Mitigating Wind Power Curtailment through Hydrogen Energy Storage Systems

Syed N. Shah
Escola Politécnica (EP-USP)
University of São Paulo
São Paulo, Brazil
syednasir@usp.br

Isabella B. Renolphi
Institute of Energy and Environment (IEE-USP)
University of São Paulo
São Paulo, Brazil
isa.brenolphi.14@usp.br

Giovani G. T. T. Vieira
EP-USP
University of São Paulo
São Paulo, Brazil
giovanigtvieira@usp.br

Walquiria N. Silva
IEE-USP
University of São Paulo
São Paulo, Brazil
walquiria_silva@usp.br

Maurício B. C. Salles
EP-USP
University of São Paulo
São Paulo, Brazil
mausalles@usp.br

Luís Felipe N. Lourenço
IEE-USP
University of São Paulo
São Paulo, Brazil
lourenco@iee.usp.br

Filipy C. Silva
PSR
Rio de Janeiro, Brazil
filipy@psr-inc.com

Ricardo C. Perez
PSR
Rio de Janeiro, Brazil
ricardo@psr-inc.com

***Abstract*—The curtailment of wind energy presents a substantial challenge for power systems with high renewable penetration, leading to energy wastage when wind generation exceeds demand. In Brazil, this issue is particularly pronounced in the Northeast, where periods of low demand frequently coincide with high wind availability. Redirecting curtailed energy to hydrogen production via electrolysis has been emerging as a promising solution for large-scale energy storage. However, its economic and operational feasibility within the Brazilian grid still needs to be explored. In this context, this research assesses the potential for utilizing curtailed wind energy to produce green hydrogen, aiming to optimize energy utilization and mitigate curtailment within Brazil's National Interconnected System (SIN). Through modeling with the SDDP software, hydrogen production operations are simulated under variable wind and demand conditions. Results indicate that hydrogen production can mitigate curtailment, enhance grid stability, and yield a positive return on investment, supporting the role of green hydrogen in advancing renewable energy integration and grid flexibility.**

***Index Terms*—curtailment, hydrogen, SDDP, and wind power.**

I. Introduction

The increasing incorporation of renewable energy sources (RES), including wind and solar power, into electricity systems has given rise to intricate challenges in both the operation and planning of transmission and distribution networks. The main challenges can be broadly categorized as follows: firstly, there is the need to guarantee the dynamic stability of the system; secondly, there is the challenge of maintaining the balance between supply and demand in an economically efficient manner; and thirdly, there is the challenge of managing congestion and restrictions on the electricity grid [1]. In Brazil's National Interconnected System (SIN), these challenges are intensified by the substantial share of RES in the energy mix, which exacerbates operational uncertainties, especially during periods of low demand, due to the inherent variability of these sources. In such instances, excess renewable generation can necessitate the adoption of mitigation measures, such as curtailment, to ensure the electricity grid's reliability [2].

Curtailment, the forced reduction of renewable energy generation, represents a critical technical measure for preventing overloads and ensuring grid reliability. This is an illustrative example of the concept of constrained-off, which describes a situation in which a plant's generation is reduced despite its position in the merit order to meet operational or energy security criteria, resulting in generation shortfalls relative to scheduled dispatch, known as negative energy allocation deviations. This scenario has become increasingly prevalent in Brazil due to structural oversupply, in which instantaneous generation, particularly RES, exceeds net demand. This has resulted in the National Electricity System Operator (ONS) implementing curtailment or ordering turbine spillage at hydroelectric plants [2].

In instances where wind generation exceeds the net load minus the mandatory generation, it is imperative to reduce wind production to maintain equilibrium between supply and demand. This reduction is classified as an energy curtailment. This challenge can be mitigated by increasing the availability of flexible resources within the system, such as energy storage and demand response. The production of green hydrogen through the electrolysis of water from renewable sources has also emerged as a promising solution for large-scale, long-term energy storage, offering a means of overcoming some of the limitations associated with conventional batteries [3]. The process of electrolysis, which involves converting electricity into hydrogen (H_2), enables the efficient storage of substantial quantities of energy, particularly in contexts characterized by significant fluctuations in renewable energy generation [4].

Despite the potential advantages, there is a lack of studies examining the economic viability of hydrogen production utilizing surplus electricity, particularly in high renewable energy penetration and low-demand scenarios [5]. The relevance of this topic has increased in conjunction with the growing prevalence of these sources in the energy matrix and the rise in electricity wastage during periods of low demand, which frequently coincide with peaks in renewable generation. In addition to its environmental benefits, hydrogen is a carbon dioxide-free energy source that can be injected into the natural gas grid or used in fuel cells for electrical generation [6]. Its storage capacity makes it a particularly advantageous energy storage solution for periods exceeding one day, offering a more competitive option than batteries in long-term energy storage scenarios [7].

The production of hydrogen through water electrolysis offers a promising solution to mitigate energy losses resulting from curtailment. By utilizing surplus renewable energy, such as wind power, to produce green hydrogen, this method effectively redirects otherwise curtailed energy, thereby enhancing the efficiency and sustainability of the electricity grid. Recent studies [8] highlight that green hydrogen production from excess renewable energy can mitigate curtailment, optimizing energy resource use and supporting a more sustainable and integrated energy management system [9].

This research evaluates the feasibility of repurposing curtailed wind energy to support the integration of a green hydrogen production plant into the SIN. The primary goal is to optimize system efficiency by reducing wind energy curtailment and hydrogen plant operation costs while maximizing the economic and environmental benefits of converting surplus renewable energy into green hydrogen. Using the SDDP software (academic version), the study simulates different operational conditions where hydrogen plants absorb excess wind energy, transforming curtailment into economic value through hydrogen production for secondary applications. By analyzing the overall operational costs, including hydrogen plant expenses, this preliminary study aims to develop strategies for enhancing the flexibility of the Brazilian electricity system.

The structure of this article is as follows: this section introduces the structure and purpose of each subsequent paragraph. Section II presents the methodology and contextual framework used for analyzing the proposed model. Section III presents the results and their interpretation. Finally, Section IV provides the study's conclusions and outlines directions for future research.

II. Methodology Proposed

This section outlines the methodology for integrating a hydrogen plant into the SIN, utilizing curtailed energy from wind farms across the national grid, and presents the main mathematical equations and key considerations for solving the problem, utilizing curtailed energy to minimize costs and maximize system efficiency. Fig. 1 presents a simplified flowchart of the methodological steps followed in this study.

The approach in Fig. 1 involves four main steps: (i) collecting historical curtailment data from wind farms connected to the SIN, which serves as the foundation for determining the hydrogen plant's electrolysis capacity and efficiency parameters; (ii) defining the hydrogen plant's capacity based on the available curtailed energy; (iii) configuring stochastic

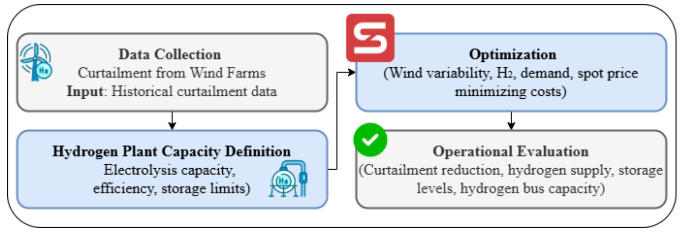

Fig. 1. Simplified methodology flowchart.

scenarios to account for variability in wind generation and electricity demand, using trends from historical data and future projections to capture uncertainties in renewable energy production and market fluctuations; and (iv) running an optimization using the SDDP software to evaluate the preliminary results and assess the technical and economic viability of the integration.

The premises adopted in this work are the following:

- **Demand Response:** The hydrogen power plant was assumed to function as a demand response mechanism to curtailment, activating when needed to increase demand and absorb curtailed energy.
- **Electrolyzer Size:** The electrolyzer capacity was designed to be sufficiently large to absorb the highest instantaneous energy curtailment observed.
- **Transmission Infrastructure:** It was assumed that the transmission infrastructure and energy exchange limits would not restrict the energy transferred to the hydrogen power plant.
- **Plant Location:** It was assumed that the plant would be located in an area that favors a balance between energy supply and demand, allowing for efficient absorption of surplus energy and contributing to a reduction in curtailment rates.
- **Requirements for H_2 Production:** The hydrogen production site was assumed to meet all necessary requirements, including access to treated water.
- **Use of H_2:** Since curtailed energy is being used, employing the produced H_2 in turbines to generate electricity would not mitigate curtailment but would likely only shift its timing. Therefore, the H_2 will be used to power a bus fleet instead.

A. Simplified Mathematical Formulation for H_2 Production

This section presents a simplified mathematical model to support the planning and operation of a hydrogen production plant. It encompasses estimating maximum hydrogen output, sizing electrolyzers, and evaluating both capital and operational costs, including considerations for storage systems.

To determine the maximum daily hydrogen production capacity, the following equation is used:

$$H_{max} = \left(\frac{E_{curt,max}}{a} \right) \times \eta \tag{1}$$

where:

- $E_{curt,max}$ represents the maximum energy available for hydrogen production during periods of low demand. This parameter is essential for determining the amount of curtailed energy that can be redirected to hydrogen production, thereby mitigating energy waste.
- a is the energy conversion factor from electricity to hydrogen, with a value of 39.4 kWh/kg, as specified in [10]. This value was selected based on standard electrolysis efficiency benchmarks, reflecting the energy required to produce 1 kg of hydrogen by electrolysis.
- η denotes the electrolyzer efficiency, set to 65.67%, according to [11]. This efficiency value aligns with recent advancements in electrolyzer technology. It represents the typical efficiency range for commercial systems, where a higher efficiency corresponds to a lower energy consumption per unit (pu) of hydrogen produced.

The sizing of the electrolyzer is determined by the peak curtailed energy available during these low-demand periods, calculated as:

$$E_{elec} = E_{curt,peak} \tag{2}$$

Where $E_{curt,peak}$ represents the peak curtailed energy the system can absorb, influencing the maximum electrolyzer capacity needed to handle energy surpluses effectively.

B. Optimization Methodology using SDDP

This research aims to optimize hydrogen production using the SDDP software, a robust tool for handling complex optimization problems in energy systems. SDDP was configured to model the interaction between curtailed wind energy and hydrogen production and storage, aiming to maximize the utilization of surplus energy while minimizing overall operational costs.

The execution of the SDDP involves two key phases: (i) policy calculation and (ii) final simulation. In the policy phase, a series of forward and backward iterations is performed to refine the approximation of the Future Cost Functions (FCFs) for each month. This step is crucial for calculating the optimal policy for utilizing hydrogen storage, which is central to this paper. Once the FCFs are determined, SDDP simulates the system operation with hourly resolution. This process aims to optimize the utilization of available energy, maximizing the efficiency of surplus energy conversion into hydrogen.

The SDDP software simulates hydrogen production, integrating data on wind energy curtailment across various operational scenarios to replicate realistic conditions. Within the "Renewable Sources" section of SDDP, curtailment data were incorporated to reflect the availability of surplus wind energy. These data were contained in an hourly granularity, which was the granularity of the curtailment data obtained from ONS.

Subsequently, the essential parameters for each scenario are defined, including the number of installed wind turbine units, the total megawatt (MW) capacity, and the operational factor presented as a unit value (pu). This stage ensures precise calculations regarding the curtailed energy available for hydrogen production.

The SDDP hydrogen system module comprehensively configures the hydrogen production system. To comprise the two parameters of converting energy to hydrogen, as previously delineated in Eq. 1, the conversion rate considered was 0.06 MWh/kg. Although version 17.4 of the software can limit the electrolyzer's capacity, this limitation was not taken into account.

To analyze the results, the outputs of the SDDP model are utilized, which include the evaluation of the hydrogen stored, the hydrogen demand met, and the resulting deficit. These files are then analyzed to assess the technical viability of introducing hydrogen-fueled buses into the local fleet, with key metrics including total hydrogen output and reduction in curtailment rates.

C. Optimizing Hydrogen Storage and Consumption Patterns Using SDDP

The possibility of using hourly generation curves and an hourly hydrogen demand curve enables a comprehensive evaluation of this research in SDDP. To provide a comprehensive evaluation of hydrogen use, Fig. 2 presents three cases.

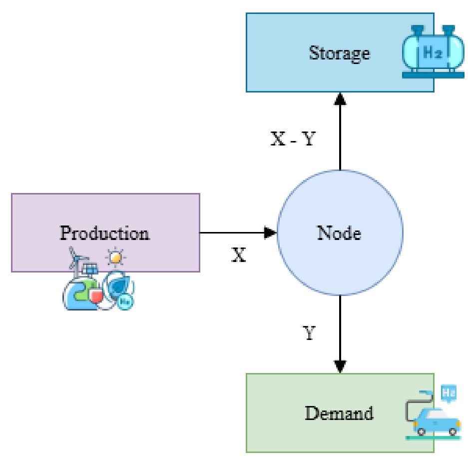

Fig. 2. Hydrogen Production Flow Using Curtailed Wind Energy. Produced hydrogen (X) meets demand (Y), and the surplus ($X - Y$) is stored.

Case 1 investigates the feasibility of maintaining a stable and uninterrupted hydrogen supply from January to December. The primary objective is to ensure a continuous and reliable production rate throughout the year, minimizing fluctuations and interruptions. To determine the hourly hydrogen demand that enables consistent supply, a trial-and-error approach was employed, whereby the demand was systematically varied to identify the configuration that resulted in the lowest total energy consumption. This case aims to evaluate whether a constant hourly hydrogen demand can be reliably met, thus supporting its role as a dependable service. If the selected hourly demand is too low or if the number of hours with unmet demand is excessively high, the viability of this service is significantly reduced.

Case 2 prioritizes minimizing hydrogen storage levels, disregarding potential demand shortfalls. In this scenario, the hydrogen supply is adjusted monthly to maintain the lowest possible storage levels, with no concern for whether demand is fully met. Each month is treated independently, and the primary objective is to reduce storage requirements as much as possible, even at the expense of supply continuity.

Case 3 adopts a more flexible strategy, in which hydrogen demand is adjusted monthly to optimize the use of available production throughout the year. The goal is to align production and consumption by adapting monthly demand profiles, ensuring consistent supply while minimizing shortages. This scenario represents a balanced operational approach that reduces both oversupply and deficits through coordinated planning and management.

This comprehensive framework explores distinct strategies for optimizing hydrogen storage and consumption using the SDDP software. By analyzing scenarios focused on continuous supply, storage minimization, and flexible demand adjustment, the methodology demonstrates how operational planning can be adapted to accommodate varying objectives and constraints.

III. Simulations and Results

This section presents the main results obtained by applying the methodology described in section II, using SDDP-PSR (academic version), a stochastic dispatching tool widely used for long-, medium-, and short-term operational studies in electricity systems. The modeling considered several detailed aspects, including the generation of variable renewable source scenarios and energy storage management, to provide a comprehensive view of the feasibility of integrating the hydrogen plant into the SIN. The main features of the case study are presented first, followed by the simulation results.

A. Case study

To assess the performance of the proposed methodology, this case study utilizes operational curtailment data from the Brazilian National Electricity System Operator (ONS) obtained in [12]. It considers two specific scenarios within the Brazilian context. Scenario 1 covers the period from September 2022 to August 2023, while Scenario 2 spans from September 2023 to August 2024, characterized by increased curtailment due to constrained-off restrictions.

B. Operational Feasibility of Hydrogen Production using Curtailed Energy

This subsection analyzes the variability in daily hydrogen production from curtailed wind energy in Brazil for two distinct scenarios, illustrating the operational feasibility and consistency of hydrogen output under varying wind availability and grid demand conditions.

Fig. 3 presents the frequency distribution of daily hydrogen production for Scenario 1, covering the period from January to August 2023. The histogram reveals a predominance of low-production days, often near zero, suggesting limited availability of curtailed energy for hydrogen generation.

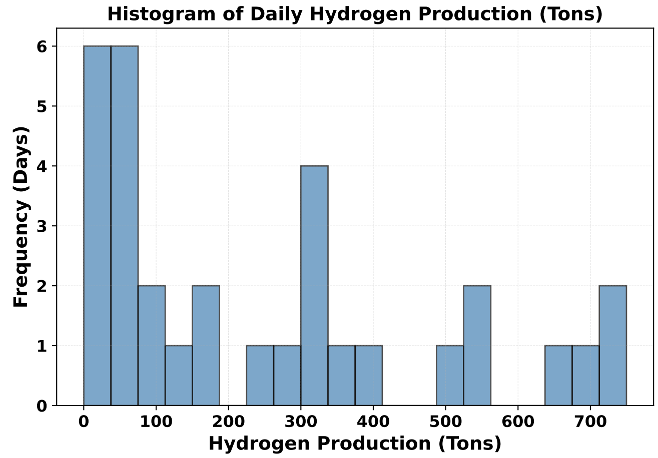

Fig. 3. Daily Hydrogen Production Histogram in Scenario 1.

In addition, Fig. 4 provides a daily breakdown of hydrogen production for Scenario 1, highlighting specific days with significant output, such as June 25, July 30, August 6, and August 13. These peaks likely correspond to periods with increased energy curtailment, allowing the system to achieve higher production. However, the inconsistency in production levels highlights the challenges of maintaining steady hydrogen generation, suggesting that additional strategies may be necessary to ensure consistent output.

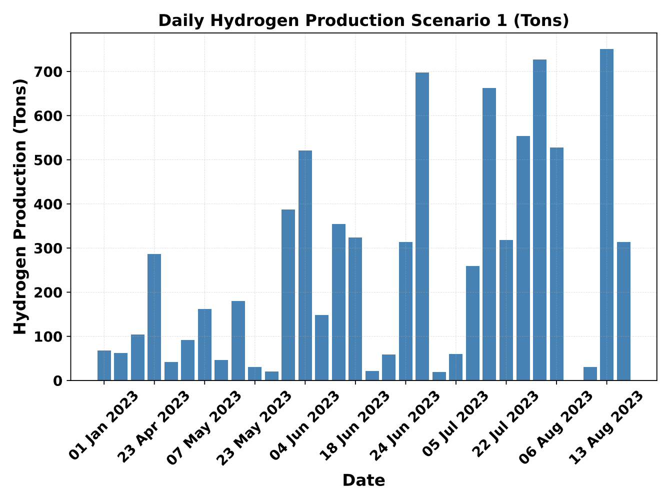

Fig. 4. Daily Hydrogen Production in Scenario 1.

For Scenario 2, covering the period from September 2023 to August 2024, Fig. 5 presents the frequency distribution of daily hydrogen production. The results highlight the intermittent nature of curtailment across both scenarios, with the highest frequency of occurrences corresponding to low levels of curtailed energy. Furthermore, an analysis of the days on which curtailment occurred reveals no discernible temporal pattern, suggesting that curtailment events are largely unpredictable. This unpredictability indicates that, in the absence of hydrogen storage, the opportunities for sustained hydrogen production from curtailed energy are significantly limited.

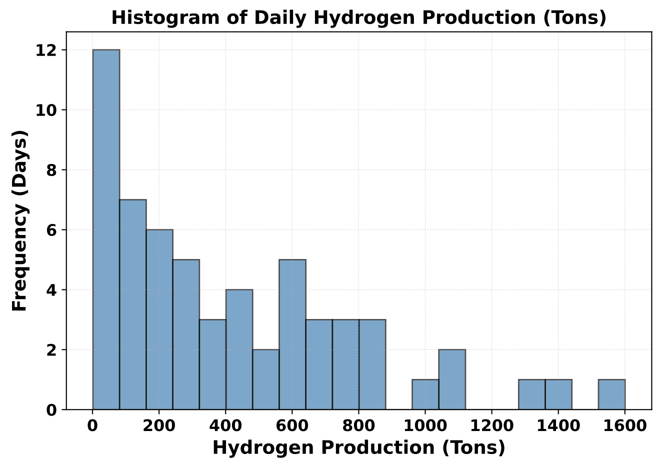

Fig. 5. Daily Hydrogen Production Histogram in Scenario 2.

Fig. 6 presents a detailed day-by-day profile of hydrogen production in Scenario 2, highlighting the variability in output. Distinct peaks observed on June 3 and July 22 correspond to periods of increased curtailment, indicating favorable conditions for redirecting surplus wind energy to hydrogen production. However, the irregular production pattern underscores the limitations of relying exclusively on curtailed energy. Given the significant increase in daily hydrogen output from Scenario 1 to Scenario 2, integrating energy storage alongside hydrogen storage may offer additional operational benefits. Specifically, energy storage could absorb curtailed electricity during peak periods and release it more gradually, enabling the use of smaller, more cost-effective electrolyzers.

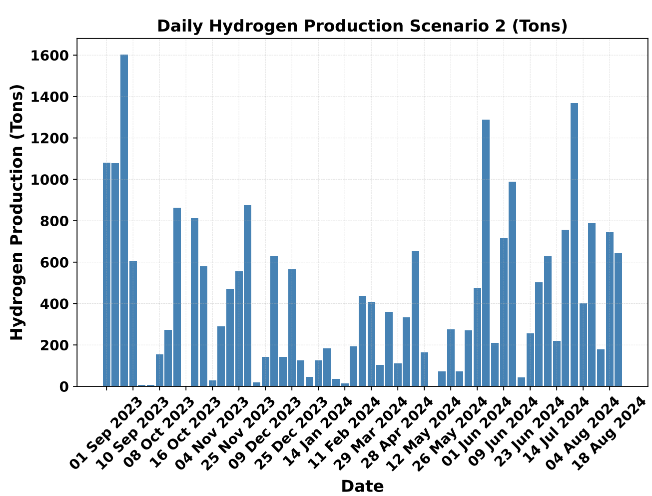

Fig. 6. Daily Hydrogen Production in Scenario 2.

Overall, the analysis across both scenarios demonstrates that while curtailed wind energy can be redirected for hydrogen production during favorable conditions, the high variability in daily output limits the system's reliability. To address these challenges, supplementary strategies, such as integrating storage solutions or diversifying energy inputs, may be required to ensure consistent and reliable hydrogen generation.

C. Cases Evaluation

In Case 1, hydrogen is produced using surplus energy that would otherwise be wasted. The system is engineered to ensure a constant and uninterrupted supply of hydrogen. From September 2023 to August 2024, as shown in Fig. 7, a consistent supply rate of 1,440 kg/hour is maintained throughout each hour of the day. To obtain this rate, a sensitivity analysis was pursued, varying the supply rate value and evaluating the deficit produced by each rate. This rate is the highest value of supply that achieved the minimal deficit hours. By the end of the year, the remaining quantity in the storage tank, ensuring a steady supply of hydrogen, was 4,443.1 tons.

Therefore, any service requiring an hourly quantity of hydrogen of less than 1,440 kg could be served by this hydrogen power plant. This value was lower compared to the numbers that follow, due to the low curtailment at the beginning of 2024. In our case study, this hydrogen will be used to serve a bus fleet. According to [13], [14], the tank of a bus powered by fuel cells and a battery carries approximately 37.5 kg of hydrogen. On average, this hydrogen power plant would be capable of powering five buses per hour. In a day, it would feed 921 buses. Considering that the São Paulo bus fleet comprises around 12,000 buses, this amount would represent 7.6% of the São Paulo fleet [15]. If we consider the fleet of Rio de Janeiro, which comprises 713 buses, this amount of hydrogen per day would be sufficient to fuel the entire fleet. Moreover, the number of buses could be increased by 29%.

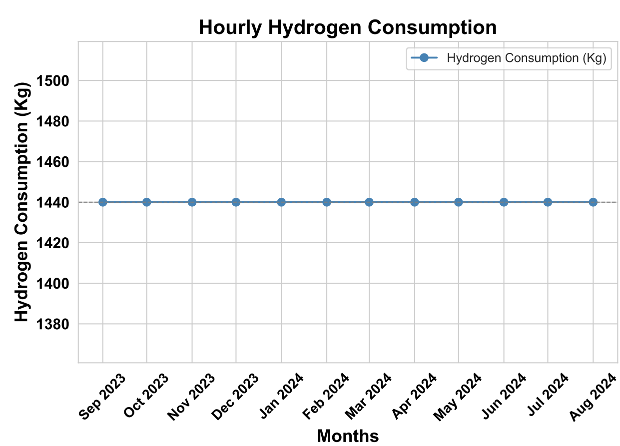

Fig. 7. Hourly Hydrogen Consumption from September 2023 to August 2024.

The results of Case 2 are shown in Fig. 8. Surplus energy is used to generate hydrogen, which is then consumed to maintain low storage levels. The hydrogen supply operates dynamically, adjusting supply in response to the monthly production capacity. In this analysis, by the end of each month, we have no hydrogen stored. For instance, Fig. 8 illustrates that peak consumption occurs in October/2023 and May/2024, with rates of 21,400 kg/h and 18,100 kg/h, respectively. In contrast, January experiences the lowest consumption at 1,450 kg per hour. Considering the lowest amount of hydrogen, the results regarding the number of buses that will be fed are similar to those presented for Case 1.

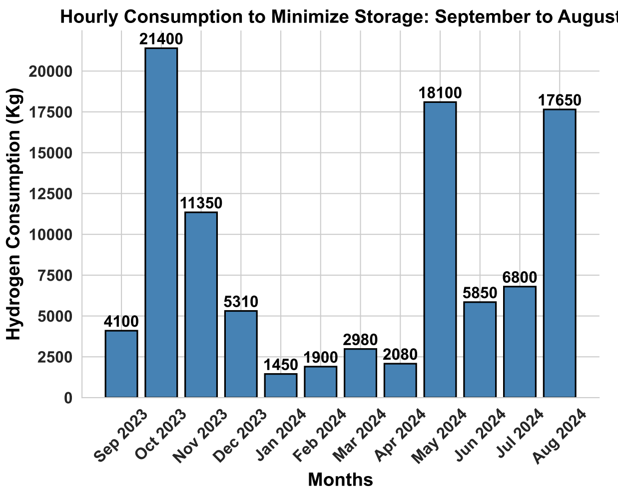

Fig. 8. Hourly Consumption to Minimize Hydrogen Storage Level from September 2023 to August 2024.

If the median of the values presented in Fig. 8 were calculated, a value of 5,580 kg would be obtained. The month closest to this value is December, with an average of 1,375 kilograms per hour. December 2023 and May 2024 are the months with the closest values to the median. Considering the lowest estimate of 5,310 kg, this plant would be able to feed 141 buses per hour or 3,398 buses per day. It represents 28% of São Paulo's bus fleet. It is essential to mention that in this scenario, they are not securing hydrogen for every hour, so that it may occur days without any bus feed. For a service, this scenario cannot be considered a standard.

The third case emphasizes maintaining a steady and uninterrupted hydrogen supply by coordinating hourly supply limits with monthly production levels. Although this steady supply was calculated for the entire period analyzed, in Fig. 7 it is calculated for each month. As can be seen, the value of 1,440 kg calculated in Case 1 was limited due to the month of January 2024. The median of the values presented in Fig. 10 is equal to 1,860 kg. Considering the values closest to the median and using the lowest, as we did for Case 2, 1,820 kg from July 2024 is assumed. This amount of hydrogen fuels 48 buses per hour, or 1,152 buses per day. This quantity will be supplied continuously throughout the month, making it a service that can be considered ongoing.

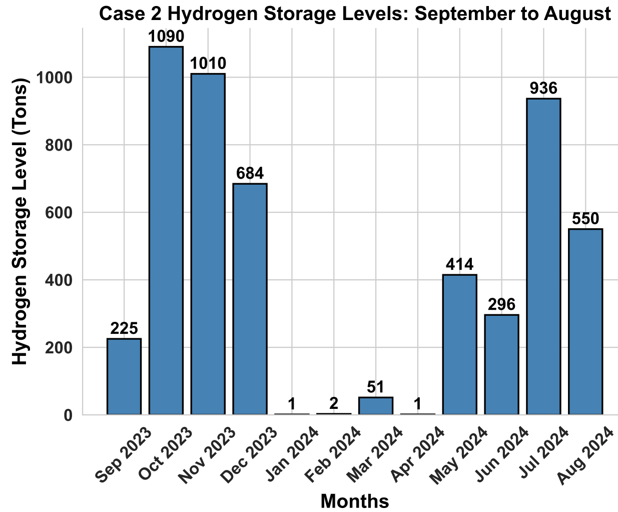

Fig. 9. Storage Level at the end of the Month.

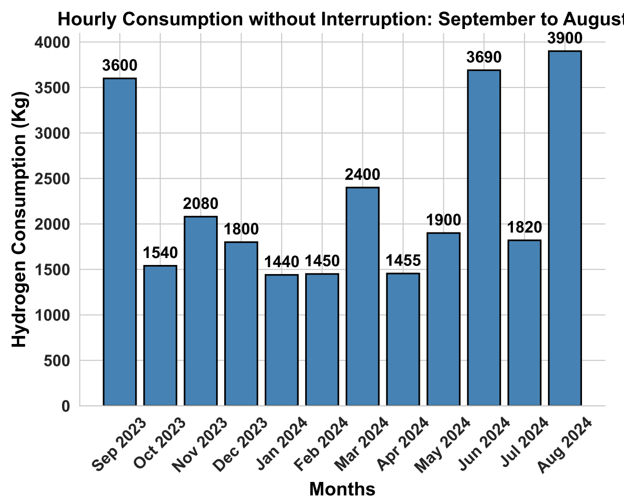

Fig. 10. Hourly Consumption Without Interruption from September 2023 to August 2024.

IV. Conclusions

This study assessed the feasibility of repurposing curtailed wind energy for green hydrogen production, with the aim of reducing energy waste and improving the operational flexibility of the Brazilian National Interconnected System (SIN). Using SDDP, a dispatch optimization tool, the results demonstrated that green hydrogen production can serve as a technically viable pathway to absorb excess wind generation during curtailment events, effectively converting otherwise wasted energy into a valuable and storable resource.

However, the analysis also revealed substantial variability in daily hydrogen production, emphasizing the challenges of relying exclusively on curtailed energy to sustain a consistent hydrogen supply. In particular, regions or periods with low levels of curtailment may limit the continuous operation of hydrogen plants, especially in the absence of complementary storage infrastructure.

The results underscore the importance of strategic plant siting, ideally near existing transmission infrastructure, to avoid additional investment in grid expansion. Among the evaluated cases, the scenario maintaining a continuous supply throughout the year was identified as the most suitable for providing hydrogen as a reliable service, such as fueling a bus fleet, despite the relatively lower hydrogen output during specific months. In contrast, strategies focused solely on minimizing storage or adjusting monthly demand may not ensure uninterrupted supply, thereby limiting their applicability for service-based use cases.

Overall, the findings suggest that green hydrogen production represents a promising alternative for economically and environmentally leveraging curtailed renewable energy. To enhance its viability, future work should focus on economic analysis, the use of batteries in combination with the electrolyzer, and consideration of transmission line constraints.

Acknowledgment

We gratefully acknowledge the support of the RCGI—Research Centre for Greenhouse Gas Innovation (23.1.8493.1.9), hosted by the University of São Paulo (USP), and sponsored by FAPESP — São Paulo Research Foundation (2020/15230-5). This study was partially financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. We also thank PSR Soluções e Consultoria LTDA for providing the academic version of the software used in this research.

References

[1] Hamideh Bitaraf and Saifur Rahman. Reducing curtailed wind energy through energy storage and demand response. *IEEE Transactions on Sustainable Energy*, 9(1):228–236, 2018.

[2] V Ribeiro, S Moreno, G Freitas, P Lino, and P Motta. O desafio da gestão dos eventos de constrainedoff eólico (curtailment) no setor elétrico brasileiro vis a vis a experiência internacional. *XXV Seminário Nacional de Produção e Transmissão de Energia Elétrica (SNPTEE). Belo Horizonte, Brazil*, pages 1–9, 2019.

[3] Paul Denholm and Trieu Mai. Timescales of energy storage needed for reducing renewable energy curtailment. *Renewable Energy*, 130:388–399, 2019.

[4] Qusay Hassan, Sameer Algburi, Aws Zuhair Sameen, Hayder M. Salman, and Marek Jaszczur. Green hydrogen: A pathway to a sustainable energy future. *International Journal of Hydrogen Energy*, 50:310–333, 2024.

[5] Ahmed Khouya. Hydrogen production costs of a polymer electrolyte membrane electrolysis powered by a renewable hybrid system. *International Journal of Hydrogen Energy*, 46(27):14005–14023, 2021.

[6] Philipp-Matthias Heuser, D. Severin Ryberg, Thomas Grube, Martin Robinius, and Detlef Stolten. Techno-economic analysis of a potential energy trading link between patagonia and japan based on co2 free hydrogen. *International Journal of Hydrogen Energy*, 44(25):12733–12747, 2019. Special Issue on Selected Contributions from the European Hydrogen Energy Conference 2018. Málaga, Spain. March 14th - 16th.

[7] Mohamed Awad, Abdelrahman Said, Mohamed H. Saad, Amr Farouk, Mohamed Metwally Mahmoud, Meshari S. Alshammari, Mamdouh L. Alghaythi, Shady H.E. Abdel Aleem, Almoataz Y. Abdelaziz, and Ahmed I. Omar. A review of water electrolysis for green hydrogen generation considering pv/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application. *Alexandria Engineering Journal*, 87:213–239, 2024.

[8] Tyler H. Ruggles, Jacqueline A. Dowling, Nathan S. Lewis, and Ken Caldeira. Opportunities for flexible electricity loads such as hydrogen production from curtailed generation. *Advances in Applied Energy*, 3:100051, 2021.

[9] M. Laimon and S. Goh. Unlocking potential in renewable energy curtailment for green ammonia production. *International Journal of Hydrogen Energy*, 71:964–971, 2024.

[10] Bernard Chukwudi Tashie-Lewis and Somtochukwu Godfrey Nnabuife. Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review. *Chemical Engineering Journal Advances*, 8:100172, 2021.

[11] Rawan A. Abdelsalam, Moataz Mohamed, Hany E.Z. Farag, and Ehab F. El-Saadany. Green hydrogen production plants: A techno-economic review. *Energy Conversion and Management*, 319:118907, 2024.

[12] ONS. Dados de Restrição de Operação por Constrained-off de Usinas Eólicas, 2024. Available at: https://dados.ons.org.br/dataset/restricao_coff_eolica_usi.

[13] New Flyer. Xcelsior charge h2 brochure. https://www.newflyer.com/site-content/uploads/sites/2/2021/01/Xccelsior-CHARGE-H2-Brochure_2021.pdf, 2021. Accessed: 2025-03-25.

[14] CaetanoBus. H2 city gold – urbano zero emissões. https://caetanobus.pt/urbano-zero-emissoes/?produto=h2-city-gold, 2025. Accessed: 2025-03-25.

[15] SPTrans. Sptrans – são paulo transporte s.a. https://www.sptrans.com.br/sptrans/, 2025. Accessed: 2025-03-25.