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Fuel cells: Optimism gone – Hard work still there☆

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ABSTRACT

A brief overview of the progress in fuel cell applications and basic technology development is presented, as a backdrop for discussing readiness for penetration into the marketplace as a solution to problems of depletion, safety, climate or environmental impact from currently used fossil and nuclear fuel-based energy technologies.

1. Introduction

The goals for commercialisation of fuel cell technologies set some ten years ago have not been met at present, and the goals set then for the upcoming decade seem equally unattainable. Despite this the future of hydrogen and fuel cell technologies still retains great hopes. The failure of the early commercialisation was due to a belief that dates for achieving scientific goals could be set by company management. This was false: scientific advance takes time and ingenuity, and pouring in money does not guarantee success. The present phase is one of allowing scientific work to precede presentations of new demonstration fleets of vehicles. Not only must cost be reduced and efficiency raised, but the lifetime of cells has to reach not only the 5000 h of operation specified by initial goal specifications, but the higher figures needed if replacement of fuel cells should not be required several times during the lifetime of a vehicle. For passenger cars, lifetimes above 15 years are today standard, and extended values would be preferable due to materials and environmental considerations. The positive appraisal offered after all is founded on the fact that fuel cell development has not been given up, but shifted from emphasis on showroom zero-series vehicles to allowing in-depth investigations of problems such as those mentioned above to be carried out and discussed in the broader scientific community. The number of scientific papers on fuel cells appearing in peer-reviewed journals is much higher today than it was 5–10 years ago, indicating that the number of people trying to find solutions to outstanding problems has not decreased. The following sections will provide an overview of current fuel cell efforts, a case study of competing options for road vehicles, and finally some remarks on cost and time-wise prospects for implementation.

Acronyms: EV, electric vehicle; FC, fuel cell; PEM, proton exchange membrane; MCFC, molten carbon fuel cell; DMFC, direct methanol fuel cell; SOFC, solid oxide fuel cell; UPS, uninterrupted power supply; CPH, combined power and heat; GPS, geographical positioning system.

☆ This paper was presented as an introductory overview lecture at the 2011 Hypothesis Conference. It is based on the 2nd edition of the author's *Hydrogen and Fuel Cells*, published by Elsevier December 2011, where more detailed analysis supporting the conclusions drawn here may be found.

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2. Short overview of fuel cell application technology

2.1. Road vehicles

Present focus is largely on *hybrid* fuel cell/battery systems. Choosing to deliver power directly from the fuel cell to the electric engine (termed *parallel operation*) is one option, another being to deliver the power from the fuel cell through the battery (*serial operation*). In any case, the hybrid concept allows the rating of the fuel cell to be below that of the motor. Equipment mass is an important parameter, as indicated by the examples presented in Table 1.

2.2. Performance modelling

Extensive modelling of PEM fuel cell performance has been made [2,3], based on a selection of small efficient cars illustrating a pure fuel cell (FC) design, a pure electric vehicle (EV) and several hybrid vehicles such as those described in Table 1. Comparison is further made with the same vehicle propelled by a common-rail diesel engine as currently used in most small passenger cars in Europe (typically some 20% more energy efficient than a similar car with gasoline engine).

The simulations are employing a mixed driving cycle put together from pieces of the driving cycles used in the United States and in the European Union for regulatory and taxation purposes, and containing both highway driving, suburban stretches, and city driving with frequent stops at red lights.

Table 2 shows by modelling a range of hybrid cars that lower than 20 kW fuel cell rating leads to insufficient battery charging, implying that the vehicle cannot be electrically autonomous, but has to obtain battery recharging from an external source, which describes a *plug-in hybrid* vehicle. Recharging of batteries can be done when the car is parked at a suitable power outlet (home garage, working place, or a public recharging station). The electricity cost is typically smaller than that of hydrogen, but both are required for a plug-in hybrid, as long as reversible fuel cell operation is not implemented. Fig. 1 illustrates the results of Table 2.

2.3. Other transport modes

Early interest concentrated on larger vehicles, such as buses, because the fuel cell equipment was bulky and because such vehicles traverse fixed routes, allowing hydrogen to be dispensed from a limited number of sites. The use of fuel cells in these and other types of vehicles, including ships, trains, and aircraft, which are described in reference [3], still offer promising market areas.

Table 1 – Characteristics of vehicles modelled [1].

Component mass (kg)	Pure FC	Hybrid	Pure EV
Basic vehicle (incl. Li-ion start battery)	570	570	570
Fuel cell equipment[a] (40, 20 and 0 kW)	150	100	0
Exhaust management	8	5	0
Li-ion batteries (0, 15 and 250 MJ)	0	70	1134
Electric motor (50 kW)	60	60	60
Transmission (manual 1-speed equivalent)	50	50	50
Passengers and cargo (average)	136	136	136
Total	974	991	1950

a Including mass of 60% filled hydrogen storage tank.

Table 2 – Summary of results for hybrid fuel cell-battery vehicle simulations [2,3].

Plug-in hybrids:					
Fuel cell rating (kW)	0	5	10	15	
Fuel cell system mass (kg)	0	43	55	68	
Fuel cell energy use (MJ/km)	0	0.435	0.666	0.751	
Battery capacity (MJ)	250	125	57.5	25	
Battery system mass (kg)	1136	567	261	113	
Battery fuel use (MJ/km)	0.617	0.263	0.1	0.028	
Battery recharging range (km)	405	468	574	890	
Self-recharging hybrids:					
Fuel cell rating (kW)	20	25	30	35	40
Fuel cell system mass (kg)	80	93	105	118	130
Fuel cell energy use (MJ/km)	0.796	0.809	0.818	0.842	1.138
Battery capacity (MJ)	15	10	10	7.5	0
Battery system mass (kg)	68	45	45	34	–

2.4. Applications in power plants and for stand-alone systems

For large-scale, stationary power generation one can use either low- or high-temperature fuel cell systems. The overall systems may employ PEMFC, MCFC, or SOFC, and will further need facilities for fuel preparation and exhaust cleaning. The detailed discussion of components and possible market entrance scenarios in [3] suggests that hydrogen might find an early application in connection with centralised power stations, using gas turbines rather than fuel cells and serving mainly to smooth the variability introduced in electric power systems employing intermittent renewable resources such as wind or photovoltaic converters.

2.5. Building-integrated systems

Building-integrated fuel cell systems may evolve as a natural extension of current efforts to replace natural gas boiler units by co-producing power-and-heat units, eventually replacing natural gas fuel by hydrogen. Such technologies constitute the largest components of a new fuel cell subsidy program implemented in Japan after the Fukushima nuclear accident. Already more than 10 000 co-generating fuel cell units rated at 0.75–1 kW have been installed [4]. The direct purpose of this policy measure is to replace demand on peak electric power from remaining nuclear plants.

In a next phase, use of reversible fuel cells could alleviate the need for hydrogen pipelines reaching each building, and could further expand the electricity plus heat supply by fuel production for a resident vehicle. The electricity supply for the reversible fuel cell could be excess power from variable renewable sources such as wind or solar electricity.

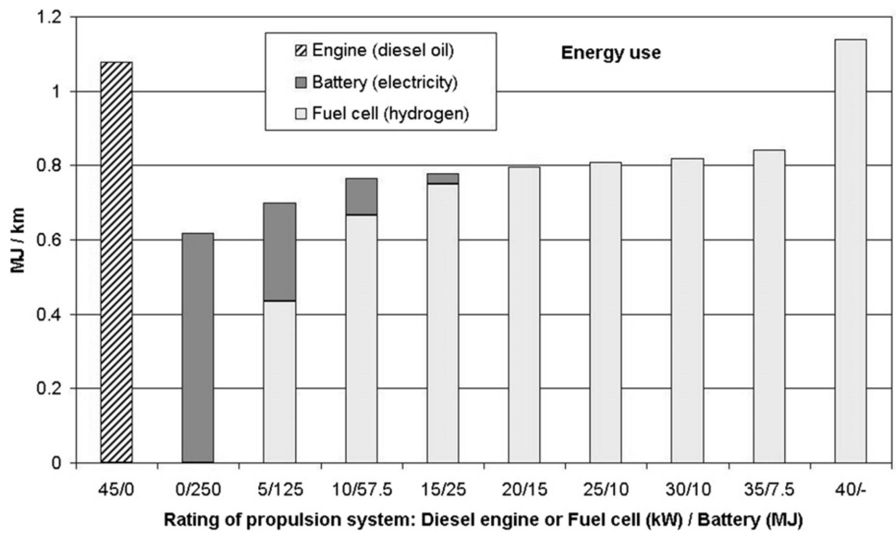

Fig. 1 – Comparison of simulated energy usage for mixed driving cycle traversed by a diesel Lupo 3L (left), and for several plug-in and self-recharging hybrids [2,3].

Implications for infrastructure layout, discussed in [3], could thus be reduced to a discussion of whether to provide central or local storage facilities to ensure time-wise matching of demand and supply. Storage of hydrogen, e.g. underground, is the most obvious solution, but other storage schemes allowing regeneration of electricity would be possible if they can economically compete with hydrogen stores.

2.6. Portable and other small-scale systems

Portable equipment for audio and video entertainment, laptop computers, and smart phones has increased the demand for batteries. Fuel cells might play a role due to their better technical performance, as regards duration of autonomous operation. Candidates at present include direct methanol fuel cells and cells with methanol micro-reformers [3]. So far, these have not reached the general marketplace but serve niche applications, such as powering equipment for military or other expeditions far away from grids.

3. Cost and learning curves

The hybrid fuel cell-battery option has been identified as the most likely technology to play a role over the next decades [2]. The cost optimisation is illustrated in Fig. 2, for different guesses regarding the relative price of fuel cell and battery systems. Comparing with Fig. 1, it is seen that the optimum

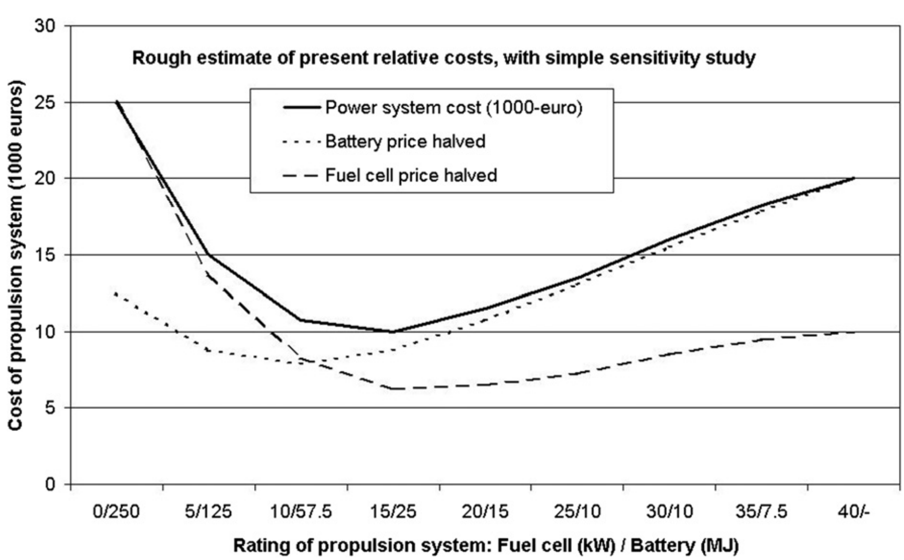

Fig. 2 – Cost of the PEM fuel cell Li-ion battery hybrid systems considered in Fig. 1, based on an estimate of the current price of a purely battery-based or purely fuel cell-based propulsion system (upper curve end-points). The effect of halving either fuel cell or battery price is indicated by the dashed curves. In all cases, the price optimum is for a hybrid configuration with a fuel cell rating of 10 to at most 20 kW and a battery rating of 15–60 MJ, which means plug-in hybrid configurations [2,3].

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price is obtained for upper-end plug-in hybrids, or perhaps for the lowest autonomous hybrids, but in any case under 50% dependence on fuel cells. Examples of learning curves have been discussed in [3], on the basis of the compilation shown in Fig. 3. To the system costs in Fig. 2 energy costs have to be added, in the case of plug-in hybrids for both hydrogen and for electricity (with costs reflecting the mix of renewable or non-renewable sources used).

3.1. Cost and prospects of using fuel cells outside the transportation sector

For building-integrated applications, cost viability is likely to have a dependence on cell durability/life that is even higher than for vehicle applications. Concepts involving hydrogen storage in or below buildings may further present safely issues, say during fires.

Current limitations of battery use for portable device autonomy above the shortest timescales suggest an upstart niche market for fuel cells with small-scale sodium silicide or methanol stores.

Bulk power production is presently dominated by coal-fired power plants and because coal reserves seem adequate for another couple of hundred years [3], the main concern is greenhouse gas emissions. The “clean coal” idea of converting primary hydrogen to hydrogen is only a solution, if the higher cost is acceptable. The cost of “carbon-free coal” depends on the cost of disposing of the large quantities of sequestered CO_2.

Central power plants would likely use the SOFC technology, potentially obtaining higher conversion efficiency than the PEM cells, but requiring high temperatures that can better be established at a large plant. Alternatively, hydrogen may as mentioned play a role as a simple store of energy (e.g. underground [3]), regenerating power through a conventional gas turbine.

3.2. Further remarks on cost and prospects of fuel cells for transportation applications

The competitors to hydrogen technologies in sustainable energy scenarios comprise batteries charged from renewable sources and biofuel combustion uses. The latter does not avoid air pollution, and is less efficient in vehicle applications than fuel cells. The reason is the extensive operation of vehicles at part load, as illustrated by the power duration curve shown in Fig. 4, constructed from the same mixed driving cycle as used in Fig. 1. It is based on a typical passenger car, used about 1140 h in a year of 8760 h, and with an average load during operation, which is less than 25% of the rated power. In any case, the power duration curve of a vehicle is very different from, say, that of a power plant.

With respect to battery vehicles, Fig. 2 indicated a likely preference for a hybrid concept, but depending on the relative cost development of battery and fuel cell technologies. Fuel cell research was stepped up during the 1990ies due to disappointment regarding the slowness of progress in advanced battery development. However, it presently appear that the (in many ways similar) fuel cell technology will also require a quite long maturing period, and there are signs that the advanced battery technology is currently becoming acceptable for passenger vehicles. This several decades of

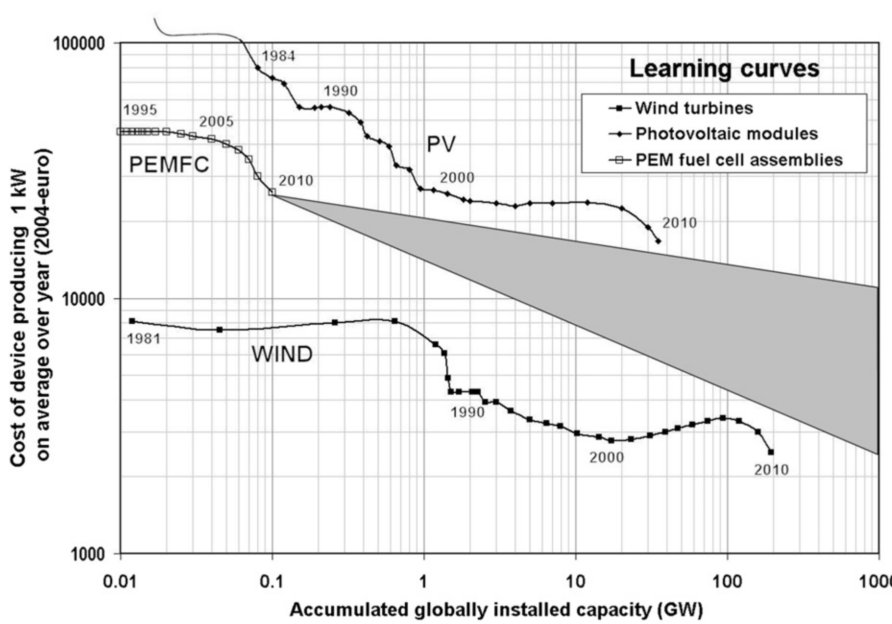

Fig. 3 – Observed learning curves for wind turbine and photovoltaic module costs used to suggest possible learning behaviour for PEM fuel cell stacks. The total accumulated capacity at a given time is along the abscissa, and the average cost of power production is along the ordinate. It is taken as the cost per kW of installed power divided by c_P, which is the ratio between average annual production and the device rated power level (i.e., the equivalent fraction of time at maximum power production). The extrapolation lines for automotive PEM fuel cells correspond to learning at typical rates characterising the wind and photovoltaic industry over prolonged periods. Data are from several sources, specified in [3].

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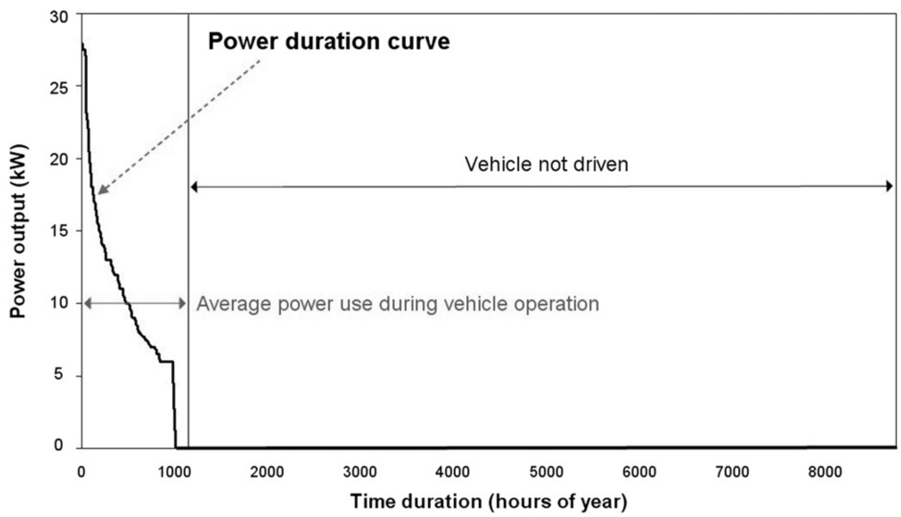

Fig. 4 – Propulsion system power-output duration-curve for annual use of a passenger car based on the same driving pattern as that underlying Fig. 1, and with a 40 kW fuel cell-system and minimal battery (1.67 MJ capacity to ensure stable input to motor). The 6 kW and 0 kW segments of the duration curve during operation represent idling and stopping (for example, at red traffic lights).

head-start for battery research may push the economic hybrid balance of Table 2 towards a larger battery share.

4. Conclusions

The related technologies of batteries (storing energy internally) and fuel cells (storing energy externally) have a clear potential in our energy system. However, both have limitations connected to the fairly low durability of electrochemical devices, and to their substantial cost. Current fuel cell producers struggle to reach fuel cell lives and costs similar to the corresponding ones for batteries, and the initial optimism regarding an early market entry has been replaced by sound appreciation of the many problems, not just of a technical nature but in several cases involving the basic physics and chemistry of the cell behaviour, that remain to overcome. Fortunately, this realization is in many places accompanied by adequate funding of activities, as evidenced by the scientific journal output seen in recent years, and strengthening the hope that the efforts will eventually succeed.

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