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Fuel cell road traction: an option for a clean global society

Pandit Patil*

United States Department of Energy, Fuel Cell Systems R&D, Washington, DC 20585 (USA)

Pieter Zegers

Commission of the European Communities, Energy Conversion R&D Committee, 1049 Brussels (Belgium)

Abstract

Government and industry around the globe are currently faced with the challenge of meeting a rapidly growing demand for transportation services while minimizing the adverse energy and environmental impacts. Within the last decade, fuel cells have emerged as one of the most promising technologies to meet this challenge (by potentially replacing the internal combustion engine in all areas of ground transportation). Accordingly, both the USA and the European Community have assigned a high priority to the research and development of fuel cell technology and, in collaboration with the private sector, have established a wide range of programs to accelerate the development and commercialization of fuel cells for transportation. This paper discusses the development plans and strategies of the USA and the European Community, the progress achieved to date, and the potential of fuel cells to contribute to a successful transition towards a clean global society.

Global challenge

Transportation exerts a major impact on energy use, the environment, and the economy. In the USA, which represents the largest single energy market, transportation is responsible for 27% of the energy consumed and 65% of the petroleum used. In fact, transportation is the major contributor to the country's growing dependence on imported petroleum (Fig. 1). In 1992, the petroleum used for transportation exceeded domestic production by 43% and this deficit is expected to keep growing [1]. Even though fuel consumption per vehicle-mile has been reduced by about 40% from 1970 levels, the number of vehicle-kilometers traveled has increased from 1.6 trillion in 1970 to 3.2 trillion in 1990. This trend is also projected to continue.

It is estimated that 140 million people in the USA live in ozone nonattainment areas based on the US Environmental Protection Agency's October 1991 designations. Energy used for transportation purposes is a major source of this air pollution, generating more than 60 million metric tons of regulated pollutants in 1991 alone. Emissions per vehicle-kilometer today are actually about 80% lower than 1970 levels; however, because of the dramatic increase in vehicle travel, transportation remains responsible for over two-thirds of national carbon monoxide (CO) emissions, nearly two-fifths of nitrogen oxides (NO_x) emissions, about a third of the (non-methane)

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*Author to whom correspondence should be addressed.

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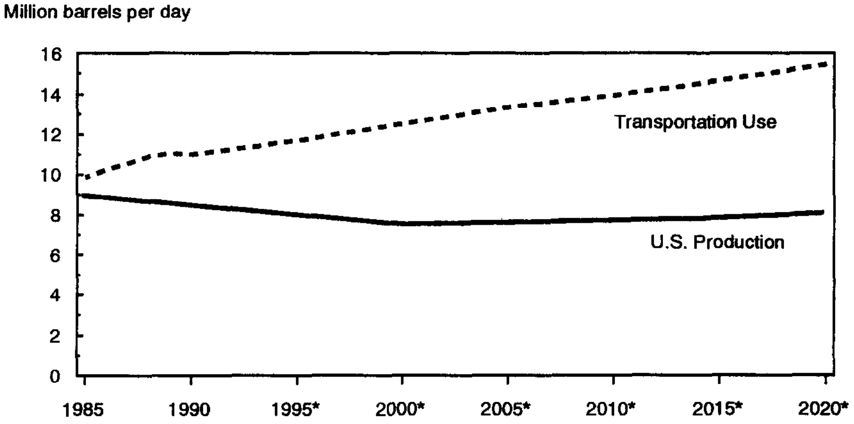

Fig. 1. US transportation petroleum use and production, 1985–2020 (*projected) [1].

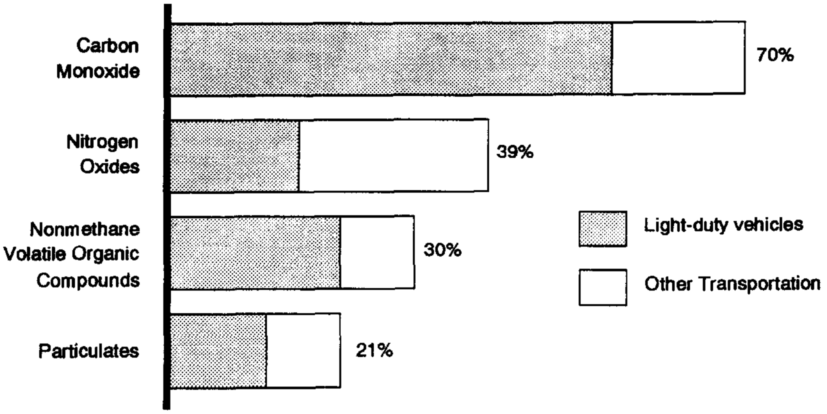

Fig. 2. Transportation share of total US emissions, 1991 [2].

volatile organic compound emissions, and over a fifth of particulate emissions, Fig. 2 [2]. Both light- and heavy-duty vehicles are major contributors to these emissions. Government policy makers and regulators in urban areas with severe air-quality problems recognize that in order to meet air-quality standards, emissions will need to be reduced dramatically – even from the levels associated with the best technology currently in use. Growing recognition of this need is reflected in the highly publicized California Low Emission Vehicle (LEV) Program, which mandates the introduction of zero-emission vehicles (ZEVs) into the California fleet before the end of the decade. Several other states have adopted these requirements.

In the European Community, approximately 20% of primary energy is used for transportation, mostly for road transportation. Transportation generates about 60% of the NO_x emissions and a major portion of the hydrocarbon (HC) and CO emissions; transportation is also the major contributor to pollution in Europe's urban areas. The adverse energy and environmental impacts of transportation in the European Community (and the USA) are forecast to worsen as the number of vehicles and the kilometers traveled per vehicle increase, offsetting any improvements resulting from gains in energy efficiency and emission controls.

In many respects, the global situation reflects the same trends. Today, there are about 500 million automobiles on the road worldwide — a tenfold increase since 1950. If one includes trucks, buses, and two-wheeled vehicles, the global motor vehicle fleet is now approaching 675 million. The historical linear growth in numbers of vehicles (5.2% per year between 1960 and 1990) exceeds the population growth rate. This trend is likely to continue into the foreseeable future, as will the rise in vehicle-kilometers traveled, Fig. 3. By early in the next century, based on current trends, the rapidly developing areas of the glove (Asia, Eastern Europe, Latin America, and the Pacific Rim) will have as many vehicles as North America and Western Europe. Simultaneously, people are using private cars and light trucks to drive much more. The projected impact of these trends on global vehicle emissions is summarized in Fig. 4 [3]. Strong, continuing emission control programs in the USA and Japan and recently tightened requirements in the European Community will keep global emissions of CO, HC, and NO_x fairly stable through the next decade. Beyond that point, HC and NO_x emissions will start to increase, due to projected continued growth in vehicle populations in OECD (Organization for Economic Cooperation and Development) countries and especially in other areas of the world where emissions controls are likely to be minimal. In the case of CO_2 emissions, the picture is even bleaker: emissions from road vehicles are estimated to increase by two-thirds over day's levels by 2030. If we are to move towards a clean global society, we must counteract these trends.

Fuel cell vehicle development in the USA

What is our best option for meeting the ever-growing demand for transportation services while minimizing adverse energy and environmental impacts? If we are to ensure a 'cleaner' world for the future, it is clear that more drastic steps are required than simply improving the fuel efficiency and lowering the emissions of the internal combustion engine (ICE). A radical change in vehicle-propulsion technology is needed.

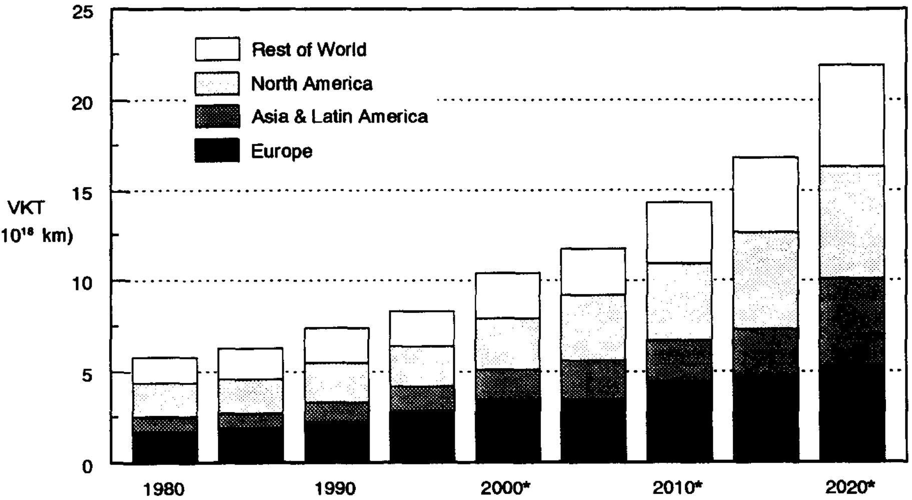

Fig. 3. Global trends in annual vehicle-kilometers traveled VKT (*projected).

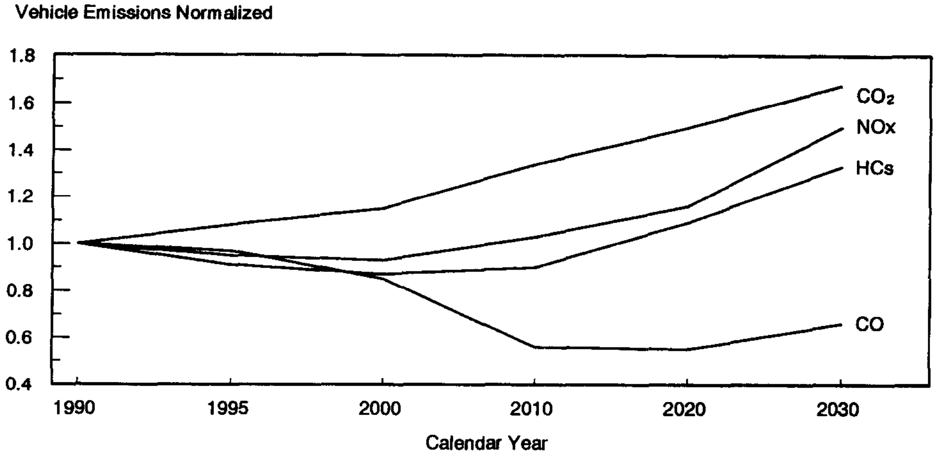

Fig. 4. Global trends in motor vehicle emissions, 1990–2030.

We need a vehicle that will produce very low levels of polluting emissions, utilize energy from secure/renewable sources, and be economical, enjoyable, and safe to drive. In short, to ensure its appeal the world over, it must provide all the comforts of today's conventional automobile. Fuel cells, with their characteristic high efficiency, very low or zero emissions, and fuel flexibility, offer the best prospects for such a vehicle. Recognizing this, the USA is cooperating with industry and academia in pursuing a strategy of aggressive research, development, and demonstration to accelerate the commercialization of fuel cell vehicles (FCVs). The fuel cell technologies that are being actively developed for transportation use include the phosphoric acid fuel cell (PAFC), the proton-exchange membrane fuel cell (PEMFC), the solid oxide fuel cell (SOFC), and the direct methanol fuel cell (DMFC). Research and development (R&D) activities are focused on overcoming the major technical, economic, and infrastructure hurdles. While fuel cells have been extensively developed for stationary applications, transportation applications are more demanding and impose several critical requirements: improved power density and rapid startup and load-following capability (critical for light-duty vehicles); reduced costs (by at least a factor of 10) as compared with current stationary systems, and a supporting alternative fuels infrastructure.

Legislative drivers

In the USA, the National Energy Strategy (NES) provided the framework for a comprehensive strategy (including fuel cell development) to improve transportation-energy efficiency, reduce emissions, and promote the use of alternative fuels. The subsequent passage of the Energy Policy Act of 1992 (Public Law 102-486) provided a further boost to the Federal Government's Fuel Cells in Transportation Program. The Energy Policy Act directs the US Department of Energy (DOE) to 'develop and demonstrate the use of fuel cells as the primary power source for private and mass transit vehicles and other mobile applications'. The Federal Clean Air Act Amendments of 1990 also provide considerable impetus to reduce mobile source emissions and increase the use of clean fuels. In addition, the President's National Critical Technologies Panel has identified fuel cells as one of the 22 technologies considered essential for the USA to achieve prosperity and maintain energy security.

National program plan for fuel cells in transportation

To meet the requirements of the Energy Policy Act, DOE has developed a comprehensive National Program Plan for Fuel Cells in Transportation [4]. This ten-year plan is based on the findings of an Ad Hoc Technical Panel, which is composed of more than 50 representatives from government, industry, and academia. The overall Program goal is to develop an alternative to the internal combustion engine for US transportation. By 1995, the Program seeks to establish the technology base that will enable early applications of fuel cells in transportation so that the commercialization process could begin by the year 2000. The four, mutually supporting elements of this comprehensive Program are:

(i) light-duty propulsion systems development;
(ii) heavy-duty propulsion systems development;
(iii) supporting research and development, and
(iv) supporting analyses.

Table 1 provides an overview of these four elements. As this Table indicates, the Program pursues multiple technology paths to reduce development risks and address different market sectors. The Program focuses on the unique technical, cost, and infrastructure hurdles that must be overcome if fuel cell technology is to become widely utilized in transportation. Some of the critical fuel cell performance and cost goals for the DOE Program and remaining R&D issues are shown in Tables 2 and 3.

Fundamental, exploratory research in basic fuel cell technology is a critical part of the DOE Program (under the supporting R&D element) and is expected to lead to improved fuel cell and systems performance for all FCV applications. As research advances are achieved, they will be quickly incorporated into the system development activities. Of necessity, the Program relies extensively on linkages with existing programs. To date, over US$ 1 billion has been expended by US government and industry in developing basic fuel cell technology, and the results from these efforts will be transferred to transportation applications, when feasible.

A successful program for FCV development and commercialization will require the effective cooperation of both public and private sectors. The DOE Program is implemented through appropriate project alliances with the principal stakeholders – automobile industry, fuel cell manufacturers, fuels industry, governmental agencies, regulators, and transportation users. This approach is illustrated in Fig. 5. The Program is structured to ensure rapid and complete transfer of scientific and technological research results to industry.

Ongoing projects and new initiatives

Since 1987, DOE has initiated several transportation fuel cell development projects with industry and the national laboratories. These projects continue to make significant progress. In accordance with its National Program Plan, DOE is developing several new initiatives to augment the existing projects. DOE's fiscal year 1993 budget allocates US$ 12 million for the Fuel Cells in Transportation Program. This budget is expected to increase substantially in the fiscal year 1994.

Light-duty vehicle systems

In 1990, DOE initiated a project to develop PEMFCs for light-duty vehicles. Led by the Allison Gas Turbine Division of General Motors, the project team also includes Los Alamos National Laboratory for reformer development and fuel cell testing, Dow Chemical for membrane development, Ballard Power Systems for fuel cell stack

TABLE 1

Elements of DOE's fuel cells for transporation program

Program element	Key developments	Milestones
Light-duty propulsion systems	Develop proton-exchange membrane fuel cell propulsion system for use in light-duty vehicles using methanol fuel	Proof-of-concept vehicles by 1999
	Develop proton-exchange membrane fuel cell propulsion system for light-duty vehicles using hydrogen fuelpropulsion system for light-duty vehicles using hydrogen fuel	Proof-of-concept vehicles by 1999
Heavy-duty propulsion systems	Adopt phosphoric acid fuel cell technology to buses	Proof-of-concept buses in 1994
	Assess feasibility for truck and marine applications	Feasibility evaluation by 1995
	Develop fuel cell-powered rail locomotive	Proof-of-concept locomotive by 1999
R&D	Develop advanced on-board fuel reformer and hydrogen-storage technologies	Full scale hardware in 1997
	Investigate advanced concepts and new technologies	Advanced or direct fuel cell demonstration by 2003
Supporting analyses	Determine energy, economic, and environmental benefits of fuel cell vehicles	Updated program priorities in 1994
	Assess environment, safety, and health aspects of fuel cells in transportation	Environmental assessment in 1994

TABLE 2

Fuel cell system performance and cost goals, US Department of Energy

Parameter	Target
Fuel cell stack (kg/kW)	0.9–1.8 (based on peak power)
Fuel cell volume (m^3/kW)	0.0014–0.0028
Fuel cell cost (US$/kW)	30–40 (at one million units/year)
Fuel cell efficiency (%)	48–60
Fuel cell cycleability (time/year)	300–2000
Start-up time (s)	2–10

TABLE 3

Remaining R&D issues: fuel cell systems for vehicles

Size
Weight
Cost
Fuel cell stack voltage
Start-up time
Transient response
Water disposal
Real-world operational considerations (road vibration, owner maintenance, cold weather, long-term storage)

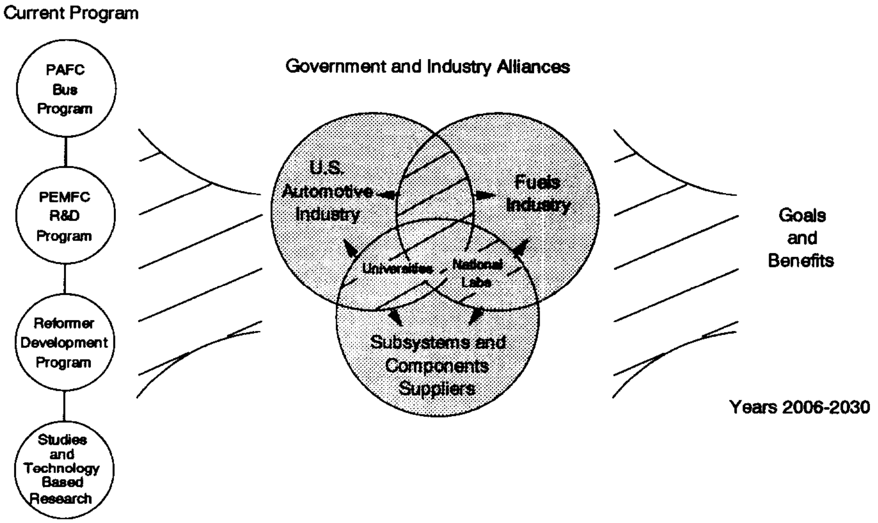

Fig. 5. Project alliances with major stakeholders are critical to the success of DOE's fuel cells in transportation program.

fabrication, General Motors North American Operations R&D Center for electrode and catalyst studies and for vehicle systems engineering. The first phase of this project, to be completed by October 1993, showed the proof-of-feasibility for a 10-kW methanol-fuelled, PEMFC system. Work will soon begin on Phase II, which involves the design, building, and testing of an advanced 30-kW system that will operate on reformed methanol. PEMFC technology from several companies will be evaluated, and the best will be selected. PEMFC technology from this project is expected to be ready for vehicle demonstrations in the late 1990s. Work is scheduled to begin in 1994 on a parallel project to develop a light-duty passenger/utility vehicle powered by a PEMFC system with on-board hydrogen storage. This effort should produce a true tailpipe ZEV.

Heavy-duty vehicle systems

Since 1987, DOE has been engaged in a joint project with the US Department of Transportation's Federal Transit Administration and the South Coast Air Quality Management District (SCAQMD of California) to develop, build, and test three PAFC-powered urban transit buses. These methanol-fuelled, 30-ft. buses, which are scheduled for completion in 1993 and 1994, are expected to perform at a level equivalent to diesel buses but with significantly improved fuel economy and negligible tailpipe emissions. The results of the PAFC bus program thus far are very promising, enhancing the prospects for early commercialization of fuel cells in an urban transportation application. H-Power Corporation, the prime contractor for the project, is working with a versatile team that includes: Booz, Allen and Hamilton, Inc.; Bus Manufacturing USA, Inc.; the Transportation Manufacturing Corporation; Fuji Electric Company, and Soleq Corporation. A new effort, a feasibility study on fuel cell-powered locomotives, will be initiated in the fiscal year 1994. This joint effort will be funded by an alliance consisting of DOE, SCAQMD, the California Department of Transportation, major railroad companies, and locomotive manufacturers.

Supporting research and development

Arthur D. Little, Inc., has completed Phase I feasibility studies and identified preliminary design concepts for an advanced reformer and hydrogen-storage system. Work has begun on Phase II to design, build, and test a proof-of-concept ethanol reformer and an advanced hydrogen-storage unit. In other efforts, the Los Alamos National Laboratory is performing studies on direct methanol oxidation in PEMFCs. A new project will be initiated in 1994 to identify, develop, and evaluate power management devices for FCVs.

Hydrogen as a transportation fuel

On-board storage and use of hydrogen is an intrinsically clean option that is a growing focus of R&D efforts in the USA, where there is increasing Congressional support for hydrogen as a fuel. In response to the Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 (Public Law 101-566), a comprehensive five-year Hydrogen Program Plan was developed by DOE to resolve the critical technical issues necessary for the development of hydrogen technologies. The Energy Policy Act requires DOE to supplement the Matsunaga Act by assessing and developing hydrogen production from renewable energy resources, the use of existing natural gas pipelines to transport hydrogen and natural gas mixtures, and hydrogen storage and fuel cells for vehicles.

Because the existing hydrogen market is very small today, to achieve significant penetration of hydrogen as a transportation fuel will require the development of an extensive production and distribution infrastructure. A 10% penetration of the US light-duty vehicle market would require an estimated 18 000 metric tons of hydrogen fuel per day. This supply would require about 330 plants, with each providing 55 metric tons per day. The infrastructure requirements will include some combination of natural gas reformers, electrolyzers, and hydrogen storage. The actual evolution path of the hydrogen infrastructure will be driven by demand patterns (vehicle type/use/population, fuel form, regulations, etc.), supply economics, and technology advances. At present, there is considerable uncertainty associated with each of these elements.

Strict safety requirements for hydrogen are likely to present a serious hurdle to overcome. Successful introduction of hydrogen as a transportation fuel will require the alleviation of perceived dangers and the development and deployment of safety features (leak detection sensors) to ease public concerns. The safety issues related to large-scale deployment and utilization of hydrogen need to be further defined and addressed by legislation and regulations.

Fuel cell vehicle development in the European Community

Fuel cells are considered an important option for transportation in Europe because they offer zero or very low polluting emissions and efficiencies that are two to three times higher than for ICEs. CO_2 emissions would be reduced by an amount inversely proportional to the increase in efficiency. Within the broader fuel cell technology option, there are different possibilities, and Fig. 6 gives an overview of the most important alternatives. These alternatives can be roughly subdivided into two categories:

(i) *Use of hydrogen as a fuel in fuel cell vehicles* (*FCVs*). This alternative offers very high efficiencies (50 to 60% as compared with 15 to 20% for gasoline engines). If hydrogen were produced by electrolysis using renewable or nuclear electricity, no CO_2 or other pollutants would be formed. If hydrogen were produced from natural gas with stationary reformers, overall pollutant emissions would be 100 to 1000 times lower (and the CO_2 emission roughly a factor of 2 lower) than for ICE-driven vehicles. This option would require an expensive distribution network for the hydrogen plus the technology for safe on-board hydrogen storage; at present, no satisfactory solutions exist to meet these requirements. In the near term, European car manufacturers favor the use of liquid hydrogen, even though the liquefaction process uses 30% of the hydrogen's energy content. The strict safety requirements for hydrogen are likely to be a serious barrier to its successful introduction.

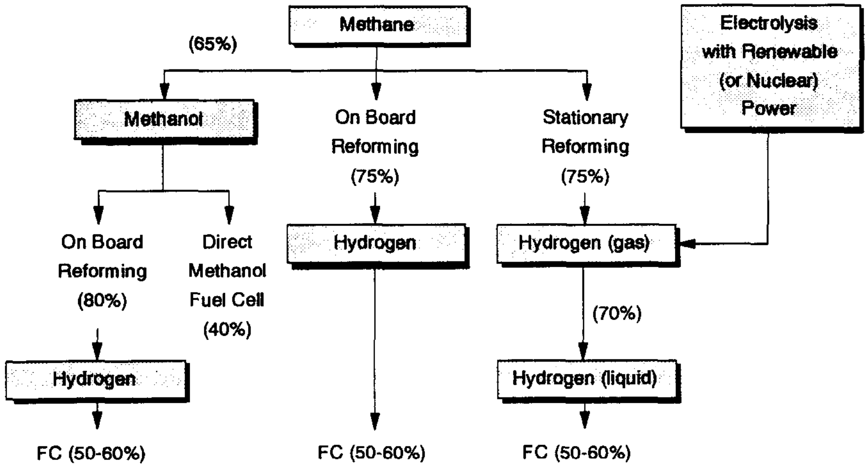

Fig. 6. Some options for fuel cell (FC) vehicles (process efficiencies are shown in parenthesis).

(ii) *Use of methanol or natural gas as a fuel in fuel cell vehicles.* Generally, an on-board reformer is used to transform these fuels into hydrogen, which is then fed into the fuel cell; under an alternative technology, methanol is oxidized directly in the fuel cell and a reformer is not required. These types of fuel cell systems also offer the advantage of 100 to 1000 times lower CO, HC, and NO_x emissions compared with ICEs and 1.5 to 2 times lower CO_2 emissions. An additional advantage, however, is that methanol requires an infrastructure that is very similar to existing liquid fuel distribution systems.

The major advantage of the first option, particularly where hydrogen is produced from renewable electricity, is that this pathway is intrinsically clean. The high level of worldwide interest in this option is reflected in such projects as the Euro–Quebec project in Europe and the World Energy NET project in Japan. These projects are exploring the possibility of using hydropower in remote areas to produce hydrogen for export to developed countries, where it would be used to provide clean energy in the industrial, building, and transportation sectors. According to a study carried out under the Euro–Quebec project, the cost of liquid hydrogen produced in Canada and shipped to Hamburg, Germany, (in transportable containers) is expected to be 0.045 ECU/kWh (US$ 0.054/kWh). By comparison, the average price of petrol in Europe without tax is around 0.035 ECU/kWh (US$ 0.042/kWh). This cost difference may be low enough for liquid hydrogen to find a number of applications in FCVs. In the long term, hydrogen costs may be further reduced through research in high-temperature electrolysis, which could lead to electricity savings of 30 to 40%, and the development of cost-effective hydrogen storage systems.

Another possibility for clean transportation is the production of hydrogen from natural gas or coal using reformers or coal gasifiers, followed by the extraction of pollutants from the exhaust gases. Clean-up of CO, HC, and NO_x would lead to a 10 to 15% cost increase. Removal of CO_2 from the exhaust gases would increase the cost by 25 to 35%; the problem of CO_2 storage, however, has not yet been solved and should be dealt carefully as a release of CO_2 stored for many years could lead to a global disaster. This option has the advantage that hydrogen can be produced cheaply (0.02–0.03 ECU/kWh (US$ 0.024–US$ 0.036/kWh) for gaseous hydrogen).

For the options that require the conversion of natural gas or methanol by an on-board reformer, the major drawbacks are the long start-up time, slow transient response, bulkiness, CO cleanup, and the need for additional components (such as batteries). R&D should therefore focus on the development of cheap, compact reformers with short start-up times and rapid transient response. Other possibilities are fuel cells that directly oxidize methanol or fuel cells that operate at around 300 °C and use waste heat for the internal reforming of methanol; in either of these cases, a reformer would not be needed.

The efficiencies of the different fuel cell options are shown in Fig. 6. Assuming transmission losses (control equipment, electric motor, etc.) of 30%, the overall (full-cycle) efficiencies lie between 18 to 21% with an on-board methane reformer, and at 18% for the direct oxidation of methanol. The full-cycle efficiency for petroleum-powered cars, from the crude oil to power at the wheels, is around 12%. In contrast to the petroleum-powered ICE, however, there is still much potential for improvement in the conversion of methane to methanol, the fuel cell, hydrogen storage, control equipment, electric motors, and other subsystems. In terms of energy efficiency, the production of hydrogen from hydropower is the least attractive option. The fact that it is intrinsically clean and that the cost may be acceptable, however, could make it a very interesting option.

A major problem for all FCV options is the high cost of producing the fuel cells. Based on current technology and a production rate of 10 to 100 MW/year, fuel cells are expected to cost 800 to 1000 ECU/kW (US$ 960–US$ 1200/kW). To make fuel cells economical for use in automobiles, this cost would need to be reduced by an order of magnitude. The situation is more favorable in the public transportation sector, since fuel cell-driven buses produced in small series are expected to be only 20% more expensive than diesel-driven buses.

The major effort of the European Community R&D is focused on reducing the cost of fuel cells. In particular, the following objectives have been targeted: increasing the current density to reduce the cost per kW; development of a fuel cell concept that allows cheap mass production, and reducing the amount of precious metal catalyst. This R&D will be reinforced by other actions aimed at enlarging the market, since additional cost reductions can be achieved with economies of scale. In addition, specific research and other actions will be needed to develop the different FCV options.

Role of the European Community

R&D on fuel cells for transportation is carried out in different national, industrial, and programs of the European Community (EC).

Although EC funding for this research in Europe forms only a relatively small part of overall funding, EC programs act as a catalyst in bringing about collaboration and information exchange between most of the FCV programs in Europe. Due to the requirement that an EC project have several partners from different EC member states, each EC project consists of four to five partners on the average. In the nine ongoing projects under the EC JOULE program, around 40 organizations participate, and these organizations are also involved in national and industrial FCV activities. Additional FCV projects are carried out under the Euro–Quebec project. Regular EC contractor meetings assure a continuous information exchange between all major FCV groups in Europe. A brief overview of fuel cell and related vehicle R&D in Europe is provided next.

Development of fuel cells that use hydrogen as a fuel

Fuel cells for transportation, such as alkaline fuel cells (AFC) and solid polymer fuel cells (SPFC), have been under development for many years by Siemens of Germany (AFC and SPFC), Elenco of Belgium (AFC), and more recently by De Nora of Italy (SPFC). Siemens developed AFC and SPFC technologies primarily for applications in submarines. More recently, Siemens decided to focus on the development of SPFCs for road traction applications and in 1992 became the project leader of an EC project to reduce the cost and improve the efficiency of SPFCs. Siemens is also currently involved in the preparations for a four-year German project (1993–1997) that has the long-term objective of lowering the cost for SPFC stacks to 100 ECU/kW (US$ 120/kW); other possible partners in this project include Daimler Benz and Dornier.

Elenco in Belgium has long been involved in the development of AFCs for road traction and space applications and has constructed a small AFC production line. At present, Elenco is currently participating in the development of an AFC-driven bus. De Nora in Italy has many years of experience in the development of electrolyzers and has been developing SPFCs for several years. At present, they are involved in the development of a 40-kW SPFC for applications in buses and boats. In the UK, no known SPFC stack development is in progress, but Vickers Shipbuilding and Engineering, Ltd. (VSEL) are closely collaborating with Ballard of Canada, and Johnson Matthey is a world leader in fuel cell components and catalysts.

Development of fuel cells that use methanol as a fuel

The EC started supporting R&D on fuel cells for vehicles in 1986. At that time, work was focused on fuel cells that do not require an expensive and bulky reformer and can use methanol directly as a fuel. This approach uses a fuel that is easy to handle and distribute and still keeps the system relatively compact and simple (since a reformer and, possible, batteries are not required). Two fuel cell types were selected for R&D:

(i) internal-reforming, solid proton-conducting fuel cell (IR–SPFC) that uses methanol as a fuel and operates at 300 °C. These cells use waste heat for reforming the methanol in the fuel cell (internal reforming), and

(ii) direct methanol fuel cells (DMFC), which oxidize methanol directly.

A group of seven laboratories worked to develop an IR–SPFC with a solid electrolyte that would be suitable for internal methanol reforming and that had little or no previous metal catalyst content. The principal aim was to develop a gas-tight, solid electrolyte with high proton conductivity that could operate at 300 °C. A number of polymer and inorganic materials were investigated. At the end of the contract period in 1989, no suitable electrolytes had been identified and the project was abandoned due to limited funding. The IR–SPFC, however, is still seen as a very interesting field for possible future research.

Development work on a DMFC with a liquid electrolyte also began in 1986. The main obstacle was the slow reaction rate of methanol oxidation at the anode with conventional platinum electrodes and the poisoning of the platinum catalysts. A group of eight laboratories conducted research to identify the mechanisms of catalyst poisoning and find ways to increase the reaction rate. This work resulted in a much better understanding of methanol oxidation and identification of a ternary platinum catalyst that increased the reaction by one order of magnitude and functioned at 40 mA/cm^2 and 0.4 V; a test cell operated for 4000 h without poisoning the catalyst. EC-funded research, in which 15 organizations (mainly universities) participated, continued this DMFC work between 1989 and 1992. The goal was to further improve methanol oxidation and oxygen reduction. This research focused heavily on the development of DMFCs with solid electrolytes that would allow operation at higher temperatures, resulting in faster reaction rates and lower precious metal catalyst loadings. Another advantage to solid electrolytes is that they would be suitable for cheap mass production. Much of the electrolyte work was based on solid electrolyte research that had been carried out previously for the IR–SPFC. A 100-W DMFC was built with 150 mA/cm^2 current density and 0.5 V at 80 °C. Future research is aimed at the development of a 1-kW DMFC that uses gaseous methanol and can achieve the following targets: 500 mA/cm^2, 0.6 V, a precious metal catalyst loading of less than 1 mg per cm^2, and an operating temperature of 120 to 150 °C.

Fuel cell systems with reformers using methanol or natural gas as a fuel

In the EC JOULE program, two projects are currently focusing on the development of methanol reformers, and two additional projects are expected to start soon; companies participating in these projects include Ansaldo and Tecnars from Italy, Haldor Topsøe from Denmark, and KFA Julich in Germany. R&D on methanol reformers is also being carried out under national programs, by VSEL and CJB Developments, Ltd. in the UK and Ansaldo and Tecnars in Italy.

From an energy efficiency point of view, the FCV with an on-board reformer for natural gas is a very attractive option. Although the development of such reformers for vehicle applications presents a difficult challenge, the EC has decided that this option merits further exploration; one such EC project has begun and another is scheduled to begin shortly.

Fuel cell vehicles

Most European projects on FCVs focus on the direct use of hydrogen as a fuel. This option is intrinsically clean if the hydrogen is produced by the electrolysis of water with renewable electricity. In the 30 MECU (US$ 36 million), three-year Euro–Quebec project, the EC is actively promoting the use of hydrogen by the industrial, building, and transportation sectors. Both hydrogen-fuelled ICE and fuel cell-driven buses are being developed under this project. Hydrogen-fuelled ICE buses are seen as the first step in a clean, hydrogen-based, road transportation system, with fuel cell-driven vehicles to be developed for use in the long term. This view is reflected in the conclusions of an EC workshop on 'Hydrogen for Transportation', which was held in June 1993:

(i) the use of hydrogen in ground transportation can substantially reduce pollution;

(ii) ICEs fuelled by hydrogen could come close to offering zero emissions and they can be made available soon (short-term option), and

(iii) FCVs using hydrogen as fuel are true zero-emission vehicles and offer a much higher efficiency than combustion engines; this technology should be developed as a long-term option.

European car companies (such as BMW and Daimler Benz) have followed this strategy for the development of hydrogen-fuelled, ICE vehicles for many years; in addition, a Belgian group is working on the development of a hydrogen ICE bus under the Euro–Quebec project. In a separate Euro–Quebec project, Ansaldo is constructing a hydrogen fuel cell bus with a 40-kW SPFC built by De Nora. The same group intends to build a fuel cell-driven ferry boat, to be used on the Lago Maggiore. Elenco, working together with Ansaldo, is developing another fuel cell bus with an 80-kW AFC. Under an EC project, Renault and Volvo will soon start development of a hydrogen-fuelled, fuel cell passenger car.

To support the development of methanol-fuelled FCVs, a stationary test facility is being set up by ECN in The Netherlands. All components, such as the fuel cell, methanol reformers, batteries, and (possibly) supercapacitors, will be integrated and optimized to simulate a three-ton van.

Towards a clean global society

Potential benefits of fuel cell vehicles

The successful development and commercialization of FCVs will provide global benefits: improved air quality, reduced emissions of greenhouse gases, energy and economic savings, reduced petroleum dependence, and increased use of alternative fuels and renewable energy sources (as the supply and distribution infrastructure is built up). Although the ICE has been substantially improved in terms of fuel efficiency and emissions, such improvements are approaching their practical limits. Even at this early stage of development, fuel cells offer operating efficiencies that (at 36 to 50%) are nearly double as those for conventional engines. In addition, fuel cells can maintain a high level of efficiency, even at partial loads. As discussed earlier, fuel cells also offer enormous potential for emissions reduction. An FCV operated on methanol will generate lower levels of CO, NO_x, and non-methane organic gas (NMOG) — substantially less, for example, than the levels established by the California Ultra Low Emission Vehicle (ULEV) standards. Figure 7 shows the current and future US passenger car standards relative to the projected emissions of FCVs. Because of their extremely low emissions, fuel cells in both light- and heavy-duty vehicles could help bring transportation sector emissions within increasingly stringent regulatory limits.

Several recent analyses have quantified the potential energy, environmental, and economic benefits that would accompany a transition from ICE vehicles to FCVs [5–7]. At the vehicle level, the Allison/General Motors team compared the energy consumption, range, acceleration, and other performance and functional parameters of methanol-fuelled, PEMFC vehicles with comparable conventional vehicles (of current design). Three sizes of passenger cars, a mini-van, and an urban transit bus were compared. Despite a projected weight penalty for the FCVs, their composite (55 city/45 highway) per kilometer energy usages were estimated to be up to 52% lower than those of the comparable conventional vehicles. Another study has estimated that using FCVs to replace 10% of light-duty vehicles in the USA would displace 800 000 barrels per day of petroleum, reduce regulated pollutants (NO_x, HC, and CO) by over one million tons per year, and reduce CO_2 emissions by over 60 million tons per year [4]. These estimates are indicative of the magnitude of the benefits that can result from the successful commercializations of FCVs worldwide.

Commercialization issues

In the final analysis, bringing into reality the transportation fuel cell's enormous potential for energy, environmental, and economic benefits will depend on successful commercialization. The long-term prospects are indeed encouraging. As compared with other advanced alternatives, FCVs can compete on an even ground with conventional

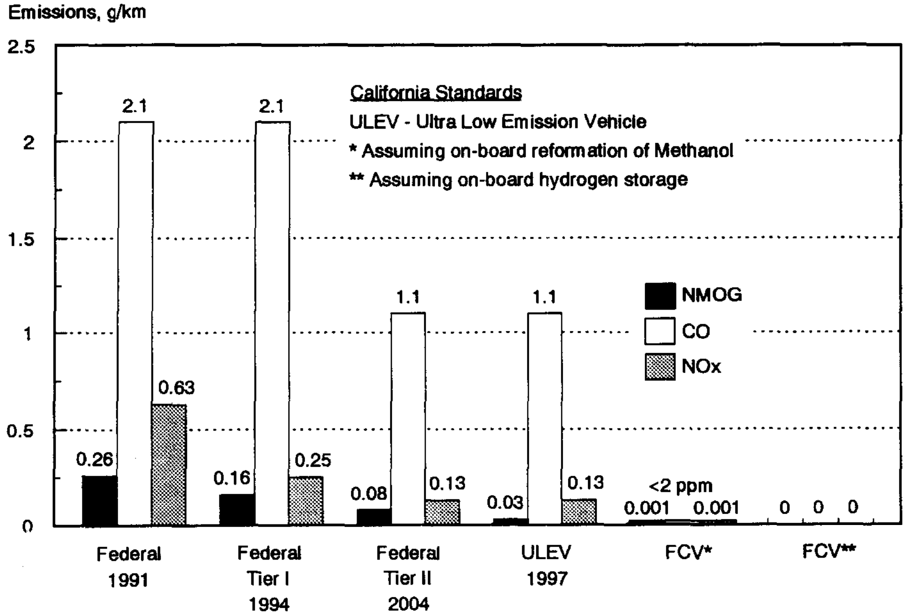

Fig. 7. Projected fuel cell passenger car emissions compared with future Federal and California standards.

ICE vehicles in several respects. They do not have the range limitations nor the long recharging times that are characteristic of battery-powered electric vehicles. In fact, FCVs can offer the same performance, range, and rapid fuelling capabilities as conventional gasoline-fuelled vehicles. Fuel cells can be applied to all areas of ground transportation that now use ICEs, from heavy-duty trucks and buses, locomotives, ships, and submarines to passenger cars, light trucks, and vans. This range of application vastly increases the market for FCVs and leverages their potential for global benefits.

A major hurdle to consumer acceptance of FCVs is the current high cost of fuel cells. Recent studies have shown that a substantial fraction of consumers (especially in California) are willing to consider the purchase of 'clean' vehicles. They are not willing, however, to pay any substantial premiums in price or to accept a penalty in performance in return for environmentally safer products [8]. Automobile industry sources strongly believe that alternatives to conventional vehicles need to be priced competitively in order to achieve and maintain penetration in the marketplace. For automotive applications, the cost of mass-produced ICEs presents a difficult target for fuel cells to achieve. As levels of fuel cell production increase, economies of scale should help to reduce the cost gap. There is considerable reason for confidence. A recent study by the Allison/General Motors team estimates that the total cost (in 1992 dollars) of an automotive-scale, 60-kW PEMFC-power system (assuming high volume production) could be substantially less than $US 100/kW on a continuously operating rated basis. In making comparisons with ICEs, it should be remembered that today's ICEs are not capable of meeting stringent future environmental regulations; may not be able to be modified to meet such regulations at all, or, may require modifications which would dictate substantial cost premiums.

FCVs offer the advantage of lower cycle life operating costs for fuel and maintenance, plus any economic credits for being much cleaner than ICE vehicles. Even in the near term, fuel cells for urban bus applications are projected to be highly competitive with competing diesel systems on a cycle-life cost basis. The 20 to 50% lower operating and maintenance costs for fuel cell buses will more than compensate for their modestly higher initial costs. The early commercial transportation market for fuel cells is expected to be in heavy-duty vehicles. In fact, urban transit buses are being targeted as the first commercialization market for fuel cells.

Summary

The near-term market for FCVs will be driven by environmental and regulatory considerations, such as California's low-emission and zero-emission vehicle requirements. The long-term market prospects for FCVs, however, will depend on their performance and cost relative to other candidate propulsion systems. Because fuel cell vehicles are expected to provide comparable performance and range as gasoline vehicles at a competitive price, it is reasonable to expect that they will penetrate the market beyond the level mandated by regulations. To realize this potential, both the US and EC strategies for fuel cell development are focused on overcoming the critical technical, cost, and infrastructure hurdles.

The USA and the EC recognize the challenges that the transportation sector poses to our energy security, our economic wellbeing, and our hopes for a transition to a clean global society.

A critical element of our collective response to this challenge is the accelerated development and commercialization of FCVs. There are strong reasons to believe that fuel cells will ultimately be the powerplants of choice for all ground vehicle systems. While we are steadily moving closer to clearing the technical and environmental hurdles, the economic risks and required levels of public/private investment remain high.

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