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Roadmap towards a sustainable hydrogen economy in Mexico

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Abstract

The fast developing of fuel cell (FC) technologies has open a window to alternative energy sources such as natural gas, methanol, ethanol, or hydrogen. This paper outlines the prospects for a hydrogen economy in Mexico.

If we consider a hydrogen economy in Mexico in the near future and if all the national energy could be produced by hydrogen, the country will require 46.5 million tons per year. By 2010, it would have approximately 3300 automobiles with fuel cells. In the initial phase of a "hydrogen economy", hydrogen could be produced from the current competitive fossil fuels. Hydrogen is a unique fuel with unmatched properties. In the Mexican hydrogen industry, we do not know yet how many tons of hydrogen per year are produced for the different uses of chemical production, oil refining, metal treating or electrical applications. At this moment, hydrogen national resources are 837.7 million tons, which reverts a huge potential in hydrocarbon resources.

Hydrogen costs from natural gas are about three times the cost of the feedstock, thus US$ 6 feedstock gas would result in the hydrogen costing US$ 18 per million of Btu, which is equivalent to gasoline costing about US$ 2 per gallon.

Keywords: Hydrogen economy; Stationary power sources; Transport power sources; Reserves of hydrogen

1. Introduction

The "hydrogen economy" phrase was used in 1970 by General Motor's (GM) engineers who foresaw hydrogen as "the fuel for all types of transport".

The fast developing of fuel cell (FC) technologies has opened a window to other alternatives of energy sources such as natural gas, methanol, ethanol or hydrogen. This last one has the advantage to produce water as the product.

"Hydrogen economy" means that hydrogen would be used to transport energy from renewable (at nuclear or solar sources) over large distances; and to store it (for supplying cities) in large amounts [1]. The hydrogen can be used in two different ways. Firstly, to create electricity from fuel cells at efficiencies of ~60% and secondly, can be cleanly combusted in air to give energy for space heating, replacing the natural gas in industry and run aircraft, trains and ships.

The notion of a "hydrogen economy" is moving beyond the realm of scientists and engineers and into the lexicon of political and business leaders. The potential of fuel cells as successors to batteries in portable electronics, power plants, and the internal combustion engines, will allow reduction in air pollution. The fact that the hydrogen economy in the future is inevitable, the hydrogen technologies have the potential to cut down on hydrocarbon consumption.

But, where would the hydrogen come from? Government and industry support the hydrocarbon economy. But they are pursuing an incremental route, using gasoline or methanol as hydrogen source, with fuel reformed on board for vehicles or in the service station.

To extract hydrogen from water in the year of 2020 would be ~20% more expensive than the current cost of gasoline production—taking into account the additional cost due to environmental and health damages of using gasoline [1].

The cost of gasoline in Mexico is US$ 0.724 per liter but the cost of pollution due to the use of gasoline must be taken into account. Bockris [1] points out that this cost is almost the same as the gasoline price, so the real cost of gasoline in Mexico could be US$ 1.45 per liter.

Differences in the marginal costs of reducing greenhouse gases (GHG) may vary significantly depending on the country. In particular, marginal costs differ between industrialized countries—the source of the majority of GHG emissions—and economies in transition or developing countries. By way of illustration, some estimations show that the cost per ton of carbon [emissions] that is produced in industrialized countries is near US$ 35–50 per ton. In contrast, the estimated cost to reduce a ton of carbon

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[emissions] in developing countries is in the range of US$ 10 per ton or less [2].

Even though, in refinery, hydrogen generation produces a significant quantity of CO_2, typically 10 kg CO_2/kg H_2 product.

Hydrogen can be produced from a variety of sources, including fossil fuels, renewable sources such as wind, solar or biomass, nuclear or solar heat-powered, thermochemical reactions and solar photolysis or biological methods.

This paper outlines the perspective of a hydrogen economy in Mexico. Different scenarios are presented for how much hydrogen we will need in a near future. These scenarios point to stationary and transportation power systems.

1.1. Planning logic of the typical vision and roadmap process

This roadmap process will need to address a number of areas:

- technologies for hydrogen production;
- technologies for hydrogen delivery and transportation;
- technologies for hydrogen storage;
- technologies for hydrogen conversion;
- scope and directions for public–private partnerships, both nationally and internationally;
- codes and standards for safe production, delivery, and use of hydrogen;
- education of public, government and private decision-makers about the potential benefits from the expanded use of hydrogen;
- end-use energy markets for hydrogen including the potential for “first use” fleet applications in federal facilities, vehicles, and equipment.

Participants in the roadmap process should include technical experts and industry practitioners from domestic and international organizations. As they have the requisite capabilities and experience to chart the critical hydrogen energy development pathways over the next several decades (see Table 1).

The roadmap needs to be systematic, from source to end-use. Interfaces matter, for example, it may not be the best to have refueling stations at one pressure and onboard storage tanks at another.

Table 1
Hydrogen energy roadmap

Roadmap areas	Roadmap participants
Technology development	Industry, universities, national laboratories
Market applications	Equipment manufacturers, industrial end users, building owners and operators, and Federal energy managers
Public education	Federal, state, and local governments; school districts; universities; media companies
Codes and standards	State and local governments, professional associations, standards organizations

1.2. Achieving the objectives by the H_2 roadmap

The roadmap provides the basic tools for the elaboration of a strategy [3]:

- basic requirements of H_2 infrastructure;
- state and development potential of the technologies;
- determination of costs and economically reasonable plant sizes;
- description of the fundamental phases for the implementation of a H_2 infrastructure, milestone definitions, analysis of minimum time requirements;
- identification of interdependencies of various societal and business sectors (politics, infrastructure industry, automotive industry, customers, financing, insurance);
- identification of interdependencies of various components and subsystems of a H_2 infrastructure (generation, transport, service stations, vehicles, approvals);
- compilation of supportive political boundary conditions;
- presentation of favorable external factors (climate change, resources availability, dependency on energy imports, global motorization, strategies of other countries like USA or Japan, European Union, technology development, etc.).

It estimates that whatever could be the scenario, the growth, the vector energy choice or the abundance selected by developing countries, these countries will consume 70% of world wide energy between the years of 2050 and 2060, this means 10 billions tons of petroleum equivalent (TPE). Today, they consume between 10 and 15% of worldwide energy [4].

The current energy situation in Mexico is presented as follows: in 2000, the national energy consumption was 6368.4 Petajoule and the expectation for this year is 6607 Petajoule.

If we consider a hydrogen economy in Mexico in the near future, and if all the national energy could be produced by hydrogen, the country will require 46.5 million tons per year (see Table 2).

Table 2
Conversion factors and economic assumptions [23]

1 GJ (gigajoule) = 0.95 millions Btu
1 EJ (exajoule) = 0.95 quadrillions 10^{15} Btu
1 million scf (standard cubic feet) = 26,850 normal cubic meters (m_N^3) = 343 GJ HHV
1 million scf per day = 2.66 ton per day = 3.97 MW H_2 (based on the HHV of hydrogen)
1 scf H_2 = 343 kJ HHV = 325 Btu HHV
1 lb H_2 = 64.4 MJ HHV = 61.4 kBtu HHV = 187.8 scf
1 m_N^3 = 12.8 MJ HHV; 1 kg H_2 = 141.9 MJ HHV = 414 scf
1 gallon gasoline = 130.8 MJ HHV = 115,400 Btu/gallon LHV
Gasoline heating value = 45.9 MJ/kg HHV = 43.0 MJ/kg LHV
US$1 per gallon gasoline = US$7.67 per GJ HHV
1 ton of petroleum = 7.33 barrel of petroleum

HHV, high heating value; LHV, low heating value.

Table 3
Final consumption of power by sector in Mexico (Petajoules) [24]

Year	Transport	Industrial	Residential, commercial, and public	Farming	Total
1995	1399	1255	816	94	3564
1996	1419	1283	838	101	3640
1997	1478	1288	841	107	3714
1998	1527	1321	869	107	3823
1999	1548	1242	805	117	3712
2000	1614	1234	837	116	3801

It is proper to use the higher heating value (HHV), heat of formation, for this energy analysis, because it reflects the real energy content of the fuel based on the energy conservation principle (First Law of Thermodynamics). Since the heat of formation or the higher heating value rules the production of hydrogen, its use should also be related to its HHV energy content. The following volumetric higher heating values for hydrogen at 1 bar and 25 °C will be used in this study.

The lower heating value (LHV) is a technical standard created in the 19th century by boiler engineers confronted with problems of corrosion in the chimneys of coal-fired furnaces caused by condensation of sulfuric acid and other aggressive substances.

The power demand in the year 2000 was distributed as follows: 37% exports, 15% transport, 13% industry, 8% residential, commercial and public sector, 8% power sector, 2% no power consumption, 1% farming sector and 16% other uses (cf. Table 3) [5].

According to data provided in Table 3 and statistical data of Secretary of Energy (SENER) estimations were made in short, mid and long term, which are shown in Table 4. Also shown is the possible hydrogen consumption that could to be required for the different sectors in Mexico in the upcoming years. It is possible to notice in Tables 3 and 4 a tendency for decrease in the power consumption required by the private industry, and this does not imply that they are closing companies in Mexico. The majority of these companies generate their own electrical consumption and the rest of them are taken from the electrical network. In some cases, they can sell their electrical excesses to the Electrical Federal Commission (abbreviation in Spanish CFE). Therefore, these data is based on the industry power consumption, which is taken from the main electrical network.

2. Transport sector

In agreement with Table 3, in the year of 2000, the power consumption for this sector was of 1614 Petajoules. This consumption would require around 11.3 million tons of H_2 to satisfy the transport sector.

2.1. Cost and consumption of H_2 by the national vehicular park

By year 2010, there will be around 16.3 million cars in Mexico; considering that only 0.5% of new cars have a FC (annual growth world-wide is 1% and in developed countries it is expected to be a lower percentage). Considering the perspective of an annual average growth of 4% in sales of the automotive industry in Mexico during the next years, there would be approximately 3300 automobiles in the year 2010 with a FC [6]. An economy size car would consume 4 kg of hydrogen for a distance of 400 km approximately. Taking into account this size of car and considering a 4-day period of refueling as an average, the consumption of H_2 would be 3.5 kg of hydrogen. It would require a total of 3 ton H_2 per day for supplying these automobiles and four mid service

Table 4
Power demand and equivalent H_2 production for different sectors in Mexico, in 2003–2030

	Year						
	2003	2005	2010	2015	2020	2025	2030
Transport							
Petajoules	1734	1820	2037	2252	2468	2684	2900
Million tons H_2	12.2	12.82	14.35	16.82	17.39	18.91	20.43
Industrial							
Petajoules	3246	3237	3213	3190	3137	3145	3122
Million tons H_2	22.87	22.81	22.64	22.48	22.10	22.16	22.00
Residential, commercial, and public							
Petajoules	1012	1066	1214	1384	1577	1797	2047
Million tons H_2	7.13	7.51	8.55	9.75	11.11	12.66	14.42
Farming							
Petajoules	131	140	163	186	208	231	253
Million tons H_2	0.92	0.98	1.14	1.31	1.46	1.62	1.78
Total							
Petajoules	6123	6263	6627	7012	7390	7857	8322
Million tons H_2	43.15	44.13	46.70	49.41	52.07	55.36	58.64

stations of 900 kg H_2 per day of capacity. In addition, there would be sales of US$ 2.8 million per year at a price of US$ 2.6 per kg H_2 [7].

In 2030, it is expected that 60% of vehicles will have a FC. In years 2010–2030, there will be a low rate growth of 2%. By then, we would have approximately 22.4 million automobiles and around 13.4 million automobiles on fuel cells in Mexico. The cost of H_2 is assumed to increase by 2% for the next decades. Hence, in the year of 2030 the price of H_2 would be US$ 3.64 per kilogram. This represents a national consumption of 11,725 ton H_2 per day and sales by US$ 42,700 million per day in the vehicular sector. Moreover, it will require around 13,000 stations for the provision of H_2 with a capacity of 900 kg per day. Mexico now has 4,173 service stations with a rate growth of 4.7%. The growth for this period has been constant and sharp. If we consider that this growth will be the same for the following years, we would have in 2030, 9.5 thousand of services stations. That means an increase in service stations capacity to 1.2 ton H_2 per day.

3. Stationary electric power generation

Electricity production using combustion of natural gas and coal (and with a substantial gain in efficiency) will be increasingly replaced by hydrogen devices such as fuel cells.

In the initial phase of a “hydrogen economy”, hydrogen could be produced from the current competitive fossil fuels. As a last step, the production system could evolve toward renewable resources [8].

Hydrogen is a unique fuel with unmatched properties. One of its unique properties is that it can be converted to electricity by electrochemical reactions in fuel cells with high efficiencies. It is not subject to the limitations of the Carnot Cycle, which is the case with the present-day thermal power plants whether they burn fossil fuels or nuclear fuels. Because of this high utilization efficiency advantage of hydrogen in electrical utilities, manufacturers of electric power equipment, power industry and organization researches have taken a particular interest in electric power generation through hydrogen fuel cells.

3.1. Consumption of H_2 for residential and commercial uses

3.1.1. First scenario

Mexico has 22 million homes that could require a total of 10.7 million tons H_2 per year and sales of US$ 27 billion per year, considering an average installed capacity of 2 kW for each home using 2.66 ton H_2 per day which are equivalent to 3.97 MW (cf. Table 2).

By the 2010, the distribution lines of compressed natural gas (CNG) will reach 9 million users. However, instead of natural gas they will be used for distribution of H_2, transporting 4.5 million tons of H_2 per year with sales of US$ 11.6 billion per year.

Table 5
Power consumption and H_2 production required for domestic and commercial sectors in 2003–2030

Year	Sales (GW-hr)		Million tons of hydrogen	
	Domestic	Commercial	Domestic	Commercial
2003	44,492	11,175	1.13	0.28
2005	50,466	11,986	1.28	0.30
2010	59,152	14,278	1.50	0.36
2015	94,756	17,008	2.40	0.43
2020	129,841	20,261	3.29	0.51
2025	177,916	24,136	4.50	0.61
2030	243,791	28,752	6.18	0.73

Table 6
Power capacity in the year 2002

	MW	(%)
CFE	36,238	83.2
LFC	827	2.0
Pemex	1,822	4.2
PIE	2,446	5.6
Self-supplying and/or co-generation	2,201	5.0
Total (%)	43,534	100.0

3.1.2. Second scenario

According to data provided by the Secretary of Energy in Table 5, the sales of electrical energy for these sectors are shown.

Based on trends reported elsewhere [8–10], different studies have been made to determine a possible percentage for fuel cells in stationary systems for electric power generation (Tables 6 and 7). At present, some companies in Mexico are participating in the aid supported by the Global Environment Facility (GEF) favoring the acquisition of fuel cells for stationary systems. This could act as a catalyst for this market indicating, by 2005 a 5–7 MW installed capacity of fuel cells.

As is observed in Table 7, the use of the fuel cells will not in the long term reach 50% of the national installed

Table 7
National capacity of stationary power systems and H_2 production required in 2003–2100

Year	National capacity installed estimated (MW)	Percent of the national capacity installed in the generation of electrical power by means of fuel cells (%)	Amount of hydrogen required (thousand tons)
2003	44,000	0	0
2005	50,329	0.016	1.9
2010	64,000	0.078	12.0
2015	74,700	0.5	89.8
2020	83,200	7.6	1,533
2025	92,800	14.2	3,212
2030	102,400	20	5,000
2050	140,800	36	12,373
2100	236,800	49	28,360

Table 8
Mexico: installed capacity, sales and large demand of electricity

	2001	2010	Increasing	Index of annual growth (%)
Installed capacity (MW)	36,659	64,000	27,340 MW + 75%	6.4
Large demand (MW)	26,197	44,767	18,570 MW + 71%	6.1

capacity of power systems. This it is not only due to the worldwide tendencies, but in addition, at the end of 1990s, 13% of the national capacity had systems of combined cycle. Moreover, by 2010 it is estimated that the CCTG will include 45% of the national electrical capacity. It is necessary to emphasize that these systems display a life cycle of 20–25 years. In 2010, Mexico does not consider the use of fuel cells within its national plan of electric generation. It is expected that the application of the fuel cells in residential uses, commerce, etc. is not already in the commercialization phase at a worldwide level, and by this year, with a lifetime greater than 5 years and with a lower cost of US$ 1000 per kilowatt installed capacity, this will allow fast penetration within the national electric market for the years after 2010. On the other hand, as it is known, the use of FC and CCTG altogether, increase the electrical efficiency to 90%. Motivation for which the fuel cells could be connected in a future to the present systems of CCTG and this estimation in the use of FC would be above 15% in 2025.

The country is prepared to undertake an important expansion in the electrical sector to satisfy increasing demand. It is anticipated that the power provision in Mexico will increase 75% during the next 9 years, a growth index above the United States or Canada (Table 8). Most of the investments planned to now, tend to use natural gas power systems, and at the end of this decade, 85% of the electricity in Mexico will be generated from fossil fuels. Although a change from petroleum to natural gas is expected, because combustion is cleaner, the emissions of atmospheric polluting agents would still be elevated.

3.2. Hydrogen production today

The best of our knowledge we do not know exactly how many tons of hydrogen per year are produced in Mexico for use in chemical production, petroleum refining, metal treating, or electrical applications. The most hydrogen production could be found in the Mexican petroleum industry (PEMEX) [11] (Table 9).

In a future, hydrogen can be produced in centralized facilities or at decentralized locations, where it will be used onsite. In centralized facilities, hydrogen is distributed to an energy conversion device via pipeline or stored to be shipped via rail or truck. When hydrogen will be produced onsite, it can be stored and/or fed directly into conversion devices for stationary, mobile and portable applications.

In Mexico, most of the H_2 produced is for auto consumption, such as in hydrodesulphurization plants. At this moment, PEMEX has reformation systems to generate its own consumption of H_2 for different uses like chemical processes where it is required. Cadereyta refinery, for example, has a reformation system for natural gas of 60 millions scfd of H_2 capacity with purity from 95 to 98% that is used in the hydrodesulphurization units. These 60 million scfd or 1.6 million normal cubic meter (ncm) per day or 58 ton per year of H_2, would be equivalent to 238 MW of electrical power that could be generated.

4. Future infrastructure required

Of course, consumption of a certain amount of energy is required to extract hydrogen from reforming of hydrocarbon molecules by means of catalysis. Alternatively, obtaining it from water, with generating cells are so highly efficient, when compensates the use of a certain degree of energy to obtain the electrical generation. A kilogram of hydrogen is equivalent in energy to 1 gallon of gasoline or diesel engine obtained from petroleum. Nowadays, a kilogram of hydrogen costs between four and six times more than 1 gallon of gasoline or diesel, nevertheless, the advantage is the energy of 1 kg of hydrogen is a double of 1 gallon of gasoline [12–14].

A national network must be in place to provide the hydrogen to users in every region, state, and locality. The network must evolve from the existing fossil fuel-based infrastructure and will accommodate both centralized and decentralized production facilities. Pipelines will be the preferred choice

Table 9
Hydrogen production in Mexico in 1990–2001

Sectors	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Refining (thousand tons)												
Hydrogen	27	26	28	31	31	30	27	49	52	48	NA	NA
Petrochemical (thousand tons)												
Hydrogen	8	12	11	12	18	19	15	15	12	15	2	NA

NA, nonavailable.

for distributing hydrogen to high-demand areas. Trucks and rails will be used to distribute hydrogen to rural and other lower-demand areas. On-site, hydrogen production and distribution facilities will be available where demand is high enough to sustain this technology.

4.1. Renewable energies

In the past, it was considered that the renewable energy was not an income-producing option for electrical production on large scale. However, the prices have a dropped to such a degree that some forms of renewable energy can already economically compete with the energy coming from conventional sources like fossil fuels, mainly if the environmental costs of these are considered. In 2000, Mexican industry paid for electricity on average 5.29 cents of dollar per kilowatt-hour [kW h]. Nowadays, it is possible to produce energy for less than 5 cents/kW h in zones where the wind reaches average speeds of more than 7 m/s. At this moment, the solar modules of photovoltaic cells allow electricity to cost from 30 to 40 cents of US$ per kilowatt-hour. However, it is expected that this cost with be less than 10 cents during the next decade.

Nevertheless, it must be indicated that the costs of construction plants for renewable energy are more elevated than those conventional power plants with fossil resources. The estimate to build a modern power plant driven by gas is US$ 400 per kilowatt. Whereas, the cost of an wind renewable energy plant is US$ 1000 per kilowatt and a solar plant can reach up to US$ 4000 per kilowatt (similar cost to a FC).

4.1.1. Aeolian energy

The country has an aeolian potential of 5000–15,000 MW. (For comparison effects, it must remark that the present capacity of electrical generation in Mexico is 40,000 MW).

4.1.2. Solar energy

Almost three fourth parts of the Mexican territory are regions of high solar irradiation. With an average of 290 sunny days in a typical year, the roof of a small average house could generate 100 times more electricity than the normal average consumption in most of the homes.

The combination of aeolian and solar type systems is a good option since usually when it is sunny, it is not windy, and vice versa, therefore, it would be good to take advantage from these two types of energy.

It should be noted that Rural Program of Electrification will be extended to supply electricity to marginalized areas with a strong indigenous presence. It can constitute a source of demand for development of renewable energies in particular with those of photovoltaic devices. If we consider that 860 of 1200 indigenous communities, could be supplied with electricity from photovoltaic modules, assuming a 25 kW h of consumption per community. We expect a development of an installed capacity of approximately 22 MW of photovoltaic cells.

On the other hand, it is expected that by the 2030 CCTG plants will correspond to 57% of the national capacity. The total hydrogen consumption considered in 2030 would be 20.5 million tons H_2, with another scenario considering the majority H_2 as the energy vector. This scenario would represent 82,000 MW of power or 80% of the national capacity by 2030.

With more than 12 million clients "Maxi Gas" will increase by 40% its number of clients in Mexico [15].

Most important will be to grow the industrial sector. With the conversion to natural gas, the industries can obtain savings of almost 50%, whereas in the domestic sector savings are between 15 and 20%.

According to trends, in 2030 it is projected that Mexico will have about 38 million homes, 30% will be in Mexico City, 6% will be in Guadalajara, and 5% will be in Monterrey. They are the biggest cities of the country, which would represent a consumption of 3.6 million tons of H_2 per year (2 kW of consumption in average for each home). This consumption of H_2 could be generated by means of gasification plants of coal, coke of petroleum or biomass, oxidizing commerce and industries within these cities (see Table 10).

More refiners now appear to be prepared to move into non-traditional areas (e.g. power generation) and look at this, at the same time, as an opportunity to address hydrogen production (through gasification of residue or coke) [16].

The national refinery system (SNR) has six refineries in the country. PEMEX represents 4% of the consumption of national electrical energy. We can consider that most of this energy generated in these six refineries comes from a large-scale partial oxidation system or from gasification. If it could as well generate 12% of electrical power required at national level, we would have an annual hydrogen production of 4 million tons (Table 10).

On the other hand, PEMEX has analyzed possible projects for co-generation, among which they emphasize those that would be located in Petroquímica Cangrejera and in Complejo Procesador de Gas de Nuevo PEMEX. The installable capacity of these projects could be located in the range 600–1000 MW in Cangrejera, and 250–500 MW in Nuevo

Table 10
Hydrogen production and infrastructure in 2030

Combination of distributed and centralized hydrogen production for year 2030	Total 20.5 million tons of hydrogen
9,500 small reformers in refueling stations	4.5 million tons
173,000 neighborhood electrolyzers	3 million tons (solar and Aeolian energy)
13 coal/biomass gasification plants for big cities	6 million tons
9 large heavy oil, coke and gas SMR/gasification power plants	9 million tons
6 large heavy oil, coke and gas SMR/gasification refineries	1 million tons of auto consumption (4% of the national capacity) 3 million tons

Table 11
National potential for co-generation

Sector	With additional fuel (MW)		Without additional fuel (MW)		Percent participation (%)
	Theoric	Technical/economic	Theoric	Technical/economic	
Industrial	5,200	1,820	9,750	3,410	62
Pemex petrochemical	1,610	565	3,000	1,060	19
Pemex refinement	780	275	1,470	515	10
Commercial	770	271	1,450	510	9
Total	8,360	2,931	15,670	5,495	100

Greater information to be address to the National Potential document of co-generation, Conae, Mexico, 1995.

PEMEX. Additionally, PEMEX also has started the analysis of co-generation potential in its refineries. The National Commission for Saving Energy (CONAE) has identified, in preliminary studies, the potential for co-generation in PEMEX from 2400 to 4500 MW of capacity. A big interest exists to impel the development of these projects to support the incorporation of new capacity of power generation in Mexico through the participation of private investment (Table 11) [17].

With prior gasification, coke could be used as a pollution free fuel (H_2-syngas) that could be used to replace natural gas for power generation, helping to reduce the demand for gas decreasing with the risk of a potential price shock. Gasification could be carried on in the refinery and H_2-syngas could be used not only to produce power for the internal needs in the refinery, but also to alleviate the high demand of hydrogen in some processes (hydrocracking, hydrodesulphurization, etc.). However, for gasification to occur, important investments should be conducted. Other means of coke disposal also exist and include burning it in furnaces of the cement industry.

4.2. Ultra clean fuels and their use of hydrogen

Due to environmental norms in the national and international sphere and the increasing trend to control sulfur, nitrogen, and aromatics, the next fuels will have to contain minimum concentrations of these compounds. The elimination of these compounds is carried out by means of hydrodesulphuration processes, denitrogenation processes, and hydrogenation of aromatics. These processes require high purity hydrogen feeding for the conversion to compounds easy to eliminate like H_2S, NH_3, and noncancerigenic compounds like the hexane. When these norms take effect, the demand of hydrogen will increase.

In order to obtain ultra clean fuel, the Fischer Tropsch process must be applied. In these two cases, hydrogen generation is indispensable for obtaining a much better and cleaner fuel.

4.3. Storage

Storage of hydrogen is one of the issues to be solved because of hydrogen is stored at pressures of 345 bars. Nowadays, tanks can store it under safe conditions but they are quite expensive. It will be required to produce them with competitive costs for transporting tanks about 500 km and having a life utility of 250,000 km. In addition, must work in the range from 40 to −40 °C. Now, these tanks are made of carbon fibers that are still very expensive.

4.4. Current hydrogen production costs

Since a gallon of gasoline has about 115,000 Btus, and its production cost is US$ 1.15 per gallon so its energy cost is US$ 10 per million Btu (mBtu). By contrast, although natural gas prices over the past decade have been in the range of US$ 2 per mBtu, current natural gas prices are now in the range of US$ 4 per mBtu.

Moreover, natural gas prices are expected to continue increasing as the available reserves are exponentially consumed. As a rule, hydrogen costs from natural gas are about three times the cost of feedstock, thus $6.00 feedstock gas would result in the hydrogen price of $18.00 per mBtu, which is equivalent to gasoline costing about $2.00 a gallon [18].

In some locations, for example in the USA, natural gas prices have shown a considerable increase and volatility. In the winter of 2000/2001, natural gas prices in the USA reached US$ 9–10 per mBtu. At these prices, gasification of low refinery residual values for power generation is the best option. Gasification can be used to meet this rising demand and at the same time allow the refineries to exit from unprofitable declining fuel oil markets and focus their efforts on the production of high margin products [19].

5. Reserves of hydrogen from non-renewable sources in Mexico

The viability of the generation of hydrogen from renewable sources has not reached the performance and cost necessary to be commercial. To make it more competitive generation from hydrocarbons is necessary.

5.1. Oil reserves

In Table 12, oil reserves will last for 40 years. After this time it will be necessary to have renewable energies. There

Table 12
World-wide petroleum reserves and their duration

	Reserve billion (bls)	Production million (bls per day)	Durability (years)
OPEP member country			
Saudi Arabia	264.2	8.7	83.1
Iraq	112.5	2.7	114.1
U.A. Emirates	98.3	2.3	117.0
Kuwait	94.1	1.8	143.2
Iran	89.7	3.5	70.2
Venezuela	77.4	3.0	71.0
Venezuela Bituminous	260.3	0.9	240.0
Libya	29.5	1.4	58.0
Nigeria	22.5	2.0	30.8
Qatar	13.2	0.7	51.6
Algeria	9.2	08	31.5
Indonesia	5.0	1.3	11.0
Sub total OPEP	815.6	28.2	79.2
No OPEP member country			
Russia	56.8	7.6	20.4
Mexico	28.3	3.0	25.8
China	24.0	3.3	20.0
USA	21.8	7.4	8.0
Norway	9.5	3.2	8.1
Brazil	8.1	1.1	20.1
England	5.0	2.5	5.4
Canada	4.7	2.0	6.4
India	4.7	0.6	21.4
Egypt	3.0	0.8	10.2
Colombia	2.8	0.7	10.9
Ecuador	2.1	0.4	14.3
Others	43.2	7.9	14.9
Sub total no OPEP	214.0	37.2	15.7
Total World	1029.6	65.4	43.1

are gas deposits at great depths in oceans and seas, whose reserves would last for more than 100 years. Nevertheless, the cost of operation would be high.

Now, proven reserves are 155 trillions cubic meters worldwide and an annual consumption of 3.09 trillions cubic meters of CNG would deplete it after 50 years [20].

Mexico counts on proven reserves of 28.3 billions of petroleum barrels. Petroleum reserves have by almost 26 years, that is means, 2030 it will be depleted.

Finally, Mexican petroleum has a composition of carbon and hydrogen of 76–86 and 10–14% by weight, respectively. This gives us a total of 386–540 million tons of H_2, which would give a total of 19–27 years of hydrogen reserves at this moment.

5.2. *Reserves of CNG*

The proven compressed natural gas reserves in Mexico are 806,109 m^3 this would allow generation of 276 million tons of H_2 (25 kmol CNG/kmol H_2) for an annual consumption of 20 million tons. This volume of production would be reached after a 14-year period of commercialization.

Table 13
Coal reserves in Mexico by state and river basin (million tons)

State	River basin	Million tons
Coahuila	Villa de Fuentes–Río Escondido	535
Nuevo León	Colombia	92
Oaxaca	La Mixteca	31
Sonora	Barranca	5
Total		663

Source: SENER, PDRSE (1995–2000) [25].

Table 14
Reserves of H_2 from nonrenewable sources

Hydrocarbon	Reserves	Million tons H_2	Durability (years)
Petroleum	3,860 million tons	463	23
CNG	306 billion m^3	276	14
Coal	663 million tons	98.7	5
Total		837.7	40

5.3. *Coal reserves*

According to Table 13, the national coal reserves ascend to 663 million tons. By means of the gasification process, 1298.7 million tons of H_2 could be generated during 5 years with the same consumption mentioned above.

In this moment, the generating plants of electricity based on coal represent 10% of the national production; a CFE mid-term project plans to reach 27% [21].

Nowadays, Mexico has hydrogen potential reserve of 837.7 million tons H_2 (see Table 14). Considering the consumption by 2030, Mexico would have reserves for 40 years.

6. Outlook

Before 2030, Mexico will be a net importer, because Mexican exploitable reserves-calculated in 28,300 billion barrels will be depleted. Current levels of production will only last 26 more years according to the Agency International of Energy (AIE), and the Organization for the Cooperation and the Economic Development (OCED) [22].

However, other sources remark that Mexico has 30.65 thousand millions of barrels of reserves. With present exploitation of 1073 billion barrels per year, this data suggests 30 years to shift from a Mexican hydrocarbon economy to 100% renewable energy. Which alternative do we have? Carbon is an undesirable product due to high content of sulfide (acid rain) and its emissions of CO_2 (green house effect).

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