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The future of fuel cell in Mexico in the third millennium

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Abstract

The warming of the earth due to green house gas emission is mainly produced by CO_2. In Mexico City, 71% of the total harmful emissions is from internal combustion engines of car and buses. Benefits from the use of fuel cells (FCs) in transportation and stationary power generating sectors will achieve satisfactory air quality standards not only in Mexico City but also throughout the country.

This paper suggests a scenario for FC technology penetration in Mexico. There are two potential markets for FCs: (i) FC transportation; and (ii) stationary power plant for electrical production. In Mexico City, 3.2 million vehicles are in circulation and represent 19.5% (16.3 million) of the country's total vehicles, and 9.02 million of natural gas users are a potential market for acquiring stationary power generation by FC systems.

Keywords: Vehicles; Fuel cell bus; Stationary fuel cells; Fuel stations; Natural gas; FCV; HFCB

1. Introduction

Modern lifestyles demand a steady and reliable supply of energy: it lies at the heart of our daily comfort [1]. Transportation will surely increase in the coming years. Energy supply should be safe, economic and reasonably clean [2].

Energy can be stored in different forms: as mechanical energy (for example, potential energy or rotational energy of a flywheel); in the electrical or magnetic field (capacitors and coils, respectively); as chemical and electric energy in the form of reactants and fuels (batteries, petrol or hydrogen); or as nuclear fuel (uranium or deuterium).

Chemical and electrical energy can be transformed easily because they both involve electronic coulomb interaction. Chemical energy is based on the energy of unpaired outer electrons (valence electrons) to be stabilized by electrons from other atoms.

The successful conversion of chemical energy into electrical energy in a primitive fuel cell (FC) was first demonstrated over 160 years ago. As we look back over the past millennium, the progression of fuel usage has been from the wood to coal and from coal to oil [3].

The main applications of fuel cells are likely to be in stationary or residential power generation, as replacements for batteries in portable equipment and as replacement for, or additions to, the internal combustion engine in automobiles. Each of these markets has different requirements and may use different fuels. However, the largest market and potentially the most interesting is the automotive sector [4].

John Dean of UBS Warbourg predicted a US$ 30 billion market for fuel cells by the year 2010 [5].

There are three potential application fields for the fuel cells: (i) stationary power plant for electricity production; (ii) portable power applications; and (iii) vehicles.

The aim of this paper is to show a scenario for fuel cell applications in Mexico. Switching from hydrocarbon fuel to hydrogen fuel, and a potential market for the introduction of fuel cell in stationary electrical devices, in vehicles, and some hydrogen refueling options or methanol.

2. Quality of air in Mexico

The warming up of the earth due to green house gas emission is mainly produced by CO_2. This gas is produced by the combustion reaction of fossil fuels, and the energy of this reaction (ΔH) is mostly converted in mechanical energy or electrical energy. Road transport accounts for 71% of air pollution in Mexico City and 45% of this emission comes from vehicles [6].

The main chemical composition of these emissions are 387 ppmv CO_2 (part per million in volume) and 3.3 Pg per

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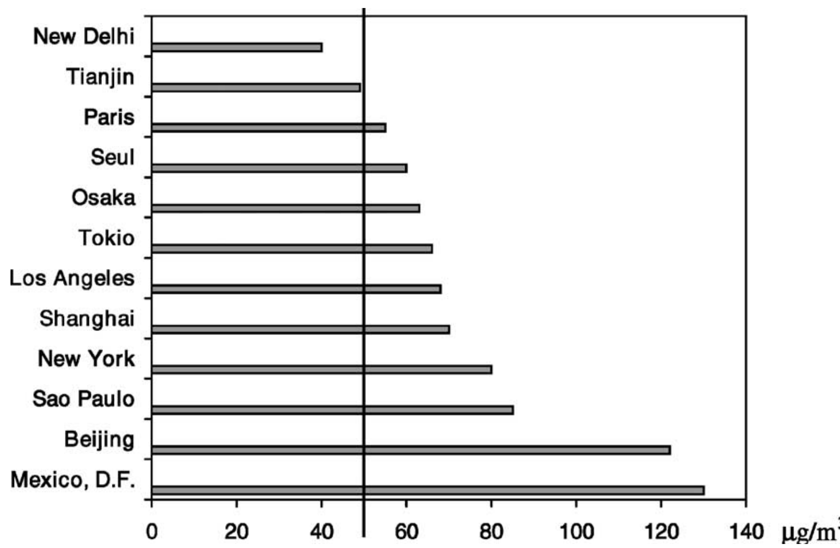

Fig. 1. Annual NO_2 concentration in the biggest cities in the world with more than 9 million habitants [22].

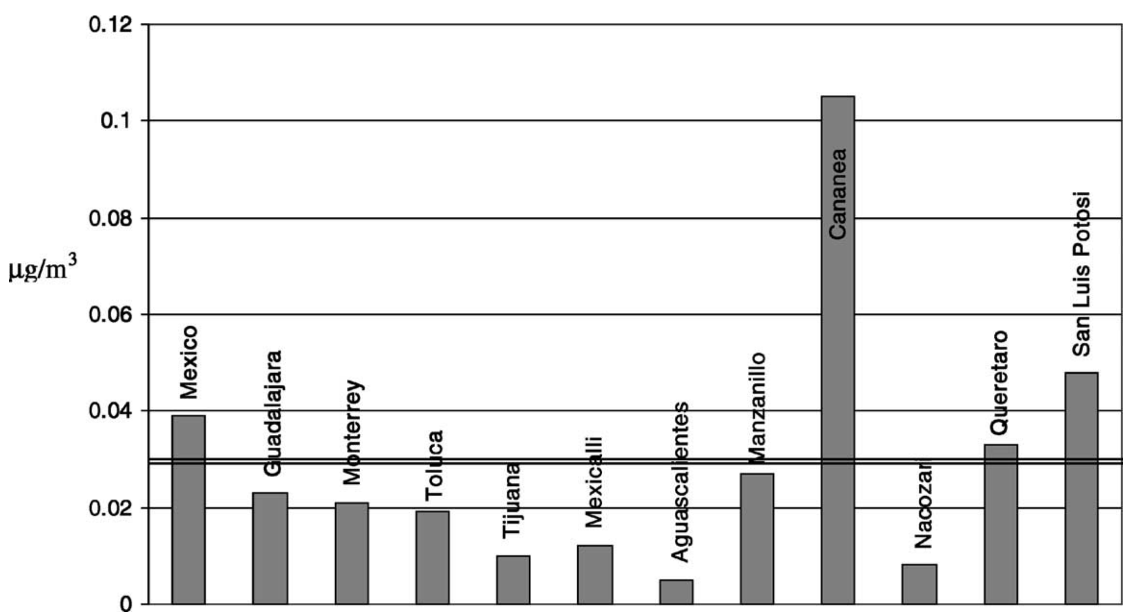

Fig. 2. Annual SO_2 concentration in the main cities in Mexico. Concentration level acceptable: <0.03 μg/m^3.

year, 1745 ppmv methane and 600 Tg per year, 314 ppmv NO_2 and 16.4 Tg per year. The residence times of these emissions are different for each chemical; residence time for CO_2 is 50–200 years, for methane 12 years, for NO_2 is 114 years. Fig. 1 compares NO_2 concentration in the biggest cities in the world and Fig. 2 compares the SO_2 concentrations in the most polluted cities in Mexico [6]. Mexico has 360 days per year of gas emissions above the limit of concentration permitted by environments legislation.

Fuel cells offer significant environmental benefits over competing technologies, hence, the environment is a strong driving force to develop fuel cell devices for transport and stationary applications.

3. Automotive transport

3.1. Alternative fuels

In the worldwide automobile market, technical developments are increasingly determined by the dramatic restriction on emissions as well as legislation on fuel consumption.

Mexico has six refining plants that process 1.555 million barrels of oil per day. Mexico comes 14th in refining capacity in the world (Table 1), and is 14th in natural gas generation with a production of 98.09 million m^3 per day. The production per day in Mexico of gasoline, diesel,

Table 1
Total world oil refining

Place	Country	Oil refining capacity (%)	Oil production (%)	Oil reserves (%)	Vehicles per 1000 habitants
1	US	20.2	10.4	2.8	765
2	Russia	11.0	8.8	4.6	124
3	China	6.6	4.4	2.3	10
4	Japan	6.1	NS	–	543
5	South Korea	2.8	NS	–	227
6	Italy	2.8	0.1	0.1	566
7	Germany	2.8	NS	–	540
8	India	2.7	1.1	0.4	12
9	France	2.4	–	–	510
10	Canada	2.3	3.6	0.6	563
11	Saudi Arabia	2.2	12.3	25.0	336
12	UK	2.2	3.6	0.5	426
13	Brazil	2.2	1.7	0.8	81
14	Mexico	1.9	4.6	2.7	138
15	Iran	1.8	5.1	8.6	23
16	Venezuela	1.6	4.3	7.3	110
17	Singapore	1.5	–	–	158
18	Spain	1.5	–	–	471
19	The Netherlands	1.5	–	–	417
20	Indonesia	1.1	1.9	0.5	21
21	Australia	1.1	1.1	0.3	619

compressed natural gas (CNG) and coke are shown in the Table 2.

The production of coke will have an additional increase of 189,000 barrels per day by the 2006 due to increase in hydrogen production. In the beginning of 2005, a new gasoline with 300 ppm of sulfide will be introduced, and by the 2010, other one with 50 ppm of sulfide (premiun). The present composition is 500–1000 ppm of sulfide for Mexican gasoline. Diesel has a concentration of 0.05% of sulfide. The use of hydrocarbons as fuel for the fuel cells requires a sulfide concentration of 30–50 ppm and less of (10 ppm) CO concentration in the gas stream [7].

In this millennium, methane gas or natural gas appear to be the preferred clean fuel of the major electricity generators. But, we are moving inexorably towards hydrogen as the ultimate clean power source of the future, with fuel cells as the electrochemical conversion devices, producing clean electricity and heat energy. In spite of the efficient systems and environmental benefits associated with fuel cell technology, it has proved difficult to convert science into commercially viable industrial products. These problems have been associated with the lack of appropriate materials or manufacturing routes that would enable the cost of electricity per kiloWatt hour to compete with the existing technology [8]. There are a large number of requirements to be met.

Table 2
Mexican fuel production and sales

Fuel	Production	Sales
Gasoline (thousand barrels per day)	392	531.4
Diesel (thousand barrels per day)	265.4	284.7
GLP (million m^3 per day)	98.09	76.17
Coke (thousand t per year)	110.2	97.0

- The fuel cell vehicle (FCV) should be able to achieve the same range of quality as a conventional car.
- The fuel should be safe.
- Refueling should be safe, quick and easy.
- Start-up and response times for the vehicle should be fast.
- The cost should be low.

Unfortunately, most hydrogen is still derived from hydrocarbons, making it expensive and difficult to store. These drawbacks will undoubtedly slow the onset of the hydrogen economy. In the meantime, we can use the hydrogen stored naturally in the hydrocarbons. The problem is a lack of understanding of the electrochemical processes involved in hydrocarbon oxidation reactions.

The direct electrochemical oxidation of dry hydrocarbon fuels to generate electrical power has the potential to accelerate substantially the use of fuel cells in transportation and distributed power applications [9].

The direct use of methanol fuel cell in a road transportation application is a promising electrochemical power source. The methanol can be derived from oil, coal or biomass. There is no limitation on the availability of methanol fuel. A liquid fuel under normal conditions of pressure and temperature, methanol can be dispensed via the existing distribution system but with some modification. The power source does not require a mini-refinery on the vehicle to convert the fuel to hydrogen. The emissions from such a vehicle would be considerably lower than that from a vehicle with a conventional internal combustion engine. Only carbon dioxide and water would be emitted [10].

But, the performance of the state-of-the-art cell at an acceptable cost is substantially lower than the requirement for road transportation applications and, almost certainly, the direct methanol fuel cell will require platinum-based catalysts for the fuel cell electrodes. If 50 million vehicles are powered by such a device, the amount of platinum required would far exceed the current production of platinum. On the other hand, if all road vehicles in the year 2010 were powered with the much better performing hydrogen air fuel cells, which use a solid polymeric acid electrolyte, then the requirements for platinum would be still about five times the total amount of metal that has been mined to date.

Nowadays, many scientists and engineers, some government and non-government companies, agencies and even finance institutions are convinced that hydrogen's physical and chemical advantages will make it an important synthetic fuel in the future. For on-board energy storage, vehicles need compact, light, safe and affordable containment. A modern, commercially available car optimized for mobility and not prestige with a range of 400 km, burns about 24 kg of petrol in a combustion engine; to cover the

Table 3
Fuel cell cost and durability targets for 2005

Application type	Road transport	Stationary
Cost (US$ kW^{-1})	<100	<1000
Durability (h)	>5000[a]	>40000

[a] Life expectancy of 10 years.

same range, 8 kg hydrogen are needed for the combustion engine version or 4 kg hydrogen for an electric car with a fuel cell [2].

3.2. Fuel cell car market

In Mexico City, 3.2 million vehicles circulate and they represent 19.5% (16.3 million) of the country's total vehicles, with a population of 22 million that represent 23% of the country's total population. The cost of each FC for a vehicle is about US$ 2000–2500 or US$ 100 kW^{-1}. The potential market will be US$ 1625 million if 0.5% of vehicles are converted from internal combustion engines to fuel cells (Table 3).

The number of cars in Mexico is assumed to grow at the rate of 5% per year. The number of fuel stations is growing at 4.7% per year and the gasoline supply is expected to increase between 2000 and 2010 at 5.3% per year.

At the present, fuel cell automobile technology must use gasoline as a source of hydrogen fuel, so a reforming process has to be utilized to produce hydrogen fuel gas. But it could be stored in a chemical form by using compressed natural gas too.

3.3. Fuel cell heavy transportation market

In the sector of the heavy vehicle, the annual growth for buses and microbuses has been of 4.9%, and the prices of diesel are assumed to grow at a rate of 4% for 2000–2010. The county's gasoline market is predicted to grow at the rate of 5.3% per year between 2000 and 2010.

The United Nations Development Program and the Global Environment Facility (UNDP-GEF) has financed projects in developing countries (mainly in Brazil, China, Egypt, India and Mexico), for hydrogen fuel cell buses, each of these countries has some of the biggest cities in the world. The GEF and the World Bank want to open the fuel cell market for public transportation and build up the hydrogen fuel cell buses (HFCB) with the lowest cost in these countries. Fuel cells could dominate the North American and Central America market if HFCBs were constructed in Mexico because of the low construction price. Another advantage is the North American Free Trade Agreement (NAFTA) between North American countries (US, Canada and Mexico); these advantages can make acceptance much faster. Many US, European or Japanese companies are installed in these countries and could take advantage of their regional position [11].

In Mexico City, in the Federal District area alone, nearly 29,575 public transportation buses—fueled by internal combustion engines—operate daily. Studies indicate that approximately 71% of the total emissions of nitrogen oxides, sulfur oxides, carbon monoxide and particulate matter are produced by internal combustion engines from car and buses circulating in Mexico City. HFCBs have become a clear technological alternative to solve the air pollution problems. Electric propulsion systems have been proved to be the most efficient both at low and high speeds.

The Secretary of Transport (SETRAVI) and Electric Transport Service (STE) of Mexico City Government with UNDP-GEF and the World Bank are investing in a demonstration project of hydrogen fuel cell buses with the objective to foster the development, manufacture and large-scale commercialization of hydrogen fuel cell buses in Mexico through the initial operation of a fleet of buses during a 5-year demonstration period. This project represents the first part of two phases [11].

Due to the high investment and maintenance cost of the trolley bus system in Mexico City, the current 450 units that will need to be replaced over the next 20 years are ideal candidates for replacement by HFCBs. It is estimated that by 2006, approximately 250 units will need to be replaced, coinciding with the proposed second phase of the project. Also, most of the large diesel buses now operating in Mexico City, and their replacements, will become candidates—due to their significant contribution to air pollution—for substitution either by HFCB or other near zero-emission hybrids, dual and electric bus alternatives, during the 2006–2010 period. But these dates may change because of problems with investment enterprises to built up and acquire chassis and FC devices respectively for HFCB construction.

Safety parameters for the proposed reformed natural gas process have been defined, and a 5000–6000 m^2 open air facility, located 600 m from a natural gas pipeline, has been identified for the reformer plant.

If this technology proves to be competitive in commercial and performance terms, the Public Transport Network (RTP) and STE would initiate the acquisition of 100 HFCBs per year starting in 2006 or 2007.

3.4. Fuel stations

There is a difficulty in bringing both a new infrastructure and a new vehicle to the market place at the same time. Obviously, hydrogen could be produced from methanol, ethanol or gasoline. Turning to methanol, there is currently no central distribution infrastructure for this fuel, but results of different studies indicate that the existing gasoline retail distribution system can be adapted to serve methanol with "few modifications." Methanol station can cost between US$ 17,000 and 70,000 per station and the equipment is very similar to a gasoline system with special attention to that ensure methanol compatible components are used. Mexico

Table 4
Fuel price in Mexico

Fuel	Price
Gasoline (US\$ l^{-1})	0.724
Diesel (US\$ l^{-1})	0.475
CNG (US\$ m^{-3})	0.217
LPG (US\$ kg^{-1})	0.621

has 4173 fuel stations and 32% of them are located in five states: Jalisco 7.1%, Mexico State 6.8%, Nuevo León 6.4%, Federal District 6.4% and Chihuahua 5.7%. If we consider 0.5% of fuel stations in Mexico will be converted from gasoline to methanol by 2011, the total cost of fuel station would be US\$ 1.45 million; at worst, a feasibility study made by Mercuri et al. [12] shows different scenarios for hydrogen production and distribution.

Mexican cars and many microbuses use gasoline as fuel, while big trucks are diesel fueled. These heavy vehicle represent 28.7% of vehicle in Mexico City and 249,500 barrels day of diesel. This constitutes the first group to convert to compressed natural gas. Seventeen thousand five hundred units have been converted to liquid petroleum gas (LPG). The prices of these fuels are shown in Table 4.

Mexico could take advantage of the market niches in the free trade agreements it has signed with the US, Canada, European Union, and most of the Latin American region, by assimilating hydrogen cells technology. Local engineering capacity in the transport sector is well developed. Of the 200 trolley buses purchased between 1997 and 1999, 4 were completely manufactured in Japan, and 19 were partially manufactured (chassis, front axis, pneumatic system, power electronics) and totally assembled in Mexico. While electric trains are not currently manufactured by national companies, three international competitors have production plants in Mexico (Alston, Mitsubishi and Siemens); and by 2005, the electronic systems should be made in Mexico, and only the fuel cell engine will be imported as we described above.

4. Stationary power generation

Producers are encouraged to promote the installation of plants that need a shorter construction time, require less risk capital and offer investment payback. Thus, in the next few decades, electricity production will be addressed preferentially towards high-efficiency large power plants. Strong efforts will be made to develop new technologies, like fuel cells, that fulfill environment safety commitments and improve production efficiency.

Fuel cell technology is a favorable candidate for the development of stationary plant for several reasons, including low environmental impact, high electrical conversion efficiency (up to 50–55%) independent of size, production of heat usable for co-generation integration with gas turbine, and flexibility.

There is a trend in many countries towards small stationary power generation plants [11,13]. These stationary systems can be used at home, residential, corporate buildings and hospitals or for UPS support. In Mexico, legislation to give one part of the electricity market to the private sector is still under debate.

Projects for the construction of four coke plants will allow an increase in the capacity in the coke national market in the next 10 years. Between 2000 and 2010, the nation's coke production will grow from 110.2 to 5854.7 Mt per year; this represent an annual increase of 48.8% (see Fig. 3).

An essential component of a fuel cell device is the electrolyte. A solid electrolyte is preferable because it allows to built more efficient and corrosion-resistant systems. The solid oxide fuel cell (SOFC) exploits the high mobility of oxygen ions O^{2-}. Commercial SOFCs are candidates for stationary power installations [14,15]. Since nowadays, the fuel cells are still relatively expensive at US\$ 3000–4000 kW^{-1}, efforts are being made to reduce the capital cost [5].

The California Power Authority has an ambitious target of acquiring 20 MW of stationary power generation in 2002 and 1000 MW by 2003 as a means to improve the

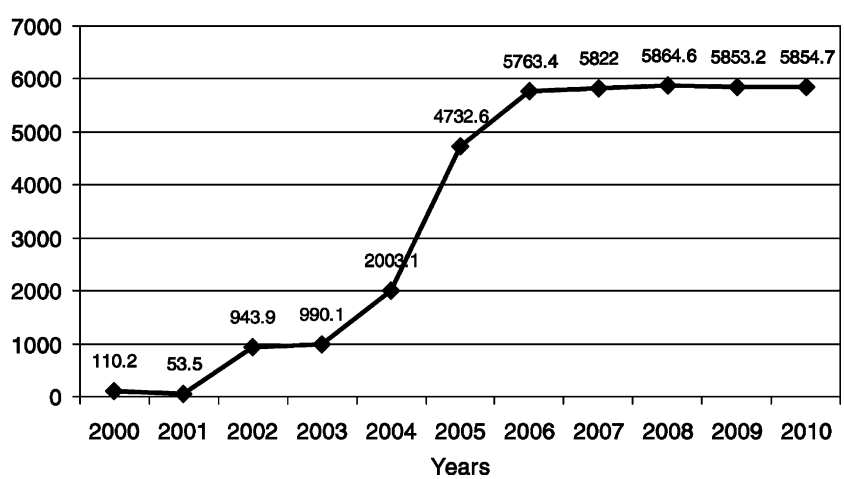

Fig. 3. Coke production between 2000 and 2010.

Table 5
Installed electrical energy capacity in Mexico (2002)

Enterprise	MW	Percentage
CFE	36238	83.2
LFC	827	2.0
Pemex	1822	4.2
Co-generation	2201	5.0
Others	2446	5.6
Total	43534	100.0

Table 7
Number of hospitals in Mexico

State	Public hospitals	Private hospitals
Veracruz	1237	60
Mexico	1028	307
Oaxaca	925	29
Chiapas	878	46
D.F.	824	162
Puebla	781	90
Jalisco	768	96
Total	14947	1740

environment and also provide reliable power supplies. The US Department of Energy through the Solid State Energy Conversion Alliance has adopted a strategy which aims to mass-produce 5 kW SOFC modular stacks with a target cost of US\$ 400 kW^{-1}.

Mexico has approximately 95 million people with 22 million homes; 6.6 million homes are in the Mexico City, 1.32 million homes in Guadalajara and 1.1 million homes in Monterey are the three biggest cities in Mexico. Electrical capacity of the plants installed in Mexico will be 43,534 MW by the end of 2002, and 90% belongs to the government (see Table 5). The electric sector will require an increment of additional capacity of 27,357 MW by 2010, 10,854 MW are in the process of construction and 16,503 MW will be developed by the private sector and a capacity of 1661 MW by 2010 has to be substituted [16].

In the future, it is planned to develop technologies to permit the use of emulsions to control residues without the use of solvents. This permits a low cost and low price of fuel. In this case, a thermoelectric generator would be favored with those combined cycle gas turbine (CCGT) plants that are considered as the base–case system for electricity generation.

The Regulation Commission of Energy (CRE) has given 21 permits for compressed natural gas distribution to the main Mexico cities (Mexico City, Guadalajara, Monterrey and Puebla). The new distribution projects represent a new fuel option for 2.3 million users in 149 municipal regions of 18 states of the country and 16 delegations of Federal Districts. Ten million inhabitants will benefit from such project (12% of the population), with a potential market of 9.02 million users (if we consider only the big cities). Until 2001, 39,708.44 km of gas network distribution has been constructed (Table 6); 9.02 million natural gas users are the potential market too for acquiring stationary power generation fuel cell systems with compressed natural gas as fuel for residential applications with 1–5 kW per user. If the price by the year 2005 is lower than US\$ 1000 kW^{-1} (see Table 3) and considering 3 kW per residence we have a potential market for stationary fuel cells of US\$ 27.06 billion.

Nowadays, there is in process in Veracruz a geographic zone project, which will permit natural gas supply to 34 municipal regions of the state with a minimum of 25,000 users by the end of 2010 [17].

Another potential market is the power supply for hospitals. In Mexico, there are 16,687 hospitals (Table 7), the average amount of electricity required by each one is approximately 100 kW with a conservative potential market of only 0.5% of hospitals to use FC power generation, we have 83 hospitals that will use FC is about 2013 with a cost US\$ 8.3 million [18–20].

5. Future R&D in FC devices in Mexico

FC research in Mexico started late, but that was 10 years ago and FC studies were started at the Mexican Petroleum

Table 6
Demand for compressed natural gas and LPG residential gas and services, 2000–2010 (million m^3 daily of equivalent natural gas)

Year	CNG	LPG	Total	Penetration natural gas as a ratio to the total	No. of people benefiting	Demand (m^3 per day per person)	Growth (%)
2000	2.46	29.04	31.50	7.8	99198613	0.316	
2001	2.58	29.49	32.07	8.0	100646110	0.319	0.4
2002	3.54	29.57	33.11	10.7	101985170	0.325	1.8
2003	4.64	29.54	34.18	13.6	103335236	0.331	1.9
2004	5.77	29.65	35.42	16.3	104643532	0.340	2.2
2005	6.79	29.91	36.70	18.5	105900036	0.345	2.4
2006	7.70	30.59	38.29	20.1	107127013	0.356	3.0
2007	8.41	30.99	39.40	21.4	108318168	0.365	1.8
2008	9.08	31.35	40.43	22.5	109474008	0.370	1.5
2009	9.79	32.03	41.82	23.4	110595414	0.379	2.3
2010	10.44	32.91	43.35	24.1	111683885	0.387	2.6

Table 8
Applications vs. the most suitable fuel cell technology

Size (kiloWatt rated)	Applications	User	FC technology
Micro (<1 kW)	Portable, personal	Commercial	PAFC/SPFC
Small (1–5 kW)	Residential (high-value entry)[a]	Utility/commercial	PAFC/SPFC/SOFC
	Uninterruptible power (UPS)	Commercial	
	Remote applications	Utility	
Medium (5–300 kW)	Commercial/industrial[a]	Utility	PAFC/MCFC/SOFC/SPFC
	Automotive	Commercial/utility	
	Aircraft	Commercial	
	UPS	Commercial/utility	
Large (100 kW–50 MW)	Transportation (locomotives, buses)	Commercial	
	Aircraft/ships	Commercial	MCFC/SOFC, possibly in combination a gas turbine
	Energy industry[a]	Commercial/utility	

[a] Possibly implies CHP.

Institute (IMP) by D.H. Cuatecontzi with a PAFC system, but this research was not continued. Since 1997, investigations have started again and many studies on the PEMFC devices were made by many universities like Chihuahua University State, UNAM, UDLA, ITESM, or government institutions such as IMP, IIE, CINVESTAV, CIDETEQ, ININ and others. They are pioneers on this domain in Mexico mainly in the development of PEMFC. But to date, SOFC device research has not yet started, and the importance of these systems for residential applications and for large plants (as it is shown at the Table 8) is high.

The advantage of MCFC and SOFC is that they use cheaper materials than PEMFC or PAFC and the benefits are mentioned by the World Bank Group report [21]. SOFC devices can be used above 1 MW. Systems of 200 kW (SOFC or PEMFC) can give enough electrical energy for 30–50 homes and can be used in rural regions or isolated villages. SOFC can substitute over the next decade the CCGT or can be integrated together as hybrid systems for large power generation with low environment impact and high efficiency (Fig. 4) [20].

In Mexico, a strategic national plan to develop, demonstrate, obtain experience, be prepared and open the market

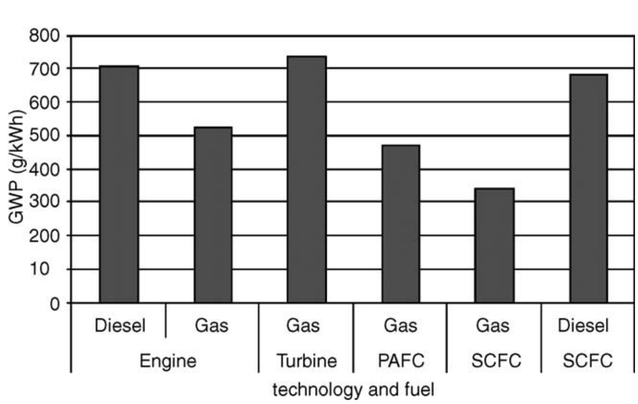

Fig. 4. Representative GWP for technologies <250 kW.

has yet not started, so the potential to address this market could be lost to foreign companies.

6. Conclusions

It is expected that fossil fuels will be less readily available, increasing dependence on energy conservation and alternative energy sources. Fuel cells are being considered as a technology for locomotion and electrical power generation systems. Large demonstration programs are being carried out in Europe, in US and Japan, particularly using polymer electrolyte fuel cells. In Mexico, such demonstration projects will allow the insertion of FC devices in transportation and are capable of introducing the concept of hydrogen energy. The HFCBs have advantages over fuel alternatives, since hydrogen can be produced on-board by means of a reformer system or with hydrogen produced at the depot. The HFCB project will serve to open markets not only for transportation systems but also for stationary and portable systems.

Introduction of FC cars is more complicated due to problems of placing reformer devices on-board or for hydrogen fueling for stations that must be installed. The development of FC technology will be able to permit the use of several possible fuels such as gasoline, natural gas or methanol, because the existence of an infrastructure to distribute gasoline and natural gas make these relatively attractive options. All the hydrogen supply options appear to have future market potential.

FC systems in stationary applications have a clear advantage in terms of emission reductions and energy use. Global benefits for the use of the FC in the transportation and stationary sectors will be the reduction of green house gas, achieving satisfactory air quality standards not only in Mexico City but all over the country. The Mexican government needs to provide a development plan not only for fuel cell transportation but also for stationary systems with legislation for the establishment of quality production standards for fuel cell vehicles, and stationary power generation and their impact on the environment.

The next step will be to consider the end-of-life management strategy option for the electrolyte, electrocatalysts, bipolar plates and ancillary component of fuel cell devices. European Union vehicle waste directive considers that 85 wt.% of vehicle must be re-usable and/or recycle at a minimum. Legislation for recycling stationary and portable systems must be taken into consideration too.

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