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Analysis of electrolytic hydrogen production models and distribution modes for public urban transport: study case in Foz do Iguacu, Brazil

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SUMMARY

Currently, governments and companies aim their concern about the environmental problems and energy security. Within this context, the use of renewable hydrogen is presented as an interesting option.

This paper presents the alternative to use a renewable resource abundant in the country: hydroelectricity. The public transport service in the urban area of Foz do Iguaçu city, Brazil, was chosen as the scenario where a simulated replacement of the current diesel bus fleet with fuel cell buses was performed.

The focus was to take advantage of the energy called Spilled Turbinable Energy (STE) verified by the ITAIPU Hydroelectric Power Plant from 2001 to 2006 in order to produce hydrogen by water electrolysis process. The paper does not contain thermodynamic analysis of the processes involved in the proposal. Based on the monthly average, the maximum value was 1,054,899 MWh and the minimum 9559 MWh. Evaluating the historic behavior of this potential energy in the considered period, from October to June, it was found that the energy demand to produce the electrolytic hydrogen needed to meet the whole demand of the public transport sector of Foz do Iguaçu city, estimated in 14,454.3 MWh/month, amounts only between 1.5% to 8.5% of total spilled energy.

This study presents two electrolytic hydrogen production models: the centralized and the decentralized associated with various distribution modes. The comparison between models shows that the centralized hydrogen production associated with central supply mode are economically more convenient for the city, and the hydrogen cost achieved was US$ 2.38/kg in contrast with the decentralized model associated with cryogenic liquid delivery which showed the highest cost, equal to US$ 4.61/kg. Finally, a sensitivity analysis was performed varying four parameters: equipment cost; rate of return; capital recovery time and electricity cost. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS

electrolytic hydrogen; hydroelectricity; public transport; renewable resource; hydrogen infrastructure; Foz do Iguaçu; ITAIPU Power Plant; fuel cell buses

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1. INTRODUCTION

At present, energy and environment-related issues are essential for companies and governments projects. In this sense, they are looking for strategies to reduce the negative environmental impact, resulting mainly from use of fossil fuels, which burning generates an increase of atmospheric carbon dioxide level, cited as the great responsible for the growth of greenhouse effect [1]. Thus, these strategies seek forms to enable greater energy efficiency linked to an increasing penetration of renewable energy sources.

For the means of public transportation, traditionally based on fossil fuels, one of the alternatives could be to encourage the increase on the use of clean technologies, such as fuel cells using electrolytic hydrogen which comes from renewable energy sources.

Within this context, several countries are developing programs and projects that, among other things, seek to create an infrastructure for the use of hydrogen as an energy vector.

On the other hand, the problem of air pollution associated with the means of transportation is even more evident in large urban centers. The daily commuting of people between home and workplace is very intense. This situation causes traffic jam downtown and access roads. These facts, together with the difficulty represented by lack of free air circulation due to the large number of buildings, cause adverse effects on local climate as well as air quality [2]. The described situation has prompted various European cities to participate on projects to demonstrate the application of hydrogen as an alternative fuel for the urban means of transport. For instance, the Scandinavian region (Norway, Sweden and Denmark), takes part in the major regional integration project through hydrogen trying to establish a regional highway with a network of refueling stations prepared to supply vehicles with this energetic vector.

In North America, the state of California in the United States is a pioneering region which, since the 1990s maintains a strong stimulus towards the development of an urban hydrogen supply network. Also, in this continent, in October 2009, Canada's BC celebrated the arrival of the first 20 busses provided with hydrogen fuel cells. These vehicles will constitute the fleet which will circulate around the city of Whistler until 2014.

In South America, Sao Paulo Metropolitan Urban Transport Company (EMTU) will operate the first Brazilian prototype hydrogen bus as a regular public transportation into a demonstration project –Brazilian Hydrogen Bus- being addressed by Brazilian Ministry of Mines and Energy and funded by the Global Environment Facility under United Nations Development Program implementation. The prototype was manufactured by a consortium and introduced in July 2009.

Some experts argue that in this context of environmental imperatives, a carbon constraint economy will encourage the development of hydrogen generation processes and fuel cells technology [3].

On the other hand, according to Padilha *et al*. [4], in many hydroelectric power plants of Brazil, there exists an excess of water that needs to be drained through the lock gates of the dams in order to alleviate the reservoir volume and to prevent overflow. Some studies have presented and discussed the available potential of this wasted energy to electrolytic hydrogen production in the country [4–8].

The proposal presented in this paper is the use of the so-called STE[1] of the ITAIPU Hydroelectric Power Plant, in order to produce hydrogen by water electrolysis process. According to Souza and Silva [8], the use of at least four months of this type of energy, cheaper, complemented with Guaranteed Energy (GE)[2] the rest of the year, could mean an important decrease in the average cost of electrolytic hydrogen production.

The hydrogen produced can be sold for chemical purposes or as fuel to the transport sector. Only the second option was considered for this study, and it took the urban public transportation in the city of *Foz do Iguaçu*, Brazil, like scenario, where a simulated replacement of the current diesel bus fleet with fuel cell buses was performed.

In Brazil, considering the large hydroelectric potential of the country, the use of this renewable energy for hydrogen production by water electrolysis becomes an important option, both for society and for the electricity companies. While society can benefit from the use of a relatively cleaner and more efficient technology, electric companies can diversify the offered products, acting as energy companies, as has been observed in companies of the oil sector. This will mean the opening of a new market segment for companies in the electric sector: the production and sale of electrolytic hydrogen.

2. OBJECTIVE

The main purpose of this study is to present and analyze different models of hydrogen production and distribution modes for the public urban transport sector of *Foz do Iguaçu* city. The analysis focused on the use of potential electricity that could be generated in the ITAIPU Hydroelectric Power Plant, taking advantage of the so-called STE. This study is expected to help in further discussions related to hydrogen introduction in the Brazilian energy matrix.

3. TOOLS AND METHODOLOGY

3.1. Electrolytic hydrogen production and supply models

In this paper, two electrolytic hydrogen production models were considered: the centralized and the decentralized model. Each model considers the respective distribution mode. The selection of the most appropriate model and mode for the city were carried out from economic perspective but considering logistical issues, too.

1. In the decentralized model, the proposal is the electrolytic hydrogen production in the garage of each company; this option does not require planning the delivery of hydrogen, so each transport operator must have its own electrolysis plant sized according to its fuel demand.
2. In the centralized model, the production would be done in one location only. After production, hydrogen has to

[1]STE is the potential energy of the water able to produce electricity in a dam when the inflows are greater than the demand for energy. Normally, this excess of water is discharged to the spillway and wasted.

[2]GE refers to the constant power that can be generated by the plant and set in supply contracts.

be delivered to each transport operator company. Yang C. and J. Ogden [9] have analyzed the most appropriate delivery mode involving central plant production, and their conclusions were taken into account for this case:

a. Compressed gas delivery by truck, using gas cylinder basket or tubes. This mode is recommended for small stations and very low demand principally due to the limited transport capacity per trip. For this work, it was considered compressed gaseous truck transport (using tubes), with a total capacity of 350 kg per trip (200 bar).
b. Cryogenic liquid hydrogen delivery by truck. This mode has the advantage of increasing the density of hydrogen transported about 10 times compared with the gaseous mode. It is recommended for smaller station sizes, low market penetration rates and low population densities. However, it has three basic drawbacks: liquefaction process requires a very large primary energy input, approximately 11 kWh/kg, which represents about 33% of the hydrogen energy content; large cost relating to liquefaction equipment, and finally, systematic hydrogen loss of 0.3% to 1% per day.

3. The third case considered in this work does not require delivery. Centralized hydrogen production and central supply mode, both would be performed in the same location. In this mode, logistics issues relating to hydrogen delivery are ignored, buses have to arrive at the place in order to refueling process. Considering that the referenced bus is supplied gaseous hydrogen, in this case only gaseous storage has been considered.

3.2. Scenario proposed

In this study the public urban transport service of the city of *Foz do Iguaçu*, located in the western extreme of Paraná State, Brazil, is the chosen scenario. The city is strategically set on the border between Paraguay and Argentina, a few kilometers from the ITAIPU Hydroelectric Power Plant, with a population of 311,336 habitants [10]. According to the municipality of the city, the total area is 617.7 km^2, the urban area corresponding to 191.5 km^2 [11].

The urban public transport service in the city is provided by four private operators, and, according to Foztrans Report 2006 [12], the urban bus fleet is composed by 191 units. The transport operator companies will be named by letters A, B, C, and D in order to preserve the confidentiality. Table I shows the data of the urban transport system.

Table I. Foz do Iguaçu Public transport service data.

Transport Operator Company	Bus fleet size	Annual distance traveled (km)
A	61	4,599,900
B	48	4,019,016
C	49	3,471,828
D	33	2,525,640
Total	191	14,616,384

The city has a central hub and an integrated city fare, most of the buses routes pass through this hub, and passengers pay a standard fare within the city zone. Each urban transport operator has a garage where fuel refueling is made.

The fuel cell bus model chosen as reference is the Mercedes-Benz Citaro Fuel Cell Bus, because this vehicle model has been in service in a variety of different world cities in order to test the feasibility of hydrogen fuel cells as part of different projects working in different operating circumstances and different conditions.

3.3. Analysis

Trolley buses could take advantage of the generated electricity by directly using it. This type of vehicle must be fixed to particular routes limiting operational flexibility, and the high cost of the cabling infrastructure must be taken into account. The proposal is to use fuel cell vehicles that have the same freedom of movement compared to diesel buses.

In the first place, the introduction of the referenced bus model in replacement of the buses presently used for the urban transport fleet of *Foz do Iguaçu* was analyzed in a practical way. The analysis focused on the range, passenger carrying capacity and hydrogen refueling time between buses.

The next step was to estimate hydrogen demand for the new fuel cell bus fleet, essential for sizing the hydrogen plant. The annual demand of hydrogen (kg/year), $D_{H(yr)}$, is obtained from Equation 1.

$$D_{H(yr)} = km_{yr}.f_c \tag{1}$$

Where km_{yr}, is the total annual distance traveled by bus fleet in operation (km/year), and fc, the average hydrogen consumption of referenced fuel cell bus (kg/km).

Due to the fact that the electrolysis plant cost depends on the capacity production and economies scale impact, different costs were considered for each analyzed model. For this goal, we have used the Equation 2, developed by Galeano [13].

$$C_{EL} = 2,424.9\ x\ C_p{}^{(-0.1062)} \tag{2}$$

Where C_{EL}, is the electrolysis plant unit cost (US$/kW); C_p, is the plant capacity production (m^3/h).

To calculate energy demand, we assumed the electrolyzer energy consumption equal to 47.9 kWh [14] plus 10.01 kWh [15] consumed by auxiliary equipment to produce 1 kg of hydrogen and the density equal to 0.0899 kg/m^3 at standard conditions. The total consumption adopted is in accordance to the literature; for instance, a Report of National Renewable Energy Laboratory [16] shows that this value can vary between 53.3 kWh and 70.07 kWh per kg.

For operators, it would be very useful for infrastructure planning to know the amount of time needed to supply the whole fleet with hydrogen (t_R) compared to diesel buses refueling. The latter is known to be 5 min per vehicle.

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Equation 3 was used for this task.

$$t_R = t_a . n . b^{-1} \quad (3)$$

where b indicates the number of dispensers, n is the quantity of buses and t_a indicates the amount of time spent on refueling one bus in the CUTE project (min), used as reference for this analysis. It was established that the refueling must be done in an interval of 12 min with a maximum of 30 min between loads; we used the average of 21 min.

3.3.1. Economic assessment

One of the critical factors to the viability of hydrogen technology is the production cost. Bartels *et al.* [17] summarized the economics of producing hydrogen from both conventional and alternative energy resources such as natural gas, coal, atoms, sunlight, wind and biomass and showed that the most economical source of hydrogen is coal, with an estimated cost of US$ 0.36 to 1.83 per kg.

After sizing the electrolysis plant for each model, the specific cost of producing hydrogen, C_H, was estimated by using Equation 4, based on the methodology followed by S. Prince-Richard *et al.* [18].

$$C_H = {}^{C}/_{Y} \quad (4)$$

where C indicates the annual cost to produce the electrolytic hydrogen in the working conditions (US$/year), defined by Equation 5; Y represents the annual hydrogen production (kg/year).

$$C = C_c + C_e \quad (5)$$

where C_c is the annual capital, operating and maintenance cost (US$/year), defined by Equation 6; C_e represents the annual cost with electricity (US$/year).

$$C_c = C_{cap}.(CRF + OM) \quad (6)$$

C_{cap} indicates total investment cost of installation that includes the cost of purchase and installation of electrolyzer, compressor and storage systems; *CRF* is the capital recovery factor; *OM* is the considered rate for operating and maintenance of the plant.

Other costs like engineering/design, plant construction and contingency are represented as a percentage of the total installed capital investment cost. Table II summarizes the principal economic assumptions considered to this work.

3.3.2. Electricity cost

This parameter has influence on the final cost of the produced hydrogen. In this analysis, the focus was to take advantage from the STE, which varies from season to season. The flow of water spilled at ITAIPU dam is a direct reflection of the water volume carried by the Parana River, which in turn depends on the rainfall rate of the Southeast Region of Brazil. In the present time, this energy is literally wasted.

Table II. Economic assumptions.

Assumption	Value	Unit
Rate of return	15	%
Capital Recovery time	20	Year
CRF	0.1598	—
Operation and maintenance cost	6% of total capital cost	US$
Engineering/Design cost	20% of total capital cost	US$
Construction cost	18% of total capital cost	US$
Contingency cost	15% of total capital cost	US$

We have evaluated the availability of the STE at the ITAIPU dam between 2001 and 2006. Figure 1 illustrates the energy availability for the considered period, while Table III shows the average values by month for the same period. During the months when GE must be used, the cost of electricity is average between the two of them. The costs considered for the STE and GE were US$ 6.50/MWh and US$ 28.23/MWh [19].

3.3.3. Vehicle cost

There are some studies that have analyzed matters regarding the cost of acquisition and maintenance of hydrogen fuel cell-powered buses [20–23]. According to [23], the current costs are four to seven times the level of an equivalent diesel bus and two to three times that of a trolley, and it is expected to reduce overall bus costs to an affordable level by 2022 to 2025.

According to [21], the capital costs are expected to be at least triple the cost of an equivalent diesel bus in the short term, but the lifecycle cost will be the same and maintenance costs will be from 15% to 20% less, particularly due to fewer moving parts and hence less lubrication, etc.

The exact cost is commercial-in-confidence, although trade publications have provided their own estimates. Based on [20] the non-subsidized cost of a Citaro bus is in the vicinity of US$ 2.0 million, value adopted for estimating the investment required for the proposal.

4. RESULTS AND DISCUSSION

The current transport fleet of Foz do Iguaçu consists principally by following: Mercedes Benz, models OF 1315 / OF 1318 / OF 1620 / OF 1721 / GVU; and VW (Volkswagem) model B-16210 [12]. These buses have the particularity of carrying capacity of 60 to 70 passengers. Compared to the referenced bus, which carrying capacity is similar, this factor does not represent changes in the number of buses in the fleet replacement to meet the existing lines.

Based on data provided by the Foztrans [12] the daily average distance travelled by a bus in the city was estimated to be about 210 km. Currently, the transport operator companies refuel the bus fleet at night, usually beginning at 19:00 and extending throughout the night. Taking into account the referenced fuel cell bus range about 250 km, with

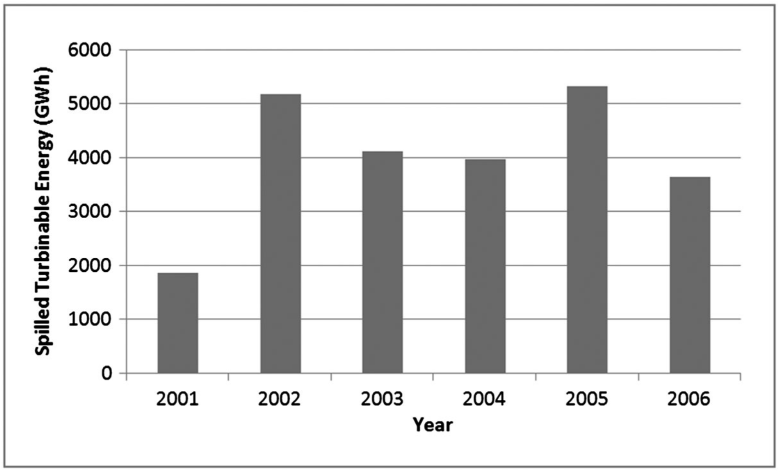

Figure 1. Availability of the STE at the ITAIPU dam between 2001 and 2006.

Table III. Average STE by month recorded between 2001 and 2006.

Month	Average STE (MWh)
Jan	528,279
Feb	1,054,899
Mar	601,683
Apr	219,329
Mai	196,654
Jun	218,258
Jul	144,943
Aug	9559
Sep	15,237
Oct	405,688
Nov	335,974
Dec	354,057

the fleet replacement, it will be possible to continue with the current pattern of refueling.

Using Equation 1 and taking into account the average hydrogen consumption of referenced fuel cell bus (0.205 kg/km) and total distance traveled recorded by different companies during year 2006 was possible to estimate hydrogen demand (by mass and volume) of each company, whose results are presented in Table IV.

Table V shows the results of application of Equation 3, where the refueling time (in hours) for the whole hydrogen buses fleet in function of the amount of installed dispensers can be observed for each company. Based on these results, the installation of various dispensers in the selected model is recommended. This would reduce the waiting time of the buses for refueling process.

The estimated electrical energy for hydrogen production to supply the total demand of transport operator companies was 14,454.3 MWh by month.

The assessment of the STE behavior in the analyzed period shows the great potential of the energy wasted in ITAIPU dam. It can be observed that July, August and September are months with the lesser potential energy, the maximum value was recorded in February (1,054,899 MWh) and the minimum value was presented in August (9559 MWh).

Figure 2 shows the comparative values between the quantification of the STE available at ITAIPU dam (Table III) and the monthly energy demand for total hydrogen production in the study case. In August alone, the available STE did not meet the energy demand for hydrogen production, and therefore on this month, it was necessary to complement with the GE.

The total capital cost of acquisition of vehicles, considering the reference cost, to implement the total replacement of the current fleet is equal to US$ 382.00 million, approximately seven to eight times the necessary investment to purchase the same number of equivalent diesel buses. This amount is the same for the different production and supply models analyzed. This work does not discuss in detail this subject, neither impact of scale economies, cost associated with O&M or lifetime of the vehicles.

Table VI summarized the results of our comparative analysis between the presented models.

The lowest cost of investment is observed in the centralized production and central supply model, equal to US$ 26.78 million. The estimated hydrogen cost in this model was US$ 2.38/kg. If the centralized production with gaseous delivery by trucks is considered, the cost amounts to US$ 28.53 million (6.5% higher). In this model, the hydrogen cost was calculated to be 5% higher than the first one, not taking into consideration costs related to truck acquisition and driver salary or fuel.

In centralized production and central supply model, the buses have to arrive at one location, and this represents a rise in the number of daily trips. For this issue, the urban area was considered as a circle with radius equal to 7.8 km. Thus, every vehicle will increase fuel consumption by 7.4% of hydrogen mass (3.2 kg/day/bus). In this case, there would be savings on the initial investment but operating expenses would increase.

Table IV. Hydrogen demand for each transport operator company.

Transport Operator Company	Hydrogen Demand (mass)[1]				Hydrogen Demand (volume)[1]			
	10^3 kg/year	10^3 kg/month	10^3 kg/day	kg/h	10^3 Nm^3/year	10^3 Nm^3/month	10^3 Nm^3/day	Nm^3/h
A	943	78.6	2.6	109	10,491	874	29.1	1214
B	824	68.6	2.3	95	9166	764	25.5	1061
C	711.7	59.3	1.9	82	7918	659	22	917
D	517.7	43.1	1.4	60	5760	480	16	667
Total	2996.4	249.6	8.2	347	33,335	2777	92.6	3859

[1]it was considered 360 days/year and 24 h/day.
[2]volume at standard conditions.

Table V. Time spent in refueling process.

Transport Operator Company	Fleet size (n)	Time spent in refueling process (h)	
		t_R ($b = 1$)	t_R ($b = 2$)
A	61	15.25	7.625
B	48	12	6
C	49	12.25	6.125
D	33	8.25	4.125

Comparing these results, the difference between the two models is not significant.

The highest investment is observed in the model involving liquid distribution; it is estimated approximately doubled if compared to the above cases.

Centralized production models take advantage of economy of scale, thus in the decentralized model the investment cost of installation is about 15% higher, and the hydrogen cost is 12% higher than the cheapest case.

The hydrogen production cost as found by different authors (Table VII) can be compared with the values obtained in the present work (US$ 2.38 to 4.61/kg).

The result obtained in this work is in a similar range to those obtained by Bartels *et al.* [17] and Leven *et al.* [24], but it is important to note that they were performed under different conditions. The cost of producing hydrogen under the conditions established in this study is competitive even with large-scale steam reforming of natural gas. This finding is an important point for further discussion of the proposal.

Finally, we have run a sensitivity analysis to determine which of the parameters the cost of hydrogen is most sensitive. For this study, four parameters were analyzed: equipment cost; rate of return; capital recovery time and electricity cost. Figure 3 shows the results.

The most sensitive parameter is the equipment cost, in Figure 3, it can be observed that a reduction of 30% in this parameter gets a 20% reduction on hydrogen cost; the second parameter that have a significant impact is the rate of return. In this case, the electricity cost does not show an important impact; a reduction of 30% just gets 7.3% reduction on hydrogen cost. The parameter that presents the less impact is the capital recovery time.

Replacing polluting diesel buses with non-polluting hydrogen fuel cell buses can represent significant

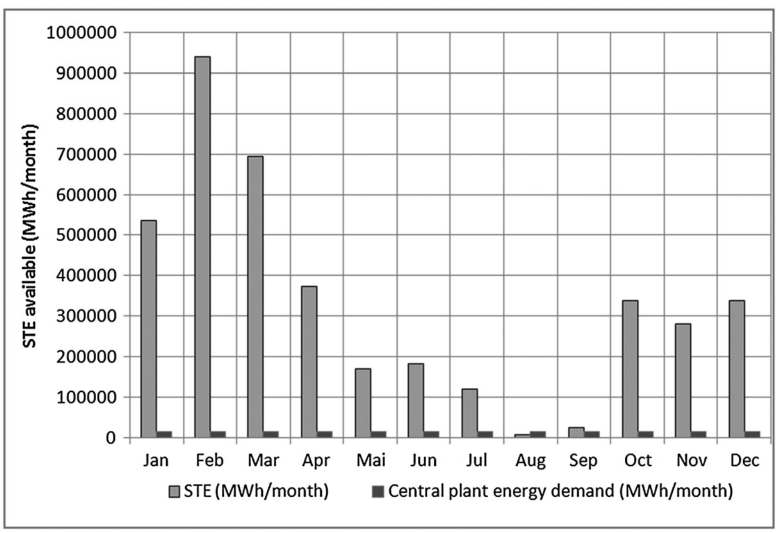

Figure 2. Comparative value between the STE available and energy demand for hydrogen production by month.

Table VI. Summary of comparison of analyzed models.

Model	Decentralized (without delivery)	Centralized production and compressed gas delivery by truck	Centralized production and cryogenic liquid delivery by truck	Centralized production and central supply
Total installed capital (million US$)	30.84	28.53	57.21	26.78
Main equipment considered cost	Electrolyzer, compressor and storage system for the four companies	Electrolyzer, compressor and trailer tubes	Electrolyzer, liquefaction system and cryogenic tank for transport	Electrolyzer, compressor and storage system
Distribution mode	No necessary	By trucks	By trucks	No necessary
Storage system	High pressure cilynders	Tubes	Cryogenic tank	High pressure cilynders
Advantages	Utilization of existing infrastructure in the garages of companies	Lower cost of electrolyzer system due the economies scale	Lower frequency delivery due higher density of hydrogen	Lower total infrastructure investment and operation cost
Disvantages	High cost of electrolysis system units	High frequency delivery	High cost of liquefaction system	Large number of buses arriving to location
Hydrogen cost (US$/kg)	2.67	2.50	4.61	2.38

Table VII. Cost of hydrogen production from different studies.

Cost (US$/kg)	Process	Plant Output (kg/day)	Reference
2.33 – 4.03	Water electrolysis (using wind energy)	1500	[24]
2.48 – 3.17	Methane steam reforming	236,239	[17]
5.56 – 8.34	Water electrolysis (sugar cane energy)[1]	560–4650	[25]
4.36 – 7.36	Water electrolysis (using nuclear energy)	1000	[26]
0.98 – 6.02	Water electrolysis (using solar energy)	np	[27]

np: not provided data
[1]this work focused in water electrolysis using the exceeding electrical energy resultant from alcohol and sugar plants that use sugar cane bagasse as fuel.

environmental benefits. A quick estimative of carbon reduction based on the total replacement of diesel (roughly 1,544,500 gallon/year) shows that annual emissions of 14,000 tons of carbon dioxide would be avoided.

From the sensitivity analysis, the competitiveness of hydrogen compared to diesel oil might be reached using a combination of strategies; the most important would be to reduce the equipment cost.

6. CONCLUSIONS

Starting with the use of hydrogen as fuel for the public transport sector can play a significant role to catalyze the penetration of hydrogen in the Brazilian energy matrix and to help in the development of a widespread refueling infrastructure for future private vehicles. The society will be able to better appreciate the technology, and investors and policy makers will be able to assess the public acceptance in an easier scenario.

The results confirmed the possibility of using the fuel cell bus used as reference, *Mercedes-Citaro Fuel Cell Bus*, without making significant changes in the operation of existing lines and without changing the number of fleet vehicles for each company. Even though it is possible to keep the present refueling schedule (during the night) unchanged, since this would require a high economic investment in hydrogen storage system, it would be advisable to extend the refueling hours all day long, taking into account that during the off-peak hours, buses are parked in their garages. This would promote a best management of the financial resources.

Even though performing a technological substitution such as the one proposed in this article could hardly be carried out on a short to medium term. The analysis of the STE verified from 2001 to 2006 reveals the enormous quantity of unexploited potential energy in the ITAIPU dam. Evaluating the historic behavior of the STE, for the study case, from October to June, it was found that the energy demand to produce the electrolytic hydrogen needed to meet the whole demand of the public transport sector of *Foz do Iguaçu* city amounts only between 1.5% and 8.5% of total spilled energy. Although this energy is very seasonal, it should be taken into account. This proposal is one of various alternatives that must be evaluated but it is unconceivable to continue to waste so much energy.

Regarding the fuel cell buses, the value used as reference is high, but it helps to indicate the magnitude of the overall cost for the operators. It is important to mention that one of the main objectives of Brazilian Hydrogen Bus project is to decrease the present cost of the fuel cell buses by promoting their mass production and generalized use. This initiative will be compared with others and will be presented in a different paper.

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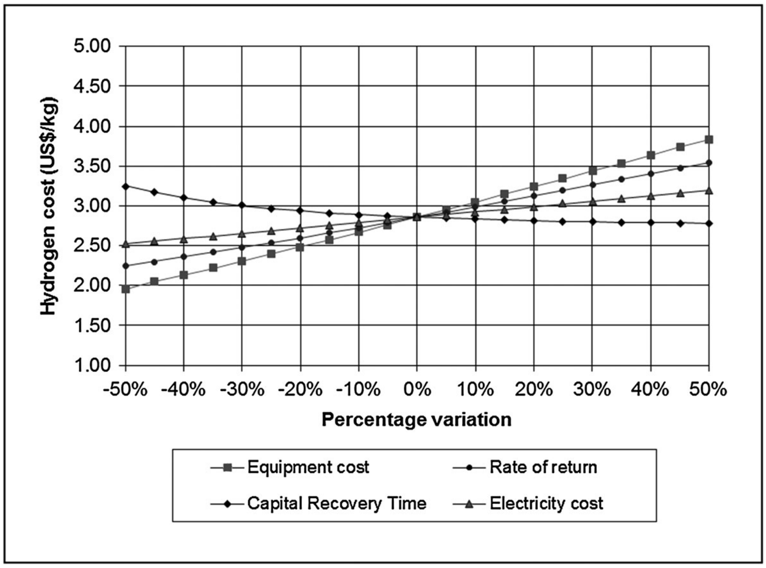

Figure 3. Sensitivity analysis on hydrogen production cost.

Despite the simplifications made, the study indicates some important points to be considered in a practical discussion about hydrogen technology use in the urban transport sector. Comparing the hydrogen production models and distribution modes presented, the conclusion is that within the transportation system under study, the most suitable option from an economical perspective would be the centralized hydrogen production, and central supply mode, with an estimated hydrogen cost equal to US$ 2.38/kg.

The highest production cost was estimated in the decentralized model associated with cryogenic liquid delivery, equal to US$ 4.61/kg.

Based on the sensitivity analysis, the main challenge for the country is to reduce the electrolyzer capital cost that represents about 95% of total capital of installation. Considering that high cost is mainly due to the fact that the equipment must be imported, the government should focus on strategies to facilitate the development of national industry in this area. Also, strategies for reducing the rate of return could help to turn the hydrogen more competitive but without decrease of interest for the potential investors.

Also note that oxygen, a byproduct in the process of water electrolysis, could be commercialized. This would depend on the existence of a market for this product in *Foz do Iguaçu*. This sale could increase business opportunities of producer.

Although electric companies already participate in the urban transportation sector (trolley buses), the opportunity to produce and sell products other than the electricity itself, provides that they will act as energy companies in a broader sense, a trend already noticed in other branches of the energy sector worldwide. Thus, the partnership of energy companies with the transport operator companies would be crucial to catalyze the penetration of hydrogen as a valid energy alternative in the transportation sector in Brazil.

Finally, the suggested replacement of technology will make a significant contribution to reducing pollution levels in a heavily populated urban area. It will also constitute a significant first step towards reducing emissions of carbon dioxide from transportation sources, one of the biggest contributors to the global greenhouse effect, and its threatening consequences. Should this proposal be approved as Clean Development Mechanism project, the carbon credits obtained might help to reduce the cost of producing hydrogen, but this subject should be addressed in a detailed study.

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