4.12 Hydrogen and Fuel Cells in Transport

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4.12.1 Introduction

Decarbonizing transport is proving to be one of the largest R&D projects of the early twenty-first century. There are around 800 million vehicles in use worldwide and the motor industry is therefore one of the largest global forces, employing millions of people, and generating about 60 million cars and 20 million trucks each year, a value chain in excess of $3 trillion per annum and 4.6 billion tons of CO₂ per annum worldwide (ca. 17% of mankind’s greenhouse gas emissions) [1]. This ever increasing demand for personal mobility and near total dependence on liquid hydrocarbons means that emission reductions from this sector will be a great challenge. Since hydrogen and fuel cells offer zero emissions and doubling of efficiency (similar to battery electric drives) when compared to conventional internal combustion engines (ICEs), there should be a large impact of these technologies on the transportation sector.

The development of alternate fuels to petrol and diesel has been ongoing since the 1970s, initially in response to the oil shocks and concerns over urban air pollution. Efforts have gained momentum more recently as the volatility of oil prices and stability of supplies, not to mention the consequences of global climate change, have risen up political agendas the world over. Low-carbon technologies are therefore rapidly advancing, with biofuel, petrol and diesel hybrids, battery electric, and hydrogen fuel cell cars being developed by nearly every major manufacturer. It seems likely that a number of technologies will move forward together, gradually evolving into an optimum low-carbon solution, with hydrogen as the accepted long-term prospect.

Projections estimate that the world fuel cell market is expected to reach nearly $19.2 billion by 2020 [2], including transport, buildings, and portable applications. In the United Kingdom, targets for hydrogen and fuel cells in transport have been set by the Department of Energy and Climate Change (DECC) and the Technology Strategy Board (TSB), with durability of fuel cells up to 8000 h and cost targets for longer term sustainable hydrogen production below £5 kg⁻¹. It is hoped that breakthroughs will allow the industry to achieve commercial cost and performance targets of €45 kWh⁻¹ for a fuel cell with membrane power densities above 1 W cm⁻² for transport.

However, there are two major problems in hydrogen and fuel cells for transport: hydrogen is rarely available to the consumer, while fuel cell cars are too expensive. Both hydrogen availability at filling stations and cheap fuel cell vehicles are needed if breakthroughs are to be achieved. The two main incentives for change, efficiency and zero emission, have not been sufficiently valued to date. Zero Emission Vehicle (ZEV) legislation initiated in the 1990s has since stalled [3], and the overall efficiency of the new vehicles has been disappointing when compared with pure battery and hybrid combustion vehicles [4], suggesting that the tank-to-wheels efficiency of fuel cell cars might be only about 22% rather than the figures of around 40% suggested by enthusiasts and available from battery electric cars.

Offsetting these problems, there have been many successful demonstration projects around the world [5] with hundreds of fuel cell vehicles and dozens of hydrogen refueling stations. All major vehicle manufacturers have created prototype vehicles and shown interesting performance data, but the date for commercialization is still some years away, typically 2015 [4]. By 2050, it has been estimated using an optimistic scenario that there will be around 50% penetration of the car market by hydrogen vehicles, with most of those in China. But such predictions are prone to error [6]. Figure 1 suggests a likely future in which trucks and other long distance vehicles will still operate largely on diesel, probably biofuel, perhaps with some hybridization, but city cars will move almost totally to electric drives, with hydrogen storage as a common option for extended range and rapid refilling. So battery electric drives will be very common as cities progressively ban hydrocarbon emissions, with hybridization using hydrogen fuel cells a key feature. Since half the world population will live in cities, they will prefer battery commuter cars, whereas the other half need longer
range hydrogen vehicles for rural driving. Therefore, our conclusion is that vehicles will be around 50/50 battery electric or battery/fuel cell hybrids in 2050, with some still running on hydrocarbons, particularly biofuel, especially in the Americas.

The purpose of this chapter is to review the progress in accepting hydrogen and fuel cell transport, starting with the most successful demonstrations today in forklifts and illustrating the competition from conventional fuels in early markets. Then, bus and car demonstrations are considered, putting the case for hydrogen fuel cell/battery hybrids, followed by specialized long-term boat and aircraft applications.

4.12.2 Choice of Fuel Cell Technology

When oil, one of the most important energy sources in the history of mankind, was first discovered in Pennsylvania almost 150 years ago, the fuel cell had already been known for 20 years, invented by Sir William Grove ‘father of the fuel cell’ in 1839. Back then it was an idea that was far ahead of its time. Today, however, it is the most important development in the history of decentralized electricity supply [7].

- A fuel cell is an ‘electrochemical’ device, operating at various temperatures, that transforms the chemical energy of a fuel (hydrogen, methanol, natural gas, etc.) into electrical energy, when reacting with an oxidant (air or oxygen) in the presence of a catalyst (also so-called electrocatalyst (EC)), producing water, heat, and electricity. There are currently five main fuel cells available on the market [7]. Alkaline fuel cells (AFCs), also known as the Bacon fuel cell after its British inventor, are the most developed fuel cells in terms of history. NASA has used AFCs since the mid-1960s in Apollo-series missions and on the Space Shuttle (it is this fuel cell that flew man to the Moon!). AFCs consume hydrogen and pure oxygen producing water, heat, and electricity and they operate below 80 °C. They are among the most efficient fuel cells, with the potential to reach up to 70% efficiency.

- Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid as the electrolyte. PAFCs consume hydrogen and oxygen or air producing water, heat, and electricity with an efficiency of up to 50%. The primary manufacturer of PAFC technology is UTC Power in the United States (also known as UTC Fuel Cells). As of 2005, there were close to 300 ‘PureCell’ 200 kW units by UTC Power in service globally.

- Solid oxide fuel cells (SOFCs) are high-temperature fuel cells, operating typically between 700 and 1000 °C with efficiencies of up to 60%. An SOFC is made up of four layers, three of which are made of ceramics. SOFCs have so far been operated on methane, propane, and butane as fuels.

- Molten-carbonate fuel cells (MCFCs) operate at temperatures of up to 650 °C. They were initially developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications.

- Proton exchange membrane fuel cells (PEMFCs), also known as polymer electrolyte membrane fuel cells, are currently being developed for transport applications as well as stationary and portable applications (Figure 2). There are two types of PEMFCs: one uses hydrogen as fuel – hydrogen PEMFC – and the other uses alcohol (e.g., ethanol, methanol) – direct alcohol fuel cell (DAFC) and direct methanol fuel cell (DMFC). Both types of PEMFCs use membrane electrode assemblies (MEAs), which are the heart of the fuel cell. Hydrogen PEMFCs consume hydrogen and oxygen/air producing water, heat, and electricity with an efficiency of up to 60% and operating at up to 150 °C. A DMFC consumes methanol in water and oxygen producing water, heat, and electricity with an efficiency of up to 40% and operating at up to 80 °C.

PEMFC is a technology that was initially developed for military and spacecraft applications at GE (General Electric, USA) in the 1960s but was abandoned in the 1970s due to high cost and poor durability issues. From the 1980s, a revival in PEMFC R&D was noticeable, mainly in the portable and vehicular applications, in several companies such as the Canadian company Ballard Power Systems. To date, PEMFC technology has been extended to wider applications, with the potential to power a portfolio of devices and
services, for example, mobile phones, personal electronic devices (PDAs) laptops, cars, buses, boats, houses, telecommunication stations, and space shuttles. In recent years, the PEMFC has been extensively demonstrated worldwide [8] in many application fields and is now being commercialized in early markets by Ballard, Hydrogenics, Intelligent Energy, and other companies.

However, cost and durability are the two major barriers for large-scale manufacturing and full commercialization of this technology. For example, the EC is the main contributor to the PEMFC’s limited performance, high cost, and poor durability. Currently, only Pt or Pt-based catalysts (e.g., Pt-Co) are practical for driving the electrochemical reactions in a PEMFC environment. Platinum comprises a large portion of the PEMFC cost due to its high price and limited supply. In a state-of-the-art PEMFC stack, the EC accounts for ca. 60% of the total cost, which is much higher than the cost of any other single component, for example, the polymeric proton exchange membrane (PEM) (10%), bipolar plate (BPP) (10%), and gas diffusion layer (GDL) (10%). Furthermore, catalyst stability is one of the major limitations on PEMFC durability, which is an important step in achieving the commercialization of PEMFC. Thus, developing high-performance, low-cost, and highly durable catalysts is the number one set of priorities for PEMFC research.

4.12.3 Hydrogen Production, Usage, and Infrastructure

Hydrogen has a very good energy content by weight: around 3 times that of gasoline and almost 7 times that of coal (hydrogen has the highest oxidation energy content of all fuels on a weight basis – 143 kJ g−1 [8]). However, the energy density of hydrogen per unit volume is quite low. Given that 5 kg of hydrogen is equivalent to about 5 gallons or 221 of petrol [7, 8], to store it under ambient conditions would require a 5 m diameter vessel, which is impractical for most applications. Its volumetric energy density can be increased by storing the hydrogen under either increased pressure, at extremely low temperatures as a liquid, or in metal-hydride (M-H) systems. So hydrogen fuel storage for transport use remains a key issue.

Fifty million tons of hydrogen are produced globally, mainly through the reformation of fossil fuels, and almost 1 million tons of hydrogen are produced in the United Kingdom annually [8]. Recent worldwide hydrogen production totals show that 48% of hydrogen is produced from natural gas, 30% from oil, 18% from coal, and only 4% from renewables, mainly by electrolysis. Hydrogen is currently used in the chemical processing and petroleum industries, for the production of fats, oils, metals, and electronics, and as a fuel in space flight. Consequently, hydrogen is available in chemical plants but is not ‘green’ at present; in other words, it is not normally produced from renewable resources.

There is currently little hydrogen infrastructure in the United Kingdom. There are around 10 functional hydrogen refueling stations in Britain with 3 located in the Midlands at the University of Birmingham (Figure 3), Loughborough University, and
Coventry University. However, plans are under way to implement a further series of hydrogen refueling stations in the Midlands, later spreading to the rest of the United Kingdom, giving more investment in infrastructure.

The refueler shown in Figure 3(a) was installed to fuel campus vehicles, with a capacity of 10–12 kg day\(^{-1}\) (1.8–2 kg per fill at 350 bar), sufficient for the five vehicle fleet. For such a small number of fillings, the refueler cost was $3 per filling, but the cost of green hydrogen, delivered by road from a waste food plant, was much more, that is, $15 per filling. Figure 3(b) shows the three 400 bar composite hydrogen storage tanks in the refueler. These were pumped up from the remote 200 bar steel cylinder store using an air-driven compressor located in the nearby building. The installation fitted the standard regulations for refueling 350 bar hydrogen vehicles defined in 2006 [9] and dispensed hydrogen into the vehicle storage tank at 350 bar by cascading from the three 400 bar tanks in the refueler. Using this standard [9] ensures that higher pressure hydrogen cannot be plugged in, nor can other gases like compressed natural gas.

### 4.12.4 Hydrogen Vehicles

#### 4.12.4.1 Forklifts

Once the hydrogen refueler has been installed, the use of a vehicle fleet on a campus or a factory site becomes attractive. This has been proven particularly for hydrogen forklifts in warehouses. Considering the 2009 world market for fuel cells, about $330 million comprising around 24 000 units shipped, mainly in telecoms and other stationary applications [10], the major emerging market is forklifts for use in the multibillion dollar warehousing and distribution business. At present, battery and hydrocarbon combustion forklifts dominate, but hydrogen has advantages of greater range, quicker charging, less downtime, and steadier voltages, taking up less space and with fewer recycling issues. In the United States, around 1000 fuel cell forklifts [11] are now operating because they are significantly more efficient than battery vehicles. The Department of Energy and Department of Defense have recently been promoting this technology with five new projects to deploy 300 forklifts at large companies such as FedEx, Genco, and Sysco. In Europe, Linde have been following a similar path using Hydrogenics fuel cells to replace batteries, with 1.6 kg of hydrogen stored in composite cylinders at 350 bar [11, 12]. Supercapacitors provide pulse power to the electric motor while batteries are completely eliminated.

A recent installation on a greenfield site took place at Joliet, Illinois, for Central Grocers where 220 Plug Power fuel cell forklifts were fueled by hydrogen stored outside in a liquid storage and pumping facility shown in Figure 4. Multiple indoor gaseous hydrogen fueling points could fill each forklift in less than 2 min. The subsidy encouraging the installation was a tax credit of $3000 per kW up to 30% of unit price.
Naturally, there has been some skepticism from the existing battery and truck providers, who claim that the investment costs are up to 50% higher and that new batteries such as lithium ion can provide solutions to the rapid charging and durability issues [12]. Two-year payback is the claim made by fuel cell manufacturers. The debate will run on for the next decade before the full results become available, and it may be that the answer is neither a pure battery nor a pure hydrogen solution. A combination of both, for example, fuel cell/lithium battery hybrid drive, may be a realistic solution as reviewed later in Section 4.12.4.4. The other option is using methanol as fuel by inserting DMFC battery chargers in conventional battery forklifts as demonstrated by Oorja [13].

4.12.4.2 Other Early Markets

The original early markets postulated 5 years ago, such as bicycles and trains, have not seen the success originally estimated [14]. Instead, in 2007, a large increase in fuel cell auxiliary power units (APUs) was observed, with the main application being APUs for recreational vehicles (RVs) in the United States and Europe. These were mainly polymer electrolyte membrane (PEM) generators built in Germany using DMFC technology. Typically 4000 units per year were supplied by Smart Fuel Cell (SFC AG) and were installed in camper vans and other leisure vehicles (Figure 5) and operated in national parks and areas where conventional combustion engine generators were restricted because of noise, fire risk, and other problems. The product EFOY (energy for you) was certified by TUV Sud in 2005 and began to sell significantly in 2007 [15, 16]. It is available from 48 RV manufacturers in Europe and there are 1400 consumer outlets for the 5 or 101 methanol cartridges which can last for weeks.

Methanol was relatively easy to package in plastic cartridges, but hydrogen has not proved so easy to distribute to consumers, although a number of companies have attempted to make hydride storage cartridges available across the counter in shops. Instead, methanol has proved to be the most readily available fuel for PEM cells. Similarly, propane and camping gas are widely available for SOFCs, which have also been suggested for the RV markets. From the mobile home market, there are possible entries into the motorbike, the invalid carriage, and other small battery fuel cell hybrid applications [17]. Since the first fuel cell bike was shown by Karl Kordesch in 1967 [18], there has been steady development, with more than 30 companies posting information about their potential products [17]. However, the pure battery electric bike has dominated over the fuel cell, especially in China where 30 million battery electric bikes and scooters are made by 150 companies each year. The problem with a pure battery energy storage is the limited range of the bike, depending on the battery technology, whether lead-acid, NiCd, or lithium ion. The benefit of the fuel cell is that it raises the power and gives extended range, as in the experimental model developed at Loughborough shown in Figure 6, which increased the range from 25 miles on the four lead-acid batteries to 100 miles with the 2.4 kWh of hydrogen stored. In this design, the hydrogen was stored as pressurized gas at 350 bar. M-H stores have also been attempted but are not satisfactory

**Figure 5** EFOY fuel cell generating 90 W, and Motorhome Globe 4 containing an SFC fuel cell running on methanol.

**Figure 6** Fuel cell hybrid bike developed by Intelligent Energy at Loughborough University.
Figure 7 (a) Hydrogen fuel cell hybrid scooter (HFCHS) and (b) component diagram of the HFCHS showing all components and electrical drive system layout.

Table 1 Characteristics and comparison of the electric, petrol, and hybrid scooter

<table>
<thead>
<tr>
<th></th>
<th>GoPed FC Plug-in</th>
<th>GoPed Plug-in</th>
<th>GoPed (29 cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle cost</td>
<td>£3000</td>
<td>£1200</td>
<td>£800</td>
</tr>
<tr>
<td>mpg equivalent</td>
<td>500 mpg (H₂)</td>
<td>383 mpg</td>
<td>100 mpg</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>37–75%</td>
<td>75%</td>
<td>20%</td>
</tr>
<tr>
<td>Tail-pipe emission</td>
<td>None/H₂O</td>
<td>None</td>
<td>Harmful air pollutions</td>
</tr>
<tr>
<td>Well-to-wheel CO₂</td>
<td>9.37–40.95 g CO₂ km⁻¹</td>
<td>24.07 g CO₂ km⁻¹</td>
<td>90–120 g CO₂ km⁻¹</td>
</tr>
<tr>
<td>Running cost on fuel</td>
<td>£0.01–£0.11 mile⁻¹</td>
<td>£0.01 mile⁻¹</td>
<td>£0.06 mile⁻¹</td>
</tr>
<tr>
<td>Refueling time</td>
<td>15 min – 5 h</td>
<td>5 h</td>
<td>1 min</td>
</tr>
<tr>
<td>Range</td>
<td>15 miles</td>
<td>8 miles</td>
<td>32 miles</td>
</tr>
<tr>
<td>Top speed</td>
<td>25.8 mph</td>
<td>20 mph</td>
<td>24 mph</td>
</tr>
<tr>
<td>Noise level</td>
<td>55 db</td>
<td>55 db</td>
<td>75 db</td>
</tr>
</tbody>
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mpg, miles per gallon.

owing to the large weight and thermal problems, while refilling is inconvenient because the hydride distribution system is not yet established. It appears therefore that larger vehicles such as buses are more appropriate for hydrogen application.

Recently, Shang and Pollet [19] showed that it is possible to develop and commission a hydrogen fuel cell hybrid scooter (HFCHS) with plug-in features (Figure 7). A commercially available ‘pure’ lead-acid battery electric scooter (GoPed) was converted to an HFCHS so as to investigate the effect of hybridization on driving duty cycles, range, performance, recharging times, well-to-wheel CO₂ footprint, and overall running costs. The HFCHS with plug-in features consisted mainly of a 500 W hydrogen PEMFC stack connected to four 12 V 9 Ah lead-acid batteries (576 Wh) and two hydrogen M-H canisters (54 kg of mass equivalent to 1.8 kWh of energy) supplying pure hydrogen (99.999%) and also acting as heat sink (due to endothermic hydrogen desorption process). In this study, the HFCHS urban driving cycle was compared with that of a conventional petrol and ‘pure’ battery electric scooter. The energy consumed by the HFCHS was 0.11 kWh km⁻¹, with an associated running cost of £0.01 km⁻¹, a well-to-wheel CO₂ of 9.37 g CO₂ km⁻¹, and a maximum range of 15 miles. It was shown that the HFCHS gave better energy efficiencies and speeds compared to battery- and petrol-powered GoPed scooters alone (Table 1).

4.12.4.3 Buses

Buses have been a focus for fuel cell development since 1995 when Geoffrey Ballard first demonstrated his early design in Vancouver [7]. This led to the propagation of fuel cell bus projects around the world, the most significant being the European-funded CUTE project [20], which started services in 2003 and ran 3 buses in each of 10 capital cities like London, Paris, and Madrid over a 2-year commercial period. These Citaro vehicles were built by Mercedes-Benz in Germany using a 250 kW Ballard PEMFC running on 44 kg pure hydrogen stored in 350 bar cylinders on the roof. Each city installed a hydrogen refueling station and these stations were designed and built by a number of companies including BP, Shell, and Air Products to test a number of technologies ranging from natural gas reforming to on-site electrolysis.
The problem with Ballard was his refusal to combine batteries with the fuel cells to form a hybrid, because he claimed that the batteries obscured the fuel cell performance. This may have been true, but there is little doubt that a combination of battery and fuel cell in the drivetrain, giving the hybrid fuel cell electric vehicle, has many advantages over the individual technologies. The hybrid drive beats the battery bus by having longer range and shorter refueling times. It also beats the fuel cell bus by providing high power peaks, allowing regenerative braking, increasing efficiency, extending fuel cell life, and reducing costs. This trend to hybridization has similarly been observed in diesel engine buses largely because it reduces emissions such that many bus suppliers now offer hybrid bus products which are used in cities such as London and Hamburg [21] to promote higher air quality.

Figure 8 shows the modern hybrid fuel cell bus made by EvoBus and supplied in 2010 to several German cities in the CHIC (Clean Hydrogen In European Cities) project [22]. This is a EU-funded project with 10 buses from three manufacturers deployed in several cities to test their performance and consumer response. The fuel cell was reduced in power to 100 kW while a 27 kWh lithium-ion battery was inserted to give 120 kW of cruise power and storage for regenerative braking and acceleration at 160 kW peak. Seven hydrogen cylinders on the roof allowed 35 kg of 700 bar gas to give a vehicle range about 250 km.

Recently, London has announced [23] that it will operate five hydrogen buses (RV1), running from Tower Gateway to Covent Garden, fueled by London’s first permanent hydrogen refueling station. The station was officially opened in December 2010 by Kit Malthouse, Deputy Mayor of London. This not only marks London’s progress in low-carbon transport innovation but means the city now has one of the largest fleets of hydrogen buses in Europe.

The key achievements by Air Products under this program are the innovative station design and operation of a dual-phase hydrogen tanker, designed to deliver high-purity gaseous or liquid hydrogen. These represent major steps forward in infrastructure development and are key to the deployment of low-cost stations in the future. Air Products will also install a second hydrogen refueling station in London as part of the Joint Technology Initiative (JTI)-funded CHIC project [22].

4.12.4.4 Cars

The design of fuel cell cars has followed the bus narrative in moving from pure fuel cell toward fuel cell/battery hybrid. The difference is that there are very few bus manufacturers, whereas every major car company has produced fuel cell prototypes, together with plans to produce large numbers by 2015 [24]. Initially, the first cars produced by Daimler, the F-cell introduced in 2002 and the B class initiated in 2005, were based on a pure fuel cell drivetrain [25] which could be fitted into designs produced to satisfy the original 1993 ZEV legislation in California. The ultimate example of this was the 2008 Honda FCX Clarity, which used a 100 kW PEMFC to provide excellent performance [26]. This much-praised design suffered from a large mass and an excessive hydrogen tank but was otherwise thoughtfully conceived. The performance was fine with good acceleration, a top speed of 100 mph, and a range of 280 miles on 4.1 kg of hydrogen, and the consumer acceptance was superb. Although the 3-year leasing arrangement was $600 per month in the US trials which began in 2007, this price was heavily subsidized and the true individual vehicle cost for the initial run of 100 cars was approximately $500k. However, the battery was too small for regenerative braking and the fuel cell was too expensive. The rational solution is to downsize the fuel cell and increase the battery. Halving the mass would also be a way to double the efficiency.

This philosophy was the one pursued in Birmingham during the past few years. The first prototype shown in Figure 9 was designed and built in 2005 by Professor John Jostins of Microcab Industries Ltd, who started a small company to deliver a novel hybrid solution [27]. The design criteria were

- fuel cell to provide cruise speed,
- larger battery to provide acceleration, regenerative braking, and plug-in capacity,
- mass around 500 kg to give maximum efficiency,
- four-seat city cab with excellent access through three doors, and
- many standard components to lower costs.
In 2006, Professor Kevin Kendall received support from Advantage West Midlands to buy the prototype plus four improved vehicles, which could then be trialed using the University campus as a test track. The Air Products refueller was opened at the School of Chemical Engineering in April 2008 and the five cars were then used to test the design calculations over a 2-year test program undertaken by a consortium of West Midlands suppliers part-funded by the UK government department BERR. The results [27, 28] showed that the initial campus design gave the desired acceleration, top speed of 20 mph, and a range of 60 miles on a campus drive cycle, but could not achieve the ECE15 urban cycle. This was not surprising because the fuel cell used was a 1.2 kW Ballard Nexa PEMFC stack (less than 1 g of Pt is used compared with 60 g for a 100 kW system), the hydrogen tank was 0.6 kg at 350 bar, and the battery was 2 kWh lead-acid. The main problem was the battery capacity, which was insufficient to give regenerative braking and plug-in range. Other issues such as the need for a lightweight aluminum chassis, the space requirements for fleet vehicles, the performance of lightweight body panels, and better heat management for window and cab temperature control were addressed in 2011 when the next batch of eight cars was assembled.

So far, Microcab Industries, in collaboration with the University of Birmingham, have made very good progress in new hydrogen hybrid fuel cell vehicle (Figure 10) [29], for example,

1. the range of the vehicle has been extended up to 200 miles (the range for a current state-of-the-art lithium-ion battery vehicle is only 60 miles),
2. refueling time of the vehicle is reduced to 3 min (battery vehicles have a domestic charging time of 5–8 h), and
3. the lifetime of the fuel cell stack has been increased up to 5000 h with a high-temperature PEMFC.

Economically, if 500 000 hydrogen hybrid vehicles were produced per annum, less than 0.5 ton of platinum would be required assuming a platinum loading of 0.6 g kW$^{-1}$. Of course, the main key issues are cost, lifetime, and reliability in both start-up and duty cycles, which
still require some attention. Based on a PEMFC stack production cost of $225 kW$^{-1}$ (mainly attributed to Pt and membrane cost) with a DoE target of ~$30 kW$^{-1}$ by 2015, fuel cell–electric hybrids become a very attractive option for commercial deployment.

Of course, another option is to convert a conventional petrol combustion hybrid car to run on hydrogen in order to test the filling station infrastructure and the performance/costs of the new systems. In 2006, Statoil did this in Norway by opening the first of its HyNor fueling stations in Stavanger with 15 modified Toyota Prius hybrids running on hydrogen gas. By 2009, there were seven hydrogen stations connecting the 600 km from Oslo to Stavanger and the number of hydrogen vehicles had increased to 50 with manufacturers Mazda, Think, and Toyota [30]. In addition, 10 Daimler B class fuel cell vehicles were planned to arrive in 2011. The advantages of demonstrating this technology in Norway were substantial:

- car taxes are high and can be reduced to incentivize consumers;
- hydrogen cars can drive in bus lanes and are exempt from road tolls;
- hydrogen is readily available from the Statoil plants; and
- hydrogen can be produced from renewables such as hydropower to give green energy.

### 4.12.4.5 Ships

Norway has also been the first to apply fuel cell technology to drive ships. Figure 11 shows the Viking Lady [31], which was fitted with a 320 kW MCFC as one of the main power supplies. Hydrogen and carbon dioxide are stored in pressurized tanks to get the MCFC warmed up to 650 °C, and then liquefied natural gas is internally reformed on the anode. The ship’s four Wartsila 2 MW engines also run on natural gas, generating additional power to drive the electric propulsion system. The fuel cell built by MTU costs
€12 million, but the cost was offset by the fall in tax due to 90% reduction in nitrogen oxide emissions. After delivery and testing in 2009, the ship was then chartered to the French oil company Total.

A recent report [32] has predicted a market of 160 GW worldwide for ship-based fuel cells. The main aim is to provide clean auxiliary power in harbors where diesel emissions are banned. The first entry should be cruise vessels, ferry vessels, and megayachts, but ultimately container ships will also be penetrated.

Although fuel cells are predicted to have a significant application on ships, the main market until now has been small APUs for leisure yachts [33]. Typically a DMFC provides 65 W of clean, silent power to drive navigation and other systems. The plastic container of methanol is sufficient to give power for weeks at sea. For example, Arcona Yachts, the second largest sailboat manufacturer in Sweden, has specified the Smart Fuel Cell EFOY system to provide around 2.2 kWh per day from methanol packs. By 2010, more than 18 000 of these units had been delivered to early markets including boats and mobile homes.

### 4.12.4.6 Aircraft

Hydrogen as an aircraft fuel, because of its buoyancy, had been suggested as long ago as 1783 when Jacques Charles and Nicolas Robert made their first ascent in a hydrogen-filled balloon in front of half the population of Paris, just 2 weeks after the Montgolfier brothers made their famous hot air journey [34]. Because hydrogen also gives 3 times lower weight than kerosene for the equivalent combustion energy, it began to be used in aircraft engines during the twentieth century [35], especially in gas turbines and rocket motors during the 1930s. For example, a Heinkel experimental turbojet was tested on hydrogen in 1937 [35]. It became clear in the last decades that large jets with cryogenic tanks of liquid hydrogen could be used as passenger airliners.

Another innovative idea for unmanned air vehicles (UAVs) was that solar photovoltaic-powered planes could produce hydrogen by electrolysis during the day and then fly at night using a fuel cell propulsion system. The Helios mission was funded by NASA and the UAV was built by Aerovironment Inc. in California, as shown in Figure 12. The design was remarkable because it was extremely light, had many electric propellers, and flew slowly at less than 100 mph to reach high altitudes well above the clouds. In 1999 the prototype first flew and then in 2001 it attained a record high altitude of 96 863 ft for a propeller plane. Unfortunately, it fell into the sea near Hawaii in 2003 as the hydrogen system was about to be tested to prove the idea that flights of several months duration were plausible. The report [36] suggested that turbulence was the cause of unstable wing oscillations.

The original project had been conceived in 1994 as a partnership between Government and Industry. Aerovironment had produced the first all-wing design, called the Pathfinder with six motors, from 1981 to 1997. This tripled in size from 30 m to almost 80 m wingspan by the fifth generation built in 2003 with 10 propellers. One of the key problems was developing the reversible fuel cell stack that would electrolyze during the day and consume hydrogen at night. The fuel cell pod in the center was heavy, with a mass of 230 kg, while two hydrogen storage pods with pressurized cylinders weighed 70 kg each. The crash appears to have slowed the project considerably.

Smaller UAVs for surveying farmland or studying traffic congestion have been powered by lithium-ion batteries, typically with a 1 h flight time [36]. To increase this mission time to 3 or even 6 h, a fuel cell range extender has been used. Hydrogen cylinders are too heavy for this duty, so propane has been preferred, with microtubular SOFCs producing about 100 W of cruise power, saving the batteries for take-off. The record for endurance is 15 h for SOFC-powered UAVs [38]. Small propane canisters are readily available and can be simply inserted into the plane after each flight.
It was not until 2008 that a manned aircraft powered by an electric motor driven by a PEMFC with pressurized hydrogen fuel took off [39]. Boeing built a two-seat electric aircraft using an Intelligent Energy fuel cell stack and lithium-ion batteries to provide climbing power. It was a modified Dimona motor glider with a 16 m wingspan built by Diamond Aircraft Industries of Austria (Figure 13). Once at 1000 m altitude, the fuel cell itself drove the aircraft for about 20 min over Ocana in Spain.

4.12.5 Legislation

Legislation takes two forms: the first relates to safety standards and the second to longer term regulation of carbon emissions. The safety standards are already being implemented in terms of designs for hydrogen production, transport, storage, and refueling nozzles [9].

Longer term legislation has been reviewed by the Committee on Climate Change (CCC), which released a report entitled ‘Fourth Carbon Budget: Reducing Emissions through the 2020s’ [40]. The report sees a need to produce hydrogen from low-carbon processes, including

• electrolysis using low-carbon electricity (the CCC recognizes thermodynamic efficiency, but envisages the benefit of hydrogen generation lying in the application of underutilized low-carbon generating capacity),
• direct production from fossil fuels with ‘precombustion carbon capture and storage’ (production of hydrogen for transport at ‘off-peak’ times), and
• production from bioenergy (though hydrogen would need to compete with other bioenergy uses for this resource).
The report considers the use of hydrogen vehicles relatively expensive due to:
- the fact that many ways of supplying hydrogen involve significant losses when compared to electricity and its use in electric cars,
- significant infrastructure costs, and
- hydrogen vehicle costs.

This results in an estimated hydrogen abatement cost of around £220 per ton CO₂ for cars in 2030.

If experience toward 2030 suggests limits on the penetration of electric vehicles, the CCC believes that there could be a scope for increased penetration of hydrogen cars and vans. The report sees the principal advantage of hydrogen over electric vehicle batteries being in applications for which pure battery electric vehicles are unsuitable (e.g., vehicles requiring longer range). Therefore, if challenges in hydrogen infrastructure development can be addressed, there may be a useful role in niche markets, in which battery electric vehicles do not fulfill current promise:
- Buses provide a good opportunity for hydrogen given depot fueling.
- Hydrogen could be used in trucks with depot fueling and fueling stations along motorways and main roads.
- High-mileage fleet vans could use hydrogen based on depot fueling.

The CCC observes that widespread uptake of hydrogen cars and vans would require major investment in a national network of hydrogen fueling stations, at a scale close to that for petrol and diesel today, together with an accompanying infrastructure for hydrogen production and distribution.

4.12.6 Conclusions

Hydrogen and fuel cells are finding a number of applications in transport. Although the predicted markets for hydrogen bikes did not deliver, fleet vehicles like forklift trucks have proved more interesting. A single hydrogen store and refueling station can provide fuel for a large number of vehicles, which offers significant advantages over both battery and combustion engines in a central location such as a warehouse. A key feature is that hybrid drives combining PEMFCs with lithium-ion batteries or supercapacitors can give advantages. This is especially true for buses which have now moved away from the Ballard concept of a pure fuel cell vehicle to a hybrid electric design where a battery assists with braking and with pulse power.

For smaller vehicles, hydrogen is not readily accessible, so methanol-powered PEMFCs have been used as auxiliary power supplies on RVs for application in national parks where combustion engines are restricted. Delivery fleets and taxis are different because centralized hydrogen storage and dispensing is feasible. Lightweight cabs at the University of Birmingham have shown the benefits of improved efficiency and reduced emissions. Again the hybrid design works best, with about 40 miles range available from the plug-in lithium-ion battery and 160 miles from the hydrogen PEMFC, running on a 350 bar hydrogen cylinder which is recharged in 3–4 min.

Ships are also turning to electric drives where fuel cells can easily be added in, especially to provide clean power in ports where pollution is costly. Natural gas is the most likely fuel in the short term. Aircraft will use kerosene for the foreseeable future but unmanned aircraft can benefit from fuel cells to extend range. Propane is used with microtubular SOFCs in some small applications to add to the lithium-ion batteries. Hydrogen has been used on solar photovoltaic aircraft.

The conclusion is that fuel cells work best in transport when used to supplement and improve battery electric drives. Hydrogen is a suitable fuel for PEMFCs used in fleets. Methanol is more readily available to consumers needing auxiliary power for leisure activities. Fuels such as natural gas and propane are more useful in ships and UAVs.

References

[22] CHIC project kick-off 4 November 2010, European Union.