Technical and Economical Analyses of the Use of Fuel Cell for Urban Buses

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ABSTRACT. The global warming is caused mainly by burning of fossil fuels (oil, diesel, gasoline, etc) that emit millions of tons of pollutants. Besides, the certainty that those fossil fuels are non-renewable resources allows more researches in cleaner energy, and particularly for vehicles. In this way, fuel cell (FC) has a special attention because it can be applied in urban transport and improves the actual environmental situation.
The FC appears like a promising technology for energy generation. Among several technologies in the present, the PEMFC (proton exchange membrane fuel cell) is the most appropriated for vehicles application, because it combines durability, high power density, high efficiency, good response and it works at relatively low temperatures. Besides that it is easy to turn it on and off and it is able to support present vibration in vehicles. A PEMFC's problem is that it needs noble catalyst, like platinum. Another problem is that CO, needs to be in low concentration, requiring a hydrogen more clean, because the cell deterioration.
One part of this paper was developed in Stockholm, where there are some buses within the CUTE (Clean Urban Transport for Europe) project that have been in operation with FC since January 2004. Another part was developed in Guaratinguetá, Brazil. Brazil intends to start up a program of FC buses. As conclusion, this paper show the economical analysis comparing buses moved by fuel cells and buses moved by internal combustion engine, as regarding the Brazilian conditions.

Keywords: fuel cell, urban buses, Hydrogen, energy, internal combustion engine, economical analyses.

1. Introduction

The criteria that have influencing the evolution of the world energy sector in the present century are complex: Both typical objectives, such as safety in supplies, exploration of resources and competitiveness of companies, and the necessity to preserve the environment (locally and globally), through the use of new technologies and sustainable use of existing resources [1].
In the energy field, an important cause of pollutant emissions is linked to increase of transportation. In fact, nearly one-quarter of the world's energy is consumed in the transportation sector [1]. In the last 40 years, some economic, social and cultural changes (increase of productivity, free time availability, decentralised urban development etc.) have encouraged a wide diffusion of vehicles, how is show in Fig. 1. The World Health Organization (WHO) estimates that urban air pollution causes 800,000 premature deaths each year (Fig. 2). Fossil fuels burned by combustion internal engines of vehicles contribute in 90 percent of urban air pollution, including lead, carbon monoxide, ozone and suspended particulate matter [2].

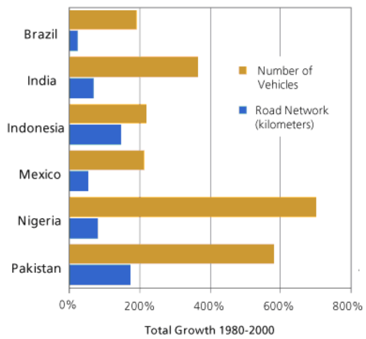


Fig1. Transport Growth in Selected Developing Countries [6]

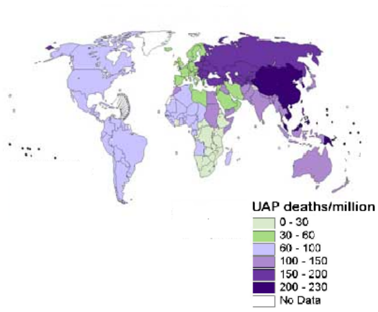


Fig 2. Deaths from urban air pollution (UAP) [6].
(Estimates by WHO sub-region for 2000)

Among several technologies in the present, FC appears like a promising technology alternative for energy generation, principally in substitution of internal combustion engine and thus is considered for transportation purposes (automotive, marine and aerospace). FC is very efficient system consisting of an electrochemistry process rather than combustion. Specifically, water, electrical energy, and heat are generated through the

combination of hydrogen and oxygen. The development of FC technology includes the project of low resistance membranes, highly diffusive electrodes, and reduced use of noble metal catalysts. [3].
In Brazil, **São Paulo Metropolitan Region (SPMR)**, composed by 39 municipalities and with a population of 18 million, diesel buses are one of the major contributors to the air pollution. This situation has doing Brazil to start up a program of environmental regulation applied for the public transport. The **Ministry of Mines and Energy (MME),** together with **São Paulo Metropolitan Urban Transport Company (EMTU/SP)**, the **United Nations Development Program (PNUD)**, **the Global Environmental Facility (GEF)** and the **Financing Agency of Studies and Projects (FINEP)** is moving forward with the Environmental Energy Strategy: Buses with Hydrogen Fuel Cell project [4].
In Europe, nine cities have been participated of the CUTE project (Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm and Stuttgart).Three buses have been operated for 24 months in each one of these cities. The first bus started to operation in 2003. In Stockholm the CUTE project was coordinated by **Stockholm Public Transport (SL)**, and Fortum – The energy and gas distributor company. KTH (the Royal Institute of Technology) made the initial studies [5].

2. How Fuel Cell Work

There are several kinds of fuel cell, but PEMFC is typically used in automobiles. This device uses hydrogen and oxygen from the air to produce electricity. Arrangements must be made for the removal of products resulted from the chemical reactions. Ideally, electrodes and electrolyte remain invariant, the overall process being the consumption of fuel and oxidant with the resulting release of electrical energy.
The Fig. 3 shows how FC works [6]:

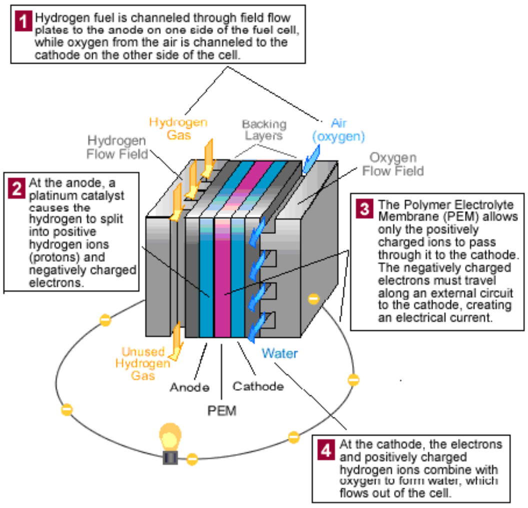


Fig 3: Proton Exchange Membrane fuel cell [6].

Most fuel cell designed for use in vehicles produce electricity containing less than 1.16 volts - far from enough to power a vehicle. Therefore, multiple cells must be assembled into a fuel cell stack.
The power generated by a fuel cell stack depends of the kind and the number of the individual fuel cells that comprise the stack and the surface area of the PEM [6].

3. Hydrogen

Hydrogen is the simplest, lightest and most plentiful element in the universe. It is made up of one proton and one electron revolving around the proton. In its normal gaseous state, hydrogen is colourless, odourless, tasteless, non-toxic and burns invisibly (in the case of air mixture). It should not be considered a "fuel", but instead, should be considered as an energy transport mechanism. Currently, most hydrogen is made from natural gas through a process known as reforming. Reforming separates hydrogen from hydrocarbons by adding heat. Hydrogen can also be produced from a variety of sources including water and biomass.

3.1. Some Processes of Hydrogen Production

3.1.1. The Electrolysis Process

In the water electrolysis process the hydrogen is produced by electrochemically splitting water molecules (H_2O) into their constituents hydrogen (H_2) and oxygen (O_2). The decomposition of water takes place in a so called

electrolysis cell and consists of two partial reactions that take place at two electrodes. The electrodes are placed in an ion-conducting electrolyte (usually an aqueous alkaline solution with 30% potassium hydroxide - KOH). Gaseous hydrogen is produced at the negative electrode (cathode) and oxygen at the positive electrode (anode). The necessary exchange of charge occurs through the flow of OH-ions in the electrolyte and current (electrons) in the electric circuit. In order to prevent a mixing of the product gases, the two reaction areas are separated by a gas-tight, ion-conducting diaphragm membrane. Energy for the water splitting is supplied in the form of electricity.
To achieve the desired production capacity, numerous cells are connected in series forming a module. Larger systems can be assembled by adding up several modules. Two types of electrolysers are typical: atmospheric and pressurised units. An advantage of the atmospheric electrolyser, working at ambient pressure, is its lower energy consumption but the required space for the unit is relatively high. Pressurised electrolysers deliver hydrogen up to 30 bar. This reduces energy demand for compression and may even make compressor stages redundant. Today, atmospheric electrolysers with capacities of up to 500 Nm^3/h and pressurised units with a capacity range of 1 – 120 Nm^3/h are standard products [7].

3.1.2. The Steam Reformer Process

The process is divided into the generation of a hydrogen-rich reformate stream by means of steam methane reforming (SMR) and the following hydrogen purification by means of pressure swing adsorption (PSA). The process route consists mainly of:

Pre-Treatment of the Feed
The hydrocarbon feedstock is desulphurised using, e.g., activated carbon filters, pressurised and, depending on the reformer design, either preheated and mixed with process steam or directly injected with water into the reformer without the need of an external heat exchanger. The fresh water is first softened and demineralised by an ion-exchange water conditioning system. One option is high pressure reforming with integrated heat exchangers and a working pressure of up to 16 bar which reduces the geometric volume of the reformer vessels and is ideal for a downstream treatment by means of PSA or compression. The other option is to operate the reformer at low pressures (1.5 bar) with an increased conversion ratio and compress the reformate prior to purification.

Steam Reforming and CO-Shift Conversion
Methane and steam are converted within the compact reformer furnace at approx. 900 °C in the presence of a nickel catalyst to a hydrogen rich reformate stream according to the following reactions:
(1) $CH_4 + H_2O \rightarrow CO + 3\ H_2$
(2) $CO + H_2O \rightarrow CO_2 + H_2$
The heat required for reaction (1) is obtained by the combustion of fuel gas and purge/tail gas from the PSA system. • Following the reforming step the synthesis gas is fed into the CO conversion reactor to produce additional hydrogen. Heat recovery • for steam or feedstock preheating takes place at different points within the process chain to optimise the energy efficiency of the reformer system (depending on the reformer design). This process can be used to reform of natural gas, biogas, ethanol, etc.

Gas Purification – PSA-System
Hydrogen purification is achieved by means of pressure swing adsorption (PSA). The PSA unit consists of four vessels filled with selected adsorbents. The PSA reaches hydrogen purities higher than 99.999 % by volume and CO impurities of less than 1 vppm (volumetric part per million) fulfilling the specifications set by the fuel cell bus supplier. Pure hydrogen from the PSA unit is sent to the hydrogen compressor, while the PSA off-gas from recovering the adsorbents, called tailgas, is fed to the reformer burner. Depending on the reformer design, a recuperative burner is used featuring high efficiency and low nitrogen oxide (NOx) emissions. During normal operation, the burner can be operated solely on the tailgas stream [7]

3.2. Storage

Because hydrogen is such a light gas, it is difficult to store a large amount in a small space. That is a challenge for auto engineers, who want to match, 300-mile vehicle range, but some recent vehicles have done it. Researchers are examining an impressive array of storage options, with U.S. Department of Energy (DOE) support. Today's prototype FCVs use compressed hydrogen tanks or liquid hydrogen tanks. New technologies such as metal hydrides and chemical hydrides may become viable in the future. Another option would be to store hydrogen compounds – methanol, gasoline, ethanol or other compounds – on board, and extract the hydrogen when the vehicle is operating [8].

3.3. Delivery

Since fuel cell convert hydrogen into electricity, the main question on everybody's mind is “Where and how am I going to get the hydrogen to fuel up my fuel cell car?” If auto engineers choose to store hydrogen compounds on board the vehicle, tomorrow's fuel infrastructure would look a lot like today's. Many other options are being explored to deliver hydrogen to fuel cell vehicles (FCVs).

Centralized production and delivery. Hydrogen production and delivery services including a limited pipeline system already serve the needs of today's industrial demand.

On-Site Production. The energy station of the future might produce hydrogen on demand from natural gas, other compounds or even water.

Innovative Approaches. Fuel cell products that generate electrical power sometimes come with hydrogen generators called Reformers or Steam Reformers. An energy station might purchase one of these units, use the electricity for operations and tap into the reformer to produce hydrogen for vehicles.

The ultimate solution might be solar or wind or hydroelectric powered hydrogen filling stations, where electricity generated is used to extract hydrogen from water. Two solar stations already are operating in Southern California for the hydrogen production. [8]

4. Interest in the use of a FC in buses for urban transport

A ground transport vehicle that seems particularly interesting for adoption of a fuel cell is the bus for urban transport [1]. It is possible also for another kind of transports and another applications. The main reasons for use in buses are:

• The dimensions and structure of the bus allow installation of fuel cells and their auxiliaries, including the hydrogen tanks (if it were stored in gaseous form on the bus). The weight percentage increase would represent a lower problem compared with private cars.

• The ratio between the engine power and the weight of the vehicle is low: a bus of 18 tons with a medium speed of 70 km/h has a power of 150 kW.

• The bus circulates in the centre of the urban areas where the air pollution is serious.

In these areas, a zero emission vehicle could gain high revenue in terms of social costs connected with air pollution, with an important benefit of public opinion and of administrators.

• A FC technology is, at present, much more expensive than traditional engines. Buses are bought and managed in fleets of a large number of units, and this allows an investment and maintenance cost reduction. Moreover, if the refuelling structure were very expensive for a single vehicle, it would decrease in case of utilisation of a fleet of 100 buses.

• The urban transport service is usually managed by a public administration, which is more interested in the acquisition of social benefits and which is less bound by short term revenue of the investment.

• Some characteristics of a fuel cell engine are particularly interesting for a bus: the engine is not noisy, vibrations are absent and the electric engine has a smooth operation, causing an increase in comfort of the users.

5. The CUTE Project and Hydrogen Fuel Cell Buses in Stockholm

The Clean Urban Transport for Europe (CUTE) project is the largest demonstration project of fuel cells and hydrogen today. In nine European cities, both hydrogen-powered fuel cell buses and hydrogen infrastructure are tested and demonstrated during two years.

Demonstration projects such as the CUTE project is a way to have the public meet and become familiarised with the technology. In fact, there is an explicit goal of the CUTE project to make hydrogen and fuel cell technology visible through the use of the fuel cell buses.

The buses in the CUTE project, all in all 27 buses, have been in operation for more than a year and the results of several studies within the project are emerging. In Stockholm, the buses were at first operated on a special demonstration route; the “Water route” in downtown Stockholm, and this introduction attracted much attention in the media. After eight months of operation, the buses were put in service on an ordinary bus route, route 66 in central Stockholm [9].

The fuel cell buses are based on a conventional bus platform, the 12m Mercedes-Benz Citaro low-floor city bus. In the fuel cell version of the bus, the internal combustion engine (ICE) has been replaced by a central electric motor, which powers a standard automatic gearbox. Similar to the configuration of the conventional bus, all the bus auxiliaries in the fuel cell bus are powered mechanically. A special feature of the fuel cell bus however is that the auxiliaries are powered by the central electric motor via a special additional gearbox on the rear end of the motor. The fuel cell system and the hydrogen storage are located on the roof of the bus for both space and safety reasons. The general bus layout is shown in Fig. 4.

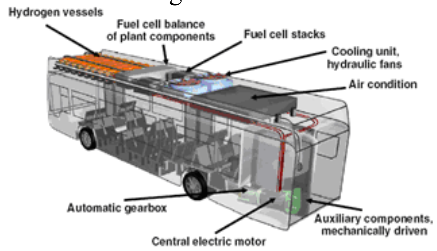


Fig.4: the Mercedez-Benz fuel cell Citaro [10].

A driver opinion poll regarding technical and environmental aspects of the fuel cell buses project in comparison to conventional diesel buses, presented in fig 5, was done. The responses were very positive.

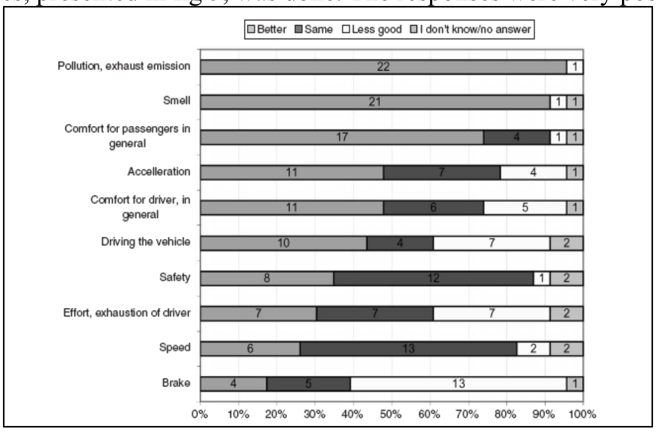


Fig.5: Summarised results from the bus driver survey in CUTE Stockholm, November 2004, after 11 months of operation of the fuel cell buses. Note that the number of respondents varies for different questions [9].

6. Economic analysis

This section compares economically buses moved by fuel cells and buses moved by internal combustion engine (ICE), using diesel oil, according the prices report by Department of Energy (DOE) in USA [11], considering large facilities (plants of hydrogen production with cost estimated to 2010) around 1.34 to 25.4 million Nm^3/day. Based in the methodology of Torres [12] and Silveira et all [13] was determinate the cost of hydrogen production by steam reform of ethanol, considering a medium facilities (7,200 Nm^3/day).
The cost of hydrogen production is show in fig.6 and was calculated using the methodology developed by Silvera et. all [13].

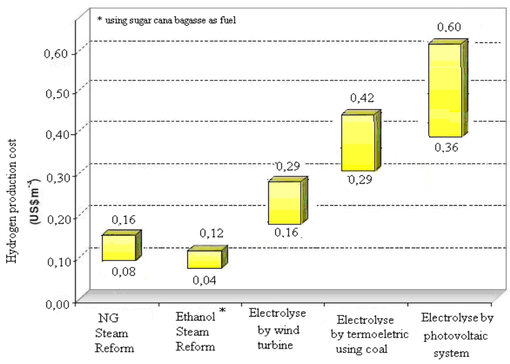


Fig.6: Comparative cost of hydrogen production.

In this paper is considered for the calculation of Urban Transportation Cost (C_{fc} and C_{ice}). In the case of use of fuel cell are considered the hydrogen produced by electrolysis (wind turbine) and natural gas (NG) steam reform. The following considerations are used: According fig.6, the medium cost of hydrogen production through electrolysis is 0.22 US$/$m^3$ and natural gas reforming is 0,12 US$/$m^3$, according to Department of Energy

(DOE) in USA [11]. Environmental aspects in the costs of hydrogen in FC buses were not considered, but in the case of ICE bus, diesel oil was considering with equivalent prices of the hydrogen, because the level of pollutant that emit to the environment.
Subsequently the costs of hydrogen production by electrolysis and GN stem reform in US$/m^3 was converted to US$/kWh. Indeed, the cost of hydrogen via electrolysis was 0.054 US$/kWh and natural gas reforming was 0.025 US$/kWh.
Although, the investment cost (***I***) of fuel cell will decrease in some years, with technological evolution and increase of production. Most of bibliographies, like Torres[12], Doty[14] and Neto[15] , show a cost between US$ 2,000/kW and US$ 3,000/kW. In this paper is considered a medium investment cost (I_{fc}) of US$ 2,500/kW.
Other parameters that were considered: $\eta_{fc} = 48\%$; W = 250 kW; LHV = 119,742.48 kJ/kg; ΔS = 1,500,000 km, H = 3,000 and 4,800 h/year (firstly 10 hours per day in 300 days were considered, and secondly 16 hours per day in 300 days were considered). The utilized equations were cited below:

$$\dot{m} = \frac{w}{\eta . LHV} \cdot 100 \quad (1)$$

where: LHV = *lower heat value (kJ/kg)*
$\dot{m}$ = *mass flow (kg/s)*
η = *FC or ICE efficiency (%)*
w = *power eletric or engine (kW)*

$$q = 1 + \frac{r}{100} \quad (2) \qquad f = \frac{q^k (q-1)}{q^k - 1} \quad (3)$$

where: *f=annuity factor (1/year)*
k=Payback period (year)
r= annual interest rate (%)

$$C_{inv} = \frac{I . f . w}{H . \Delta S} \quad (4)$$

where: C_{inv} = *part of investment in urban transport cost (US$/km.h)*
H = *equivalent period of operation (h/year)*
$I.$ = *investment cost (US$/kW)*
ΔS = *useful life of the bus (km)*

$$C_f = \frac{C . LHV . \dot{m}}{\Delta S} \quad (5)$$

where: C_f = *part of operation in urban transport cost (US$/km.h)*
C = *fuel cos (US$/kWh)*

$$C_{main} = (0.1 \, . \, C_{inv}) \quad (6)$$

where: C_{main} = *part of maintenance in urban transport cost (US$/km.h)*

Subsequently, the global equation was written below:

$$C_{fc} = \left(\frac{I_{fc} . f . w}{H . \Delta S}\right) + \left(\frac{C_{H2} . LHV . \dot{m}}{\Delta S}\right) + 0{,}1 \cdot \left(\frac{I_{ice} . f . w}{H . \Delta S}\right) \quad (7)$$

where: C_{fc} = Urban transport cost with FC systems (US$/km.h)

$$C_{ICE} = \left(\frac{I_{ice} f . w}{H . \Delta S}\right) + \left(\frac{C_{diese} LHV . \dot{m}}{\Delta S}\right) + 0{,}1 \cdot \left(\frac{I_{ice} f . w}{H . \Delta S}\right) \quad \textbf{(8)}$$

where: C_{ICE} = Urban transport cost with ICE (US$/km.h)

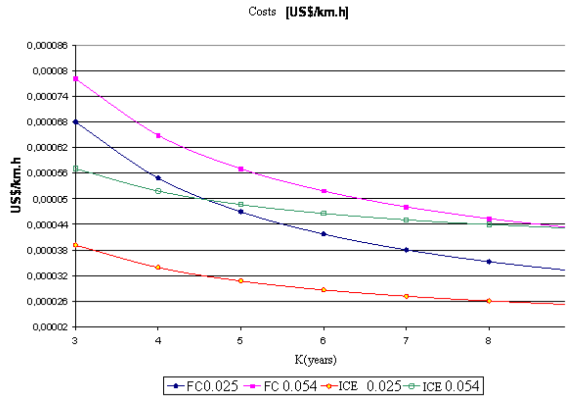
$$C_{ICE} = \left(\frac{I_{ice} \cdot f}{H}\right) + \left(\frac{C_{diesel} LHV . \dot{m}}{w}\right) + 0{,}1 \cdot \left(\frac{I_{ice} \cdot f}{H}\right) \quad \textbf{(10)}$$

where: C_{ICE} = Urban transport cost with ICE (US$/kWh)

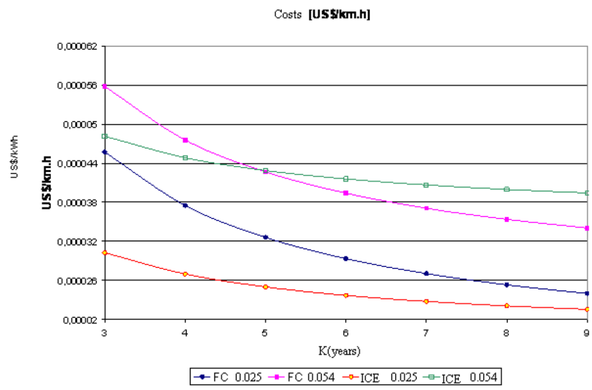
$$C_{fc} = \left(\frac{I_{cc} \cdot f}{H}\right) + \left(\frac{C_{H2} . PCI . \dot{m}}{w}\right) + 0{,}1 \cdot \left(\frac{I_{fc} \cdot f}{H}\right) \quad (9)$$

where: C_{fc} = Urban transport cost with FC systems (US$/kWh)

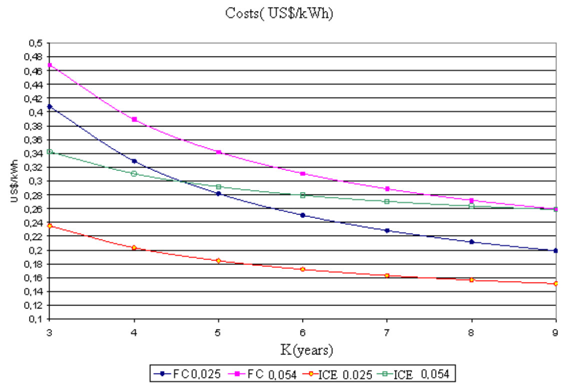
To compare both technologies, the same methodology was used to ICE and FC and the efficiency of ICE was considered 27%, its efficiency is lower than efficiency of fuel cell. As ICE is an ancient technology, the investment is also lower. Indeed cost (I_{ice}) of US$1,000/kW [11] was attributed. The results are show in the graphics 1, 2, 3 and 4:



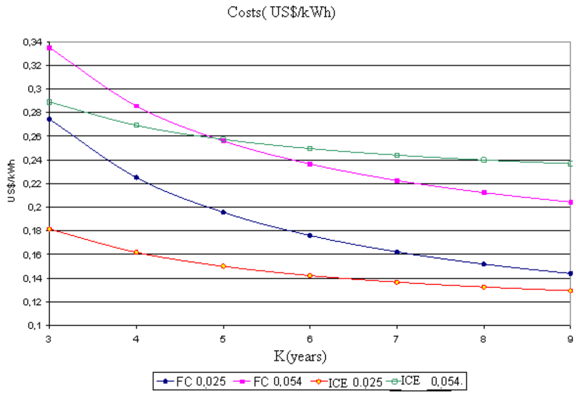
Graph. 1: Urban tranportation cost with FC systems and ICE (US$/km.h) taking as H=3,000h/year



Graph. 2: Urban tranportation cost with FC systems and ICE (US$/km.h) taking as H=4,800 h/year



Graph. 3: Urban transportation cost with FC systems and ICE (US$/kWh) taking as base H=3,000 h/year



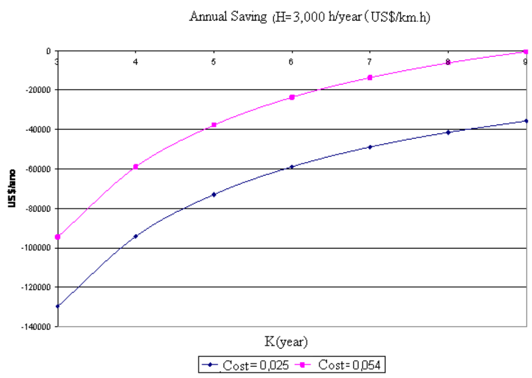
Graph. 4: Urban transportation cost with FC systems and ICE (US$/kWh) taking as base H= 4,800 h/year

The Graphs. 1 and 3 shows, that for 3,000 h/year, the FC bus becomes more economically feasible than ICE bus, considering the diesel cost 0.054 US$/kWh and hydrogen cost 0.025 US$/kWh. It can happen because the fuel consumption in a ICE is higher than fuel consumption in a FC system. Observe that a payback different of the investment in FC bus about the 4.5 years.

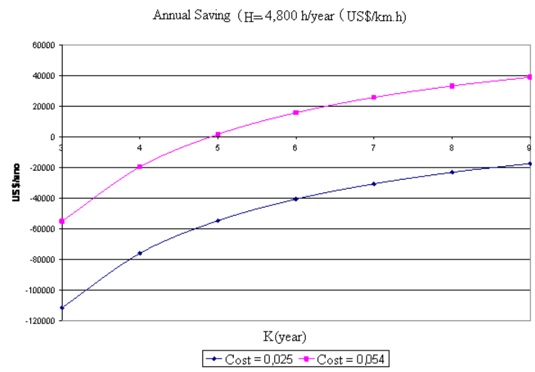
The economical analyses between FC buses and ICE buses were performed applying the equation 11, showing the annual saving [12].

$$R = (C_{ICE} - C_{fc}).H.\Delta S \qquad \textbf{(11)}$$

where: R= annual saving expected (US$/year)



Graph. 5: Annual saving expeted for urban transportation in USS/km.h with H=3,000 h/year



Graph. 6: Annual saving expeted for urban transportation in USS/km.h with H=4,800 h/year

Analysing the graphs 5 and 6, it was showed that FC bus are economically feasible for payback of 9 years considering 3,000 h/year of equivalent period of operation, and for payback about 5 year with 4,800 h/year of operation. When the vehicle is used in more time during a year (4,800 h/year), it brings better cost/benefit, whereas the investment decrease with more utilization and the fuel cost became more present.

7. Conclusion

The present work was developed to try proving that fuel cell could be a promising alternative to internal combustion engines in the urban transport, become better the environmental quality and consequently the life quality.
Comparing with ICE, the FC vehicles offer many advantages:

• Combustion process is not necessary, consisting in a direct energy conversion, decreasing pollutants emissions.
• Gasoline engines have efficiency between 13-25%, diesel engines, between 30-35%, and fuel cells have global efficiency about to 48%
• The ICE could be substituted easily by an electric engine, and as electric engine is smaller, the vehicle gain internal space.
• Transmission systems are not necessary, seeing that the push-on and brake systems are controlled by carrying-on electric, could decrease operation, maintenance and fuel consuming costs.
•As the push-on and brake are controlled by electric system, the vehicle is noiseless.

Urban buses was focused because public transportation is responsible for a great part of pollutants emissions and by the fact to be possible settle fuel cells in fleets and to put into practice easily.
The hydrogen, the principal energy carrier to fuel cells, can be produced by many ways, but natural gas reforming and water electrolysis were cited. The most viable in this case, is natural gas reforming, because it is a simple process and cheaper than electrolysis, but as this process uses hydrocarbon fuel, it emits pollutants into the environment. When hydrogen is produced by water electrolyzers, pollutants emissions are not emitted, but great amount of energy is necessary, and that is what becomes the process expensive. On the other hand, if the excess of energy from hydroelectric is used, it could be one viable alternative.
However, as showed in this economic analysis, at the present time the fuel cell technology is not viable, but in the medium-term, fuel cell buses will become competitive compared to internal combustion engine. Breaking down some barriers and start a market with sufficient scale is necessary to justify the investments in further development of fuel cell engines and in the scaling-up of production, which will bring this technology to acceptable levels of cost, availability and reliability. In next paper will be presented the use of ethanol stem reform to hydrogen production, including ecological efficiency concepts.

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