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Fuel Cells: A Solution to Climate Change?

Environmental Fellowship report for the German Marshall Fund written by Giulio Volpi, WWF Climate Policy Officer

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EXECUTIVE SUMMARY

In the last few years, both public media and policy makers have been increasingly interested in fuel cells, as a technological option or even "the" solution to the significant environmental impacts of the transport sector. This technology is said to have the potential to reduce local air emissions, greenhouse gases (GHGs) emissions and the oil dependency of our economies, while offering the same performances of the conventional vehicle. The automotive and fuel cell industry has even announced fuel cells vehicles to be available on the market by 2003-2004.

At the Climate Change Campaign of the World Wide Fund for Nature (WWF), we are interested in identifying and supporting innovative technologies that can address the growing climate impacts of energy and transports. In particular, the latter represents one of the greatest challenges for climate protection across the Atlantic. In Europe, transport is the fastest growing source of CO2 emissions. Even with the European car industry commitment of a 25% improvement in fleet's average fuel economy, CO2 emissions from passenger cars are expected to be between 20-30% above 1990 levels, by 2010.

In the United States, the challenge is even greater. Transportation energy demand and carbon dioxide emissions are projected to grow at an average annual rate of 1.8 % between 1999- 2020. Ultimately, along with demand-management measures, the deployment of groundbreaking technologies will be crucial to achieve the needed cuts in CO2 emissions.

In this context, the primary aim of my 2000 Environmental Fellowship of the German Marshall Fund was to assess the potential of FC technology to contribute to climate protection. During the summer 2000, I travelled across the United States to meet all major representatives of the US fuel cell community, ranging from the fuel cells manufactures to the fuel providers, from car manufactures to policy makers. I have also reviewed a number of American and European studies on fuel cells.

The questions that have guided my research include: What is the current development of fuel cells technology? What are the climate benefits of FC vehicles compared to alternative technologies? When will FC vehicles enter the market? And, what is the role of public policies to support the deployment of climate friendly FC technology? The answers are discussed in details in the report, but the conclusions and recommendation can be summarised as follows:

- **Technology status**. Fuel cells vehicles can be powered directly by hydrogen or methanol stored on the vehicle, and indirectly by using a fuel processor to extract hydrogen from onboard liquid fuels such as methanol, ethanol, and gasoline. Depending on the fuel choice, the technological development of fuel cells changes significantly. The direct hydrogen FC is clearly the most developed technology to date. Reformed-based fuel cells still pose difficult problems and seem to be in a later stage of development. Direct methanol FC is even more far behind. If FC vehicles are to enter the market in a relatively near future (10 years), this is likely to happen with direct hydrogen fuel cells.

- **Climate benefits**. The climate benefits of fuel cells depend on the choice of fuel. Only direct hydrogen FC vehicles would cut GHG emissions significantly below the current internal combustion engines (ICE) -between 40 and 70%. Although alternative technologies (eg. hybrids and natural gas vehicles) can generate similar climate benefits, hydrogen FCs remain the best option to reduce also local air pollution and oil dependency.

  Nevertheless, FC vehicles are expected to enter the market only by 2015 (5% of the US car fleet). Even in this optimistic scenario, measurable reductions of GHG emissions due to FC vehicles will not happen before 2020. Until then, other technologies will be needed to address the growing CO2 emission from transports, including lightweight fuel efficient ICE, natural gas and hybrid vehicles.

- **FC vehicle costs**. Currently, the cost of FC systems for vehicles is estimated to be much higher than the ICE. Mass production would bring cost down significantly, making fuel cells vehicle cost-competitive with ICE vehicles, but this is not likely to happen before 2015. Because of initial high unit costs, fuel cells will be first used in captive fleets and public transports. To speed up the entering into the market of fuel cell private cars, it is suggested that these need to be - at least in part - marketed as products for car sharing rather than ownership.

- **The role of public policies**. Government funding plays a key in addressing the technological barriers to the use of FC vehicles. Support for fuel cell R&D in the US averages 120 Mil Euro per year, which about the double spent in the European Union. Public funding should be focused to support early commercialisation of the most environmentally favourable FC technology, that is the direct-hydrogen FC.

  Barriers to its deployment that need to be overcome urgently include the on-board storage of hydrogen and the fuel infrastructure. Nevertheless, there is also a need to ensure funding for alternative transport technologies based on low-carbon fuels.

1. INTRODUCTION

In the last few years, both public media and policy makers have been increasingly interested in fuel cells, as a technological option or even "the" solution to the significant environmental impacts of the transport sector. This technology is said to have the potential to reduce local air emissions, greenhouse gases (GHGs) emissions and the oil dependency of our economies, while offering the same performances of the conventional vehicle. The automotive and fuel cell industry has announced fuel cells vehicles on the market by 2003-2004.

At the Climate Change Campaign of the World Wide Fund for Nature (WWF), we are interested in identifying and supporting innovative technologies that can address the growing climate impacts of the energy and transport sectors. In fact, the latter represents one of the greatest challenges for climate protection across the Atlantic. In the EU, transport is the fastest growing source of CO2 emissions. Even with the industry commitment of a 25% improvement in fleet's average fuel economy, CO2 emissions from passenger cars are expected to be between 20-30% above 1990 levels, by 2010. In the US, the challenge is even greater. Transportation energy demand and carbon dioxide emissions are projected to grow at an average annual rate of 1.8 % between 1999- 2020. Ultimately, along with demand-management measures, the deployment of groundbreaking technologies will be crucial to achieve the needed cuts in CO2 emissions.

In this context, the primary aim of my 2000 Environmental Fellowship of the German Marshall Fund was to assess the potential of FC technology to contribute to climate protection. During the summer 2000, I travelled across the United States to meet all major representatives of the US fuel cell community, ranging from the fuel cells manufactures to the fuel providers, from car manufactures to policy makers. I have also reviewed a number of American and European studies on fuel cells. The question surrounding fuel cells seemed to have shifted from “can fuel cells work?” to should they and how will they be done?”. The following report is structured on the basis of the research questions which are summarised in Box 1.

Box 1. Questions addressed during the fellowship

- What is the current development of fuel cells technology?
- What are the climate benefits of FC vehicles compared to alternative technologies?
- What are the costs of FC vehicles and of their fuels?
- What can public policies do to support the deployment of climate friendly fuel cells vehicles?

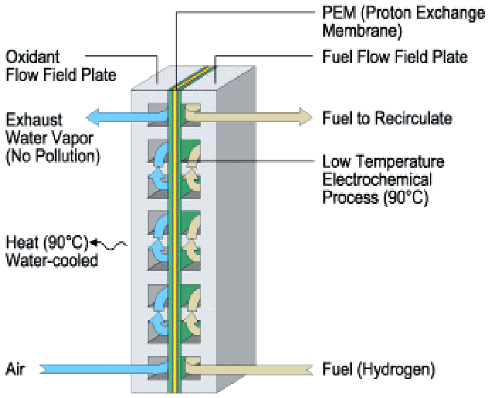
2. Fuel Cells Technology

Fuel cells operate somewhat like a battery, in that they convert chemical energy directly into electrical energy. In a battery, however, the fuel is stored inside the battery itself, when the fuel no longer reacts inside the battery to produce power the battery must be recharged. In a fuel cells instead the fuel is stored in a separate storage container and delivered to the fuel cell when needed.

Box 2. How does it work?

A fuel cell consists of an anode, a cathode, and a electrolyte. In a typical fuel cell, hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric engine.

Figure 1. Proton Exchange Membrane Fuel Cell (www.ballard.com)



A fuel cell consists of an anode, a cathode, and a electrolyte. In a typical fuel cell, hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric engine.

There are five types of types of fuel cells technology, depending on the electrolyte used: phosphoric acid, solid polymer, molten carbonate, solid oxide and alkaline. Table 1 provides an overview of the basic characteristics of all five families of FC.

The leading fuel cell technology at the moment is generally considered to be the solid polymer, also known as Proton Exchange Membrane (PEM) cell. The PEM cell is the focus of the car industry because of its low temperature operation, high output rates, and its potential for low-cost mass production. It must be noted that what is commonly know as a FC engine is a sophisticated system, including the fuel cell stack plus a number of system components. The higher is the number of the components, the more complicated the design and the performance of the FC vehicle becomes.

Table 1. Comparison of five fuel cell technologies

<table>
<tr><th>Fuel cell</th><th>Electrolyte</th><th>Operating temperature °C</th><th>Applications</th><th>+ Advantage – Disadvantage</th></tr>
<tr><td>Polymer Electrolyte Membrane (PEM)</td><td>Solid organic polymer</td><td>80</td><td>Power generation portable power, transportation</td><td>+ Potential low cost, quick start-up, low temperature
- Costly catalyst, sensitivity to CO2</td></tr>
<tr><td>Alkaline (AFC)</td><td>Potassium hydroxide solution</td><td>100</td><td>Military space</td><td>+ High performance, low-cost catalyst
- High sensitivity to CO2</td></tr>
<tr><td>Phosphoric Acid (PAFC)</td><td>Liquid phosphoric acid</td><td>200</td><td>Power generation</td><td>+ Tolerance to input impurities
- Catalyst cost, low power density, slow start-up</td></tr>
<tr><td>Molten Carbonate (MCFC)</td><td>Liquid solution of sodium or potassium carbonate</td><td>600+</td><td>Power generation</td><td rowspan="2">+ High efficiency, low catalyst cost, in-cell reforming of natural gas
- Corrosion durability, slow start-up</td></tr>
<tr><td>Solid Oxide (SOFC)</td><td>Solid zirconium oxide</td><td>800+</td><td>Power generation</td></tr>
</table>

Source: Adapted from Thomas 1999

Fuel cells can be both used for transportation applications and power generation (including portable power). Table 2 reviews the different requirements for these two uses. As performance standards are lower for power generation, it is expected that FC could enter this market in a relatively short time. As said earlier, give the limited time and resources, my fellowship focused on the transportation sector.

Table 2. Comparison of attributes between transport and stationary fuel cells

Transportation requirements	*Stationary requirements*
• Short life (2,500-3,000 hours total, discrete)	• Long life (>40,000 hours, continuos)
• Quick start-up (a few seconds, preferably less)	• High efficiency (50-60% LHV)
• Fast dynamic response (for acceleration)	• High-grade waste heat (>500°C)
• High power density (to be small and light)	• Resistance to fuel impurities (hydrocarbons, others)
• Little waste heat (otherwise leads to complex system management)	• Ability to operate on various fuels (natural gas, biogas, coal and gas, etc.)

Source: Hart 1999

3. Fuel Choice Options

The fundamental obstacle to FC vehicles commercialisation regards the choice of fuel. FC vehicles can be powered directly by hydrogen stored on the vehicle or methanol, and indirectly by using a fuel processor to extract hydrogen from onboard liquid fuels such as methanol, ethanol, and gasoline. Depending on the choice, the technological barriers to the commercialisation of FC vehicles change significantly.

a. Direct hydrogen fuel cells

The only proven FC type for vehicles is the direct hydrogen PEM cell. In the last 15 years, there have been significant advances that most experts agree that PEM fuel cells do not present fundamental technical barriers to attaining the high performances needed for cars. In particular, PEM power density level appear good, start-up at freezing temperature has been developed, and platinum catalyst costs have dropped. However, the PEM durability remains a critical issue as it has not yet been reported. Furthermore, much more room exists for further development to bring the costs down.

The use of direct hydrogen FC reduces the complexity of FC vehicles. In fact, it eliminates the need to develop a onboard fuel processor (which is needed to convert other fuels into pure hydrogen, see below). However, it faces two major issues. First, the tank used to store hydrogen on board the vehicle has to be lightweight and compact. A number of studies argue that existing compressed gas storage technology is adequate for extensive use of hydrogen FC vehicles (Ogden 1999). Most experts agree that no new breakthroughs seem to be required, though significant R&D is needed to bring down costs. Box 2 presents the different on-board technologies. Second, it requires some development of a hydrogen distribution network. This issue will be discussed in details later in section 6.

Box 2. On board hydrogen storage technologies

- **Compressed hydrogen (CI)** offers the simplest and least expensive method for on-board storage. The refilling time of compressed hydrogen tanks is similar to gasoline tanks. Its storage uses similar technology used for compressed natural gas, though it requires more volume for the same energy equivalent amount of natural gas. Increased hydrogen pressure requires, however, more expensive storage containers, increasing compression costs and safety issues.
- **Liquefied hydrogen (LI)** does not have the high storage weight penalty seen with compressed hydrogen, but still is bulkier than gasoline storage. LI uses similar technologies utilised with liquid natural gas. The challenge is that a large amount of energy is needed for liquefying hydrogen, and to avoid the boiling off of the fuel (0.5% per day).
- **Metal hydrides (MI)** are used to attract and store the hydrogen. Since heat is needed to release the hydrogen, safety issues of CI and LI are avoided. The metals compounds are, however, very heavy resulting in only 1.0 to 1.5% hydrogen by weight. Less heavy MI option are currently being developed.
- **Carbon nanotubes (CN)** are microscopic carbon tube -synthesised in the laboratory- which absorb hydrogen. CN can significantly increase the density of hydrogen storage. Though there is not no commercial application to date, they represent a promising storage option.

Source: Thomas 2000

b. Reformer based fuel cells

Given the storage and infrastructure barriers confronting hydrogen, FC developers are also investing the use of more conventional fuels (gasoline and methanol or ethanol) through a fuel processor on-board the vehicle. The latter would convert the liquid fuel into hydrogen-rich gas to feed the fuel cell, producing CO2 and small amounts of some other pollutants (CO, HC). The oil industry clearly supports this approach, because it would continue the use of oil for transports. However, the presence of a on-board reformer has its important limitations: it greatly complicates the design, raises the costs, and lowers the efficiency of the resulting fuel cell system.

No fully workable prototype fuel processor either for methanol or gasoline have been developed to date (DeChicco 2000). Experts consider the methanol processor to be further developed than gasoline processors, with a number of prototypes vehicles released. For example, Daimler-Benz' NECAR 3 utilises a methanol processor with a PEM fuel cell. Gasoline processors have been demonstrated in the laboratories but no vehicle has been built to date.

c. Direct methanol fuel cells

The only fuel cell capable of running directly on a fuel other than hydrogen is the direct methanol fuel cells (DMFC). There is an increasing commercial interest on this technology because carmakers tend to view a liquid fuel as essential for initial application of FC vehicles. However, this fuel cell technology appears to be still at a more early stage of development compared to hydrogen FC (at least 10-15 years behind). Laboratory work is still needed to address fundamental limitations. Furthermore, like hydrogen direct FC, methanol fuel cells also face the refuelling infrastructure barrier.

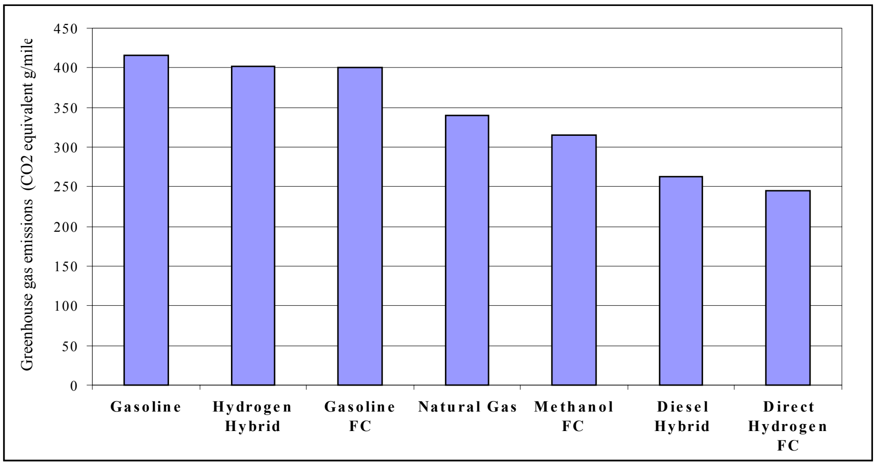
In conclusion, the direct hydrogen PEMFC is clearly the most developed technology to date. In fact, the first FC vehicle on sale is Daimler Chrysler's direct hydrogen fuel cell bus, with compressed hydrogen on roof. On the other hand, reformed based fuel cells still pose difficult problems and seem to be in a later stage of development. Direct methanol FC is even more far behind. If FC vehicle are to enter the market in a relatively near future, this is likely to happen with direct hydrogen fuel cells.

4. Climate benefits

The interest in developing fuel cells lays in their claimed environmental and particularly climate benefits. When assessing the greenhouse gas emissions of a fuel cell vehicle, all emissions must be considered, including those from extracting, transporting, refining, dispensing the fuel, and any emissions from the vehicle itself. A number of analyses have been carried out, both in the US (Thomas et al 2000, Pembina 2000) and in the EU (Bauen et al. 1999, Azar et al. 2000), comparing the main fuel option: direct hydrogen (produced by steam reforming of natural gas), and on-board reforming of methanol and gasoline. Broadly, similar results have been reached.

Among these analyses, I choose to present the results of Thomas et al. 2000, which have carried out a detailed study for the Ford Motor Company and the US Department of Energy. Figure 1 summarises the key estimates for GHG emissions for the same vehicle options. Direct hydrogen FC results in a significant GHG emission reduction: between 40 and 70% below the current gasoline ICE. Methanol follows with 23%. As stated earlier, also in the case of GHG emissions, gasoline fuel cells bring little or no improvement (7%) compared to a conventional gasoline car. Clearly the best option to reduce GHG emissions result to be the direct hydrogen FC vehicles. Nevertheless, when this is compared to existing alternative technologies, the picture is less clear, as hybrids and natural gas vehicles are projected to generate similar climate benefits than the hydrogen FC car, with even equal or lower incremental vehicle costs. When air quality and oil import reduction are added to the picture, however, the hydrogen direct FC vehicle becomes again the preferred option over either gasoline FCVs, gas or diesel hybrid vehicles.

Figure 1. Expected GHG Emissions Performance of PEM Fuel Cell Vehicle



Source: Thomas et al 1998, figure p.12. Diesel hybrid is load-following series hybrid, Thomas 1999, p. 3 Hydrogen is considered produced from steam reforming of natural gas. Study comparisons are based on a Ford AIV (aluminium intensive vehicle) Sable as the glider for al vehicles.

The GHG emissions of Figure 1 assume that the hydrogen is generated by steam reforming of natural gas. Of course, the long-term objective is to use renewably generated electricity from PV or wind to produce hydrogen (through the process known as electrolysis of water). However, only in a scenario in which eventually renewables will supply a large fraction of the electricity demand, then electrolytic hydrogen in a FC vehicle would provide a net reduction in greenhouse emissions compared to a gasoline conventional car. However, until that time, it is more effective in terms of GHG emission reductions to displace the existing fossil fuel electricity than using the same power to make hydrogen for FC vehicle use.

5. Current and expected cost of Fuel Cells vehicles

In addition to the technology challenges mentioned section 3, the cost remains the biggest obstacle to the commercialisation of fuel cells vehicles. Currently, the cost of FC systems for vehicles is estimated much higher than that needed to be competitive with the internal combustion engine. Power from stationary FC (the only commercialised to date) costs between 2500-3000 USD/kW. This will need to fell by a factor of 50 to be competitive with today's conventional engines (USD 50/kW). Several factors affect the price of fuel cells vehicles. First, most fuel cells are currently built using expensive materials, especially precious metal catalyst such as platinum used in the PEM fuel cells. Progress reported in the past 10 years shows that significant cost reduction can be achieved in the use of platinum. For instance, platinum loading has dropped from 16 g per kW in 1986 to the current 0.4 g per kW (Azar 2000).

Second, currently fuel cells are constructed in limited quantities thereby not achieving economies of scale necessary for decreases in pricing. Indeed, several studies suggest that mass production would bring cost down significantly. Given a production volume of at least 100,000 engines per year, estimates of FC vehicle premium costs range between USD 4,000 and 13,000 (Ogden 1999). A direct hydrogen vehicle is estimated to be less expensive of about USD 500-1000 that one involving on board fuel processor. The reason being that the fuel processor is estimated to be more expensive than the hydrogen storage tank.

The key question is therefore when the estimated costs will be reached through mass production. On the basis of the earlier experience with the development of the electric engine, some experts suggest that 2015 might be a more plausible but still optimistic date for volume production (DeChicco 2000). In this scenario, assuming a initial cost at USD100 per kW, production of FC vehicles would start as soon as 2005 at a volume of 20,000 units per year. The learning curve, as experience with other technologies (PV, gas turbines) suggests that costs drop by 30% every doubling of production. After about 10 years, for production at 1 million units per year, cost of FC vehicles could be reduced by the order of a magnitude. By around 2015, a fuel cell stack alone might then cost USD 25 kW, which would make it cost-competitive with today's gasoline engine.

From the above analysis it results that in contrast with automakers claims and press-releases, announcing commercial availability of fuel cells vehicles by 2004, experts' opinion suggests that the situation is far more likely to be one of limited sales for fleets or other trial evaluations. Instead than the hundreds of thousands that would count as full-scale automotive production, there will more likely to be hundred of vehicles. Table 4 summaries the main FC plans announced by car companies.

Table 3. Fuel Cell vehicle commercialisation timetables

Company	***Year***	***Remarks***
Ballard Bus	2002	To open a factory with production capacity of 500/yr, initially 20/yr
Daimler Chrysler	2001-2004	Limited buses, demonstration car fleets of up to 50 vehicles by 2004
Ford	2001-2004	Demonstration car fleets
General Motors	2004	Production intent
Honda	2003	Limited production, 300 FC cars/yr on Electric Vehicle-Plus platform
Nissan	2003	Production intent
Toyota	2004	Production intent

6. Costs of fuel choice

The commercialisation of FC vehicles will depend also on the cost of fuel and investments in the fuel infrastructure. As no fuel infrastructure exists for hydrogen and methanol fuels, the common perception is that the deployment of hydrogen fuel cell vehicles needs a completely new infrastructure, which cost would be excessive. Conversely, most people believe that the gasoline option would require no new infrastructure investments, because it is assumed that current gasoline infrastructure would be sufficient. A number of detailed analysis have been carried out in the US on the fuel and infrastructure costs (Thomas 2000, Sweden 2000), and their conclusions can be summarised as follows:

- **Methanol** production capacity should not be an issue initially, since the estimated excess methanol capacity could supply about 2.8 million of FC vehicles. Converting 10% of US petrol stations to at least one methanol pump would cost in total just under $ 1 billion. This does not appears to be excessive if compared with the estimate of $11 billion spent annually to maintain and expand the current gasoline fuelling infrastructure system (including new drilling, new gasoline tanker trucks etc). Finally, the retail price of methanol should be similar to the price of gasoline per mile drive (65 cents per gallon).
- **Hydrogen** production has some excess capacity in some areas of the US. In the Los Angeles basin, for instance, excess hydrogen capacity could supply up to 100,000 FCV (Ogden 1999). A plausible option to initiate an hydrogen infrastructure is that hydrogen could be produced economically onsite at local gasoline stations or fleet operator's garages by steam reforming of natural gas. In this scenario, hydrogen is made locally, when and where it is needed, in quantities that match the incremental growth of FC vehicles sales. Thus, hydrogen could be produced locally at a cost similar to that of gasoline per mile driven, assuming a mass production of steam methane reformers (above 1000 units). This would minimise the need for multi-billion dollar investments for a national pipeline system prior to the introduction of sufficient numbers of FCVs to provide adequate return of investment.
- **Gasoline**. Differently from conventional wisdom, gasoline FC vehicles could not use the petrol currently available at the pump station. The oil companies may need to supply a separate "fuel-cell grade" of gasoline. Sulphur may have to be reduced substantially lower than current or even projected levels of 30 PPM, and other gasoline additives that could foul the fuel processor catalyst may have to be removed. At a minimum, this new gasoline might require separate tanks, tanker trucks, dispenser etc. In addition, refinery costs could also be substantial to produce this cleaner gasoline. As said earlier, the cost of maintaining and expanding the current gasoline infrastructure are already significant.

The conclusions indicate that both methanol and hydrogen could be made available for FCVs at a cost comparable to gasoline per mile driven. Initially, methanol has the advantage of relative small investments in local retail infrastructure ($1 billion). Hydrogen requires a more substantial investment initially ($4 billion), but offer the potential of lower investment cost per vehicle in the long run, particularly when new methanol production capacity must be built. Given this broad equity in fuel and infrastructure costs, it results that the vehicle costs may be the key factor for consumer acceptance. For this reason, it is likely that initially FCs will be used in captive commercial fleets or in the public transport system. Because of high per unit costs, commercialisation of fuel cell cars is likely to be well in the future. A way to speed up this process, and achieve the needed economies of scale, would have to be that FC cars are- at least in part - marketed as products for car sharing rather than ownership. A pool of different cars all powered by the fuel cell and shared among large numbers of people would offer both mobility and convenience.

7. Public policies and programmes for FC development

On the basis of the cost assessments made earlier, it is evident that governmental R&D support is crucial for the development of FC vehicles. At policy level, the primary drover for supporting FC vehicles in the US seems to air quality objectives. A major driver is clearly represented by the California's zero emissions vehicle (ZEV) programme, which requires that 10% of cars produced for sale in 2003 be ZEVs. As a carmakers stated: *'without the ZEV programme, we would have not invested hundred of million dollars to develop FC technology in-house*". In fact, the most specific programme for fuel cells vehicles has been developed is California (see Box 3).

US support for R&D in fuel cells for transportation amounts roughly to 120 MEURO per year. Despite its claims of fuel neutrality, the Federal government is providing substantially greater support for fuel cell vehicles with onboard fuel processors over the direct-hydrogen option. In particular, like the industry, the DOE supports the gasoline fuel processor because of its fuel flexibility over the methanol processor.

Box 3. The California Fuel Cell Partnership

Thus far, the most specific programme for fuel cells vehicles is developed in the US through the California Fuel Cell Partnership. This 1999-2003 voluntary programme includes: auto manufactures (Ford, Daimler Chrysler, Nissan, Honda, Hyundai, Volkswagen, and Toyota); energy providers (Arco, Shell, Texaco, BP Amoco, Air Products and Chemicals, Praxair, and Linde AG); fuel cells companies (Ballard Power Systems and International Fuel Cells); and governmental agencies (California Air Resource Board, California Energy Commission, US Department of Energy and Department of Transportation, SCAQMD). The California Partnership has the following objectives: demonstrate vehicle technology in real world conditions; demonstrate fuel infrastructure technology; investigate the potential commercialisation path; and develop public awareness on FC vehicles. The partnership is constructing a new infrastructure capacity by opening a storage/repair/fuelling centre in Western Sacramento. Bp Amoco, Shell and Texaco will jointly bear the $ 2 Mil cost of the refuelling station. The Partnership plans to place about 50 fuel cells vehicles by 2003: 20 FC buses (the first 5 using hydrogen fuel), and 30 FC cars. More information is available on: www.drivingthefuture.org.

The overall spending on fuel cell R&D in Europe, taking into account EU, national and industrial programmes, amounts to around 60 MEURO/y. This is about half the public funded support made available for fuel cell R&D in the US, as shown in Table 3. At EU level supports has increasingly grown– from 8 M EURO in the period 1988-1992 to 54 MEURO between 1994-1998. Again, broadly half of this budget was allocated to transportation applications. Among the addressed alternative FC systems requirements is the development of on-board fuel processor for commercial grade gasoline and bioethanol.

Table 4. Caparison between EU and US total public R&D investments

Country	*FC type*	*Period*	*Budget (ME/yr)*	*Applications*
Denmark	SOFC	1990-1999	2.7	CHP and large scale electricity
France	All types	1999-2002	8	All types
Germany	SOFC, MCFC, PEMFC	1998-2002	5	CHP and large scale electricity
Italy	SOFC, MCFC, PEMFC	1994-1999	5	All types
Spain	MCFC, PEMFC	1991-1999	3.5	Large to small scale electricity Transport
UK	SOFC, PEMFC, PAFC	1991-1999	2	Transport, CHP and DG
European Community research			30	Stationary (50%) and mobile (50%)
Total EU			***60***	
Total USA			***120***	Stationary and mobile

Source: European Commission 2000

8. Conclusions and recommendations

The results of the previous discussion on technological status, GHG emission reductions and FC infrastructure costs are summarised in Table 4. This provides an overall picture of the current state of FC vehicle development and of trade-offs among the different fuel options: hydrogen (from natural gas), methanol, and gasoline.

A significant number of barriers still have to be addressed before FC vehicles can enter the market. Methanol and gasoline FCs both face serious technical barriers to any kind of commercialisation deployment. Thus, even limited deployment beyond very few demonstration cars appears likely to require hydrogen for the immediate future. Furthermore, the direct hydrogen FCVs would appear to be the only technology that can contribute to reduce significantly GHG emissions compared to the current ICE vehicles.

Table 4: Trade-offs between different technologies

FC type	*Technology status*	*GHG reduction*	*Infrastructure*	*Cost*
Direct Hydrogen	+	++	-	-
Direct Methanol	---	?	-	---
Gasoline	-	--	+/-	--
Methanol	-	+/-	-	--

Note: + indicate advantages, - indicate disadvantages and barriers

The information and data presented above suggest the following priority for public policies dealing with the climate impacts of transports and the role of fuel cells:

- Given that even in an optimistic scenario, measurable reductions of GHG emissions due to FC vehicles will not happen before 2020. Until then other technologies will be needed to address the growing CO2 emission from transports, including lightweight fuel efficient IC, hybrid and electric vehicle -the development of the latter will indeed contribute to a faster deployment of FC electric vehicles;
- The role of public research in addressing the barriers that still remain in the use of FC is fundamental. Given that public funding is limited, this should be focused on the perceived barriers for the use of direct hydrogen fuel cells: on-board storage and fuel infrastructure. Nevertheless, there is also a need to ensure funding for alternative transport technologies based on low-carbon fuels.
- Because of initial high unit costs, fuel cell vehicles would have to be - at least in part - marketed as products for car sharing rather than ownership. Public bodies should facilitate and support this approach. A pool of different cars all powered by the fuel cell and shared among large numbers of people offers both mobility and convenience. Of course, in this scenario, the car could become a tool rather than the aim – literally a vehicle for mobility.

To conclude, my research restated the fact that new technologies are needed but alone will be insufficient. To achieve sustainable mobility, new regulatory and market frameworks will be needed alongside improved technology to reverse the current trends in vehicle growth and ownership.

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Annex 1. Industry overview
(Sources: California Resource Air Board, 1998, DeChicco 2000, Companies press-releases)

1. Fuel cell companies

Ballard Power Systems. Over the past 10 years, Ballard has achieved recognition as a world leader in automotive PEM fuel cell technology. Employing more than 200 people, it has delivered more than 500 developmental stacks to a wide variety of customers. Ballard has the resources and capabilities to pursue extensive programs of technology improvement. Ballard's series "700" stacks, co-developed with Daimler Benz before their joint venture, are now being used in the NeCar 3 experimental fuel cell vehicle of Daimler- Chrysler. The Ballard series "800" 50 kW stack is used in General Motors' program. Ongoing efforts at Ballard are focusing on the series "900" 75 kW automotive fuel cell stack which is intended for volume production and application in the fuel cell vehicle Daimler- Chrysler plans to commercialise in 2004/5. The company claims that it will produce about 40,000 stacks per year in 2004 and 100,000 units/year in 2006. Stack costs are likely to drop to $35/kw at the 40,000-units/year level and ultimately to $20/kW. In 1998, Ballard, and Daimler-Chrysler made a joint venture company called XCELLIS, which is now responsible for the development and manufacturing of fuel cell engines for cars and buses

International Fuel Cells (IFC). IFC involvement in fuel cell development and fabrication dates back more than three decades, as they supplied NASA with the first space shuttle fuel cells.Work on automotive PEM fuel cell technology began only in the last years with IFC's successful response to a Ford procurement of a hydrogen-air PEM stacks for testing and evaluation purposes under DOE's automotive fuel cell R&D program. Under a $11 million DOE contract IFC plans to develop a fuel-flexible 50 kW power plant that can operate on gasoline, methanol or natural gas. This effort is now part of a larger UTC/IFC program to accelerate the development of gasoline-fuelled PEM fuel cell power plants for automobiles, building on IFC's extensive background in fuel cell stack and fuel processing technologies.

Plug Power (PP). PP is an organisation established in 1997 by Mechanical Technologies Inc. (MTI) and Detroit Edison Development Co. as a partnership to commercialise the PEM fuel cell technology developed at MTI since the early 1990s. Plug Power has grown rapidly and now has more than 100 staff engaged in PEM fuel cell technology development. The primary business goal is to develop PEM fuel cell stack and system technology for stationary power generation in the residential sector, drawing on the energy technology system expertise of MTI and the electricity market knowledge of Detroit Edison. PP also has become engaged in DOE's PEM fuel cell program, first as a supplier of a 10 kW stack under the Ford procurement, presently as one of the organisations selected to develop and deliver by the year 2000 a 50 kW PEM fuel cell power system capable of operating on processed gasoline.

H-Power. H-Power is a small company that has been active in phosphoric acid and PEM fuel cell development for 15 years. From an earlier emphasis on military applications, H-Power in the early 1990s expanded activities into PEM fuel cell technology for small stationary and portable power applications. H-Power believes that PEM fuel cells are best suited for power applications where the value of high reliability and efficiency can justify fuel cell costs in the range of a few 100 $/kW to perhaps 1000 $/kW. H-Power has a unique metallic separator plate technology particularly suited for the fabrication of compact, high performance automotive PEM fuel cell stacks.

2. Car Companies

In the past years, virtually all auto-makers made announcements about investments in fuel cell technology research and development, and most of them have announced demonstration programmes no later than 2004. Regarding the fuel choice, a broad agreement between the major U.S. automobile manufacturers has divided the initial research: GM focuses particularly on methanol, Chrysler on gasoline and Ford on hydrogen.

Daimler Chrysler (DM) is the first automaker to invest significantly in FC vehicles and to announce ambitious fuel cell commercialisation plans. Already in 1997, the then Daimler-Benz bought a 25% share of Ballard Power Systems, declaring that it was investing $ 450 million in fuel cell development. DM announced production plans starting in 2003 and reaching 100,000 vehicles per year within three years. In recent reports, however, DM has somewhat moderated its earlier announcements, by stating that a few thousand FC vehicles will be built in 2004 and 50,000 to 100,000 by the end of 2010. Regarding pricing, DM intends to price the first saleable cars at 10-15% higher than conventional vehicles. For the European market, DM will either price A-class based fuel cell cars similarly to current to A-class diesel ones, or add luxury features, such as air conditioning or a refrigerator. DM seems not to have decided yet on the fuel choice, but it seems to support methanol in Europe and ethanol in the US. The next three fuel cell prototypes are slated to be power by methanol.

Ford Motor company unveiled the Th!nk FC5 in January 2000 as part of their announcement of the Th!nk subsidiary commercialisation of various electric and alternative mobility products. In contrast to their recent P2000 compressed hydrogen FC concept car, the FC5 use a methanol reformer. Nevertheless, the company preference seems to be strongly in favour of the direct hydrogen fuel option. Ford indicates the company plans to begin low-volume commercial production of FC vehicle by 2004.

General Motors (GM) goal has been to develop its own proprietary fuel cell stack and systems development programme. GM has announced it will have a production-ready prototype fuel cell car ready in 2004. On the fuel choice, GM has been working on a methanol fuel processor for an automotive PEM fuel cell. It has announced a partnership with Exxon Mobil aimed at developing a gasoline processor. Its European branch Opel seems to have carried out more work on direct hydrogen FCs.

Toyota's fuel cell program began around 1990, with emphasis on development of hydrogen storage alloys and PEM stacks. The Toyota experimental fuel cell-battery hybrid EV, shown first in 1996, had a 15 kW hydrogen-air fuel cell, with hydrogen stored in form of a metal hydride. has announced a doubling in research spending, from $800m to $1.6b with the difference to be invested in “alternative fuel vehicles,” the most prominent of which is fuel cell vehicles.

BMW argues that FC are unlikely to be feasible as a passenger car for the immediate future. Instead, BMW is pursuing an hydrogen car model where the fuel cell is used to supply only auxiliary power.

3. Oil Companies

BPAmoco has taken a less public stance, though it is closely examining the potential for hydrogen internally, partly for transport applications. It has also said that hydrogen is likely to be the future of energy, though is less vocal about the timeframe.

Shell has set up Shell Hydrogen in 1999, with a budget of about $500m , to oversee fuel cell development. It is working with Daimler-Chrysler, the State of California, Norsk Hydro and Simens to develop technology and distribution systems. According to its president Don Huberts, the day for direct hydrogen is "'still some way off".

Annex 2. Web resources

A great deal of information in Fuel Cells technology is available on the internet. The best web site are below:

Overview site
http://www.fuelcells.org/biblio.html

FC developers
http://www.ballard.com
http://www.xcellis.com
http://www.internationalfuelcells.com
http://www.plugpower.com
http://www.hpower.com

Fuel providers
http://www.shellhydrogen.com
http://www/airliquide.com
http://www.texaco.com
http://www.bp.com
http://www.hydrogenburge.com

US Government agencies
http://www.drivingthefuture.org
http://www.arb.ca.gov/msprog/zevprog/zevprog.htm
http://www.energy.ca.gov/
http://www.ott.doe.gov/
http://www.aqmd.gov/

NGOs and research institutes
http://www.ucsusa.org/
http://www.aceee.org/
http://www.directedtechnologies.com/