

lean H₂ and NH₃ large production in Paraguay by the 14 GW Itaipu hydroelectric facility

G. Riveros-Godoy^{1, 3}, M. Rivarolo², A.F. Massardo², G. Arevalos³*

¹ Parque Tecnológico Itaipu, Hernandarias, Paraguay

² Thermochemical Power Group, University of Genoa, Via Montallegro 1, 16145 Genoa, Italy

³ Facultad de Ciencias y Tecnologías, Universidad Privada del Este, Pdte. Franco, Paraguay

Abstract. This paper aims to present a feasibility study for clean production, storage and distribution of large amounts of hydrogen, starting from low-cost available renewable electrical energy. Paraguay and Brazil own equally the binational company ITAIPU Hydroelectric Plant (14 GW, about 96,000 GWh/year of production). 50% of this energy corresponds to Paraguay: however, since its energy demand is quite low, a large amount of this energy is sold to Brazil, receiving a compensation of 10 \$/MWh. In this context, seeking for ways of adding value to generated electricity, this paper assesses the potential of clean H₂ production by water electrolysis, simulating the use of one generator unit of the mentioned company (700 MW) and discussing two alternatives for the produced hydrogen: a) using it for ammonia production as base for fertilizers; b) using it for passenger cars. A detailed thermo-economic analysis is performed using a dedicated software developed by the authors. The results show that production is economically feasible for both cases, moreover the process is completely clean and significant amounts of oxygen are produced, potentially representing an additional revenue for the process.

1 Introduction

Hydrogen represents a solution of great interest toward a future sustainable energy system: it represents a clean energy vector, with zero emissions in terms of CO₂ and local pollutants (CO, SO_x and particulate). Hydrogen can be produced by water electrolysis, employing electrical energy surplus from Renewable Energy Sources (RES): in this case, the production would be zero emission as well, leading to a completely sustainable solution, as reported in [1]. The most developed kind of devices for production are Alkaline Electrolysers (AEC): since they are a mature and well-developed technology, different solutions are available in terms of capacity (from kW to multi-MW for unit) and operating pressure (from 1 to 30 bar); costs are relatively low, about 1000-1200 €/kW for large scale units, as reported in [2]. The most critical issues of hydrogen are related to its storage. In fact, since its low energy density (0.09 kg/m³ at standard conditions), H₂ transportation requires large volumes and, consequently, high costs. H₂ is usually stored in form of compressed gas (200 – 700 bar, energy density 12 – 35 kg/m³) or in liquid form (70 kg/m³, at -253 °C): however, both the solutions require large energy amounts and management aspects, i.e. related to safety [3].

Another interesting option can be represented by the conversion of H₂ into other “chemicals”, with higher energy density and easier to be managed and transported. The

* Corresponding author: gustavo.riveros@pti.org.py

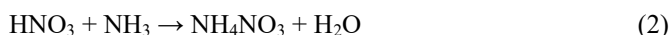
possibility of converting H₂ into bio-methane or methanol was investigated in [4]: in this case, the use of ammonia (NH₃) as chemical has been investigated.

According to Ortiz et al [5] the use of chemical fertilizers in Paraguay shows an important growth from 2002 to 2014, the annual demand for nitrogenous fertilizers has increased from 34,934 ton up to 132,558 ton (+379%). Ammonia is produced throughout to the Haber-Bosch process, according to the following reaction (1), which occurs at 500 °C and 150-200 bar [6]; the reaction is exothermic, with the production of 92.4 kJ/mol.



The reaction takes place with N₂ (sequestered from air by a commercial Air Separation Unit, ASU) and H₂ (produced from renewable hydraulic energy by electrolysis). The mass balance of Eq. (1) indicates that, around 176 kg of H₂ are necessary to synthesize 1 ton of ammonia.

From ammonia is possible to obtain Ammonium nitrate, which is commonly used as fertilizer. Based on Eq. (2), it is possible to calculate that about 212 kg of NH₃ are necessary to produce 1 ton of Ammonium nitrate (NH₄NO₃); this reaction is highly exothermic:



In the present study, the production of hydrogen and ammonia from renewable hydraulic energy produced in Itaipu is analysed: in particular, the economic feasibility of this solution is investigated.

2 Case study

The case study focuses in the energy from Itaipu Hydroelectric Power Plant, located on Parana River and owned equally by Paraguay and Brazil. The power plant includes 20 generating unities and 14 GW of installed power and provides around 15% of the energy consumed in Brazil and 90% of the energy consumed in Paraguay [7]. Thus, for Paraguay, hydropower comprises nearly 100% of electricity; approximately 90% of the generated energy is exported, 47,365 GWh in 2017 [8]. Alternatives to increase the electricity usage in the country have been widely discussed at different fields. For instance, Rivarolo et al [4] have proposed the production of electrolytic hydrogen as input for hydro-methane and methanol production as a means to increase and storage the electricity produced in Paraguay. All the time local politicians present the adoption of electric vehicles as the best way to use the electricity, so far without any success [9]. For this paper, the department of Alto Parana is taken into account, currently has registered 111,309 passenger cars [10]. Regarding to nitrogenous fertilizers, the demand is roughly 157,000 ton/year based on 2017 [11].

3 Energy and economic analysis

The analysis is carried out throughout the W-ECOMP software tool, developed at Thermochemical Power Group (TPG) at University of Genoa [12]: W-ECOMP performs a thermo-economic, time-dependent analysis and optimization of energy systems, including off-design conditions [13][14]. It is characterized by a modular approach (50 modules): each component is described by subroutines, which define mass and energy flows, off-design performance curves, variable and capital costs. The determination of cost functions

for the different modules has been performed thanks to many contributions by TPG's industrial partners over the last years, by market data and by reference to literature. The software also includes a dedicated subroutine for the calculation of purchased equipment cost (PEC, based on cost functions) and of total capital investment (TCI, based on the scenario where the plant operates).

Fig. 1 shows a simplified scheme of H₂ production and storage plant from clean energy produced by the Itaipu hydroelectric plant: the system's size is based on hydrogen demand (100 ton/day). More in detail, in this case the hydrogen is produced by a system of commercial large scale alkaline electrolyzers (2 MW each, for a total of 220 MW), operating at 30 bar with an electrical consumption of 4.7 kWh/Nm³ H₂. Hydrogen is then compressed up to 350 bar by diaphragm compressors (installed power 4 MW, efficiency 70%) to be stored in tanks and transported to end users (H₂ refuelling stations). The high availability of Itaipu plant (97.2% on year basis, minimum of 95.6% in April), is employed to calculate the production of H₂ and O₂: Oxygen sale is not considered in this particular case. Considering the amounts above reported, the produced hydrogen would allow to power about 30% of the whole amount of passenger cars circulating in the Alto Paraná department (about 33,000 cars, with a maximum consumption of 3 kg/day of H₂ per car, corresponding to more than 200 km per day, as reported in market data [15]).

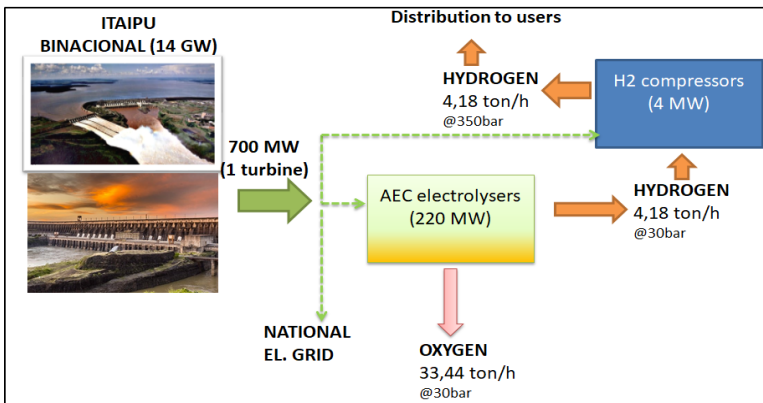


Fig. 1. Simplified scheme for H₂ production by RES

Fig. 2 shows the configuration including ammonia synthesis as well: the produced H₂ is mixed with N₂ (obtained by an Air Separation Unit, ASU); both are compressed and sent to the Haber-Bosch synthesis unit, with a capacity of about 30,000 tons/year of ammonia. Ammonia is then stored and transported to final users (i.e. industries for fertilizers' production), as in the previous case: according to Eq. (2), the above-reported amount of NH₃ is sufficient to produce the whole amount of fertilizers necessary for Paraguay's needs. The size of the AECs' system is considered the same: a part of the H₂ amount is used for ammonia synthesis, together with N₂ obtained by a commercial ASU (3 MW of electrical consumptions, including compression for bringing the gases up to 150 bar). It is worth noting that a relatively low amount of H₂ is necessary in order to produce the amount of fertilizers necessary to satisfy Paraguay national demand.

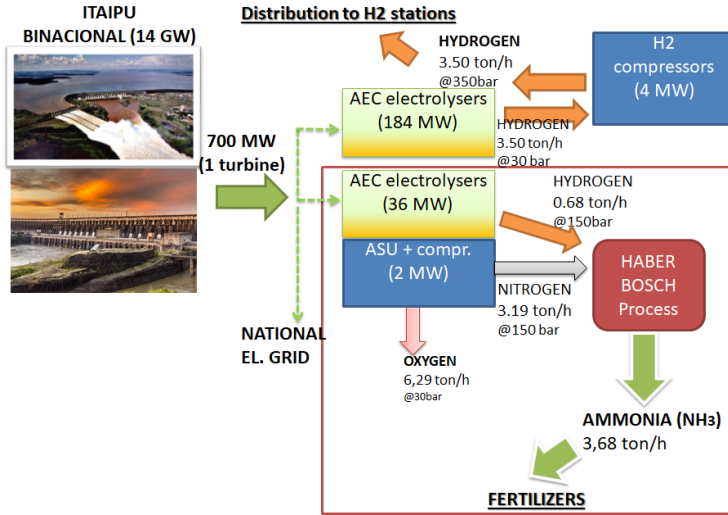


Fig. 2. Simplified scheme for NH₃ synthesis by RES

In order to evaluate the solutions from the economic standpoint, the determination of production costs is mandatory. Annual costs are determined as the sum of capital and variable costs, including O&M. For variable costs calculation, the main voice is represented by electrical energy: an average price of 30 \$/MWh is considered, which is the market price in Paraguay. The calculation is performed by W-ECOMP, taking into account the cost functions implemented in the software. Tab. 1 reports the comparison of total annual costs in the two cases.

Tab. 1. Comparison of total annual costs

H2 production			NH3 production		
Fixed Costs			Fixed Cost		
AECs (220 MW)	19.2	M\$/yr	AECs (36 MW)	3.8	M\$/yr
Compressor H2	1.7	M\$/yr	ASU	1.9	M\$/yr
			Haber Bosch	2.6	M\$/yr
Variable Costs			Variable Cost		
Electrical energy	52.8	M\$/yr	Electrical energy	8.6	M\$/yr
TOTAL ANNUAL COST	73.7	M\$/yr	TOTAL ANNUAL COST	16.9	M\$/yr
Annual H ₂ production	33440	ton/yr	Annual NH ₃ production	29500	ton/yr
H ₂ production cost	2.2	\$/kgH ₂	NH ₃ production cost	575	\$/ton

Fig. 3 shows cost distribution for the plant for H₂ production only. Total annual costs are about 70 M\$/year, most of them related to electrical energy consumption, mostly by alkaline electrolyzers, which represent the most significant voice in terms of investment costs as well. Taking into account that the system capacity in terms of H₂ production is about 100 ton/year, average production cost can be easily calculated and it is about 2.2 \$/kg H₂, which is lower than the IEA target set up for 2028 (2.3 \$/kg H₂). However, it is worth noting that the analysis has been carried out considering full cost for electrical energy produced in Itaipu and not considering a possible sale of the large amounts of pure Oxygen

co-produced by AECs, for example to hospitals or industries; therefore, the production cost is conservative and could be lowered in case of additional products selling.

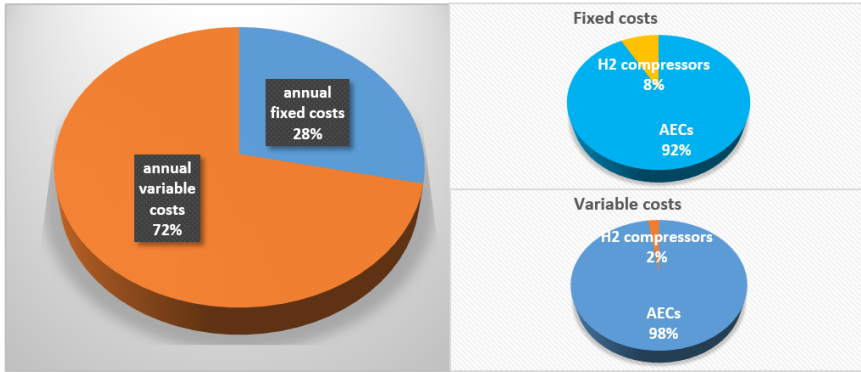


Fig. 3. Costs distribution for H₂ production plant (annual costs on the left, fixed and variable costs detail on the right)

In the same way, ammonia production cost can be performed, estimating the distribution of both fixed and variable costs for the second configuration. In this specific case, the calculation is performed considering only the AECs related to H₂ produced and sent to Haber-Bosch section for NH₃ synthesis (about 36 MW). It is worth noting that, in this case, the half of the annual costs are related to fixed costs (about 6 M\$/year on a total of nearly 12 M\$/year). The distribution of investment cost is different from the one shown in Figure 3: in fact, even if AECs still represent the most important voice, in this case the new plant sections (ASU and Haber-Bosch synthesis unit) have a strong impact. On the other hand, it is possible to note that the most of variable costs, as in the previous configuration, is related to AECs electrical consumptions. In this case, about 30,000 ton/year of ammonia are synthesized, at an average production cost of 590 \$/ton, which is quite close to market price of 550 \$/ton reported in [16] for ammonia production from methane steam reforming. This amount is enough to produce around 142,000 ton/year of Ammonium nitrate.

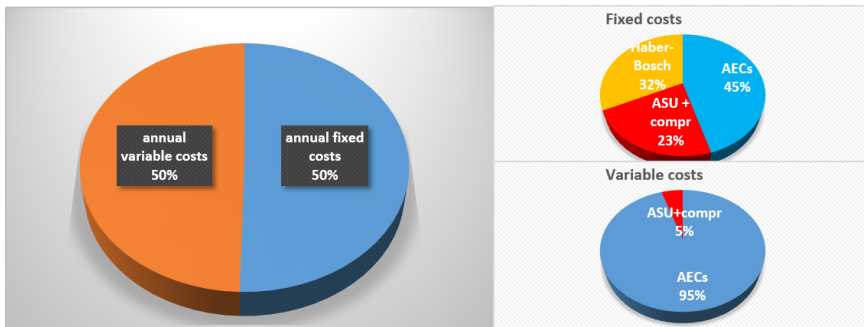


Fig. 4. Costs distribution for NH₃ production plant (annual costs on the left, fixed and variable costs detail on the right)

4 Conclusions

In this paper the production of H₂ by alkaline electrolysers is investigated. AECs are fed by employing electrical energy produced by one of the twenty 700 MW size hydraulic

turbines installed in Itaipu. The economic analysis is performed with the W-ECOMP tool, developed by Thermochemical Power Group at University of Genoa for time-dependent thermo-economic analysis. Two different lay-outs were investigated:

1. H₂ production and storage (at 350 bar) to refuel 30% of the passenger cars circulating in Alto Parana department (33,000 cars);
2. H₂ and NH₃ production and storage: in this case, the size of the NH₃ is produced in order to satisfy around 90% of the whole demand of nitrogenous fertilizers in Paraguay.

It should be noted that the NH₃ also is an interesting way for transporting hydrogen.

The size of the AECs system was determined in about 220 MW, considering the energy balance of the whole system. In the second layout, the total capacity is assumed the same, but a part of the H₂ production is sent to Haber-Bosch process in order to synthesize ammonia.

In both cases, H₂ and NH₃ production costs are competitive, compared respectively to IEA targets for 2028 and to present market costs. It is worth noting that the feasibility study was performed not considering to sell the large amounts of pure Oxygen on the market: in that case, economic results could be significantly improved.

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