Chapter 7 - Feedback of the Study

7.1 - The Debate - Towards hydrogen economy or just technological improvement ?

One of the personal conclusions I have come to through this research concerns the evolution of private transportation : car firms, utilities, electronics, chemical and oil industry *are* concerned by the consequences - meaning geopolitical as well as environmental - of the present oil-based economy. The changes in sight are not only due to inventions which make them possible, they are basically provoked by urgent constraints and willingness to take decisions - more than making inventions - which will generate turnover in sustainable technologies. The switch to fuels like hydrogen and methanol for FC, even if transitionally sourced from natural gas, is a radical change : from petrochemistry to electrochemistry. The use of fuel cell engines might be the major techological feature of the 21^{th} century industry.

7.2 - Engineering

Research on membranes concerns electrolyte performance and cost. Membranes from PSI and DAIS do not need to be fed with 100%-humidified gas, simplifying the hydrogen side of the cell. It is interesting to note that although the membrane-electrolyte is the core component of the PEMFC, the hardest tasks of FC construction are mechanical : reactants and water management, *i.e.* the task of Bipolar Plates.

Ballard has reached an impressive record in power density in the NeCar II : 1kW/liter. This result exceeds the requirements set by the Partnership for a New Generation of Vehicles and the U.S. Department of Energy, but, unfortunately, costs goals are not so close : the NeCar II FC, realized by Ballard (proprietary membranes and graphite bipolar plates) with Daimler-Benz (Johnson Matthey provided the gas diffusion electrodes), is still a very expensive engine. Technically, a graphite BP is weak in case of strong vibration (or crash); that is why metals as titanium, aluminium, niobium or different superalloys are commonly used to improve resistance.

Besides the material cost, minimized using aluminium, a major cost penalty is due to the machining of the raw metal sheet to « cut » grooves in the BP (the flow fields). This accurate work requires heavy-equipment investment and many hours/unit. In the recent years, the most urgent problem of the FC industry was the construction of an efficient, industrially-oriented bipolar plate, which if mass-produced would result in price reduction of the stack from the present situation (10.000$/kW).

DeNora's metallic BP, derived from the electrolysis technology, is made of woven metal wire and it is low cost.[1] The Italian company's improved design has an original solution to reduce volume and weight by an optimisation in the cooling system.[2] It was estimated that stacks up to 2 kW can be air cooled. Moreover, « air-breathing » FC, which eliminate the air blower, are also being developed for < 1kW stacks.

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[1] The mass production of DeNora bipolar plates is one of the objectives of the FC busproject led by Ansaldo Ricerche, Air Liquide, Neoplan, DeNora and others, and it can be seen as the final condition for economical stack production in Europe.

[2] G. Maggio, V. Recupero, C. Mantegazza : « Modelling of temperature distribution in a solid polymer electrolyte fuel cell stack ». Journal of Power Sources No.62, pag.167-174

7.3 - Economy.

As PEMFC are at the pilot-project stage, cost of mass production are limited to cost evaluation of separate components. Hence, only estimates of PEFC systems costs, assuming mass-production conditions are available.

Membranes are now around 10 % of the stack cost. Membrane development has been justified by the hight costs of DuPont's NAFION (US$700 /0.8$m^3$) : cheaper material with similar, or better performance is available such as PSI's styrene-grafted, DAIS' triblock, Gore's or Ballard's.[3] The main step-up in production is the switch from lamination to extrusion process. Since more producers appear every year it is logical to think that the cost of the membranes will lower to 200/400$/$m^2$, *i.e.* (100/200$/kW), but, in mass production, a cost of 50$/$m^2$ is considered possible in the future.

The cost of electrodes is determined by the amount of catalyst, which is considered acceptable between 0.6/1 mg Pt/cm^2. MEA with loadings as low as 0.1 mg Pt have already been realised.

The FC stacks available today are still very expensive and can only be delivered by constructors in joint-project frames under secrecy agreements.[4] Costs might lower soon to 3000$/kW. Ballard plans to charge 35$/kW in 2004, when the company will produce 40.000 units per year.

PEMFC systems are not commercial. Their present status and future targets are summarized in Table 7.1 below. We can see how the stack has a major importance in the cost of a FC system ; this is due to the small production volume and payback of the engineering required to achive the performance.

COMPONENT	Current Cost	CHP Target	Transport Target
Total System cost	14.000 $/$kW_{el}$	800 $/$kW_{el}$	150 $/$kW_{el}$
Stack	10.000	180	45
Fuel processing	1500	180	40
Air delivery system	75	45	15
Humidifier	112.5	52	25
Power conditioner	30	180	-
Buffer system	60	52	-
Control & Instrument.	1200	105	30

Table 7.1 - PEM Fuel Cell System components : present and target costs (source ETSU) [5]

In the European Commission strategy report [6] the 2005 targets are :

200 ECU/kW for stack
1500 ECU/kW for the system

[3] PSI estimates, in mass-production conditions, are around 200 US$/$m^3$. Dais membrane is approx. 30% less expensive than Nafion, but it is today only available on 12``X 12`` surface.
[4] De Nora, today's only short-term supplier able to deliver a 10kW unit in two months, proposes a lease/test contract for 2 years.
[5] ETSU Report No.131. New and Renewable Energy Enquiries Bureau, Harwell, Didcot, Oxfordshire, OX11 0RA. We converted values from UK£ using an exchange rate of 1.5.
[6] European Commission, Directorate General XVII : « A Ten Years FuelCell Research, Development and Demonstration Strategy for Europe », Version 1995, pag 15.

7.4 - Ecology

As we have seen, hydrogen can be produced in many ways : emission-free via electrolysis from renewable energy, *e.g.* wind, PV or hydroelectric sources, although it is very energy-expensive. In such schemes PEMFC systems with renewable hydrogen engage a central hydrogen production-storage facility, developed with utilities and distributors. If Authorities are sensitive to the problem of peak-shaving, a possibility is the use of a central electrolyser, in an existing plant, to be operated in off-peak hours, or for frequency regulation in the electric grid.[7]

Although, today's most economic way to produce hydrogen is natural gas reforming at a central facility, the main emission is a fairly-pure CO_2, which can be used dirently in greenhouses or chemicals.

FC are contemporary with the invention of electricity : as D. Hart sharply puts it « Grove had discovered a way of producing electricity when not even Michael Faraday had found a use for it ! ». It is highly symbolic that electrochemistry was the *berceau* of early electricity works, whilst later progress led to thermomechanical systems, burning high Carbon-to-Hydrogen ratio fuels to generate rotary power to exite the Von Siemens dynamo. Are FC at the threshold of a revenge at the dawn of the 21st century ? Be it as it may, the issues of security of supply and emission concern strengthen this belief : even though resources depletion might not be *the* environmental problem in the energy domain, since it is unlikely that we will be able to burn existing fossil resources at present rates before the greenhouse effect becomes unsustainable, the likelihood of having a diversified oil production decreases while companies pump in deep off-shore oil fields and Gulf countries keep 70% of oil reserves on storage.

In 1996 oil price rose by around \$8/bbl, which represented an increase of ≈ 40%. It is estimatedthat if the US embargo against Lybia, Iran and Iraq is maintained, oil demand may edge the very near supply capacity, causing the price to hit \$40/bbl in 2005.[8]

The option of methanol for FCV has some toxic emissions problems, but they can be overcome by keeping the reaction temperature high enough to prevent aldehyde formation and it is compatible with biomass processing. The drawback is that traditional energy crops, as in Brasil, mainly produce ethanol, only reformable at much higher temperatures (700°C), and so useless in a methanol cycle. Their conversion will be eased by experience gained in alcohols. Methanol is easy to store and vaporize, its reforming process is simpler than any other liquid fuel (250°C), and it is renewable. These reasons, plus the recent agreement between Daimler-Benz and Ballard Power Systems to found a joint company for the production of buses, trucks and private vehicles, boosted the option of methanol-fuel for mobile FC system mass-production. In fact, although critics say that in the whole chain of methanol production 50% of available energy is lost going from methane to methanol to hydrogen, the complete methanol FC system will better fit in a car than any other fuel because of inherent simplicity (storage, processing) and car range can compete with conventional gasoline ICE whilst being (at worst) an ULEV [9].

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[7] Projects are led in Germany, as the 100kW MTU 30 bar electrolyser.
[8] M. G. Salameh : « Crude Oil Prices on an Upward Trend », International Association for Energy Economics Newsletter, Summer 1997.
[9] In the same direction the voluntary 25% CO_2 reduction proposed by German car manufacturers

FC industry recycles used membranes by liquefaction of Nafion, for subsequent mixing with the catalyst in « coating » the electrode. The platinum electrocatalyst is also recycled in used electrodes. These possibilities add profitability in mass manufacturing.

7.5 - Durability & Maintenability.

These fields are of major relevance for PEMFC technology today and very few data are available. DeNora has a small stack which has been running discontinuously for five years now ; it is meant to prove the validity of their design. Stationary FC should reach 40.000 hours lifetimes before stack replacement. The field-tested reference ONSI PC25 PAFC are proven successfully in the field of durability: 5 years. Mobile applications need operation lives of 5000 hours min.

The issue of maintenance and personnel training oughts to be fairly negotiated between FC suppliers, utilities and research institutes. It is believed that the durability limit for most applications will be set, not by the stack as such, but by the performance of CO abatement unit.

7.6 - Conclusions

Within a historical perspective, hydrogen certainly is one of the most fascinating elements : we dare to talk by now of a possible Hydrogen Economy.[10] Only uranium and carbon, as a single elements,[11] have given as much as hydrogen, and engaged science on fertile fields, in visions and applications. The FC had to make improvements over almost two centuries to answer new energy needs and pass the laboratory stage toward commercial takeoff. Saying this, it would be wrong to contemplate the unusually slow development of FC technology, forgetting the massive, vested interests of oil-based industry or mentioning oil price trends and safety aspects of gaseous fuels. Remarkable engagements are undertaken by major chemical groups (Dow, DuPont, Hoechst), car industry (Mercedes, BMW, Toyota, Chrysler, , Honda,GM) and energy industry (RuhrGas, ERC, GPU, British Gas) to develop FC systems, and the most ambitious goal is the private car.

Deregulation in the energy sector might have affected negatively FC technology penetration in the utility market. In the past electric utilities have pioneered new technologies, moderating the risks with the monopoly status, but by now the enhanced competition has rather eased lowest-cost providers, who rely on an assessed maintenance infrastructure. Therefore, it could be harder for energy suppliers to purchase hight-cost, market-entry units without subsidies. Although, the ecological and technical features of the Fuel Cell, associated with proven reliability, can match the marketing goals of efficiency-oriented municipal utilities, which act in a competitive market where an "ecological label" is constantly pursited as an essential element with respect to politicians and consumers.

[10] J.O'M. Bockris : « Energy. The Solar Hydrogen Alternative », The Architectural Press, London, 1975.
[11] We refer here to elements as seen from the Periodic Table, the aim being to underline the variety of properties (reduction, refining, fuel, lifting agent etc.) and the applications which follow from it.

Ultimately, the PEMFC generator will become economical if either :

- down-scaling of **refining equipment** (as ATR) make the FC system compatible with conventional fuels like natural gas and liquid fuels. The advantage is that no retreatement or end-of-pipe cleaning devices are needed. Or :

- novel (light, high-capacity) **hydride storage** creates the conditions for an hydrogen refuelling infrastructure based on traditional central reforming plants. Or :

- the FC system justifies a price premium compared to conventional motor generators either by appropriate credits for its efficiency, cleanliness and noiselessness, or because of its high-value **flexibility** in case multi-use FC system, as power generator in the house and as powertrain for a vehicle.

PEMFC systems should be investigated for both small (1-20 kW) and medium (100-500 kW) powerband.

7.6.1 - Renewables vs. Hydrogen ?

Since 1973, conscious of oil-dependance for electricity production and transport, the search for an alternative energy system has started. This effort has brought new technologies to the market, *e.g.* nuclear, PV, and led to improve old ones, as the wind generators. The technologies based on renewable sources have since become cheaper but do not yet provide an alternative energy system, be it for electricity demand peak shaving or transport.

The dispersed character of windmills and discontinuity of photovoltaic have restrained a resolute gensets market penetration, because of storage weaknesses. Concerning mobile applications little is feasible without a convenient fuel. Green municipalities finance battery-vehicles to reduce urban pollution, albeit pushing the emissions back to the power plant. The lower overall efficiency, when electricity is generated from fossil fuels should be reason for reflection. Range autonomy and time of recharge of battery vehicles will probably stop their suburban and rural use anyway.[12]

R&D on alternative energies has been focused on details of each renewable energy source without the necessary global assessment of the whole energy system: basically electric and fuel networks and their maintenance. From such a state of things FC, which need fuel and electric subsystems and have as principal advantages high efficiency and no emissions, have been neglected by institutions and medium entreprises. Subventions for re-buying energy produced from PV would have more sense with a clean energy carrier for storage - hydrogen - and an efficient conversion device : the fuel cell.

The transmission & distribution energy sector is typically a natural monopoly in every real case and if one follows economic theory. Decentralized hydrogen production and electricity generation via dispersed FC systems could reverse the situation.

In this sense was planned the most ambitious (unaccomplished) project of the European Community Fuel Cell Programme : the Dispersed Hydrogen Network, which should have

[12] An interesting experiment is led in Turin, where 20 electric Panda with a 50 km autonomy are rented for 5000 It.£/h.

carried centrally reformed hydrogen through a pipeline to the FC users for cogeneration and in refilling station for city buses.

It is my opinion that hydrogen production could be the distinctive feature of the national energy systems in the future. The We-Net program in Japan and current projects in Iceland [13] are the closest approach to the hydrogen economy concept.

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[13] See : « The Economist » August 16, 1997, where the government plans to convert fisherman's diesel boats (in Iceland there are more boats than cars !) to alkaline FC drive, with hydrogen produced in a former ammonia plant.

Industrial Contacts

Company	Activity	Contact
Ansaldo (CLC)	PAFC commercialisation	Tullio Bozzoni, Director
Ansaldo Ricerche	MCFC, PEMFC	Angelo Dufour, Vice Director
Arthur D. Little	Fuel processor, market development	J. M. Bentley, Director technology and product development
		Robert S. Weber, Catalysis
BMW	FC systems	Wolfang Strobl, Joachim Tachtler
Carbotech	Pressure Swing absorption	Klaus Giessler, Dep. Management
De Nora	PEMFC stacks	Michele Tettamanti, sales
		Antonio Maggiore PEMFC development
Haldor Topsoe	Steam reformers systems	Ernst Jansen, C. Lau Larsen
Johnson Matthey	Catalysis electrodes, noble metals	Robert Evans, Market development
		Thomas Purcell product manager
Siemens	PEMFC stacks	Johachim Grosse

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