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Techno-economical study of the use of Itaipu dam spilled turbinable energy to produce ammonia

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ABSTRACT

In many hydroelectric dams, when the inflows are greater than the demand for energy, a portion of the water that could be used to generate electricity is diverted to the spillway and literally wasted. This energy, designated as "spilled turbinable energy", could be used advantageously to generate other products or an energy vector that could be stored for later use, since in these situations the dam is full. This work studies the feasibility of using the spilled turbinable energy from Itaipu dam to produce electrolytic hydrogen that, together with the nitrogen from air, is an important feedstock for ammonia synthesis, used to produce nitrogen fertilizers. The minimum electrolytic hydrogen production cost was estimated in US\$ 0,25/m^3 or US\$ 2,75/kg, for a plant capacity of 55 x 10^3 m^3/h, which corresponds to 247,5 MW of electrical power deriving from 82% of spilled turbinable energy and 18% of guaranteed energy. Next to the electrolytic hydrogen plant it is possible to install an ammonia plant of approximately 500 t/day, operating 350 days/year, with a production cost of approximately US\$ 562, 81/t. This capacity is enough to supply 38,5% of the ammonia demand estimated for the region focused in the project, that is, 1300 t/day. Nowadays, ammonia is commercialized in the Brazilian market by approximately US\$ 525, 60/t. For this reason, it can be concluded that ammonia production via the association of spilled turbinable energy and guaranteed energy next to Itaipu dam is not economically feasible by the moment due to the high cost of imported electrolysers. Nevertheless, with the installation of an ammonia plant based on water electrolysis next to Itaipu dam and considering methane and carbon dioxide emissions of the Itaipu reservoir, an annual carbon emission of 234 x 10^3 tons could be avoided. If the project is approved by the Clean Development Mechanism, that environmental impact decrease would represent approximately US\$ 5, 5 million. Considering that revenue, the project is not economically feasible.

Keywords

Electrolytic hydrogen, spilled turbinable energy, ammonia, nitrogen fertilizers.

1. Introduction

Itaipu dam is situated between Brazil and Paraguay, in the Paraná River. It has an installed power of 14 GW and currently it is the biggest hydroelectric dam of the world supplying electricity for Brazil and Paraguay. During the year a hydroelectric dam presents an electricity excess, therefore its reservoir is dimensioned to take care of the load when a favourable hydrologic situation occurs. Also it occurs when a hydroelectric dam has a transmission system underdimensioned in relation to the electricity production, spilled turbinable energy is originated. This type of energy, being of hydraulical origin, can be characterized as a renewable source of energy and during its generation it does not have emission of pollutants to the atmosphere, in contrast with the

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electricity production from fossil fuels, such as mineral coal and natural gas (thermoelectric generation). The electricity can be stored in different ways. One of them is to transform it into another product, as for example electrolytic hydrogen (by electrolysis of water). In this study the use of the available spilled turbinable energy in Itaipu dam for electrolytic hydrogen production to use it in ammonia synthesis for nitrogen fertilizers was considered. The minimum electrolytic hydrogen production cost and the corresponding production capacity were determined. From technical literature data the amount of ammonia that could be produced with electrolytic hydrogen from Itaipu dam was calculated. Considering the quantity of imported nitrogen fertilisers and those distributed to the final consumer the ammonia demand for Brazilian Center/South region and the potential ammonia plant capacity that could be installed in the neighborhoods of Itaipu dam were calculated.

2. Economic analysis

Firstly, a survey of monthly spilled turbinable energy availability at Itaipu dam was done between 1991 and 2007 and, after that, it was determined the spilled turbinable energy average availability to each month during one year (average between 2001 and 2007). The spilled turbinable energy availability varies monthly and year by year due to hidraulicity. An evaluation of the seasonal and annual behavior of the spilled turbinable energy at the Itaipu dam was done.

The electricity cost was determined via association of guaranteed energy and spilled turbinable energy of Itaipu dam for several electrolytic hydrogen production capacities: a plant with lesser capacity will use more spilled turbinable energy during the year, if electrolysis plant capacity increases it will use more guaranteed energy. The final electricity cost is the average cost between guaranteed energy and spilled turbinable energy. On the other hand, the electrolytic plant cost depends on the production capacity (economy of scale). Utilizing the Excel Program in the calculation of electrolytic hydrogen cost considering Itaipu dam spilled turbinable energy availability, it was possible to determine the electrolytic plant capacity to get a minimum electrolytic hydrogen production cost. After the calculation of the optimum electrolysis plant capacity and the respective electrolytic hydrogen production cost, it was possible to plan for an ammonia production plant and its cost, and to compare the plant capacity with the ammonia production necessary to satisfy the fertilizer demand of the considered region. The specific electrolysis plant capital cost (C_{EL}) depends on plant size. The increase in production allows better use of capacity and the fixed costs and the invariable costs are divided by bigger amounts of product (SOUZA, 1998). According to [1], [2], [3], [4], [5], [6], [7] and [8], it was posible to determine the specific electrolysis plant cost for different production capacities. Fig.1 shows data from Table 1. If production capacity increases, electrolytic process unit cost diminishes and the corresponding curve is represented by Equation 1:

$$C_{EL} = 2.424{,}9 \times C_p^{\,(-0{,}1062)} \qquad (1)$$

$$R^2 = 0{,}9536$$

Where C_p is the plant capacity, in m^3/h, and C_{EL} is the electrolysis plant unit cost, in USS/kW. Equation 1 allows the calculation of unit capital cost of the plant (C_{EL}).

Table 1. Electrolytic Plant Cost Versus production capacity.

Production capacity (m^3 H_2/h)	**Power (MW)**	**Electrolysis plant cost (US$/kW)**
485	2,3	1.304,35
3.907	18,6	944,68
15.627	74,5	853,01
31.254	149,0	841,16
46.880	223,5	780,52

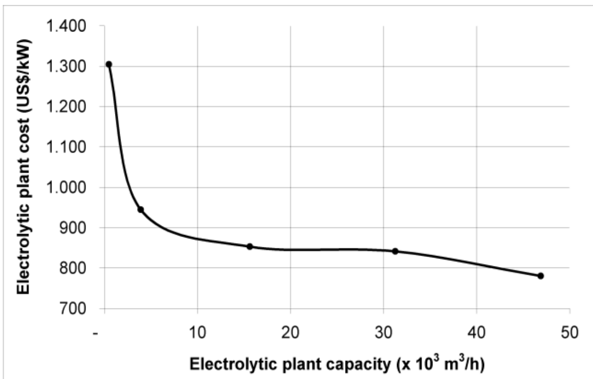

Fig.1: Electrolysis plant cost vs production capacity.

2.3 Economical evaluation of electrolytic hydrogen use for ammonia synthesis.

A competitiveness evaluation was done between ammonia produced from association of spilled turbinable energy and guaranteed energy at Itaipu dam. Calculations include the economic evaluation using the following criteria: Net Present Value and Return On Investment.

2.4 Environmental impact evaluation and the possibilities to obtain carbon credits via the clean development mechanism.

A comparison was done between avoided carbon dioxide emissions from ammonia production via electrolysis of water next to Itaipu dam and greenhouse gas emissions from Itaipu reservoir, to verify if carbon credits could be gotten via the Clean Development Mechanism.

When hydrogen is produced via electrolysis of water using hydroelectricity, local emissions will be lesser along the complete production chain. Carbon dioxide generation during hydrogen production from fossil fuels is linearly dependent on the used fuel amount, assuming an efficiency of 100% in natural gas or petrochemical naphta reformation and in coal gasification processes [11]. In this work the following equation was used to calculate carbon dioxide emissions assuming the efficiency of 100% in natural gas and petrochemical reformation and coal gasification processes:

$$e_{CO2} = 3{,}67 \text{ x } m_F \text{ x } m_{fc}, \quad (2)$$

e_{CO2} = carbon dioxide emissions (kg);

m_F = fuel mass (kg);

m_{fc} = carbon mass fraction (c) in the fuel; 3,67 = reason between carbon dioxide molar mass and pure carbon molar mass (C).

The value of US$ 23,88/t of carbon was adopted to calculate the economical benefits from carbon credits.

3. Results

3.1 Analysis and quantification of spilled turbinable energy available at Itaipu dam.

Table 2 presents the annual values of spilled turbinable energy at Itaipu dam between 1991 and 2006.

Table 2. Spilled turbinable energy availability at Itaipu dam between 1991 and 2006.

Year	Spilled Turbinable Energy (TWh)
1991	34,8
1992	44,9
1993	34,0
1994	24,4
1995	17,3
1996	11,7
1997	10,4
1998	11,7
1999	5,2
2000	1,0
2001	1,8
2002	5,2
2003	4,1
2004	4,0
2005	5,3
2006	3,6

Source: [12]

Fig.2 shows spilled turbinable energy availability at Itaipu dam between 1991 and 2006.

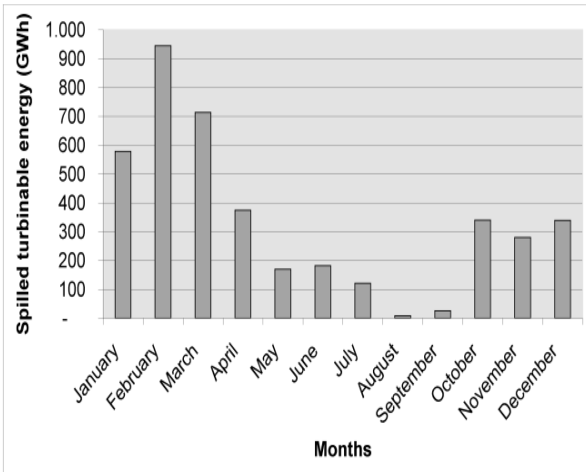

Fig.2: Spilled turbinable energy availability at Itaipu dam between 1991 and 2007.

Source: [12]

According to Fig.2 it can be observed that between 1991 and 1999 there was considerable amounts of spilled turbinable energy due to the lack of electricity demand in those years. In 2000 the lesser value for spilled turbinable energy was due to a bad hydrologic year (low rain occurrence). Therefore, in this work spilled turbinable energy availability between 2001 and 2007 was considered. From October to April the biggest spill, occurs or either, this period corresponds to the rainy time of the dam.

Table 3. Spilled turbinable energy average availability at Itaipu dam between 2001 and 2007.

Month	GWh	Frequency
January	578	14%
February	944	23%
March	713	17%
April	374	9%
May	170	4%
June	182	4%
July	121	3%
August	8	0%
September	26	1%
October	339	8%
November	280	7%
December	339	8%
TOTAL	**4.074**	**100%**

Source: [12]

According to SANTOS Jr. (2007), between 2005 and 2006, it was registered 218 days and 254 days without spilled turbinable energy at Itaipu dam.

Spilled turbinable energy at Itaipu dam is very seasonal. The rainy months are October, November, December, January, February, March and April, coincident with the rainy period in the South-eastern region of Brazil.

3.2 Determination of minimal electrolytic hydrogen production cost and corresponding production capacity.

Calculations were done in Excel Program to determine the association cost of guaranteed energy and spilled turbinable energy for an electrolysis plant working 8400 hours/year, that is, 350 days per year. The month by month electricity requirement of electrolysis plants of different capacities is satisfied completely by spilled turbinable energy or by the association of guaranteed and spilled turbinable energy.

The electrolytic hydrogen cost is a function of the costs of electricity and electrolysis plant, that, in turn, depend on the variation of electrolysis plant production capacity. The minimum electrolytic hydrogen cost is US\$ 0,246/m^3 (US\$ 2,750/kg) for an electrolysis plant capacity of 55 x 10^3 m^3/h and 247,5 MW, being supplied by 82% of spilled turbinable energy and 18% of guaranteed energy. It is important to remark that the calculated production cost does not include electrolytic hydrogen storage and transportation costs.

According to Table 4 electrolytic hydrogen cost produced at Itaipu dam via association of guaranteed energy and spilled turbinable energy is coherent with values from the literature. The electrolytic hydrogen cost produced at Itaipu dam is lesser compared with plants of bigger production capacity due to the lesser cost of the available electricity at Itaipu dam (US\$ 10,04/MWh), which is five times lesser that values from literature (USS 49,00/MWh).

Electrolytic hydrogen production cost in electrolysis plants of smaller capacity that Itaipu dam is influenced by the economy of scale and by the electricity cost considered in these studies. However, the electrolytic hydrogen produced at Itaipu dam (US\$ 2,75/kg) still cannot get compete with hydrogen produced from natural gas or petrochemical naphta reformation (US\$ 1,25/kg) and refinery gas not catalytic partial oxidation (US\$ 1,24/kg) processes.

According to [13], commercial hydrogen price depends on its pureness. Currently, hydrogen is commercialized in small volumes in cylinders of 50 L.

Table 4. Comparison between obtained result and values from literature.

Production capacity (10^3 m^3/day)	Electricity cost (US\$/MWh)	Hydrogen cost (US\$/kg)
1320,0	10,04	2,75
2800,0	49,00	3,76
6750,0	49,00	3,89
96,0	49,00	4,38
162,0	223,00	10,94
14,0	35,88	4,08
11,2	50,00	4,09

Table 5. Current commercial hydrogen price distributed in cylinders of 7,2 m^3.

Classification	Minimum purity (mol/mol)	Price (US\$/m^3)
Hydrogen 6.0	99,9999%	87,91
Analytical Hydrogen 5.0	99,9990%	24,00
Hydrogen 4.5 FID	99,9950%	22,34
Hydrogen 4.5	99,9950%	19,03
Hydrogen 4.0	99,9900%	18,30

Source: [13]

Considering that electrolytic hydrogen production via association of guaranteed and spilled turbinable energy (99,99% pureness) costs US$ 0,246/m^3 and commercial hydrogen price distributed in cylinders of 7,20 m^3 is approximately US$ 18,30/m^3, electrolytic hydrogen cost produced at Itaipu dam seems to be attractive for companies who use it as chemical feedstock (metallurgical industry, pharmaceutical industry, petrochemical industry, etc.).

According to [14], most of the hydrogen is consumed in the proper place of production (refinery, petrochemical complex). When commercialized, it is treated as "special gas" and its price can vary in function, mainly, of marketing strategies of the supplier. unofficial information of the main supplier in Brazil (Praxair) had indicated prices between US$ 1,00/m^3 and US$ 6,00/m^3. Usually hydrogen is produced from natural gas reformation. As a general rule, it is considered that hydrogen production cost, for energy unit (US$/kJ), is 3 times the price of natural gas used as raw material [15]. The difficulties of hydrogen distribution explain the great difference between production cost and price to the final consumer. An economic evaluation of electrolytic hydrogen use for ammonia synthesis of nitrogen fertilizers was done. Ammonia production cost from water electrolysis via association of spilled turbinable energy and guaranteed energy at Itaipu dam is approximately US$ 562,81/t for a 500 t/day plant capacity working 350 days/year, that is, 8400 hours per year. According to [16], currently commercial ammonia price in the Brazilian markets is US$ 525,60/t approximately. It can be concluded that the use of electrolytic hydrogen produced next to Itaipu dam for ammonia synthesis is not economically feasible by the moment. Commercialisation of electrolytic hydrogen like chemical feedstock would be the most interesting economical option.

Table 6. Ammonia cost comparison

Manufacturer	Process	NH_3 cost (US$/t)
Itaipu	Water electrolysis	562,81
FOSFERTIL Company (Brazil)	Heavy oil partial oxidation	525,60

Ammonia produced from electrolysis of water via association of guaranteed energy and spilled FOSFERTIL from asphalt residue partial oxidation. Turbinable energy at Itaipu dam cannot get compete with ammonia produced by the company Fig.3 shows the results of sensitivity analysis. Calculations had been done varying the following parameters: equipment cost, electricity cost, discount rate and electrolysis plant availability. These calculations had been done to verify electrolytic hydrogen cost sensitivity to some of its main components.

In Fig.3 it can be observed that equipment costs, mainly the imported electrolysers, have a strong impact on the electrolytic hydrogen production cost. With a reduction of 50% on equipment costs, electrolytic hydrogen production cost gets close to hydrogen production cost via natural gas reformation. Electricity cost, however, does not have a significant impact because a reduction in 50% of electricity cost, electrolytic hydrogen production cost was reduced only in 9,4%

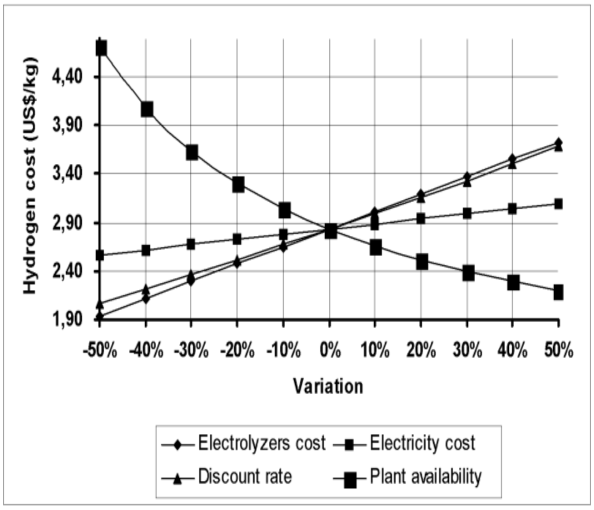

Fig.3: Sensitivity analysis

Table 7. Itaipu dam and carbon emissions.

Parameter	Units	Value
CH_4 emission index	$kg.km^{-2}.day^{-1}$	20,8
CO_2 emission index	$kg.km^{-2}.day^{-1}$	171
Total carbon emissions*	**t/year**	**93269**

*Include CH_4 carbon (with GWP according to IPCC, 1996) and of CO_2: (CH_4 x 12/16 x 7,6 + CO_2 x 12/44) x 365/1000.

Source: [17]

3.3 Environmental impact evaluation and the possibilities to obtain carbon credits via the Clean Development Mechanism.

According to [17], carbon emissions at Itaipu dam are 93269 t/year.

For the production of one ton of ammonia via light hydrocarbons reformation is emitted approximately 0,706 ton of carbon dioxide [18]. A 500 t/day ammonia plant via natural gas reformation would emit 327500 carbon tons per year. Therefore, it can be concluded that with the installation of an ammonia plant via electrolysis of water next to Itaipu dam and considering methane and carbon dioxide emissions from Itaipu reservoir, annual emissions of 234231 tons of carbon would be avoided. In case the Clean Development Mechanism approves this project, this environmental impact reduction would represent US$ 5,5 million annually. Although natural gas reformation is the cheapest commercial process to produce hydrogen, natural gas is a hydrocarbon, and emits carbon dioxide in the production process.

According to [19], it is possible to reduce electrolysers capital and operation costs, however, electricity price is the most important factor in electrolytic hydrogen production cost. According to [20], centralized or distributed production is another important factor in the economics of electrolytic hydrogen. Centralized or distributed hydrogen production systems need to increase electrolysers efficiency and reduce capital costs considering current values. [21] suggests that other countries with cheap hydroelectricity, like Canada, Norway, Sweden and Iceland, can be the first ones to use in wide scales renewable electrolysis. Electrolytic hydrogen is thus a good alternative according to Quioto Protocol, worldwide agreement that establishes rules for greenhouse gases reduction, mainly carbon dioxide, in the entire planet.

4. Conclusions

Considering the obtained results, it can be concluded that the prediction of spilled turbinable energy availability to use it for electrolytic hydrogen production for ammonia synthesis next to Itaipu dam is not trivial because frequency distribution of spilled turbinable energy is antisymmetrical, presenting high dispersion. Spilled turbinable energy availability at Itaipu dam is approximately 4,0 TWh/year. October, November, December, January, February, March and April present greater spilled turbinable energy availability due to a bigger rain incidence; the other months are dry. According to the data supplied by manufacturers, commercial electrolysers have a typical efficiency between 45% and 75%, in a way that the required electricity to produce 1,0 m^3 of electrolytic hydrogen varies from 4 kWh to 7 kWh. Electrolytic hydrogen production via association of guaranteed energy and spilled turbinable energy cannot get compete, by the moment, with hydrogen production via natural gas reformation. In this work it was verified that main responsible factor for electrolytic hydrogen high cost is electrolysers cost. Electricity cost does not have a significant impact. For an electricity null cost, electrolytic hydrogen production cost would reflect the amortization of investment, operation, maintenance, and materials. The sum of these components, independent of electricity, diminishes with the increase of production capacity. This reduction is in accordance with the data from literature. Therefore, electrolysers cost represents the biggest component of electrolytic hydrogen plant total cost and this fact is aggravated by the current necessity of importation of electrolysers and its auxiliaries. For this reason, the development of a national industrial park is necessary to produce these equipment, in order to reduce investment costs of electrolytic hydrogen production systems.

It is important to remark that electrolytic oxygen, by-products in electrolysis process, can be stored and commercialized, increasing business opportunities in hydroelectric dams.

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