## Chapter 6 - Fuel Cells Economics.

No other single technology has the widespread potential for major impacts across almost all energy generation and consumption sectors.[1]

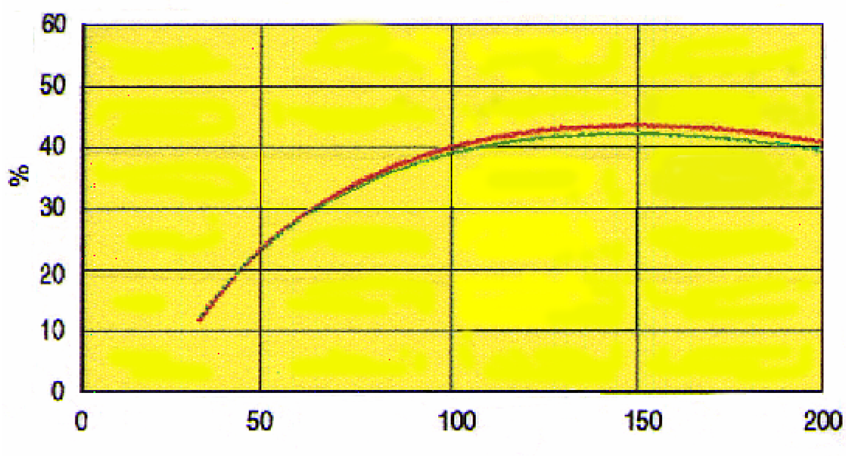
### 6.1 – FC Power Systems

Standard scheduling of a power system considers fossil, run-of-river and nuclear plants for base load because they are not efficient at part load, while dam-stored hydropower and gas turbine (GT) technologies are energy limited, meaning that they are more suited to supply high-cost peak demand. Power plants may be energy limited either because of limited total available energy, or because fuel and operation & maintenance (O&M) costs are important in the case of GT. The FC do not belong to either. If the dispatching of an electric system is marginal cost-based only, the FC will supply peak power (at the top of the load curve, above GT), during a few hours per year only. Instead, real environment operation of commercial FC, as the PC25C by ONSI operated, for instance, at *Services Industriels de Genève*, shows that the PAFC system is for base-load operation ; this is the logical consequence of the high investment costs (3000$/kW), but also the very low O&M (3% of the investment cost per year) and fuel costs, due to the absence of moving parts and the high electrical efficiency respectively.

It is expected that in Europe the use of natural gas for power generation will rise from 50MTOE to 100MTOE in 2005.[2] More methane will be available in Europe thanks to the investments under way which will ensure large supplies from Russia, Algeria and Nigeria.[3] Therefore, it is likely that gas availability will continue during the first half of the XXI century. Electricity prices are, of course, more interesting for peak supply and are increasingly being met by GT technology, because of the limited availability of economical hydrogeological sites. Meanwhile, persistance of nuclear and large fossil plants to supply base load power is uncertain, this is mainly due to increased environmental concerns.

In this context, the hypothesis of a FC-network system to provide peak load electricity may become realistic : the FC can match daily variations in demand because it is rapidly responsive from part to full load. In this strategy the fuel cells can generate peak power on demand, while being in continuous operation during the rest of the day because featuring a higher part load efficiency (see Graph 6.1). Further in the future, when autothermal reformers will be available, fast shut-down and start up will be possible for small, off-grid CHP units (5-100kW). Hospitals, heavy users of telecommunications and computer equipment are likely to find FC attractive, because they would otherwise have to invest in a back-up system with no benefit for the time the generator is standing by. The availability of small cogeneration FC sets will open up a new market, because even though engines are competitive on cost and may have good efficiency (diesel 43%, gas 38%) the environmental performance of the FC is a considerable advantage. FC avoid high rotating engines maintenance (up to 3 ct./kWh) and decentralized heat production can be the driving force, enhanced by legislation.

[1] B.M. Barnett, W.P. Teagan, A.D.Little Inc.
[2] P.G. Claus : « L'avenir du secteur gazier en Europe », Secr.Gen EUROGAS. Présentation à la Conférence ASIG, 22 mai 1997, Lausanne.
[3] A relevant exemple is the Jamal Project led by Gasprom and BASF, which will have a capacity supply of $14*10^9$ $m^3/y$.




KW

Graph 6.1 - Efficiency vs. Load of PAFC (source D.L. Nguyen, SIG)

### 6.2 - Economies of scale & Learning Courve

The *two thirds rule* of economies of scale is geometry : if one needs to double the volume of gas treated in a reactor, material expense (metal surface) is two-thirds higher (larger). The relation can be written as :

$$\mathbf{C = kxP^{\alpha-1}}$$

C : unit cost (\$/kW, \$/m$^3$ ),
P : capacity (kW, m$^3$),
k : technical constant,
$\alpha$ : scale exponent ($0<\alpha<1$).

This formula is applicable to the fuel processor, in particular for standard methane steam reformers and PSA purifiers, which, as seen in Ch.5, need respectively large surface heat exchangers and molecular sieve tanks.

Compared to the SR/PSA - or SR/membrane - scheme, the ATR/PROX processor scale effect is probably reduced - the $\alpha$ factor is closer to one - and the technical constant might also be lower. In ATR/PROX FC system direct reactions occur on the catalyst surfaces (fuel and CO oxidation by just air and water stoichiometries), rather than through exchange of heat, thus widening flows boundaries for a given size.

Learning curves can be expressed as in the Graph 6.2 below, for PAFC, with the cost per kW as a function of cumulative production in MW. The learning process may vary largely for companies producing similar goods. It has been suggested for the PAFC industry [4] that a 85% cost reduction (per kW) will results for each doubling of cumulative production till commercialisation phase. Estimations for PEMFC do not exist yet, but it is expected to be higher because lower temperature and flexibility of size should allow a faster standardisation.

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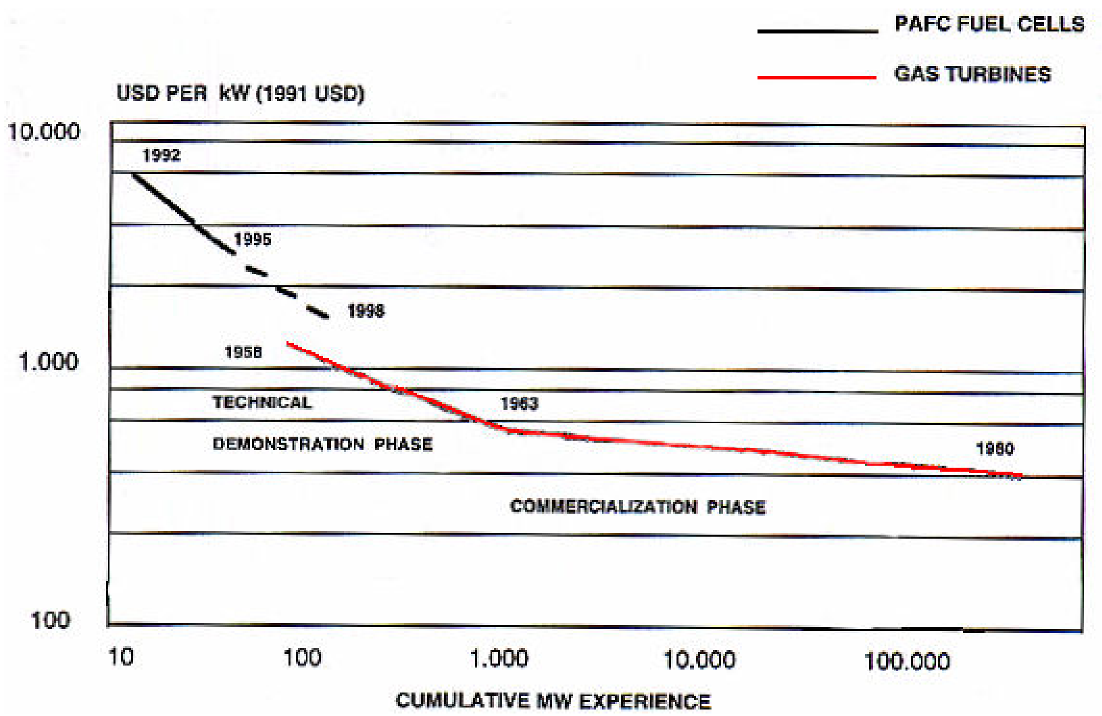
[4] D. Hart : « An Analysis of Fuel Cels and Gas Turbines in Small-Scale Distributed Power Generation », pag.45. Master Thesis, Imperial College of Science, Technology and Medicine, September 1995.

Learning curves are expressed by the power function :

$$y = ax^{-b}$$

where : y : number of direct labour hours to produce the $x^{th}$ unit
a : number of labour hours to produce the first unit
x : cumulative units produced
b : measure of labour hour reduction rate for cumulative production increase.




Graph. 6.2 - Learning curve of PAFC (source : T. Bozzoni, CLC Ansaldo)

The PEMFC stack costs should decrease to 500 $/kW in the next five years and special effort is devoted for it by the European Community programme.

### 6.3 - Markets

Main tools for market analysis are provided by studies on I) stationary and II) mobile FC systems :

I - Scenarios for *vehicle introduction*[5] : the main disadvantages reported for this application are the low investment cost targets (100$/kW), the fuel (stations implementation, fuel processor spares) and FC (spares) infrastructure and general maintenance (garages etc). The major advantages are the great economies of scale resulting from the vehicle market, which is strategic for individual mobility.

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[5] An exaustive overview is found in : Gene D. Barry « Hydrogen infrastructure for vehicles » Lawrence Livermore National Laboratory, October 1996.

II - Scenarios for *power generation systems* [6] : the reported disadvantages are the overall high efficiency & reliability targets required. PAFC are the reference and have 0.5% efficiency decrease per year ; availability is 90-95%. Moreover, because of the high capital cost FC investments are very sensitive to interest rate. Advantages : existance of niche markets, where either cheap fuel or high emissions value, justify the high investment cost. Dimension targets and fuel infrastructure requirements are relaxed. FC are by far the best technological prospect for small cogeneration in term of efficiency and low pollution.

### *6.3.1 - Sizes & Types*

FC are not expected to take more than one percent of the **large scale** ( >30 MW) power generation market, which corresponds to 1.3 GW, in the year 2020.[7] This market will be composed of :

- integrated power systems, where a gas turbine remains the main generating component and a high temperature FC forms a topping cycle,

- large-scale industrial processes, where hydrogen is available as a by-product ( chlor-alkali).

The high temperature MCFC and SOFC will take the big share, while PAFC will be following, disadvantaged by the low thermal performance (200°C). The market is rather small because the high temperature FC technology needs proof by field-testing for stack materials and BOP.

The booming **medium size market** ( 1-30 MW ) raises essential interest of FC industry. Distributed Power Generation (DPG) represents the growing need for small plants located near load centers. Gas turbines are the technology to beat because, despite the low cost, in the few MW power ranges they loose some of their efficiency ; FC's silent and clean operation will be appreciated in populated areas. Therefore, economical and environmental criteria will determine the choice, case by case. This market is expected to go from present 15 GW to 55 GW in 2020 ; FC could take 10 GW of it. Either MCFC or SOFC technology will be leader.

In the **10 kW - 1 MW powerband** FC have a strong competitor : diesel engines can attain 43% (38% with gas) electrical efficiency with a flat behaviour from 40 to 80%.[8] Turbines have low (25%) efficiency, but can now lower $NO_X$ to 15 ppm.[9] Thus, FC need to lower their cost and take advantage of air and noise pollution high value since the user is near. The estimations by EscoVale of this market, including standby, cogeneration and site supplies, might rise to 45 GW from the actual 20 GW. FC will take around 7 GW. The most promising application is for cogeneration installations, where cost goal is to go lower than 2000 $/kW. SOFC are expected to be the leading contender followed by PAFC, PEMFC and MCFC. We believe that the share of the power generating market for PEMFC will ultimately be determined by the reliability and cost of the fuel processing and clean up system. The stack

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[6] D. Hart : « An Analysis of Fuel Cells and Gas Turbines in Small-Scale Distributed Power Generation », pag.45. Master Thesis, Imperial College of Science, Technology and Medicine, September 1995.
[7] The market penetration estimates are provided by the three-year study from EscoVale : « Fuel Cells : Applications and opportunities ». Three-volume management report, UK£2,800. Source : Electrical Review Vol 229 No 18.
[8] Source LENI.
[9] E. Benvenuti : « Combined cycles with Advanced Technology GT and their contribution to lowering $CO_2$ Emissions to the Atmosphere ». Data Nuovo Pignone, August 1997.

will need to operate at high voltage, while size and density relaxation - compared to mobile application - will be an advantage.

The market **below 10 kW** is satisfied by small motor generators and rechargeable-battery sets ; the PEMFC and SOFC are the main contenders in the FC family. Interest comes from the military and aerospace industry ; considering that more than a million small diesel and petrol gensets are sold each year, it is more than a 1000MW market. Uncertainties concern what part of power-only and what CHP will be demanded. By 2020 CHP sales might reach 100.000 units for a combined capacity of 400MW, while electricity generators (1-10kW) will be around 100MW. Strong demand for electricity-only FC may come from the army to replace battery-powered military kit (30-300W), such as night vision systems and communication devices, but the civil customer may emerge from the growing need for reliable power in high value applications : portable computers, home smart metering and communication equipment. 2020 sales estimates for battery replacement vary largely : from 250 to 800 MW.

**Vehicles** demand represent a possible market of 57 GW by 2020, composed for 42GW of FCV and 15GW of commercial vehicles such as vans, buses, trucks and fork-lift trucks. The commercial vehicles are favoured in early commercialisation because they are intensely used, have central refuelling stations and government might take an active role to enhance their introduction (perceived environmental benefit). Other studies[10] foresee 800 units for commercial vehicles by 2010-2015, while FC cars are mass-produced by 2018-2019. The vehicle market will entirely be taken by PEMFC, some applications, as vans and boats, might also present chances for alkaline technology.

### 6.4 - Top Down Approach for Electricity Cost

The investment for a FC system is evaluated for two stationary hydrogen production schemes[11] :

A - Hydrogen produced in a neighborhood-scale MSR (100kW min.) with a PSA unit. Electricity is delivered through existing lines to the customers. The utility is the FC owner.

B - A modular 50kW ATR/PROX fuel processor producing hydrogen for a private user from gas or liquid hydrocarbon.

Hydrogen might also be produced in a large-scale reforming plant, to be delivered in high pressure tanks, but this in not a realistic system in our case. The interest rate is 7%, availability is 7500h/y (85.6%) for the MSR and 5000h/y (57%) for the ATR. We compare below capital, operating and variable costs for the two FC systems.

[10] Robert J.D. Evans, Market Development Manager, Fuel Cells: « The Solid Polymer FC ; Market Prospects & the Challenge for Commecialisation ». Johnson Matthey Plc.

[11] In this case we consider the ADLittle ATR reformer, developped for FCV, as a stationary power plant. This assumption, although objectable, can be justified by the fact that the still-high economic estimates for a drivetrain (400$/kW + stack) compensate the normally higher cost of a stationary FC system.

| | 200kW | 50kW |
|---|---|---|
| **MSR** | 1000$/kW$_{el}$ | |
| **Stack ( present price)** | 3000$/kW$_{el}$ | 3000$/kW |
| **PSA**[1] | 800$/kW$_{el}$ | |
| **ATR**[2] | | 130$/kW |
| **PROX**[3] | | 20$/kW |
| **BOP**[4] | 250$/kW$_{el}$ | 250$/kW |
| **Amortization (years)** | 10 | 10 |
| **Capital cost** | **5050$/kW** | **3400$/kW** |

Table 6.1 - Capital cost assumptions.

1) PSA units above 100kW$_{el}$ are assumed to have linear costs.
2) ATR production conditions of 100 units per year
3) Costs are approx. 100$ for the catalyst only in a 50kW PROX (source A.D. Little).
4) BOP is assumed to be the same, since state-of-the art equipment is used.

The results of the **electricity cost** below are derived from the following assumptions :

- Insurance cost is 0.3% of investment cost,
- Maintenance cost is 2.5% of investment cost,
- Operation cost (personnel) represents two people at 50% (≈ 75.000 sFr.) for MSR and one operator at 30% for ATR technology (22.500sFr.), which has comparatively a lower reliability.

| | | *200kW MSR* | *50kW ATR* |
|---|---|---|---|
| ***Capital cost*** | Annuity | 236910 | 45'633 |
| | Annuity/kW | 1184.55 | 912.66 |
| | Hours/y | 8322 | 7'884 |
| | Tot | 0.14234 | 0.11576 |
| ***Operating costs*** | Insurance | 0.00268565 | 0.00218 |
| | Personnel | 0.04506128 | 0.05708 |
| | Maintenance | 0.09449518 | 0.01820 |
| | Tot | 0.142242 | 0.07746 |
| ***Fuel costs*** | Gas 0.4eff. | 0.07500 | 0.07500 |
| ***COE SFrs./kWh)*** | | 0.35958 | 0.26822 |

Table 6.2 - Cost of Electricity for 50 and 200 kW systems.

### 6.5 - Financial Boost : The Dutch Exemple[12]

The Dutch Government has edicted several measures to support energy conservation and reduce greenhouse emissions by putting ecological energy investments under a low VAT regime (6%). An innovative taxation measure now experienced in the Netherlands, aims at speeding environmental investments by allowing an arbitrary amortization : the « VAMIL depreciation », introduced in 1996 by the Ministry of Housing, Spatial Planning and Environment.

[12] See : P.H. van Dijkum : « Specific Taxation Measures include Fuel Cells », European Fuel Cell News, Merch 1997.

An even more recent tax initiative of the Ministry of Economic Affairs is the « Energy-investment deduction ». This measure, which includes FC CHP systems and FC electrical drive systems for powers < $1000kW_{el}$ , enhances the VAMIL depreciation by setting energy-investment deduction rates spanning from 52 to 40% of the investment. FC projects can save on tax payments by fast amortization and strong deductions.

## 6.6 - Legislative Enhancement

The energy markets are changing a lot : the principles of efficiency and competition are entering in a traditionally state-owned monopoly by mean of international legislation and long term concerns. If it was economical to achieve economies of scale by GW-size plants in the past, today utilities find it more economical to build decentralized, user-sited plants that will release the energy suppliers from building new central plants and upgrading - or expanding - the grid.

### *6.6.1 - Unbundling*

The principle of Unbundling is likely to advantage small-scale, efficient power generation, because lower investment costs, construction delays and high reliability - *i.e.* low maintenance and operation costs - will favour a packaged product, which can be commercialised by small, highly-specialized companies. The product supplier is licensee of the basic components, *i.e.* reformer, stack, and can mandate for spare parts replacement. Since production, transmission and distribution take place simultaneously there is no need for separate, and heavy accounting, as data transmission via modem is sufficient.

### *6.6.2 - Third Party Access (TPA)*

The principle of TPA is one of the major drivers in the energy policy of the European Union : it simply means that access to the network is possible to the independent producer. In the Electricity sector the discussions on tariffs and frequency regulation responsability are animating the implementation of the TPA. The liberalised market begins on January 1st 1999. TPA is a major advantage for FC commercialisation.

## 6.7 - FC Commercialisation - Swiss case

Main criteria for FC system development are :

- WHAT is needed for the BOP, e.g. Components, Mass production feasibility
- HOW operation is possible, e.g. O&M, Back-up system.
- WHERE are the weaknesses in the fuel processing, *e.g.* CO removal, integration.

In order to clarify what are the possible **behaviours** of the parties involved in FC system research, it is interesting to specify the more or less vested interests and strategies of potential FC actors. The table below, valid for the Swiss case, where neither a car manufacturer, nor an oil company are present is not applicable elsewhere, but it may be valid for more than the present case.

| Actor | Goals | Strategy |
|---|---|---|
| **FC producer** | Test, Pilot plant, strategic licensing, vehicles | Integration of technology, patent protection, mass production techno-economics |
| **Research Institute** | Presence in new technologies, data, costs, fundings, tests, patents | System integration Applied research, Technology diffusion, Diffusion of learning, appraisal studies, |
| **IPP** | Market segment identification, product evolution, Customers requirements | Interface between developers and applications, In-depht knowledge of local environment. |
| **Utility** | Emissions reduction, networks regulation, supply security | Demand side management, price flexibility, pilot projects |

Table 6.3 - FC Research Goals and Strategies

None of these agents alone can develop a complete FC system with hydrocarbons or alcohols fuel processing. We believe that even in the absence of a power plant builder, *e.g.* ABB (CH), Ansaldo (I), Siemens (D), it is likely that the need of system integration will be the driving force to establish a co-operation. The technical bottlenecks in the conclusions of Ch. 5, *i.e.* CO clean-up system and system integration, can be worked out by a collaboration electrochemists, thermodynamicists and electricians.

The Table 6.4 below summarizes the interrelated **research priorities**, associated with their applications.

| # | Activity | Che. | Mech. | Ele. | IPP | Utilit | Application |
|---|---|---|---|---|---|---|---|
| 1 | On-$H_2$ stack operation | | ● | | | ● | operational data for ALL other #, $H_2$ boat |
| 2 | ATR catalysis, | ● | | | | | FCV, CHP station |
| 3 | CO-removal : PROX,PSA | ● | ● | | ● | | CHP station, FCV if dynamic |
| 4 | DC-DC Regulator, inverter, ECM | | | ● | | | higher efficiency |
| 5 | Power recovery, heat exchangers, thermal integration | | ● | | ● | ● | FCV, CHP station design |
| 6 | Sensors, meters, pumps | ● | ● | | ● | | PROX design |
| 7 | Spares production | | | | ● | | lower cost |

Table 6.4 - Research activities and applications in Switzerland

The following research shedule might be suggested :

| Step | Power (kW) | Mission | Means |
|---|---|---|---|
| 1 | 10 | Stack lifetime Gas reforming | Extreme operation, Technology Assessment |
| 2 | 10 | Stack optimisation RAM of $H_2$ system | Storage implem. Spares production |
| 3 | 10-200 | Overall system optimisation | Industrial synergies Simul. tests results |
| 4 | 10-100-200 | Commercialisation Tests | Marketing, Political engagement |

Table 6.5 - 4-Steps Development Schedule

## 6.8 - Remarks

- The PEMFC technology is entering both the power generation and the transportation sector but the specific features of these two markets - *e.g.* lifetime, infrastructure and cost - do not necessarily allow technology improvements in one to benefit the other.

- The hydrogen production development activity, needed for fuelling the FC, can be more attractive if FC are used for power generation and traction at the same time. Later, an increased share of electricity generated from renewable energy can find application in hydrogen generation.

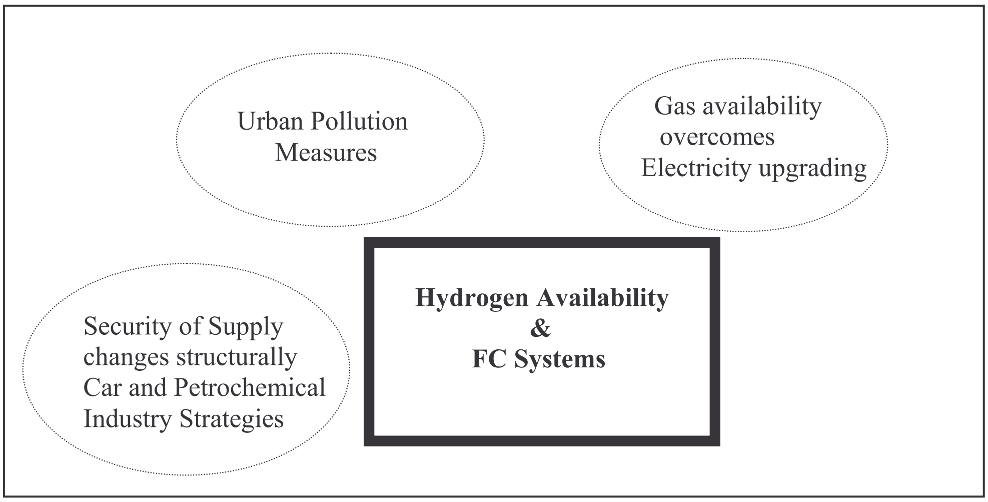


Figure 6.1 - Relevant MacroEconomic Factors for Fuel Cell System Introduction

Utilities and Industries have interest in parallel development of both power and vehicle market since, as it is clearly explained by G. D. Barry :

« The *chicken & egg* dilemma facing vehicle manufacturers and fuel suppliers can be resolved through production of small-scale hydrogen generation and storage equipment, manufactured at rates in coordination with hydrogen vehicle production rates. On-site fuel production can guarantee fuel availability for fleets and perhaps homes ».[13]

We conclude that :

I - Infrastructure for vehicles leads to strong standardisation and rapid economies of scale because integrated mass production conditions create synergies between an alternative fuel and the current energy and industrial infrastructure.

II - Dispersed small-scale reformers, peak-shaving electrolysers and storage equipment for stationary FC systems increase gas demand and optimize electricity production, enabling FCV mass production through hydrogen refuelling station.

[13] Gene D. Barry : « Hydrogen as a Transportation Fuel : Costs and Benefits », Lawrence Livermore National Laboratory, March 1996 page 6.