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Future of the production of green hydrogen in Paraguay

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Abstract. Paraguay is also joining the worldwide movement towards economy decarbonization by considering hydrogen as a viable option. Given Paraguay's abundant renewable energy resources, boasting approximately 8.7 GW of installed hydroelectric capacity, as well as its cost-effective electricity, the country is attracting significant interest from various companies looking to engage in large-scale production of green hydrogen. However, Paraguay is currently experiencing a significant increase in electricity demand, with a growth rate of approximately 8% per year. By 2033, the country's power system has the potential to attain a generation reserve margin of 12% if this pattern persists. An additional crucial aspect to consider is that the operator of the national electricity grid (ANDE) is currently developing various scenarios to accommodate the increasing demand for electricity energy. Nevertheless, these scenarios fail to consider the potential impact of widespread hydrogen production on the power grid. This paper aims to close the existing gap by introducing multiple scenarios for electricity demand that incorporate hydrogen production facilities linked to the National Interconnected System.

1 Introduction

Hydroelectric power is an exceptionally valuable strategic resource for Paraguay, crucial for its current and future socioeconomic growth. The more a country utilizes electricity, the higher their social development indexes (IDH) and economic growth (GDP) become [1]. Latin America holds the largest water wealth in both surface and groundwater, providing abundant opportunities for national and foreign investment. Please provide the original text for me to rephrase.

In Paraguay, the energy sector solely relies on renewable energy sources, specifically hydroenergy and biomass. Hydropower is responsible for 65% of the nation's total energy supply [1].

The energy sector in Paraguay is characterized by a lack of harmony. The entire national production of primary energy relies exclusively on renewable energy sources, specifically hydroelectric and biomass energy. In theory, renewable sources can be sustained as long as policies supporting sustainable forest management are put into practice. Paraguay is among the leading countries in hydroelectric energy generation per capita. Its power is derived from hydroelectric plants that were established through collaboration between Brazil (Itaipú) and Argentina (Yacyretá), with each country having an equal 50% stake in these ventures. Almost 95% of local electricity consumption is generated by binational hydroelectric power plants. Acaray power plant contributes with the final 5% [3].

To redirect Paraguay's economic and social development process, it is crucial to strategically utilize the surplus of hydroelectricity that is currently being exported. We can

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leverage this surplus through a carefully designed strategy to encourage initiatives that drive socioeconomic progress, such as the production of environmentally-friendly green hydrogen.

In recent years, several feasibility studies have been conducted to assess the potential of green hydrogen in Paraguay. Several studies have focused specifically on exploring aspects related to the production, distribution, and final usage of it [4, 5, 6, 7].

2 Electricity System in Paraguay

Paraguay has one of the lowest levels of electricity consumption per capita in the region. In Paraguay, the consumption of energy per person per year is below 1,400 kWh, whereas in Argentina and Uruguay it reaches an average of 2,000 kWh per person per year. [8]

Paraguay exports about 62% of the hydroelectricity it produces due to the abundance of hydroelectricity compared to internal demand, thus positioning itself as one of the world's top per capita exporters of hydroelectricity. In 2020, the total electricity generation in the country reached an impressive 46,372.96 GWh. In that particular year, a whopping 28,472.99 GWh (61.4%) of energy was exported and left unused [9].

Last year, the three hydroelectric power plants supplying the national system experienced a decline in their gross generation. In comparison to 2019 statistics, the Acaray power plant registered the most significant reduction by 40.9%, followed by the Yacyreta power station at 14.0%, and the Itaipu plant at 3.7%.

Paraguay is facing an unfavorable situation. The country suffers from a clear energy imbalance that is detrimental to its energy security, the sustainability of its energy sources, and the environment. Although facing unfavorable conditions, the country fails to effectively harness its excess electricity and heavily depends on unsustainable biomass and oil-based energy sources. Not only does this situation impact the populace's quality of life, but it also leads to detrimental social, economic and environmental consequences.

The legal framework controlling the Paraguayan electricity sector determines the legal system for its primary participants. The National Electricity Administration (ANDE), a state-owned company, holds exclusive rights to provide electricity services within this framework. Moreover, ANDE has been granted the authority to utilize water resources in order to fulfill the energy demands of the nation. Binational entities in the sector, namely the Itaipu and Yacyreta plants, are governed by international law. Furthermore, there exist small-scale distributors that act as buyers of ANDE energy.

The hydroelectricity potential of Paraguay is tremendous. Its potential electricity generation capacity is huge, surpassing 100 TWh/year, which includes the already existing 60 TWh that are not fully utilized in the domestic market. By achieving this, it has the potential to establish itself as a leading global supplier of entirely hydroelectric power. The demand for electricity is substantial, representing 19% of the final energy demand, and there is tremendous potential for its integration across various sectors [9].

The significant increase in the electrical installed power has been crucial and has surpassed the demand levels of the Paraguayan system, resulting in an impressive reserve level of 223%. Table I displays the installed capacity and availability of Acaray, as well as the binational plants managed separately by Itaipú and Yacyreta entities. These plants have a direct connection to the National Electric System.

Table I. Electricity generation plants of the interconnected system 2020 [3].

Hydroelectric plants	Installed power (MW)	Corresponding to Paraguay (MW)
Itaipú	14,000	7,000
Yacyreta	3,200	1,600
Acaray	210	210
Total	17,410	8,810

2.1 Projection of electricity supply demand

The United Nations Development Program (UNDP) has conducted a recent prospective study indicating a gradual rise in electricity consumption. Table II presents the electricity demand values projected for the period until 2050.

Table II. Electricity Demand projection (GWh).

Year	2.018	2.023	2.030	2.040	2.050
Demand	12,988.50	14,687.64	18,285.50	24,611.64	32,636.22

It is evident from consumption projections that by the year 2050, there will be an ample excess of electrical energy readily available for use, thanks to the installed capacity of hydroelectric plants. It's crucial to emphasize that, while surplus energy is feasible, ANDE reports highlight the pressing need for SIN to possess extra capacity to meet the high electric load during peak hours. The ANDE master plan [11] has provided a forecast for the expansion of electricity generation in Paraguay, which is presented in Table III.

Table III. Summary of the ANDE generation master plan.

Year	Additional Power	[MW]
2027/2030	CH Acaray	200
2024/2026	CH Aña Cuá	135
2035	CH on Paraguay River, location A	72
2039	CH on Paraguay River, location B	72
2021/2029	Photovoltaic	425
2021/2031	Hybrid*	5.03
2025/2033	PCH	203.44
Total		1,112.47

3 Hydrogen production

Several studies suggest that hydrogen has the capability to offer economically viable, energy-efficient, and ecologically sustainable alternatives as opposed to traditional fossil fuels. Hydrogen can be considered as a highly efficient and environment-friendly source of energy, as it does not emit CO2 or any other harmful pollutants. In addition, by using renewable energy sources (RES) and relying solely on water as an input, hydrogen can be generated via the process of water electrolysis [12]. This highlights its potential as a crucial component in the energy transition, serving as a vector for the elimination of carbon emissions from the economy [13].

Paraguay developed a comprehensive strategy titled "Towards the Green Hydrogen Roadmap in Paraguay". This initiative is in line with the National Energy Agenda and highlights the importance of green hydrogen as a crucial source of energy for the country's transportation sector. The proposed plan has the capacity to revolutionize the energy scenario of the nation and promote the progress of renewable energy sources. The Agenda emphasizes the numerous benefits of adopting a forward-thinking and inventive strategy towards utilizing H2 energy, particularly green H2 that taps into the abundant surplus of hydroelectric power [14].

3.1 Cost of hydrogen production

The variations in installation costs, CAPEX, price of purchased electricity, and the percentage of load to be used are closely linked to the levelized costs of hydrogen production in several cases. According to [2], the final cost of the produced hydrogen depends significantly on both the electricity cost and the operating hours.

Reference [2] provides a summary of the expenses used in this research. Green Hydrogen can be produced at a cost of 2.8 USD/kg, based on the electricity cost defined in ANDE's Tariff 21. The Alkaline Liquid Electrolyte (AEL) technology, widely known as AEL Alkaline Electrolysis, has firmly established itself as the most commercially successful technology worldwide for producing hydrogen up to the megawatt (MW) range.

With this technology, it is possible to achieve an impressive operation time of up to 90,000 – 100,000 hours. In addition to that, it also offers significant commercial efficiencies, with savings ranging from 60% to 75%. Alkaline electrolyzers stand out for their remarkable efficiency and compelling affordability. Obtaining hydrogen through electrolysis using this particular equipment ensures a remarkably high level of purity, reaching values as exceptional as 99.7% to 99.9%.

Table IV illustrates the installation schedule and power of the electrolyzers, taking into consideration the surplus of electricity presented earlier and the costs associated with their installation. The present study examines the potential impact of a 1,000 MW power plant installation on SIN in the year 2030.

Table IV. Installation schedule of green industries in Paraguay.

Year	Installed Power [MW]	Energy demand per year [GWh]	Hydrogen production [ton/year]
2.023	20	175	3,818
2.025	200	1,752	38,185
2.030	1,000	8,760	190,923

4 Methodology

For this work is analyzed the installation of a hub of hydrogen industries in Paraguay, for this purpose it is used the acronym ZEBC (in Spanish Zona Economica de Bajo Carbono).

By examining the ANDE's peak demand in 2030, the ZEBC interconnection's effectiveness is evaluated. The Transmission Master Plan of ANDE takes into account the incorporation of the Yguazú Hydroelectric Power Plant, also known as the Yguazú Dam, starting in 2028 with 35 MW of power, out of a total availability of 70 MW. Moreover, there are intentions to build the Third Powerhouse in the Acaray bypass by 2030, aiming to enhance the power supply with an additional 45 MW. As a result of these advancements, the peak dispatchable power will reach an impressive 285 MW. The CH Acaray modernization plan aims to retrofit and repower Groups 1 and 2, alongside the modernization of Groups 1, 2, 3, and 4. It is anticipated that these improvements will be completed by 2025.

The Master Generation Plan provides for the incorporation of new solar generation capacity to equivalent SIN models as detailed in the table:

Table V. Photovoltaic plants for next years.

Technology	Capacity	Interconnection node
Photovoltaic plant	200 MW	Loma Plata
Photovoltaic plant	100 MW	Valenzuela
Photovoltaic plant	200 MW	Carayaó

During the simulations, it is taken into account that the new photovoltaic facilities will possess operational adaptability alongside energy storage technologies. This will allow them to generate energy at their maximum capacity specifically during SIN's peak hours of charging multiple devices at the same time.

The voltage parameters, including module and phase angle, of the new solar power plants are adjusted to match the values of the interconnection bars they are connected to.

The variable cost of generating new plants is expected to be the same as the variable cost of generating ANDE, which is approximately 15 USD/MWh. The cost is considerably lower when compared to the production expenses of the cross-border hydroelectric facilities..

5 Results

In the evaluated scenario, it is verified that:

- There is no power deficit
- Voltage magnitude restrictions are activated in:
    - 1404 – Guarambaré Compensator – Metropolitan System
    - 411 – Limpio Compensator – Metropolitan System
    - 4403 – San Lorenzo Statcom – Metropolitan System
    - 4468 – Horqueta Compensator – North System
    - 1479 – Loma Plata Compensator – West System
    - 185 – Yguazú Dam G1 – East System
    - 890 – Yacyreta B1 500 kV – South System
    - 471 – Cerro Cora 220 kV Substation – North System
    - 2474 – Agua Dulce Substation 220 kV – West System
- Generation capacity restrictions are activated in:
    - 181 – Acaray G1
    - 182 – Acaray G2
    - 183 – Acaray G3
    - 184 – Acaray G4
    - 185 – Yguazú Dam G1
    - 187 – Acaray G5
    - 7479 – Loma Plata Photovoltaic Plant
    - 7426 – Valenzuela Photovoltaic Power Plant
    - 7485 – Carayaó Photovoltaic Power Plant
- Transmission capacity restrictions are activated in:
    - 220 kV LT (489) Presidente Franco – (451) Paranambú – East System

Analysis of Energy Commercialization

To analyze energy trading, three scenarios are assumed

- Preferential rate: implies billing according to the CUSE of Itaipu Binacional, adding a proportion as a toll for the use of ANDE facilities, under two variants:
  - Current CUSE: 20.75 USD/kWmonth (+ 5.15 USD/kWmonth)
  - Minimum CUSE: 09.05 USD/kWmonth (+ 2.25 USD/kWmonth)
- ANDE Schedule: implies billing according to ANDE's current Tariff Schedule, that is, Tariff Schedule No. 21 for Extra High Voltage consumption groups (220 kV)
- Marginal cost: implies billing according to the marginal cost of supply at the Yguazú node, considering the following variable generation costs:
  - Itaipu Hydroelectric Plant: 30.25 USD/MWh (equivalent)
  - Yacyretá Hydroelectric Plant: 40.25 USD/MWh
  - Power plants owned by ANDE: USD 15.00/MWh

The simulation results do not show significant contribution from the operation of the photovoltaic plants to the electricity supply. One possible reason for this is their remote location, which is distant from the centers of energy demand.

During peak load hours of these simulations, the ZEBC assumes a base load modulation of 0%, in addition to implementing the Transmission and Generation Master Plan. This hypothesis is based on the nature of the business, as it is understood that having excess electricity enables this type of operation. Furthermore, this will ensure that the SIN's operation is checked under the worst-case scenario.

Below are the results of the possible benefits to which the ANDE can access according to the rate model to be applied in the ZEBC:

Table VI. Possible benefits.

Scenario	Model	Annual flow
Preferential rate	P x (CUSE + Toll) x 12	Variant 1: USD 217,560 millones Variant 2: USD 94,920 millones
Tariff Sheet ANDE No. 21	A. Contract = P x Tpres x 12 B. Eep = P x 4 x Tpeak x 365 C. Efp = P x 20 x Tmedium x 365	A. G .260.677,2 millones B. G. 237.512,8 millones C. G. 845.194,0 millones Total A. + B. + C. = G. 1.343.384,0 millones USD 191,912 millones (aprox.)
Marginal cost	P x MargCost x 24 x 365	USD 241,478 millones

6 Conclusions

The ZEBC interconnection has been analyzed in detail, taking into account both the Transmission and Generation Plans.

The model successfully addresses the optimal power flow constraints, incorporating the ZEBC's demand into the Yguazú Station, despite the projected work plan and SIN load for 2030. Three distinct scenarios enable us to attain this objective.

Taking into account the demand situation of ZEBC, which is 1,000 MW, the model indicates that there is no shortage of power supply in SIN. Furthermore, this situation proves that the expenses of producing and distributing electricity are genuinely affordable, with a moderate cost of 40.04 USD/MWh.

Similarly, the commercialization of electricity has been examined in three remuneration scenarios, assuming the complete implementation of the Master Plan (Transmission + Generation) with no modulation during peak hours.

We have analyzed various scenarios for tariff application, and we found that ANDE's Tariff Sheet No. 21 is positioned in between directly applying the Itaipu Binacional CUSE and applying the marginal cost of supply, which is determined through power flow optimization.

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