



INTEGRATED OPTIMIZATION OF ENERGY STORAGE SYSTEMS AND HYDROGEN PRODUCTION COMBINED WITH VARIABLE GENERATION SOURCES

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ABSTRACT

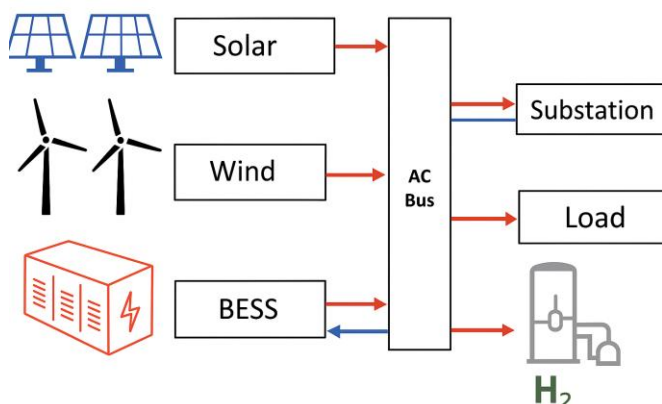
This article discusses the integration of renewable energy sources, specifically wind and photovoltaic generation, with a Battery Energy Storage System (BESS) for green hydrogen production (H_2), aiming to optimize economic profit within a predefined hydrogen extraction range established, with an efficiently managing the available energy resources. To achieve the proposed goal, a mathematical optimization model was implemented using AMPL. The simulations revealed that the inclusion of BESS improves operational efficiency enabling optimized use of the available renewable energy, reducing dependence on the power grid, and resulting in greater economic sustainability. The study contributes to the advancement of research in green hydrogen production, highlighting the relevance of implementing optimization algorithms that support the feasibility of using and operating hybrid systems in the context of the energy transition.

Keywords: AMPL; BESS; Hydrogen; Optimization.

1. INTRODUCTION

The use of sustainable energy sources has become a global priority to mitigate the impacts of climate change and reduce dependence on fossil fuels. In this context, green H_2 production—obtained through water electrolysis using exclusively electricity from renewable sources—emerges as a promising alternative due to its potential as a versatile carrier of clean energy. However, the variable nature of renewable energy sources, such as wind and solar, represents a significant challenge to the stability and efficiency of the systems in which they are integrated. A potential solution to face this variability is the use of hybrid systems, as shown in Figure 1, which integrate renewable sources, the conventional power grid, and BESS with green H_2 production.

Figure 1 – Hybrid system for H_2 production.





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In recent years, studies have focused on optimizing the integration of variable renewable sources together with energy storage systems and H_2 production, using advanced optimization algorithms. In this regard, CHEN et al. (2022) developed models for the operational scheduling of hybrid wind and solar generation systems coupled with H_2 storage using Particle Swarm Optimization (PSO) algorithms, achieving a significant reduction in daily operational costs. SERRANO-ARÉVALO et al. (2023) focused on developing strategies to maximize the economic efficiency of H_2 production, taking into account capital and operational costs as well as the associated environmental impact. The text emphasizes the need for public policies and financial incentives to support large-scale production, considering the variability of renewable sources and market prices. ABOMAZID et al. (2022) focus on the optimal management of an H_2 production system coupled with a BESS and photovoltaic (PV) solar panels. In this model, an energy management system (EMS) scheduling strategy is proposed to optimize production costs by controlling the operating points of the electrolyzer. This system allows H_2 to be stored during periods of low electricity prices and to utilize the stored energy during higher-demand periods. In this way, both operational costs and the cost of produced H_2 are minimized, optimizing system efficiency.

Seeking to contribute to the topic, the present work proposes a model aimed at optimizing economic return through H_2 production in a hybrid system that integrates wind and photovoltaic generation with the conventional power grid, complemented by a BESS energy storage system, which acts as a key support to balance periods when renewable generation is insufficient to hold production demand. The adopted methodology considers the variability of renewable generation, the hourly “blue” tariff established in Brazil for the A4 connection group, and the selling price of H_2 in nowadays international markets, aiming not only to supply energy demand but also to optimize H_2 production within the limits established by the system’s technical conditions for its sale in emerging markets.

This article is organized into five sections: Section 1 introduction to the problem to be discussed; Section 2 presents the methodology used; Section 3 details the mathematical model; Section 4 presents the results obtained from the simulations, and some final discussions and suggestions for future work are presented in Section 5.

2. METHODOLOGY

The proposed optimization will be achieved through the implementation of a linear programming model in the AMPL software package (FOURER; GAY; KERNIGHAN, 2003), using the CPLEX solver (IBM, 2019), which is primarily developed to solve linear mathematical optimization problems, such as the one presented in this article. The problem involves a 24-hour planning horizon with multiple variables and constraints that define the model’s total dimension, with 96 continuous variables representing H_2 production in each hour, BESS charge and discharge power, stored energy, as well as the grid power required to hold the energy balance, and 147 constraints represented by power balance, battery operating limits, and charge/discharge balance. The search space is determined by the decision variables, along with their respective limits and constraints. The Variables: stored battery energy, battery charge/discharge, H_2 production, and grid energy flow are continuous. Although the number of possible



combinations in the search space is large, it is limited by the constraints associated with each variable, determining which combinations are feasible in the search for the optimal objective function point.

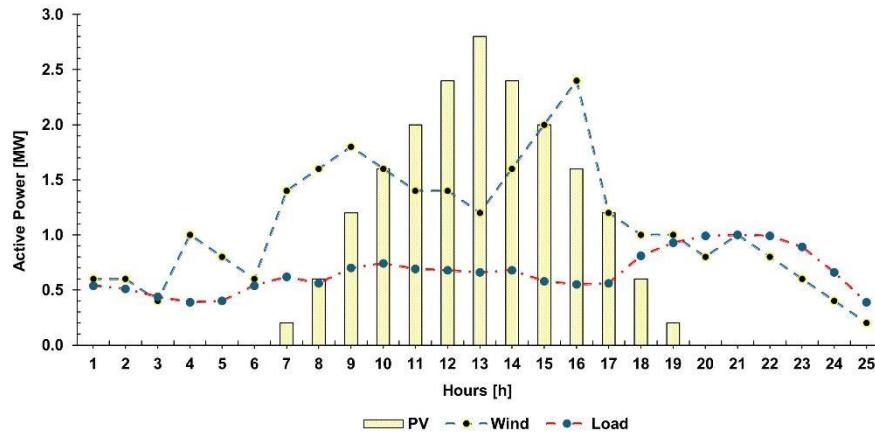
3. OPTIMIZATION MODEL

The proposed optimization model is presented below, in table 1, the objective function, aims to optimize the profit from H₂ production over a one-day horizon, discretized hourly. The optimization considers the base selling price of H₂ and the grid energy value, used as a slack variable to satisfy the active power balance constraint. The production model is described by the amount of power required to produce 1 m³ of H₂ per hour, reducing dependence on the power grid and seeking the lowest impact on total profit (CHEN et al., 2022).

Table 1 – Optimization Model.

OBJECTIVE FUNCTION	
$Max OF = \sum_{t=1}^T [(P_{H_2}^t * \rho * \eta_{elec}) * C_{H_2} - (C_R^t * P_R^t)]$	
MODEL CONSTRAINTS	
Power Balance	$C_R^t + P_{PV}^t + P_E^t = P_C^t + P_B^t + (P_{H_2}^t * \rho * \eta_{elec})$
BESS Operation	$B_S^t = \{B_S^t - \frac{1}{\eta_d} P_B^t, \quad P_B < 0 \quad B_S^t + \eta_c P_B^t, \quad P_B \geq 0\}$
BESS Charge and Discharge	$P_{Bmin}^t \leq P_B^t \leq P_{Bmax}^t$
Stored Energy in the BESS	$B_{smin}^t \leq B_S^t \leq B_{smax}^t$
H ₂ Production	$P_{Hmin}^t \leq P_H^t \leq P_{Hmax}^t$

Figure 2 – Generation and load curves.



4. SIMULATION RESULTS

This section presents the results of the proposed problem; the scheme of the studied system is shown in Figure 1. The generation and demand data represented in Figure 2, required as inputs for the algorithm, were adapted from VARGAS et al. (2024). The profiles used for photovoltaic and wind generation are based on hourly series obtained from public databases of the National



Electric System Operator (ONS) and were adapted to represent standard generation conditions. The article focuses on the integrated optimization of energy storage systems and H₂ production; therefore, simplified and representative series were used without entering real generation details. The load curve used corresponds to a standard consumption profile that allows evaluating the model's adaptation under these operating conditions.

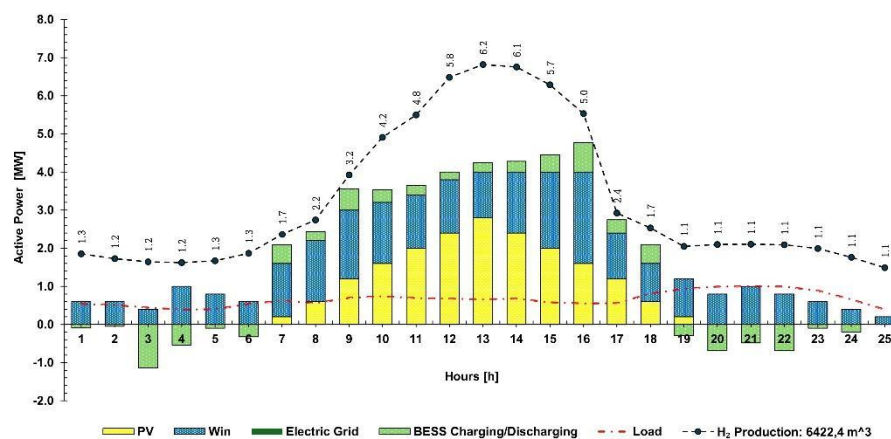
4.1. Input Data and Assumptions

The BESS used has a charge and discharge capacity of 2 MWh and a maximum storage capacity of 5 MWh, starting and ending the operation period at 50% of its maximum capacity. It is assumed that the BESS charge and discharge efficiency is 100%. Continuous H₂ production is considered, assuming a minimum and maximum production capacity between 100 m³ and 5,000 m³. A PEM (Proton Exchange Membrane) unit is used, with an energy consumption rate of 4.5 kWh/m³ and a production efficiency of 75% (PÉREZ-VIGUERAS et al., 2023). To analyze with a reference selling price as close as possible to the current Latin American market reality, an average base price of 1.6 USD/kg of produced H₂ is considered, which corresponds to approximately 8.728 R/m³ according to the currency conversion at the time of consultation (13/11/2024). The conversion takes into account the density of H₂ in kg/m³ under standard conditions (0°C and 1 atm), approximately 0.08988 kg/m³ (BUSINESS ANALYSIS, 2024).

4.2. H₂ Production vs. Generation – Operation with BESS

Figure 3 shows the obtained result, where the objective is to optimize H₂ production while considering the balance between energy generation, charge, and BESS operation.

Figure 3 – H₂ Production Vs. Generation.



The results show that H₂ production remained within the established limits. The H₂ produced follows the renewable generation profile (photovoltaic and wind) during hours with higher energy availability (between 8:00 and 18:00), indicating that the



operation takes advantage of excess of renewable energy, optimizing production during generation peaks. The BESS operates within its charge (2 MW) and discharge (-2 MW) limits, acting as a key support to balance periods when renewable generation is insufficient to meet production demand. During periods of high H_2 production (between 9:00 and 18:00), the renewable sources exhibit significant combined generation. The joint operation of renewable sources and the BESS deal with the load during the operation period and demonstrates how H_2 production is aligned with renewable generation peaks, showing good integration between renewable resources and the optimization system. During periods of lower renewable generation (hours 1–7 and 18–24), the storage system compensates, allowing supply to be maintained for H_2 production. The analysis demonstrates that the model effectively optimizes H_2 production within the established limits, efficiently utilizing available resources such as the BESS and renewable generation.

Figure 4 – H_2 Production Vs. Profit – Operation with BESS.

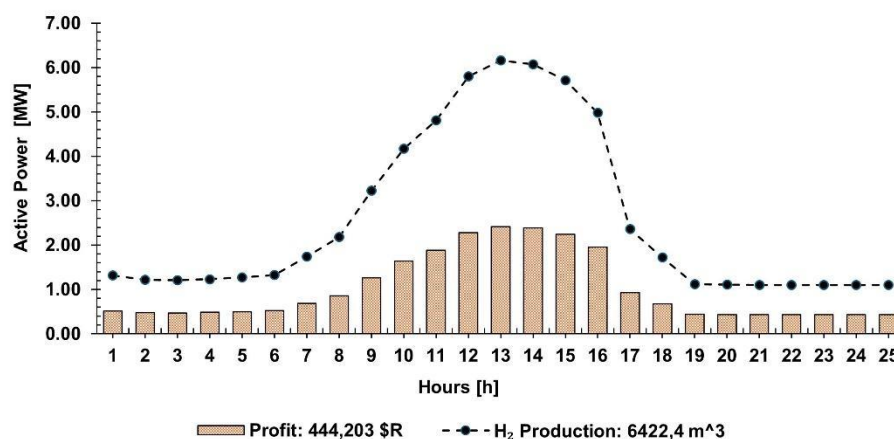
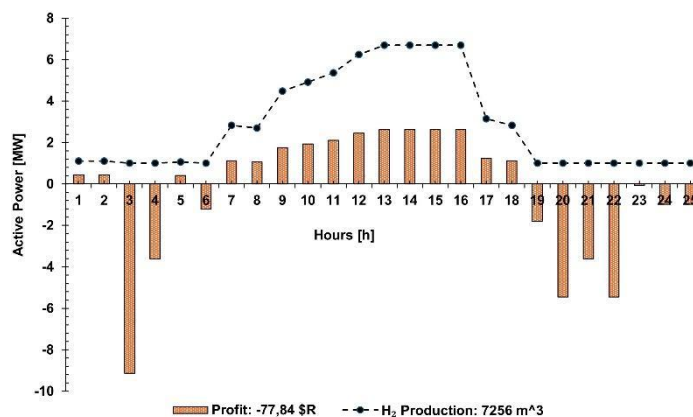


Figure 5 – H_2 Production Vs. Profit – Operation without BESS.



4.3. H_2 Production vs. Profit – Operation with BESS

Figure 4 shows the profit obtained (orange bars) during H_2 production over the established 24-hour period. It can be observed that production is not constant throughout the day, with significant peaks at certain times, for example between hours 8:00 and



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17:00. This indicates that the model prioritizes production during periods of higher renewable energy generation in order to optimize the objective function. The dotted line represents production volumes in each period of the day.

The accumulated profit from H₂ production (6,422.4 m³) reaches a total of R\$ 444,203 by the end of the day. There are periods of low production, as the model is subject to production constraints. During periods such as hours 1–7 and 19–25, production is low, which demonstrates the model's efficient decision-making to optimize profit given the minimal contribution from renewable sources.

4.4. H₂ Production Vs. Profit – Operation without BESS

Figure 5 shows that without the energy storage system, H₂ production is sustained even during periods when renewable energy is insufficient to hold the demand. This occurs because the system uses grid electricity to maintain production. This approach allows a higher total daily production volume (7,256.0 m³), but incurs high costs due to reliance on the grid. Despite of the increase in production, the costs associated with grid energy consumption result in a negative total profit at the end of the day (R\$ -77.84). This demonstrates that, although the objective of optimizing H₂ production is achieved, it is not done in an economically viable way. Compared to the operation with BESS in Figure 5, the system with batteries can store excess of renewable energy to compensate for periods of low generation, minimizing grid dependence and making operation more profitable. Although total production with BESS is lower, the savings in costs from using stored energy compensate for the reduction in total H₂ production, resulting in a positive profit.

5. FINAL DISCUSSIONS AND SUGGESTIONS FOR FUTURE ANALYSES

The simulations show that the inclusion of a BESS allows H₂ production to be optimized by making more efficient use of the available renewable energy, while reducing reliance on the grid and benefiting the optimization strategy. In the scenario without a BESS, although H₂ production is higher during certain periods, the energy costs associated with using grid electricity result in economic losses by the end of the day. This highlights the importance of incorporating storage to optimize both the economic operation and the sustainability of the system.

Beyond the scope of this article, new approaches could be suggested for future research. For example, analyses could be conducted over longer periods, such as weeks or months, to assess how seasonal variations affect H₂ production efficiency. Additionally, a techno-economic analysis that includes all costs associated with the H₂ production chain and renewable generation, as well as all costs related to the storage system, testing the algorithm's adaptation to operational scenarios under real generation and load conditions, would allow validation of the proposed strategy's performance and ensure the maximum achievable profit.



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