically fleets have opted to install depot based refuelling facilities.

In terms of reduction in greenhouse gas emissions, LPG offers a 10-15% reduction of life cycle $CO_2$ emissions compared to petrol and approximately a 5% reduction when compared to diesel (DTI, 2000). With heavy-duty vehicles life-cycle $CO_2$ emissions are comparable to diesel (DTI, 2000). CNG offers reduced carbon dioxide emissions but these can be offset by the fact that CNG is derived from methane. In cars it can offer a 20% reduction in greenhouse gas emissions compared with petrol. However when compared to diesel it offers a slight increase for light duty vehicles, and a comparable or slight increase for panel vans and heavy duty vehicles over 3.5 tonnes. It is in these heavy-duty vehicles that CNG is typically used (DTI, 2000), suggesting no gains in greenhouse gas reduction. Both LPG and CNG offer reduced noise and local air pollution reductions.

A key benefit that LPG, CNG and hybrids have is getting people used to idea of using alternative fuels and vehicles. However, neither fuel produces clear gains in $CO_2$ emissions.

### 5.3 ACEA agreement

One means of offering carbon dioxide reductions without the use of alternative vehicles or fuels is to have more efficient vehicles. The European Environment Ministers have set a target of reducing average carbon dioxide emissions from new cars to 120 grams of carbon dioxide per kilometre by 2005 or 2010. For comparison the average carbon dioxide emissions from new cars sold in the UK is currently around 185g/km. The key element of this strategy is the voluntary agreement between the European Commission and European car manufacturers (ACEA, 1998) to reduce average carbon dioxide emissions from new cars to 25% below 1995 levels by 2008. Climate Change the UK Programme (DETR, 2000) details technology that could be used; direct injection gasoline and direct injection diesel engines, engine improvements, weight reduction, reduced rolling resistance and aerodynamic improvements.

If these reductions were achieved in a conventional vehicle they would be comparable to the reductions offered by the use of hydrogen in fuel cells, if the hydrogen was produced by natural gas. However they would not offer the long-term benefits that hydrogen produced from carbon free sources could.

However, it is worth noting that over the past decade efficiency improvements in Internal Combustion Engines have been off set by a range of factors including: increased size of vehicles, better safety standards, increased power, and wider uptake of additional features for example air conditioning. These trends are likely to continue (Bristow, 1996, Fergusson, 2001) and therefore improvements in individual vehicle efficiency will not necessarily translate into an equivalent reduction in fleet fuel consumption.

## 5.4 Fleet Vehicles

Hydrogen vehicles are most likely to make a breakthrough in the bus market (Foley 2001, DTLR *et al* 2001) and that for certain fleet vehicles e.g. Local Authority vehicles, before the private vehicle market for several reasons:

- Buses have central depots and fixed routes, which makes re-fuelling easier
- The relatively short distances that certain fleet vehicles and buses are used for also eases refuelling
- Because of their larger size, storage of hydrogen is not an issue
- Bus companies/Local Authorities may be willing to accept a higher purchase price in return for a reduced life cycle cost
- Air pollution and noise benefits, particularly for buses/Local Authority vehicles in city centres and compared to diesel, are high
- Speed is less important
- Policy intervention is easier

Though there are certain issues still to be resolved including: the durability of a fuel cell bus compared to a diesel bus, the cost, and the refuelling times involved (Perl, 2002) the more optimistic estimates suggest that hydrogen buses could be cost competitive by 2012 (Hart *et al* 2000, Mauro 2001). However, these assume Government involvement in encouraging take up which will in turn drive down costs, for example: subsidising the purchase of the buses, and/or ensuring that all levels of Government are early adopters of the vehicles (Mauro, 2001).

## 5.5 Trial Schemes in the UK

The initial hydrogen cars are also likely to be used in fleet operations for example business or local authority pool cars. Examples so far are:

***Fuel Cell Taxi***
A traditional London taxi powered by a 5kW alkaline fuel cell was demonstrated in 1997/8 (Hydrogen and Fuel Cell Letter, 1998). This vehicle was shown at the 1997 Motor Show. However, it is understood that the vehicle was a one-off that was not put into normal operation (Godfrey, 2002).

***Fuel Cell Van***
Westminster Council obtained a 1.5 ton hybrid van, powered by a 5kW alkaline fuel cell, with battery support for the Parks Department (Hydrogen and Fuel Cell Letter, 2000). This vehicle was in operation, but is no longer functioning (Thompson, 2002).

Two projects will be introducing hydrogen buses into the UK soon:

***CUTE (Clean Urban Transport in Europe) Project***
The European Commission are funding the trial of 30 hydrogen fuel cell buses in 10 European countries, with three in London. The buses are low floor Mercedes-Benz Citaro buses each of which will have the fuel cell with the compressed hydrogen in gas bottles mounted in the roof. The vehicle range will be 200-250 kilometres and performance will be comparable to a conventional diesel bus. Evobus, the bus

division of DaimlerChrysler are providing the buses, which will be operated by First Group. Transport for London (TfL) are also involved and BP will provide the dedicated hydrogen refuelling facility. The hydrogen for the project will be produced by different means, including the electrolysis of water and the use of photovoltaic cells, to allow comparisons to be made (Jones, 2002). Both liquid and gaseous fuel infrastructures will be trialed. The first buses will be delivered at the end of 2002 and will be trialed until 2005. TfL are expecting to use more fuel cell buses at the end of the trials, though adoption of a wider route network would be dependent on the development of a wider hydrogen fuel infrastructure.

***USHER (Urban Integrated Solar to Hydrogen Energy Realisation)***

The University of Cambridge, Whitby Bird and Partners and the Municipality of Gotland in Sweden, have developed 'Usher', the world's largest solar hydrogen energy project. 3,500sq m of photovoltaic cells will be installed at Cambridge University and the electricity used to generate hydrogen, which will power a fuel cell bus service between the University and the city centre (Whitby Bird and Partners, 2001). The bus service will therefore be truly emission free. A similar scheme will be in operation in Gotland, Sweden. The 'Usher' project has also received funding from the European Commission, a £1.38 million grant.

## 5.6 Supportive Policy Measures

The key driver for hydrogen to be introduced on a wide scale will be the need to meet future, tougher climate change commitments. Government intervention to encourage take up will be necessary, since the initial costs of using hydrogen are likely to be high. At present and from a transport perspective the UK Government recognises the importance of policy measures in encouraging the take up of low carbon vehicles and the Powering Future Vehicles Strategy, which is currently out to consultation includes various suggestions: the continuation and extension of tax advantages to encourage new low carbon vehicles and fuels, and government use of new vehicles and fuels in their own fleets (DTLR *et al*, 2001). Other commentators emphasise the importance of perception and the challenge in presenting hydrogen as the intelligent and trendy option (Willson, 2002).

Fiscal and other incentives could include:

- No or minimal tax on fuel for a guaranteed length of time
- Marketing to raise awareness of hydrogen as a fuel
- Government funding of research and development
- Grants to offset the cost of vehicle purchase
- Lower VED, widening of existing band
- Where Workplace parking levies and Congestion Charging schemes are in place they should favour alternative/hydrogen fuelled vehicles
- Introduction of low emission zones.

# 6 CONCLUSIONS AND FURTHER WORK

It is widely expected that hydrogen fuel cell vehicles are likely to replace the internal combustion engine (PIU, 2002, DTLR *et al* 2001) possibly by 2050 (PIU, 2002). Motor manufacturers also emphasise the importance of hydrogen as a future fuel, and suggest that it can be used in both a fuel cell and a spark ignition engine (Society of Motor Manufacturers and Traders (SMMT), 2001). However at the present time there are still cost and technological issues that need to be resolved, most notably concerning the storage of hydrogen, the cost of the fuel cells, and the potential to produce carbon free hydrogen.

Therefore although transport powered by the use of carbon free hydrogen is regarded as being the 'ultimate destination' it is not going to happen in the short term. Steps along the way, which offer lower carbon, a move towards a hydrogen future and a means of allowing the public experience of new fuels and new vehicles are therefore considered very important. These include the use of LPG, CNG and hybrids as well as the use of hydrogen in demonstration projects.

Another important step is to ensure current petrol powered vehicles are as efficient and low emission as possible. If the ACEA 25% carbon dioxide reductions are achieved then a petrol vehicle could potentially offer the carbon dioxide emission reductions of a fuel cell vehicle powered by hydrogen produced by natural gas. However neither the ACEA agreement, nor hybrid vehicles can offer the long-term benefits of truly zero emission transport that carbon free hydrogen can.

The use and role of renewables, carbon sequestration and nuclear power in providing this carbon free hydrogen is not yet clear. It is highly likely that hydrogen will initially be produced from natural gas. However one potential route could be the small scale on site provision of hydrogen by renewable energy.

However it is important to note that even if hydrogen cars do become widespread, and produce zero emissions that road transport's current problems of congestion (Begg, 2002), land-take, and social exclusion are still not resolved. There is also no guarantee that the technological issues will be resolved or that hydrogen use will be economically viable. These issues mean that the potential for hydrogen should not distract from existing transport issues (Cousins, 2002).

The key area for further work is to establish what steps need to be taken to encourage the use of sustainable hydrogen in transport. This paper has established several areas where further research is required. A key gap is in the assessment of the costs and benefits of hydrogen, for individual vehicles, and larger systems this should be set against not just conventional vehicles but other future possibilities. There is a significant amount of information required to underpin such an analysis, much of which is difficult to identify in the UK context and some of which is uncertain; this includes: costs of vehicles, infrastructures and operations, pace at which vehicles will be introduced, likely take-up rates, comparison of the environmental impacts of various alternative fuels and the pace at which renewable methods of production will become viable. The policy measures that would encourage development towards a renewable hydrogen economy are also key and an assessment of their relative effectiveness and cost is desirable.

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