MASS PRODUCTION OF HYDROGEN IN BRAZIL

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Abstract

The so-called Hydrogen Economy seems to be one of the most important pillars of sustainable development. As a developing country, Brazil must be prepared for the changes imposed by the reduction of its reserves of fossil fuels as well as for a growing energy demand. This study is an effort to forecast how energy will be available in Brazil in the future by assessing the possibilities and costs of mass production of hydrogen.

Keywords: Sustainable development; Hydrogen production; Fuel cells.

1 Introduction

Although very abundant, hydrogen is not available in its gaseous state (H_2), which is needed for use directly in future fuel cell systems. Thus, the mass scale use of this fuel demands its production from its other forms by means of water electrolysis and reforming of other fuels. Both processes require energy usually obtained from the so-called "primary energy sources". Particular characteristics of Brazil give it a competitive edge in producing two types of primary energy: ethanol from sugar cane and electricity from hydraulic energy.

Historically the industrial sector has been the largest consumer of hydrogen [illegible] 2001]. This remains true today in that the main uses of hydrogen [illegible] processes: the production of fertilizers, the production of various chemical [illegible] refining of crude oil. All three processes are well established in Brazilian [illegible] indicating that a small beginning of the Hydrogen Economy already exists in the country.

The final costs of hydrogen presented in this study are approximate production costs of hypothetical companies established in Brazil, whose core business is the mass production of hydrogen to be used in fuel cell systems. The final costs of hydrogen include neither taxes nor profit.

2 Hydrogen production by water electrolysis

The technology of water electrolysis for producing hydrogen is over 100 years old and is well known today [Walters et al., 2002]. The lower cost of fossil fuels is the main reason for hydrogen not having been used as a source of energy before now. But this cost excludes the price that society has to pay for the impacts on health and the environment.

Value A1 (See Appendix) is the amount of electrical energy necessary to produce one kmol of hydrogen gas (H_2) by water electrolysis. It is considered that electricity will be [illegible] the following primary energy sources: nuclear, hydraulic and solar (photovoltaic) energies and natural gas-fueled power plants. In the case of electrolysis, electricity will be used as a key element of hydrogen production. Thus the market price of electricity is considered a cost factor for companies producing hydrogen in this way.

2.1 Nuclear energy:

Of the 435 nuclear reactors worldwide which are in commercial operation for the purpose of producing electricity, the vast majority are of the type PWR. This means that they are refrigerated with pressurized water and they consume natural or low enriched uranium [Walters et al., 2002]. This is the case in Brazil. Nuclear energy is commercially produced in Brazil by only two nuclear power plants. The price of this energy is set by the Brazilian National Agency of Electrical Energy (ANEEL). Profits and losses of the nuclear power plants are usually absorbed by the Brazilian State. The price of US$ 50.00 per MWh for nuclear energy is an average value in the international market [Walters et al., 2002] and this is the value that will be considered in this study. This results in a cost of US$ 3.955 per kmol of H_2 by means of water electrolysis.

2.2 Hydraulic power:

whereas only 25% of Brazil's hydraulic potential is used to produce electricity, there is still much room for growth in this field. The hydrologic data of recent decades show that Brazilian rivers have more water than the existing power plants can use to produce energy. Water, which is not used for electricity production is simply released downstream by the power plant. Hydraulic power plants in Brazil release water downstream frequently. This happens at off-peak hours and when there is an excess of water entering the reservoir because of rain upstream. In both cases, the water level at the dam approaches its safety level and forces the plant to release water downstream without generating electricity [Ramos, 2003]. This part of the water can be used for hydrogen production at an estimated price of US$ 5.00 per MWh.

The price of hydro-electricity in Brazil varies according to the power plant itself, its location, the hydric loading rates of the hydrographic basins and mainly because of the distance between the power plants and the consumption centers. Transmission of electricity is a major cost factor for hydroelectricity because most Brazilian rivers suitable for energy production are located far away from the consumption centers. One example is the future Belomonte hydraulic power plant on the Xingú River in the Amazon Region. The price of the energy is projected to be US$ 15.00 per MWh at the power plant. It is projected that Belomonte will supply electricity to the city of Recife, where its energy will have a final price of US$ 30.00 per MWh [Ramos, 2003]. The average market price for hydro-electricity in Brazil in the year 2003 is US$ 40.00 per MWh [Ramos, 2003]. Applying this price to the process of water electrolysis and to value 1 above, the cost of one kmol of H_2 will be US$ 3.164. Doing the same calculations for the price of hydraulic energy at the power plant (US$ 15.00 per MWh) the resulting cost of one kmol of H_2 will be US$ 1.186. And at US$ 5.00 per MWh the resulting cost of one kmol of H_2 will be US$ 0.369.

2.3 Natural gas-fueled power plants:

Hydraulic energy supplies 79 % of Brazil's entire demand for electricity [CAP 03], making the country practically dependent on this kind of electricity. This fact has forced the Government to look for other forms of energy. The preferred method is natural gas-fueled power plants because of the following reasons:

- availability of natural gas throughout the country;
- possibility of building power plants near the end user;

- the costs and times of building this kind of power plant are lower than the ones for hydraulic power plants, and
- the turbines of one power plant can be used in other ones. This is not feasible in hydraulic power plants.

But this technology depends on natural gas prices, which are likely to rise in the future. The average market price of this kind of electricity in the year of 2003 is US$ 40.00 per MWh [Ramos, 2003], leading to a cost of US$ 3.164 per kmol of H_2 by water electrolysis.

2.4 Solar (photovoltaic) electricity:

solar electricity, or photovoltaic technology, expanded in Brazil over the last decade. This was due to governmental development programs similar to those in other parts of the world. However, this technology is still in the experimental phase. Thus, there is still no offer of electricity from solar sources in the energy market. For the purpose of this study the value of US$ 525.00 per MWh will be used, leading to a final cost of US$ 41.522 per kmol of H_2.

3 Hydrogen production by reforming of fuels

Another way to produce H_2 is by reforming fuels, both fossil and renewable. The reaction of reforming requires energy in order to occur. In this study this energy will be provided by combustion of part of the fuel being reformed. The reforming processes of some fuels presented are made in two or more different chemical reactions. In the following cases it will be assumed that the heat used in the endothermic reactions will be provided by the exothermic reactions involved in the same process. In the case of reforming, hydrogen production companies will use the fuels presented as a raw material in their production processes. Thus the market price of the mentioned fuels is considered a cost factor for these companies. The reforming of all fuels presented produces hydrogen-rich gases with high carbon contents. Such gases can not be used directly in low-temperature fuel cells because of the technical characteristics of these fuel cells. As the cost of purification of such gases was not considered in this study, it is therefore impossible to compare the presented hydrogen costs for the operation of low-temperature fuel cells. Thus the comparisons of the different hydrogen costs apply only to medium- or high-temperature fuel cells.

3.1 Natural gas:

natural gas is a mix of several gaseous hydrocarbons. The main component [illegible] which composes 90% of the mix, and will therefore be the only gas considered [illegible]. The reforming process of methane is presented in the Appendix. Natural gas in Brazil is both imported from Bolivia and produced internally. Because of the different locations of the sources, the prices of natural gas vary greatly within the country. In this study the price of US$ 0.031842 per m^3 of natural gas will be considered [TGN 03]. This price, when applied to the reforming of natural gas, leads to a cost of US$ 0.243 per kmol de H_2.

3.2 Gasoline:

the price of gasoline in Brazil is similar throughout the country and it is connected to the price of ethanol [CUE 03]. For this study the price of gasoline will be considered [illegible] liter. This price applied to the reaction of steam reforming of gasoline [illegible] US$ 2.70 per kmol of H_2.

3.3 Methanol

methanol is an alcohol used both as fuel and storage of hydrogen for fuel cells. It is usually considered a fossil fuel because of its raw material, which is mainly natural gas, although it can also be obtained from wood. For the purpose of this study the price of US$ 0.145 per liter will be considered [MET 03]. This price, when applied to the reforming of methanol, leads to a cost of US$ 2.387 per kmol of H_2.

3.4 Biogas:

biogas is the name given to the gas mix (similar to natural gas) resulting from anaerobic decomposition and fermentation of organic material by some classes of bacteria. It is produced by refuse from agricultural activities, dairy factories and slaughterhouses. This gas mix is usually made up of methane (CH_4) and carbon dioxide (CO_2). One of best known methods for obtaining biogas is the rural digestor, of which there are a large number of installed units, mainly in India (with approximately 300,000) and China (with over 8 millions). The process of producing and using biogas independently of its final use is called recovery of biogas, which is not an economical activity registered in Brazil. There are also no significant records of its recovery in developing countries [Alves, 2000]. However it is possible to use data available from sugar cane farms that use biogas for their own generation of electricity. The owners of such farms do not buy electricity from the grid, thus making it possible to assign the energy from biogas with the same price as the fee charged by the local distributor of electricity. By means of this and other approaches it is possible to arrive at an estimated price of US$ 0.29 per m^3 of biogas [Alves, 2000]. This price, when applied to the reaction of biogas reforming, leads to a cost of US$ 3.427 per kmol of H_2.

3.5 Ethanol:

the Brazilian Program of Alcohol Fuel started in 1975 as a Brazilian solution to the first worldwide oil crisis which happened two years earlier. The consequences of this crisis were very severe for Brazil because the country imported 80% of its needs of oil at that time. In the beginning ethanol was only added to gasoline. At the same time car manufacturers in Brazil started to develop engines that would work exclusively with ethanol. The program was so successful that in 1984 alcohol-fueled cars corresponded to 94.4% of car manufacturers' entire production [ACC 03]. In order to further the program the Brazilian Government began a huge financing operation, which was also supported by the World Bank. The investments in the 1980s promoted a growth in the areas planted with sugar cane, construction of new sugar [illegible] factories, and the development of the Brazilian boiler shop industry. To boost the use of ethanol the Government set the price of it for the end user as a percentage of the price of gasoline and the price of gasoline was set at almost two times its price in the United States. The over-pricing of gasoline was used to balance the cost of ethanol, the production of which was more expensive than importing crude oil and refining it into gasoline. There was the expectation that the price of ethanol would fall to a level where it could compete with gasoline. But this did not happen. Later there were continuous drops in the price of crude oil in the international market, thus making it impossible for the Brazilian Government to keep financing ethanol producers. Since 1985 the percentage of alcohol-fueled cars being produced by automobile manufacturers has continually fallen: 60% in 1989, 20% in 1990 and only 0.3% in 1996 [ACC 03]. The price of ethanol considered in this study will be the one connected to the price of gasoline as previously explained, i.e., US$ 0.40 per liter [CUE 03]. Applying this price to the reforming reaction of ethanol - using part of it for the energy required by the reaction - leads to the cost of US$ 3.904 per kmol of H_2 (cost A). Applying that same price to the reforming of ethanol, but using natural gas to provide the energy required by the reaction, leads to the cost of US$ 2.911 per kmol of H_2 (Cost B).

4 Results

In the Table A1 the total costs of the production of hydrogen in Brazil are presented, with each cost being related to its production form.

Table A1: Costs of hydrogen production in Brazil

Means of production		Cost in US$ per kmol of H_2
Electrolysis using electricity from different primary sources	Nuclear energy	3.955
	Hydraulic energy	
	Spot market	3.164
	At power plant	1.186
	Unused water	0.396
	Natural gas power plant	3.164
	Photovoltaic	41.522
Reforming of fossil fuels	Natural gas	0.243
	Gasoline	2.700
	Methanol	[illegible].287
Reforming of renewable fuels	Biogas	3.427
	Ethanol – A	[illegible].904
	Ethanol – B	2.911

The cost of photovolatic energy is the highest value in the table, indicating that this energy form will not be competitive with the remaining sources of primary energy in the near future.

The cost of hydrogen produced by hydraulic and nuclear electricity can vary greatly, depending on the distance between the user and the power plant, the hydrology of the rivers and the market situation.

The transmission of electricity over long distances is not a cost factor to the natural gas-fueled power plants. But such power plants depend on the price of natural gas, which is likely to rise in the future.

The costs of hydrogen production by means of reforming were calculated assuming that the necessary energy to activate the reactions would be obtained from combustion of a part of the fuel being processed. There is an important reduction in the cost of hydrogen produced from ethanol, when its reforming is activated by natural gas rather than ethanol.

5 Conclusions

The results shown in the table lead to the conclusion that the most economical way for mass production of hydrogen in Brazil is, in the short term, the reforming of natural gas. However, this procedure has emissions of greenhouse effect gases, which should be eliminated. In the mid to long-term the end of the reserves of natural gas must be taken into account. Thus another primary energy form should be available. This second source could be hydraulic electricity or nuclear energy, because their costs are also attractive. However, their environmental impacts should also be considered. The cost of hydrogen produced by ethanol reforming is very attractive and strategic for Brazil. The price of US$ 2.911 per kmol of H_2 is comparable to the above-cited sources.

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Appendix

The reaction of water electrolysis is endothermic and is represented by Equation A1.

$$H_2O \rightarrow H_2 + 1/2\ O_2 \qquad \Delta H = 242.000\ kJ\ kmol^{-1}\ \text{of}\ H_2 \qquad (A1)$$

The efficiency of this reaction is about 85%, which means that 284.706 kJ will be necessary to produce one kmol of H_2. However, the cost of electricity is usually expressed in US dollars for each Megawatt per hour (US\$ MWh^{-1}). It is therefore useful to have said value of energy expressed in such units. Thus 284.706 kJ are the same as 0.07909 MWh (Value A1).

The reforming process of methane usually happens in the two reactions represented by Equations A2 and A3.

$$CH_4 + H_2O \rightarrow 3\ H_2 + CO \qquad \Delta H = 205\ KJ\ mol^{-1} \qquad (A2)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad \Delta H = -37,8\ KJ\ mol^{-1} \qquad (A3)$$

The reaction of steam reforming of ethanol is represented by Equation A4.

$$C_2H_5OH\ (l) + 3\ H_2O\ 9(l) \rightarrow 2\ CO_2 + 6\ H_2 \qquad \Delta H = 348\ kJ\ mol^{-1}\ (1\ atm, 298\ K) \qquad (A4)$$

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