

UK SHEC

## Technological Characterisation of Hydrogen Fuel Cell Vehicles



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# 1 Executive Summary

The Proton Exchange Membrane fuel cell (PEM FC) is the leading technology for powering fuel cell vehicles, due to its high power, fast start up time and flexible load following characteristics. It is thought that if produced at levels of 500,000 units per year, PEM FC stack systems could be produced for just over US\$100 / kW. In order to meet the US DOE commercialisation target for 2015, they would have to reach US\$30 / kW. This would require not only high production levels but significant and step change technological improvements.

Studies designed to project cost reductions for whole fuel cell vehicles suggest that they will begin to approach competitiveness with conventional vehicles when cumulative production exceeds 5 million units. Given that demand is likely to be slow until fuel cell vehicles do approach cost competitiveness, it is difficult to put a date on when such cumulative production levels will be reached. Government and public procurement may provide a crucial means of increasing cumulative production and thus bringing costs down in the early stages of development.

Apart from the stack, hydrogen storage is a key area for development for fuel cell vehicles. At present no technology meets the US Department of Energy cost levels or performance criteria, which are designed to reflect consumer demand.

Hydrogen internal combustion engines are potential competitors to fuel cell vehicles, as they are likely to be cost competitive at an earlier stage. However, their lower efficiency may mean that fuel cell vehicles are nevertheless preferred in the long run.

## 2 Introduction

The possibility of using hydrogen as a transportation fuel is considered to be an important, if not fundamental aspect of most future visions of a hydrogen economy (Eames and McDowall, 2005). Moreover, in the UK the argument that stationary power generation from hydrogen is unlikely to offer cost effective carbon cuts is increasingly winning support, placing the emphasis of hydrogen technology development increasingly in the automotive sector (E4 Tech et al, 2004). However, after decades of development, fuel cell vehicles (FCVs) are still not close to commercialisation. If FCVs are to achieve a significant market share, the extent of progress on cost reductions and performance improvements over the next ten years will be crucial.

Until recently, emerging FCV prototypes have employed a fairly wide range of technological solutions including the on board reforming of methanol and gasoline, direct methanol fuel cells, and alkaline fuel cells. In the last few years, however, car companies have been increasingly coalescing around the production of Proton Exchange Membrane (PEM) fuel cells running on pure hydrogen. This report focuses therefore on the technological status of the direct hydrogen PEM fuel cell vehicle, and in particular on the progress of improvements to the PEM fuel cell stack. Current and future costs are analysed primarily as applied to LDVs, but the future prospects for larger public vehicles, as well as for niche vehicles are also considered.

A serious competitor with the fuel cell vehicle for the use of hydrogen fuel is the hydrogen internal combustion engine. Although this technology has a lower tank to wheels efficiency than fuel cells, and has some small amounts of NO<sub>x</sub> emissions, it emits no more carbon than a fuel cell, and its more conventional engine may bring it sooner to commercialisation. The prospects for this technology are therefore also considered, as well as its potential to contribute to the development of a hydrogen economy, or to delay the development of fuel cell vehicles.

## 3 PEM Fuel Cell Vehicles

Proton Exchange Membrane fuel cells (PEM FCs) are well suited to automotive use due to their high power, fast start up times and flexible load following characteristics. The majority of fuel cell research and development for automotive applications is therefore focussed on mid-sized passenger vehicles powered by PEM fuel cells, with compressed H<sub>2</sub> gas storage.

No other technologies appear to be competing with PEM for fuel cell cars. Research into FCVs with on-board gasoline reformers has largely stopped due to problems with weight, expense, and responsiveness (NRC 2004 p27).

### 3.1 PEM FC systems: technology status and cost

#### 3.1.1 Government / institutional targets

The US DOE targets for costs of PEM FC systems (including BOP but not storage) are given below:

Year	2005	2010	2015
Cost (\$)	125	45	30

The US DOE's hydrogen strategy is focussed on a commercialisation decision on all hydrogen and fuel cell technologies in 2015. This means that DOE targets are designed to deliver cost competitive vehicles by this point. These targets appear to have had a positive effect in focussing the activities of companies, and announcements are beginning to emerge predicting mass production and / or commercialisation within the next decade.

The EU HyWays project also provides cost reduction targets. It estimates the current cost of a fuel cell system for a passenger car to be over €4,000 / kW, and sets a target of €100 / kW by 2010 (HyWays, 2006), a little more than the US DOE target of \$45 / kW for the same year.

In the UK, the Department of Trade and Industry (DTI) has as yet set no specific cost reduction targets. However, it launched a hydrogen strategic framework in June 2005, and has pledged £15m for a demonstration fund for hydrogen and fuel cells.

#### 3.1.2 Studies 1998 - 2004

A summary of literature dating from 1998 – 2004 on PEM FC costs is provided in Table 1. All costs have been adjusted to year 2000 US\$. A more detailed literature review is given by Dixon et al (2002); while Owen and Gordon (2002) provide a good technical summary of the status of vehicle technologies, and Ashley (2005) gives a good overview of the potential for, and barriers to, the commercialisation of fuel cell vehicles.

The PEM FC system includes the PEM stack and balance of plant (BOP) such as such as air filters, humidifiers, coolers and pumps. Such systems are crucial to the operation of the stack; therefore most of the cost studies have included the BOP costs as well as the stack costs. Most studies of this kind however do not include the cost of hydrogen storage.

Most studies are connected to US Department of Energy (DoE) contracts e.g. (Lomax et al. 1998; ADL 2000; ADL 2002; James 2002; James 2003; TIAX 2003), and are focused quite narrowly on cost per kW comparisons, driven by targets of \$30-\$45/kW for PEM fuel cell systems (US DOE 2004) which would make fuel cells directly competitive with internal combustion engines.

Table 1 presents a huge range in cost projections of PEM FC systems, varying between \$22 and 181 / kW. The large degree of variation is due to differing assumptions, both of significant future technological developments, and volumes of production. It is particularly noticeable that the earlier studies (James et al. 1997; Lomax, James et al. 1998) produce extremely low estimates. This largely seems to have been a result of highly optimistic assumptions regarding technical development. Lipman et al (1999) notes the methodology used by Lomax et al (1998) was specifically designed to identify the lowest cost stack design, and comment that it would be “difficult to construct a lower cost case”, and therefore treat this estimate as a lower bound. More recent estimates (ADL 2001; ADL 2002; James 2002; CMR, 2004) have begun to narrow the range towards \$100 / kW.

Reference	Timeframe	Technology			Production costs					Notes
		Net output kWe	Cell voltage V	Stack efficiency	Stack only	BOP, auxiliaries and assembly	Total	Total/kW <sub>net</sub>	@ production level	
ADL 2001	mid-term	52	-	-	-	-	5 480	105	-	Projected costs assuming technical improvements and reductions in manufacturing cost.
ADL 2001	mid-term	33	-	-	-	-	4 240	127	-	Projected costs assuming an aggressive hybridisation occurs, accelerating the reduction in component costs
ADL 2002	mid-term	50	0.8	51	2 750	2 250	5 000	100	500 000	Assumes optimistic and aggressive development of technology.
CMR 2004	current	50	0.8	57	9 050	-	9 050	181	500 000	Conventional PEM, based on ADL2001's cost model.
CMR 2004	future	50	0.8	57	4 650	-	4 650	93	500 000	As above, but using CMR technology. Significant savings come from elimination of bi-polar plates and gaskets, and reduction in Pt loading
James et al 1997	current	50	-	-	1 165	938	2 103	42	500 000	Uses a MEA assembly designed for mass production. Includes the cost of hydrogen storage. Appears low in comparison with later estimates
James et al 2002	current	50	0.6	37	6 000	3 000	9 000	180	500	Current technology
James et al 2002	current	50	0.6	37	2 500	2 350	4 850	97	10 000	As above but higher production level
James et al 2002	current	50	0.6	37	2 400	2 050	4 450	89	30 000	As above but higher production level
James et al 2002	current	50	0.6	37	2 200	1 600	3 800	76	500 000	As above but higher production level
Lomax et al 1998	current	64	0.6	-	1 790	-	1 790	28	500 000	Current technology. Does not include cooling system or humidifiers and is lower than later estimates
Lomax et al 1998	future	64	0.6	-	1 425	-	1 425	22	500 000	Future technology. Uses a carbon-polymer composite fuel cell which can be molded for mass-manufacture. Does not include cooling system or humidifiers
Tsuchiya & Kobayashi	future	50	0.6	-	-	-	8 350	167	50 000	Projects future costs for PEM fuel cells based on learning curves. Moderate scenario assumes an aggregate progres ratio of 82%, initial production 40 units at \$1833/unit
Tsuchiya & Kobayashi	future	50	0.6	-	-	-	1 900	38	5 000 000	Projects future costs for PEM fuel cells based on learning curves. Moderate scenario assumes an aggregate progres ratio of 82%, initial production 40 units at \$1833/unit

*Table 3: Cost of PEM stacks: summarr of literature, 1998 - 2004*

### 3.1.3 More recent studies

#### 3.1.3.1 TIAX (2005) conclusions on cost reduction

TIAX (2005) is the final report of the ongoing ADL / TIAX programme. It is designed to assess the likely cost and performance of the PEM system, including BOP, in relation to the US DOE goals. The assumption is made of production levels of 500,000 units per year- as such the report acknowledges that further work is required to calculate costs at lower production volumes, as would be the case for early market entrants. However, the technology focus is current, which means the report potentially gives a good impression of the state of technology and the prospects for future development.

Earlier studies considered 50-60kW peak net electrical power sufficient to achieve acceptable performance for a family-sized passenger car. TIAX (2005 p.3) however assume 80kW, as being more in line with the current practice of car companies.

Table 2 indicates the 2005 projected costs of a fuel cell stack with BOP.

Cost contributor	2005 cost (\$ / kW)	2005 DOE target (\$ / kW)
80 kWe Net Stack	67	65
BOP and assembly	41	60
PEMFC system	108	125

*Table 2: 2005 System costs compared to DOE targets (TIAX, 2005)*

System cost was set at \$108 / kW, and a monte carlo analysis suggested there was a 98% probability that the current system cost would be within the DOE 2005 target of \$125 / kW. A sensitivity analysis showed that the major contributing factors to the overall cost of the fuel cell stack were power density, price of platinum and platinum loading.

The success of current technology in meeting the 2005 US DOE goals, according to this report, gives some encouragement to the prospects of the crucial 2015 target being met. However, as the targets for 2010 and 2015 are \$45 / kW and \$30 / kW respectively, the additional cost reductions which must be made are somewhat steep. The key question will be whether the remaining changes should be considered incremental or step change in nature.

#### 3.1.3.2 IEA (2005) conclusions on cost reduction

The IEA (2005) estimates the current cost of manually produced fuel cell stacks to be US\$ 1,826 / kW. It concludes that the following changes are required to reduce stack cost to \$ 103 / kW:

- Mass production of membranes and possibly use of new materials (other than Nafion)
- Mass production of electrodes based on the new Gas Diffusion Layer technology
- Mass production of either plastic or coated steel bipolar plates
- An increase in power density from 2 kW / m<sup>2</sup> to 3 kW / m<sup>2</sup>
- Production of 100, 000 m<sup>2</sup> per year of fuel cell stacks, equivalent to 4, 000 vehicles per year

This production volume is significantly less than that assumed by TIAX (2005), however the savings in materials costs and technological advances assumed are more radical.

IEA (2005) also projects the possibility of a future cost of \$ 50 / kW, however this is based on 'new membrane technologies, a new electrode production technology and a different, unspecified method to produce bipolar plates'. This implies significant uncertainty surrounding the physical potential of fuel cell technology to reach the required cost levels.

### **3.1.4 Component contribution to system cost**

The stack components and their contribution to overall PEM system cost are discussed below.

#### **3.1.4.1 Membranes**

Current PEMFC technology is designed around DuPont patented Nafion membrane technology. This requires low operating temperatures (less than 80°C) which necessitate a platinum catalyst. The membranes must be kept within a narrow hydration range to operate, requiring recycling and careful management of water from the exhaust stream. As well as being a high cost material, they degrade if operated above 80°C, and are chemically degraded by impurities (such as CO) in the fuel. Membrane materials capable of withstanding higher temperatures would allow the use of less expensive catalysts and are less expensive. More durable membranes would allow simpler water and heat management, and extend the lifetime of the membranes. At present Nafion membranes can add up to \$ 250-300 / kW to the stack cost (IEA, 2005).

It has been reported that organically modified silicates (ORMOSILs) may offer a factor 10-20 cost reduction (IEA, 2005). A new hydrocarbon membrane used in Honda's latest FCX vehicles operates at 90°C, requires less hydration, may have 50% longer lifetime, and at half the price (Ashley 2005).

#### **3.1.4.2 Electrode and Platinum Catalyst**

Current PEMFC systems using Nafion membranes require platinum loading of 1.3 grams / kW. The US DOE goal for 2015 is to reduce platinum loading to 0.2 grams / kW. If membrane materials were found which enabled the system to operate at higher temperatures, significantly less platinum would be required. New electrode production technology such as Gas Diffusion Layer technology, which increases the surface area of platinum available for the reaction, can reduce the total amount of platinum required. Mass production on a large scale could reduce costs by a factor of 10 (IEA, 2005).

The price of platinum has historically been stable at around \$450 / troz (31g), but has now risen to around \$900 / troz (TIAX, 2005). This undoubtedly has a significant effect on the overall stack price. As part of their study, TIAX (2005) ran a sensitivity analysis with a low platinum price scenario, with a platinum price at the historical level of \$ 450 / troz. In this scenario, the stack cost was reduced by about 20%. The question of whether platinum prices will return to previous levels is, however, difficult to answer. If fuel cells become widely produced, the increased demand for platinum could have an inflationary influence on prices.

If mass production of fuel cells sees costs of bipolar plates greatly reduced, the share of platinum cost in the overall cost is likely to become more significant. According to Tsuchiya and Kobayashi (2004),

the share of platinum cost could reach 7- 11 % of stack cost at cumulative production levels of 5 million vehicles.

#### **3.1.4.3 Bipolar Plates**

Bipolar plates are currently manufactured from milled graphite or gold-coated stainless steel. The use of low cost steel alloys or polymers would reduce costs, the latter in particular by allowing injection-moulding production techniques. Achieving higher power densities is also key to reducing costs of bipolar plates (IEA, 2005).

#### **3.1.4.4 Power Density**

A greater stack power density can reduce the size of the stack, resulting in lower costs. Higher power densities have been achieved since 2002 due to the increasing use of pure hydrogen fuel, and through lower stack voltages (TIAX, 2005). However, lower stack voltages entail a decrease in stack efficiency. There is therefore a trade off between power (and by extension stack cost) and efficiency (IEA, 2005; TIAX, 2005)

#### **3.1.4.5 BOP**

In the 2005 FC system considered by TIAX (2005) BOP represented 34% of the system cost. As stack costs come down, BOP costs will represent a greater proportion of the system cost, therefore the report points out that more consideration of BOP costs will be necessary to achieve the most stringent cost targets. Simplification of the system will be an important aspect of this.

As with stack cost, mass production is also an important factor in bringing BOP costs down. According to IEA (2005), the current cost of BOP is around \$ 1, 000 – 1, 500 / kW (for hand manufactured systems). Large scale production could reduce it to \$ 56 – 17 / kW.

#### **3.1.4.6 Mass production**

TIAX (2005) and Ballard both predict fuel cell stack costs of a little over \$100 / kW with current technology, assuming production volumes of 500, 000. By way of comparison, there are about 2.7 million new passenger cars registered in the UK each year (ONS 2005), and about 16 million new cars and trucks (including SUVs) are sold annually in the US (EPA 2005). A small assembly line, such as the SMART car assembly line in Hambach, France might produce 180 000 vehicles per year, whereas a major assembly line, such as the Nissan assembly line in Smyrna US, might produce 730 000 vehicles. Therefore studies making such an assumption will not provide estimates of costs applying to the earliest fuel cell vehicle market entrants. TIAX (2005) acknowledge the need for research into FCV costs at low production volumes.

The process of moving technologies from demonstration and prototype stage, to any significant level of production, is often underestimated. Mass production techniques can require a significant redesign of the way products are assembled, which can entail hidden costs and complications.

Mass production reduces costs across the system. The US DOE National Hydrogen Energy Roadmap has stated, 'the most necessary breakthrough [in order for the hydrogen economy to develop] will have to be cost reductions of fuel cells through the development of large-scale manufacturing capabilities for

stationary and mobile units' (DOE, 2002). Mass production is now a key part of the US DOE Hydrogen plan, as shown by the Roadmap on Manufacturing R&D for the Hydrogen Economy (DOE, 2005). This is envisaged to play a key role leading up to the commercialisation decision scheduled for 2015. In a related development, the Flexible Manufacturing Center (FMC), in partnership with the Center for Automation Technologies and Systems (CATS) has announced the formation of a research consortium focused on the automated assembly of fuel cell stacks (Fuel Cell Today, 2006a).

### 3.1.5 The effects of mass production- Learning curves

Various studies have attempted to estimate the impact of production volumes on cost using learning curves. Tsuchiya and Kobayashi (2004)'s estimate of fuel cell stack cost based on current technology and low volume manufacturing processes is \$1,833 / kW. Their study included nine scenarios involving different combinations of power density improvement and cost reduction speed. Learning curves were constructed for each component cost of the stack based on evidence of learning rates in different but related technologies, and on industry assessments of bottom line material costs. The moderate cost reduction combined with medium power density improvement scenario forecast stack costs for production levels of 50, 000 and 5 million as \$167 / kW and \$ 38 / kW respectively.

Tsuchiya and Kobayashi's study is summarised alongside another by Lipman and Sperling (1999) in Table 3. To avoid predicting unrealistic reductions in cost in the long-term, progress ratios are often bounded. Lipman et al (1999) used the estimate of \$37 (Lomax, James et al. 1998), while Tsuchiya et al (2004) developed a separate lower estimate based on material costs, which came out almost exactly the same at \$38/kW.

Progress ratio	(Lipman and Sperling 1999)			(Tsuchiya and Kobayashi 2004)
	0.75	0.8	0.85	0.82
Cumulative production (no. of 50kW FCVs)	Production cost (\$/kW)			
100	1 800	2 000	2 200	1 359
2000	200	363	635	496
20 000	77	173	370	224
200 000	37	83	216	107
2 000 000	37	39	126	51
5 000 000				38
20 000 000	37	37	73	

**Table 3:** Estimates of PEM cost reductions using progress ratios. For a progress ratio  $F$ , the cost of producing the  $2^{nd}$  unit =  $F \times$  cost of  $n^{th}$  unit.

Clearly the validity of such studies is hugely dependant on the progress ratio assumed. It is most useful where possible to derive a progress ratio from empirically observed conditions. In the coming years it may become increasingly possible to derive empirical learning curves relating directly to fuel cell technologies, as cost data become more available.

## 3.2 PEM FC vehicle costs

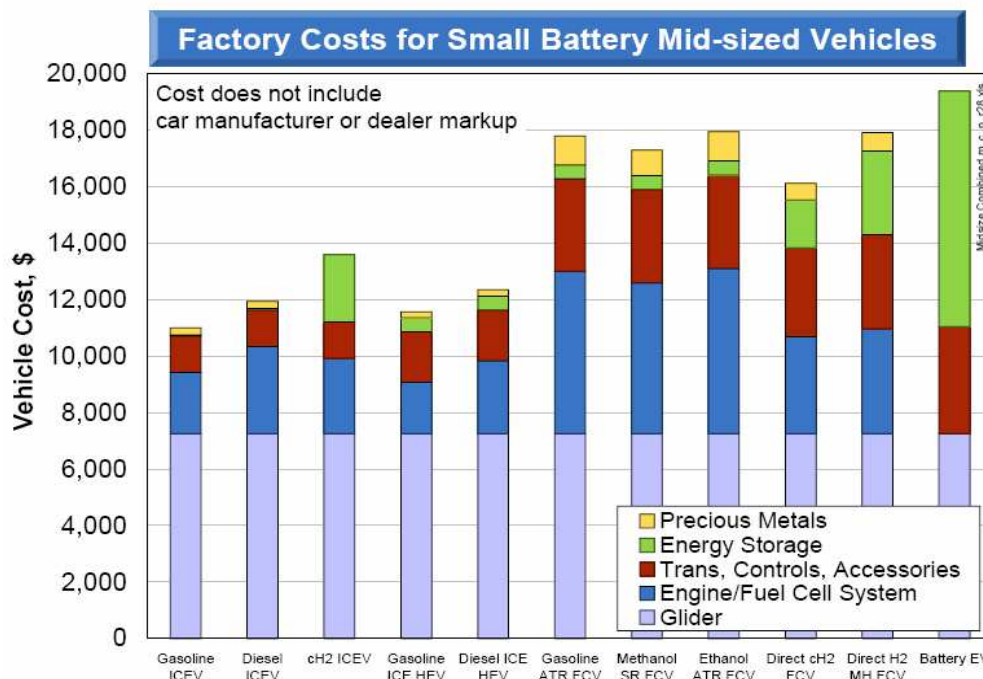
Translating fuel-cell costs into FCV costs are subject to more uncertainties. As well as the fuel cell stack., vehicles require an electrical drivetrain, control electronics, and hydrogen storage. Some models, such as GMs HyWire concept, represent a complete redesign of the vehicle.

### **3.2.1 Total cost estimates**

Projected costs for commercial production are summarised in Table 4. Since each study uses its own set of assumptions, comparison between studies is not necessarily valid. OTT (2002) explicitly state their data is not valid for external comparisons. Wherever possible a baseline vehicle has been included, so that relative changes can be considered. Prices are given in year 2000 US\$.

Reference	Technology notes	Technology year	Fuel economy mpgge	MJ/km	Cost (2000\$)	Other notes
ADL 2001	37kW H <sub>2</sub> PEM with 29kW battery	2015	31	2.65	18 462	Unclear if this includes manufacturer's mark-up
ADL 2001	58kW H <sub>2</sub> PEM with 9kW battery	2015	76	1.07	27 518	Projected costs assuming technical improvements and reductions in manufacturing cost.
ADL 2001	37kW H <sub>2</sub> PEM with 29kW battery	2015	84	0.97	27 225	Projected costs assuming an aggressive hybridisation occurs, accelerating reduction in component costs
ADL 2002	50kWe net, designed for high efficiency, small battery	2010	75	1.08	15 630	Assumes optimistic and aggressive development of technology. Efficient fuel cell with small battery. Excludes manufacturers mark-up. Manufacturing at 500 000 units/yr, which is unlikely until after 2010
ADL 2002	50kWe net, designed for high efficiency, large battery	2010	85	0.96	15 630	Assumes aggressive development of technology. As above but with large battery
IEA 2005	80 kWe net FCV	2030	-	-	21 950	Optimistic scenario, PEM FC costs reduce to US\$ 35 / kW
IEA 2005	80 kWe net FCV	2030	-	-	27 075	Pessimistic scenario, PEM FC costs reduce to US\$ 75 / kW
OTT 2002	Baseline gasoline large car	2000	27	3.04	26 072	Not clear whether costs are given as present or future values. Not clear whether it includes manufacturer's mark up
OTT 2002	Baseline gasoline large car in 2030	2030	28	2.86	26 502	
OTT 2002	H <sub>2</sub> FCV large car in 2007	2007	59	1.38	36 501	
OTT 2002	H <sub>2</sub> FCV large car in 2030	2030	85	0.95	34 452	
Owen & Gordon 2002	Baseline - average UK 5 door petrol hatchback	2002	51	1.90	26 799	combined ECE+EUDC driving cycle
Owen & Gordon 2002	H <sub>2</sub> internal combustion engine with regenerative braking.	2008	-	-	29 008	CO <sub>2</sub> emissions are given, but not fuel economies
Owen & Gordon 2002	H <sub>2</sub> FCV. Introduced in 2020	2020	-	-	33 775	
Owen & Gordon 2002	H <sub>2</sub> FCV. As above but Introduced in 2030	2030	-	-	32 757	
Weiss et al 2000	Reference case. 1996 Toyota Camry	1996	30	2.73	18 029	
Weiss et al 2000	Base case, gradual evolution of ICE to 2020	2020	47	1.75	18 868	
Weiss et al 2000	Fuel cell hybrid.	2020	101	0.81	23 166	Assumes a fuel cell cost of \$60/kW, which is towards the low end of estimates.
Weiss et al 2003	Reference case, 2001 US family sedan	2001	30	2.48	-	Vehicle costs not re-estimated since (Weiss et al 2000), but seem optimistic in light of other studies. Driving cycle 55% urban / 45% highway.
Weiss et al 2003	2020 baseline. Evolution of technology to 2020	2020	43	1.75	18 000	
Weiss et al 2003	2020 advanced diesel hybrid	2020	83	0.92	22 140	
Weiss et al 2003	H <sub>2</sub> PEM non-hybrid	2020	117	0.65	22 140	

**Table 4: Estimates of fuel cell vehicle cost**



**Figure 1:** One estimate of projected costs for future vehicle technologies (ADL 2002). Costs do not include manufacturers markup. ‘Glider’ refers to the vehicle minus the powertrain.

The cost estimates summarised in Table 4 suggests that once the technology has matured, FCVs are expected to cost between 20 and 50% more than conventional vehicles. Figure 1 shows a comparison of vehicle technologies from ADL (2002) who estimated: “Typical annual mid-sized FCV costs are projected to be around \$1200 to \$1800 more than that of conventional vehicles”. Padro and Putsche (1999) state a hydrogen FCV costs \$20,200, compared to \$19,900 a hydrogen hybrid, and \$18,000 for a conventional gasoline vehicle. Most of these estimates are somewhat lower than the most recent studies available (IEA, 2005; HyWays, 2005), which are summarised below.

### 3.2.2 Component costs of hydrogen vehicles

Factors contributing to vehicle cost in addition to the stack cost are summarised below.

#### 3.2.2.1 Hydrogen storage costs

Due to the high current cost of stacks, storage is not a major contributor by proportion to the overall cost of a fuel cell vehicle, however this contribution will become more significant as the stack cost comes down. All recent FCV prototypes have used compressed hydrogen gas storage (H2mobility.org). Research is ongoing into alternative storage methods such as metal and chemical hydrides.

Improved performance of storage technology is crucial to the success of hydrogen vehicles; no current technologies are capable of meeting the storage requirements set by US DOE targets for satisfactory performance of hydrogen vehicles (NRC, 2005). Storage capacity directly affects the range of the vehicle, which will ultimately be an important area of consumer demand. Table 5 compares the US DOE FreedomCar goals with current performance metrics. The goals are intended to drive the progress

of the technologies towards being competitive with current vehicles in terms of cost, performance, durability and volume, and to achieve a vehicle range of over 300 miles.

	Energy Capacity		System cost (\$ / kWh)
	Volumetric (kWh / l)	Gravimetric (kWh / kg)	
Chemical Hydrides	1.0	1.4	8
Metal hydrides	0.6	0.8	16
Liquid H2	1.2	1.7	6
10,000 psi gas	0.8	1.6	18
5,000 psi gas	0.5	1.9	15
<b>2010 target</b>	<b>1.5</b>	<b>2.0</b>	<b>4</b>
<b>2015 target</b>	<b>2.7</b>	<b>3.0</b>	<b>2</b>

*Table 5: Status of hydrogen storage technologies relative to targets (data from NRC, 2005)*

The reviewing committee of the FreedomCar programme reported hydrogen storage to be one of the ‘greater risks for reaching the programme goals in 2015’, stressing that the area needs a ‘breakthrough discovery as the forerunner of development and innovation.’ (NRC, 2005, p.68)

From the above table, liquid hydrogen storage appears favourable from a cost and energy density point of view, but is disadvantaged by the higher cost of producing the hydrogen in liquid form (Hawkins, 2005), and from a necessary leakage of hydrogen (approximately 1-2% per day) to compensate for thermal losses (Avadikyan et al, 2003). BMW favours liquid hydrogen storage in its hydrogen ICE vehicle, as the lower efficiency of the ICE engine compared to a fuel cell means that a storage method providing any lower energy density would offer an unacceptably low driving range. Chemical and metal hydrides have the potential to offer good volumetric energy densities, and are still at an early stage of development.

The storage methods which are ultimately to be favoured by automobile companies are strongly related to the infrastructure which is provided for them; for example combining an infrastructure which stored hydrogen in a different form to that used by the majority of vehicles would involve costly conversion processes. There may be some degree of iteration in this relationship, as the storage demands of vehicle manufacturers are likely to find a response from infrastructure providers.

### **3.2.2.2 Electrical energy storage**

Another way of improving the range of a hydrogen vehicle is by incorporating regenerative braking into the system, and many of the new FCV prototypes are now employing this technology (H2Mobility.org). This achieves the same aim as in gasoline hybrid vehicles, improving the overall efficiency of the engine. In fuel cell vehicles it has the significant advantage of improving the driving range, a major obstacle to the market appeal of such vehicles. Recent fuel cell hybrid prototypes are reportedly reaching ranges of 370 miles (H2 Mobility.org) compared to the 150-250 miles typical range (FCC, 2005).

The cost of electrical energy storage however is an additional consideration - the FreedomCar target for 2010 is \$400 per FC vehicle (NRC, 2005).

### **3.2.2.3 Electronics and electrical drivetrain**

The 2010 FreedomCar cost target for power electronics is under US\$ 5 / kW, while the 2003 status was US\$ 6 / kW. A greater challenge is the reduction of the cost of the electric motor, from US\$15 / kW in 2003 to US\$ 7 / kW 2010. This may not be achievable, as the cost is principally driven by the prices of the materials used (copper and iron), and are unlikely to see much reduction through research (NRC, 2005).

#### **3.2.2.4 Commercial margins**

The extent to which commercial margins affect value chain costs depends on the degree of vertical integration in the manufacturing process of the stack and other components. By way of illustration, TIAX (2005 p. 88) assumed an OEM acting as a stack integrator, with some outsourcing of components. This was found to increase the FC system cost by 19% compared to a simple vertically integrated model.

#### **3.2.2.5 O&M Costs**

Very little data exists on O&M costs for hydrogen vehicles. Some treat depreciation as an O&M cost, estimating it may add \$1200 to \$1800 annual ownership cost of an FCV (ADL 2001). Physical maintenance might be expected to be less as fuel cells have fewer moving parts than a mechanical engine. However, they can suffer membrane degradation and catalyst poisoning. Also, BOP and auxiliary equipment such as fuel pumps, air compressors, heat management, water management and control electronics must be taken into consideration. And, since this is a new technology, the skills base for maintenance will be less developed. In the absence of information, FCVs are often assumed to have the same maintenance cost as ICE vehicles (ADL 2002; Dixon, Porche et al. 2002).

### **3.2.3 Future cost projections and progress ratios for whole vehicles**

Projections of future cost reductions have been made for whole vehicles as well as PEM systems. The progress of cost reductions is assumed to be related to levels of cumulative production; however, production levels are themselves related to demand for the vehicles which will undoubtedly be influenced by vehicle price. This interrelationship of the two factors makes predictions of one factor highly contingent upon assumptions about the other. The progress ratio chosen is also crucial, as discussed above (section on PEM PRs)

#### **3.2.3.1 The IEA study**

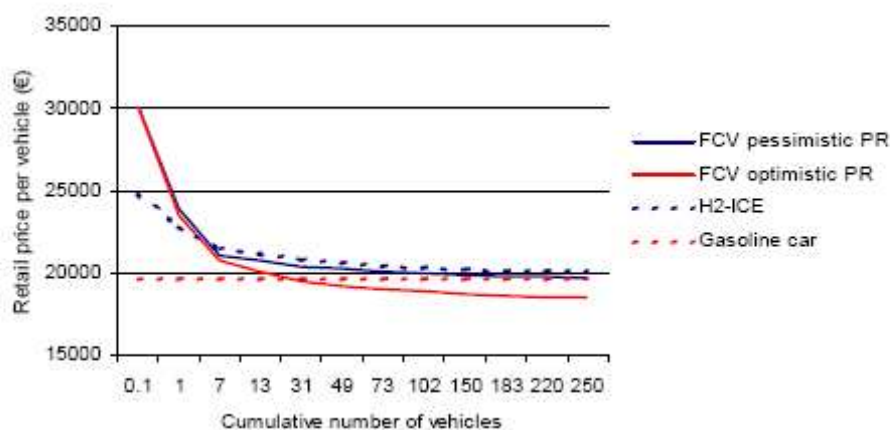
According to the IEA (2005), the incremental cost of fuel cell vehicles over conventional vehicles in 2030 could range from US\$ 2,500 to US\$ 7, 625. The key factor in the range is the reduction in cost of the PEM FC (including power electronics and peripherals) to US\$ 35 / kW in the optimistic case, and US\$ 75 / kW in the pessimistic case. The cost breakdown is given in Table 6.

	2005	2010	2030 Optimistic reduction	2030 Optimistic but slower	2030 Pessimistic reduction
PEM fuel cell stack (US\$ / kW)	1,800	500	35	65	75
Gaseous H storage at 700 bar (US\$ / kg)	1,000	500	225	375	500
PEM fuel cell stack (US\$)	144,000	40,000	2,800	5,200	6,000
Gaseous H storage at 700 bar (US\$)	4,000	2,000	900	1,500	2,000
Electric engine (US\$)	1,900	1,700	1,200	1,400	2,025
Ref: Conventional ICE vehicle (US\$)	19,450	19,450	19,450	19,450	19,450
Ref: Conventional vehicle w/o engine (US\$)	17,050	17,050	17,050	17,050	17,050
<b>Hydrogen FCV (US\$)</b>	<b>167,000</b>	<b>60,750</b>	<b>21,950</b>	<b>25,150</b>	<b>27,075</b>
<b>H FCV drive system cost (US\$ / kW)</b>	<b>1,875</b>	<b>545</b>	<b>60</b>	<b>100</b>	<b>125</b>

**Table 6:** Estimated costs of a Hydrogen Fuel Cell Vehicle (80kW FCV) (adapted from IEA, 2005)

### 3.2.3.2 EU HyWays study

This study derives its progress ratios from the research activities of automotive partners within the HyWays consortium. The progress ratios for FC systems used are in the optimistic scenario, 0.80 initially and 0.90 after the first 10 years; and in the pessimistic scenario 0.82 initially and 0.92 after the first 10 years. Towards the end of the initial steep curve, with cumulative production around 5 million, fuel cell vehicles are priced around US\$ 28, 000.



**Figure 2:** Cost reduction of hydrogen cars (only the medium class cars are shown) for the two progress ratio scenarios and as a reference the gasoline car figure for 2010 (from HyWays, 2005)

### 3.2.3.3 Commercial announcements

Although many FCVs have been built, since they are prototypes costs are (a) high, (b) not publicly available, and (c) not representative of commercial production. A hint as to current prototype costs was given in the Financial Times in June 2005, which stated that Toyota aims to cut the cost of FCVs “from more than \$1m to \$50 000 by 2015 when it hopes to begin selling the vehicles” (Mackintosh 2005). Meanwhile, General Motors have also recently announced their intentions to be mass producing commercially priced vehicles by 2010.

With regard to stacks, Toyota's PEM FC stack is currently produced at a price of \$500 / kW (IEA, 2005). This would be expected to decrease significantly with higher production levels. Ballard have claimed that their fuel cell stacks, at current technology but at production volumes of 500, 000 would be manufactured for \$ 103 / kW (IEA, 2005). This coincides very closely with the conclusions of the IEA (2005) and TIAX (2005) studies.

Table 7 summarises some of the recent commercial announcements.

<b>Manufacturer</b>	<b>Year</b>	<b>Numbers</b>	<b>Notes</b>
Daimler Chrysler (Germany)	2012 2015	10,000	Initial launch Mass market
Ford (USA)	2015		'commercial readiness'
GM (USA)	2010 – 2015 2025		Commercial viability Mass market
Honda (Japan)	2010 2020	12,000 (in USA) 50,000 (in USA)	Start production
Hyundai (Korea)	2010		Road tests 2009
Toyota (Japan)	2015		Will cost US\$ 50,000

*Table 7: Fuel Cell Vehicle Manufacturer's Current Timetable for Launch (Adamson and Crawley, 2006)*

### 3.3 Performance of current FCVs, and competition with other technologies

Performance of current prototypes is worse than conventional vehicles, but the gap is not huge given their relatively early stage of development compared with combustion engines. Current prototypes have a top speed around 90-100 mph, 0-60 mph in 12-16 seconds, a range between refuelling of about 150-250 miles, equivalent fuel economy around 50-70 mpg (FCC 2005).

Performance is improving with each generation, with newer prototypes claiming to achieve 300 miles between refuelling, and 0-60mph in under 10 seconds (e.g. General Motor's 'Sequel'), and fuel economies of 100mpgge (e.g. General Motors's 'Precept').

This report has focussed on PEM FCs for automotive applications. However, given the significant steps that must still be made by fuel cell vehicles in terms of cost reduction and performance, and the uncertainties relating to infrastructure provision, there are various other low carbon vehicle technologies which may also see development in the future.

#### 3.3.1 Direct methanol fuel cells

The possibility of 'packaging' hydrogen within a synthetic fuel such as methanol, is believed by some to offer a more feasible option for the transportation and storage of hydrogen. The work of Eames and McDowall (2005) shows that there is support amongst some expert stakeholders for this scenario, and it may play a significant role in Iceland's proposed hydrogen economy (Arnasson and Sigfusson, 2000). Whilst Ford and Daimler Chrysler produced PEM FC vehicles equipped with on board methanol

reformers in 2000 – 2001, more recently interest in any on board reforming has significantly declined. There are very few prototypes of Direct Methanol Fuel Cells (DMFCs) used in automotive applications. In 2001, Daimler Chrysler produced a 3 kW DMFC go kart, and in 2005 Yamaha presented the 'FC-me', a 1 kW 50cc scooter. The majority of DMFC work is focussed on the portable fuel cell market- however, if this portable market expands, and particularly if it contributes to developing methanol infrastructure, it is possible that the benefits could increase development of DMFCs in the automotive sector.

### **3.3.2 Hydrogen Internal Combustion Engines**

Hydrogen internal combustion engines are believed by some to offer an effective route towards hydrogen fuel cell commercialisation by stimulating demand for the necessary hydrogen infrastructure; others believe that hydrogen ICEs may have efficiency and cost benefits which will render further development of fuel cell technology superfluous.

Hydrogen ICEs have clear benefits, particularly in the context of near term commercialisation prospects. They are likely to achieve cost competitiveness far more quickly than fuel cell vehicles, and they can be designed as flex-fuel vehicles, capable of running on gasoline as well as on hydrogen, removing the potentially large limitations placed on the consumer by the near term lack of infrastructure. BMW, the principle manufacturer involved with hydrogen ICEs, has recently announced that it will start rolling out hydrogen powered vehicles 'within two years' (by 2008) (Fuel Cells Today, 2006). The vehicles will have two tanks, one for pure hydrogen and one for gasoline, and also incorporate fuel cell technology in an APU unit, designed to run on hydrogen while the vehicle is stationary.

### **3.3.3 Relative efficiencies of hydrogen and gasoline vehicles**

Hydrogen ICEs are currently not as efficient as FCVs, although BMW have announced expectations of reaching a future target of 50% tank-to-wheels efficiency. If this claim holds true it could affect demand for fuel cell vehicles.

H<sub>2</sub> FCVs have zero tank to wheels (TTW) emissions (they emit only water vapour); H<sub>2</sub> ICEs produce some NO<sub>x</sub>, but this can be reduced to a fraction of the strictest vehicle standards today.

Typical peak TTW efficiencies (often quoted in LHV terms for engines) are around 30% for gasoline ICE, 40-45% for a turbo-diesel engine, approaching the same for a H<sub>2</sub> ICE, and 50-60% for a H<sub>2</sub> fuel cell. Furthermore, fuel cell efficiency is maintained at low loads whereas ICE efficiency is not. Recent studies have estimated H<sub>2</sub> FCVs will be around 2-3 times more fuel-efficient than conventional gasoline ICEs, whereas diesel hybrids will be about 1.5-2 times more efficient (Figure 3).

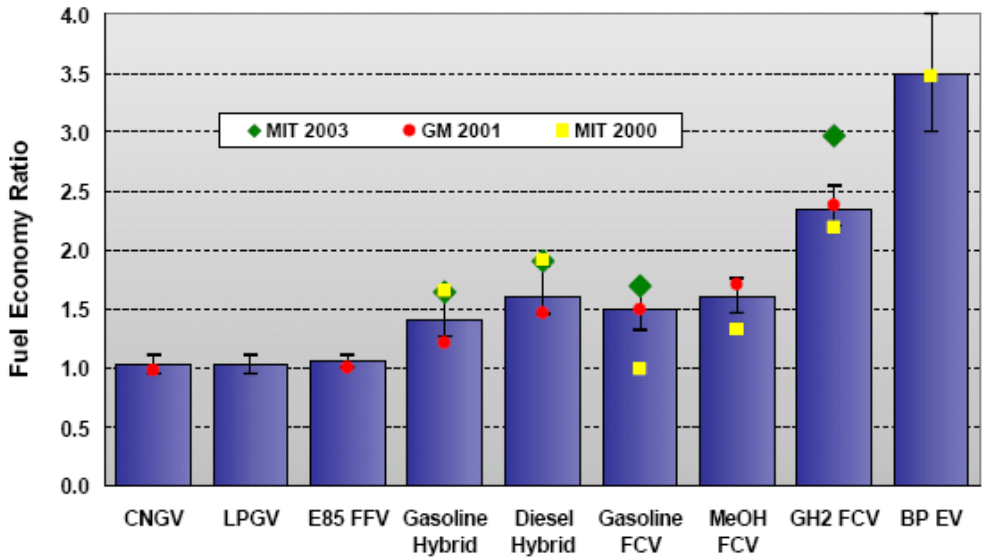


Figure 3: Relative fuel economies from (Wang 2003) compared to recent US studies (Wang 2003a).

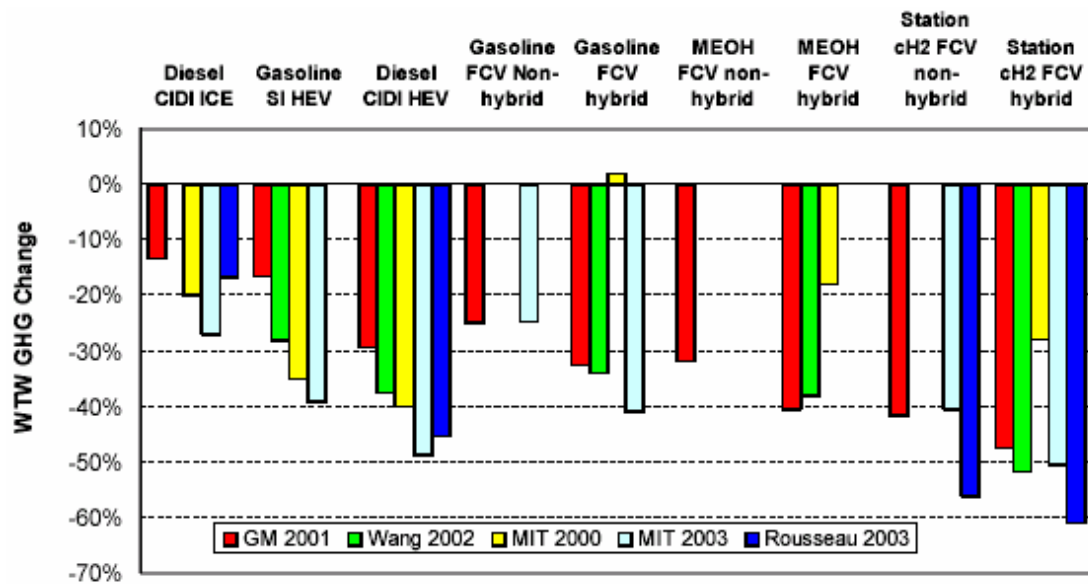


Figure 4: WTW assessments of different vehicle technologies (Wang 2003a). Hydrogen is assumed to be produced from steam methane reforming.

The well-to-wheels (WTW) impacts on greenhouse gas emissions are also important to consider. Figure 4 compares the greenhouse gas emissions of various WTW pathways, according to a number of recent studies (Weiss et al. 2000; GM 2002; Wang 2002; Wang 2003a; Wang 2003b; Rousseau and Sharer 2004). Hydrogen chains have been assumed to derive from steam methane reforming. It can be seen that hydrogen pathways, where hydrogen is produced by SMR, give a GHG reduction between 30 and 60% compared to a gasoline base case. However, it appears comparable reductions (25 – 50%) may be achievable with diesel electric hybrids. Clearly, hydrogen chains involving renewably produced hydrogen would be likely to provide better improvements over the base case.

### **3.3.4 Other competitors- biofuel and electric vehicles**

Other major competitors in terms of environmental benefits offered are biofuel and electric vehicles. It might be argued that rather than using renewably produced electricity to make hydrogen, a more efficient use of the energy would be to transit it through the existing grid and use it in electric vehicles. Battery storage capacities currently limit the range of electric vehicles, however they are already gaining popularity for short distance urban use.

Biofuels have a lot of potential- the technology is established and affordable, and there are far fewer infrastructure problems than with hydrogen. They have achieved large scale penetration in Brazil, and various countries including Japan, China and India, as well as the EU, have established biofuel penetration targets. There is a strong political interest in biofuels, for security of supply as well as environmental reasons. There is still significant uncertainty as to whether sufficient land will be available for significant quantities of fuel; however 'second generation' biofuels, involving lignocellulosic production which converts a greater proportion of the plant biomass to fuel, could positively affect the land availability issue.

Following a collapse in the production of ethanol cars in Brazil in the nineties, the fortunes of the ethanol industry were revived by the development of flex-fuel vehicles, as customers were much more willing to invest in new technology when the possibility of falling back on gasoline in the event of high ethanol prices was retained. This precedent could provide lessons for hydrogen and fuel cell development: in the context of consumer uncertainties surrounding which technology will be the long term 'winner', flex-fuel vehicles may offer a sense of risk minimisation in the early stages of infrastructure development. Ford has produced a Focus fuel cell vehicle which can also run on ethanol or petrol (Adamson and Crawley, 2006).

Another important consideration is the possibility that consumers may begin to perceive fuel cell vehicles as having private benefits over other technologies which may justify a price premium. For some the low noise levels during operation may be considered a benefit. Additionally, the potential for radical redesign of the vehicle concept might yield unexpected benefits- for example the Toyota Fine-X is designed to allow improved accessibility for those with impaired mobility (Adamson and Crawley, 2006).

## 4 Other fuel cell vehicles

Research has often focused on passenger cars since they dominate the energy use and GHG emissions in the transport sector. However, due to the costs, uncertainties, and rapid development cycle of hydrogen technologies, combined with the lack of infrastructure, other transportation modes such as heavy duty freight, buses or shipping might be better suited to the early adoption of hydrogen, acting as niches where the technology can develop and mature (Farrell et al. 2003).

### 4.1 Buses

Hydrogen buses have attracted much attention, and there are a number of demonstration projects around the world, including the Clean Urban Transport for Europe (CUTE) project which is introducing 27 hydrogen buses across nine European cities. Buses are a good candidate for conversion to hydrogen since diesel buses are a significant source of local pollutants in urban centres. Buses tend to operate at low engine loads, they have room for hydrogen storage, do not require high speeds or very fast acceleration, and a fleet of buses can be re-fuelled and maintained from a central depot. Additionally, when municipalities work together in joint procurement arrangements, costs can be brought down due to higher quantities ordered at once.

Initial feedback from the CUTE project suggests the buses are reasonably reliable (initially 75% availability, rising to 85% in later months). Fuel economy was found to be worse than diesel buses, about 35MJ/km compared to 23MJ/km (Haraldsson et al. 2005). This was due to increased weight (an extra 2000kg) and to inefficiencies arising from fitting a fuel-cell to an essentially unmodified diesel drive train with mechanically-driven auxiliaries (e.g. air conditioning). In contrast the 'ThunderPower' fuel cell bus in California, which has been designed for fuel cell propulsion, reported a fuel use of 9 MJ/km (Chandler and Fudy 2003 Table 6), about 2.4 times better than the compressed natural gas (CNG) buses that usually operate on the route (fuel consumption between the studies is not directly comparable due to different driving conditions). Its availability was 71% over the six-month trial period which was considered good for a prototype vehicle. Current fuel cell bus costs are high - over US\$1 million, compared to under \$500 000 for a top-of-the range diesel bus (Haraldsson, Folkesson et al. 2005).

A recently announced target from the London Hydrogen Plan aims to have around 70 hydrogen powered vehicles on the streets of London by 2010 / 11, of which 10-12 will be buses. Other than that they must be hydrogen fuelled, the tender will not be technology specific.

### 4.2 Boats

Marine engines are significant contributors to hydrocarbons (HC), nitrogen oxide (NO<sub>x</sub>) and sulphur emissions in many parts of the world, and emissions from marine engines are only just beginning to be regulated (Corbett and Koehler 2003). Uncertainty exists, but shipping may account for 28% of global NO<sub>x</sub> emissions from fossil-fuels, and over 5% of sulphur emissions from all fuels, including coal (Corbett et al. 1999; Corbett and Koehler 2003) in comparison, shipping accounts for less than 2% of global GHG emissions (IMO 2000).

Reducing 'traditional air pollutants' is likely to be a bigger driver for hydrogen technologies in shipping than energy efficiency savings, since large diesel engines commonly used are relatively

efficient (50% LHV or more), and low grade diesel is comparatively cheap. Hydrogen for marine transportation is still a relatively unexplored system (Forster 2000), although a number of ships use liquefied natural gas (LNG), and hydrogen fuel cells have been successfully adopted in many submarines due to their low noise and thermal signature, extended operation, and non-toxic emissions streams. Iceland have expressed much interest in converting their fishing fleet to hydrogen, to save money and cut CO<sub>2</sub> emissions.

### 4.3 Planes

Hydrogen has long attracted interest as an air-transport fuel, and since the 1940s a number of jet aircraft have been adapted carry and run on liquid hydrogen. Liquid hydrogen appears to be the only feasible way of carrying sufficient energy: compressed gas would require large tanks which would add to drag. Recent military research has focused on fuel cell / propeller aircraft at high altitude, and long range surveillance aircraft, however current fuel cells are too heavy and expensive to compete with jet engines on larger aircraft.

### 4.4 Trains

There is some research into hydrogen trains for military and commercial uses. The Fuel Cell Propulsion Institute in the US has plans for A 109 tonne 1MW fuel cell train, and there are plans in Denmark for the first European hydrogen train.

## 5 Conclusions

### 5.1 Stack systems

The current cost of making PEM FC automotive stack system at low production volumes is reported to be around US\$ 500 / kW (IEA, 2005). Both a recent study by TIAX (2005), and an announcement by Ballard suggest that current technologies, if mass produced at the rate of 500,000 units per year, could be produced for just over US\$ 100 / kW. This is well within the DOE target for 2005, despite the current high price of platinum, a fact which may bode well regarding the achievement of future targets- however, these more stringent future targets would require significant technological development.

Mass production was an inherent assumption in the TIAX (2005) report, and will be key to commercialisation of automotive fuel cells. However, in order to approach the US DOE target of \$30 / kW by 2015, substantial technical improvements must be made, in addition to increasing production volumes. The most significant areas are:

- Development of cheaper membrane materials, capable of withstanding higher temperatures
- Reduction of precious metal loading
- Increasing power density
- Simplification of balance of plant system

These improvements are not merely incremental in nature, and will require considerable research to achieve.

### 5.2 Whole vehicles

Aside from the stack, perhaps the most important component both for cost reduction and consumer acceptability for the whole fuel cell vehicle is hydrogen storage. Storage is currently costly and does not provide a range that is competitive with existing technologies. One way of addressing this might be to market fuel cell vehicles as short range urban vehicles, and encourage consumers to see them as a strong option for most every day uses. However, it is also possible that the less mature technologies (such as metal and chemical hydrides) could show major improvements in the next few years.

It is important to consider storage in conjunction with both production, distribution and end uses. The likelihood of hydrogen being provided by infrastructure in a certain form will influence designs of vehicles towards storing that form. On the other hand, the activities of car companies are also likely to have some influence on distribution companies.

FCVs are estimated to be about 2-3 times more efficient than conventional gasoline vehicles, and 1.5-2 times more efficient than diesel electric hybrids. Well-to-wheels analysis suggests greenhouse gas reductions of 30-60% compared with conventional gasoline vehicles, if hydrogen is produced by SMR and transported by pipeline. Comparable savings, 25-50% compared with conventional gasoline, appear to be achievable with advanced diesel hybrids. GHG gas savings will be far greater if carbon capture technologies, renewables, or nuclear energy is used to produce hydrogen.

Studies employing learning curves suggest that costs could drop to around US \$ 22, 000 – 28, 000 once cumulative production has reached levels of 5-10 million. However, in which year cumulative production could reach such levels is highly open to question, being related to questions of social

acceptability, infrastructure and crucially, the cost of the vehicles. This aspect creates a strong element of circularity in learning curve based conclusions, making putting a date on any future cost projections extremely difficult. A recent spate of announcements from car manufacturers has promised commercially competitive fuel cell vehicles within the next decade. However, it may be that these are more responses to US DOE 2015 targets, rather than evidence of a clear road map to technological development. The progress required is still significant, as 'in most cases, solutions depend on yet-to-be-conceived or -proven component and manufacturing technology rather than incremental improvement' (NRC, 2005) It is also unlikely that manufacturers would commit themselves to mass production, another crucial factor in cost reduction, in the absence of clear evidence of infrastructure development.

Policy interventions are crucial therefore; public and government procurement could play a crucial role in stimulating the early production necessary to bring costs down. Technologies may be able to mature in niche and fleet applications where infrastructure requirements are more manageable.

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