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Optimizing renewable energy: advanced strategies for enhanced efficiency and sustainability

SIMULAÇÃO MODULAR PARA A PRODUÇÃO DE HIDROGÉNIO VERDE: UM CASO DE ESTUDO EM FORTALEZA, CEARÁ

MODULAR SIMULATION APPROACH FOR GREEN HYDROGEN PRODUCTION: A CASE STUDY IN FORTALEZA, CEARÁ

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RESUMO

Este artigo apresenta uma ferramenta de simulação modular para apoio à avaliação da viabilidade técnico-económica de centrais de produção de hidrogénio renovável. De um modo geral, o utilizador define as características dos principais componentes existentes na central, desde a produção de energia renovável até aos diferentes pontos de consumo de hidrogénio. Com estes inputs a ferramenta simula as interações entre os componentes indicados tendo em conta uma base horária para todo o seu tempo de vida – 20 anos. Deste modo, ao se modelar os fluxos de energia existentes, seja na produção de eletricidade, hidrogénio renovável, no funcionamento do armazenamento e possíveis trocas com a rede elétrica, procede-se, através de um processo iterativo à otimização das capacidades dos diversos componentes. O funcionamento da ferramenta foca-se nas necessidades dos promotores tendo por base de otimização o custo nivelado de produção do hidrogénio e a maximização de conformidade com a procura do mesmo. Um caso de estudo em Fortaleza, Brasil, demonstra a sua aplicação, revelando que as configurações pré-otimizadas podem reduzir o custo de produção do hidrogénio (LCOH) até 20% - 6.08 €/kg - e aumentar o cumprimento da procura de 50% para mais de 92%. Estes resultados realçam o potencial da ferramenta para ajudar os promotores de projetos a explorarem as soluções de compromisso entre custo e fiabilidade durante a fase inicial do planeamento. Dado encontrar-se em desenvolvimento, a ferramenta continuará a ser aprimorada e alargada para incorporar funcionalidades adicionais e análises mais pormenorizadas em iterações futuras.

Palavras-chave: Simulação da produção de hidrogénio; Otimização de layouts; Apoio à decisão de conceção de centrais;

ABSTRACT

This article presents a modular simulation tool, developed using object-oriented programming, to support the technical and economic assessment of renewable hydrogen production plants. In general, the user defines the characteristics of the main components in the plant, from renewable energy production to the different hydrogen consumption points. With these inputs, the tool simulates the interactions between the indicated components on an hourly basis for their entire lifetime – 20 years. In this way, by modelling the existing energy flows, whether in the production of electricity, renewable hydrogen, the operation of storage and possible exchanges with the electricity grid, the capacities of the various components are optimised through an iterative process. The tool's operation focuses on the promoters' needs, based on optimising the levelised cost of hydrogen production and maximising compliance with demand. A case study in Fortaleza, Brazil, demonstrates its application, revealing that pre-optimized configurations can reduce the levelized cost of hydrogen (LCOH) by up to 20% - 6.08 €/kg - and increase demand fulfillment from 50% to over 92%. These results highlight the tool's potential to assist project developers in exploring



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trade-offs between cost and reliability during early-stage planning. As a work in progress, the tool will continue to be developed and extended to incorporate additional functionalities and more detailed analyses in future iterations.

Keywords: Hydrogen Production Simulation; Layout Optimization; Plant Design Decision Support;



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1 INTRODUCTION

The integration of renewable hydrogen in different sectors has become one of the strategic solutions to address the challenges of deep decarbonisation. Beyond its role in enabling the transition of energy-intensive industries, it is also increasingly recognised as a possible key vector for supporting the management of electricity systems that have high shares of renewables by providing long-term storage and sector coupling opportunities. In this sense, many countries and companies in different regions worldwide are implementing their strategies on the topic, announcing projected investments and partnerships to develop large-scale renewable hydrogen hubs. A notable example is the Ceará region, where the Ceará hydrogen hub in Pecém recently secured support from the World Bank for 134 million dollars to expand the Pecém Industrial and Port Complex for green hydrogen production (World Bank Group, 2025).

However, the deployment of renewable hydrogen production plants presents significant technical and economic challenges. The intermittent availability of key resources for renewable electricity generation (solar and wind), possible temporal mismatches between hydrogen production and demand and the large economic investments associated with it represent risks that must be well taken care of and studied. Besides that, the integration of different components such as PV arrays, electrolyzers, hydrogen storage, and grid interfaces adds layers of complexity that critically affect the calculation of the levelised cost of hydrogen (LCOH).

To support project developers and decision-makers during the early stages of planning, an advanced simulation tool has been developed, allowing hourly operational modelling over a 20-year horizon, coupled with a heuristic pre-optimisation procedure. This method automatically adjusts the capacities of main system components - PV, electrolyzers, storage - to approach efficient configurations, guaranteeing it is usable for different layouts and plant types. Ultimately, it is intended to provide promoters and investors with a fast and reliable starting point for conducting robust techno-economic analyses.

This paper details the architecture of the simulation tool, explains the pre-optimisation heuristic, and demonstrates its usefulness through a practical case study in Ceará, Fortaleza. By focusing on rapid but effective capacity adjustments, the tool aids in producing technically reliable, economically competitive hydrogen production configurations, supporting the acceleration of renewable hydrogen projects.

2 METHODOLOGY

The main objective of this tool is to simulate the operation of the key modules of a renewable hydrogen production plant, taking into account their technical and operational specificities over the plant's whole lifetime (assumed as 20 years). The tool enables a resolution of hourly simulations, allowing the user to assess how the system responds to variations in renewable energy availability, demand profiles, and operational constraints. The hourly demand profile acts as the driver for system operation, determining how production, storage, and grid interactions are managed in order to meet consumption needs. This level of refinement is important for renewable hydrogen projects, where the variability of solar and wind resources, as well as temporal mismatches between production and consumption, can significantly affect both technical feasibility and economic performance. It was also intended to develop a flexible tool so that different types of study scenarios can be assessed. To this end, the tool was developed using Python's object-orientated programming (OOP) logic, which, thanks to its modularity, allows the user to define



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which equipment modules are present in a given plant and how they are interconnected, avoiding the need to study fixed layouts. Additionally, the user can specify the economic parameters associated with each module, such as capital expenditure (CAPEX), operational expenditure (OPEX), enabling tailored techno-economic analyses.

Lastly, in order to guarantee a user-friendly interface, the front-end of the developed tool was developed in Streamlit, an open-source Python framework. From this it was possible to have a structured input section, to insert all the needed parameters and an output section where it is possible to get the studied scenario key figures and a dynamic visualization of each equipment time-series plots and economic data.

2.1 Component modelling

The renewable energy supply can be modelled by 4 different manners: Photovoltaic plant, Wind plant, PPA contract or grid connection.

PV Plant/ Wind plant: For this case the user inputs an hourly electricity production profile via an Excel file. The simulations run in this study used simulated data generated by a software, which provides location-specific solar irradiance and temperature profiles. This enables site-specific modeling of PV output variability.

Electrolyser: The electrolyser model is implemented with a variable efficiency dependent on its load factor following the work developed by (Koponen et al., 2016). Additionally, electrolyser's degradation is considered at a fixed rate of 0.25% per 1,000 operating hours (U.S. Department of Energy, [S.d.]). The entire efficiency curve decreases over time according to this factor, ensuring that long-term performance degradation is accounted for in the simulation.

Compressor: The compressor is modeled using theoretical thermodynamic equations. Since different compressor models exhibit varying behaviors, a generic approach based on fundamental thermodynamic principles was chosen. First, the number of compression stages (N) is calculated using (Khan et al., 2021):

$$N = \frac{\log(P_{out}/P_{in})}{\log(x)}$$

Where P_{in} and P_{out} are the outlet and inlet pressures, respectively, and x is the compression ratio per stage. The energy required for compressing hydrogen is calculated assuming an isentropic compression with an efficiency of 80%. Finally, the power required by the compression system (P) to fulfill the plant's hydrogen needs is given by (Khan et al., 2021):

$$P = N \left(\frac{k}{k-1} \right) \left(\frac{z}{\eta} \right) T_{in} Q R \left[\left(\frac{P_{out}}{P_{in}} \right)^{\left(\frac{k-1}{Nk} \right)} - 1 \right]$$

Where z is the compressibility factor, k is the ratio of specific heat under constant pressure to specific heat under constant volume, T_{in} is the inlet temperature [K], Q is the molar flow rate [mol/s], η is the efficiency and R the universal gas constant [J/(K.mol)]. Importantly, the compressor does not act as a bottleneck in hydrogen supply, as its capacity is determined only after the simulation, based on the peak power demand observed during the simulation period.

Hydrogen Storage: Hydrogen storage is modeled based on user inputs, including the maximum storage pressure and the maximum hydrogen mass capacity.

Demand: Hydrogen demand is modeled based on user input. It can be set as a fixed value or as a variable profile, in which case it is defined through an Excel file provided by the user.



2.2 Pre-optimisation

As already stated, one of the main features set for the work in progress was to develop a technical and economic analysis tool that would enable an in-depth study of different variants of renewable hydrogen production plants, making it possible to understand how the different pieces of equipment work in each case, while guaranteeing timely processing. To this end, in order to optimise the sizing of the different pieces of equipment, a pre-optimisation module was developed, which is run before the 20-year simulation so that the user is aware of the changes that can make to the base scenario, in order to reduce the levelised cost of hydrogen (LCOH) and maximising the level of fulfillment of the existing demand. To achieve faster processing, the pre-sizing module relies on a one-year simulation with representative operational conditions, rather than simulating the entire plant lifetime. Additionally, an average electrolyser degradation factor is applied to approximate long-term performance impacts without introducing excessive computational load.

2.3 Case study

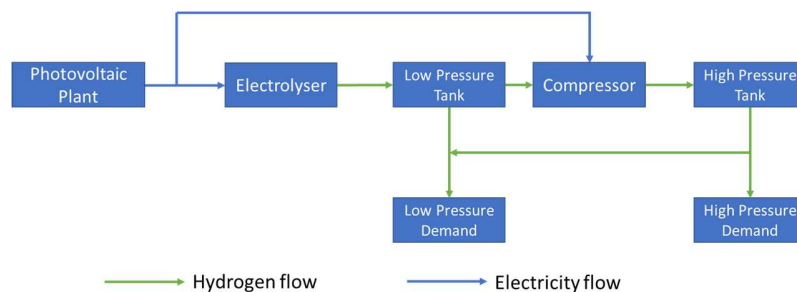
Given the importance of the study topic in the Ceará region, both due to the high availability of renewable energy and the interest of various promoters of developing projects in this location, a base study will be presented for this location. Tabela 1 summarises the main parameters for the base scenario.

Tabela 1 – Characteristics of the base study scenario for the renewable hydrogen production plant

Item	Scenario
Plant's location	Ceará, Fortaleza
Photovoltaic plant [MW]	300
Electrolyser [MW]	100
Low pressure tank [kg]	75 000
High pressure tank [kg]	20 000
Low pressure demand [kg/h]	750
High pressure demand [kg/h]	350

In Figura 1 the case study layout and the equipment's connection are presented.

Figura 1 – Case study layout





3 RESULTS AND DISCUSSIONS

This section presents and analyses the outcomes of the case study simulations, comparing the base scenario to the pre-optimised configurations generated by the tool.

The pre-optimisation process aims to define two configurations of interest. The first one focuses on defining the scenario with the lowest LCOH, without any other constraint. The second one prioritises an optimal balance between LCOH and demand fulfillment. As it is presented in Tabela 2, the capacities for the majority of the equipments were significantly modified when compared with the base scenario.

Tabela 2 – Characteristics of the pre-optimized scenarios for the renewable hydrogen production plant

Item	Best LCOH Scenario	Best relation between LCOH and fulfillment ratio
Plant's location	Ceará, Fortaleza	
Photovoltaic plant [MW]	360	480
Electrolyser [MW]	200	
Low pressure tank [kg]	37 500	
High pressure tank [kg]	10 000	
Low pressure demand [kg/h]	750	
High pressure demand [kg/h]	350	

The photovoltaic plant increased from 300 MW to 360 MW in Scenario 1 and to 480 MW in Scenario 2, making it possible to have a greater renewable energy input. Similarly, the electrolyser capacity doubled to 200 MW in both scenarios, increasing the plant's ability to produce more hydrogen and store it effectively. Contrarily, the storage tanks were reduced to half, indicating that the first ones were oversized and underutilized. Tabela 3 summarizes the key techno-economic indicators for each scenario.

Tabela 3 – Summary of the results of the study scenarios

Item	Base scenario	Best LCOH Scenario	Best relation between LCOH/fulfillment ratio
Plant CAPEX [M€]	392	511	595
Electrolyser CAPEX [M€]	108	215	331
OPEX [M€]	357	495	562
Total hydrogen produced [ton]	98 834	165 669	182 644
Demand fulfillment [%]	50.14	84.05	92.66
LCOH [€/kg]	7.58	6.08	6.33

The optimized scenarios demonstrate significant improvements over the base one. Hydrogen production increased by approximately 67% in the best LCOH Scenario and 85% in the balanced configuration. Demand fulfillment rose from 50.14%



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in the base case to 84.05% and 92.66%, respectively. Moreover, these performance gains were achieved while reducing LCOH by around 20%, from €7.58/kg in the base scenario to €6.08/kg in the configuration with the lowest cost.

Figura 2 and 3 illustrate what can be analysed through the dynamic visualization of the technical parameters. The first one illustrates the temporal dynamics of renewable energy gross production and the part of it that is actually transferred to the other plant's equipment's while the second shows the evolution of the electrolyser's efficiency in a given timespan.

Figura 2 – Photovoltaic energy production

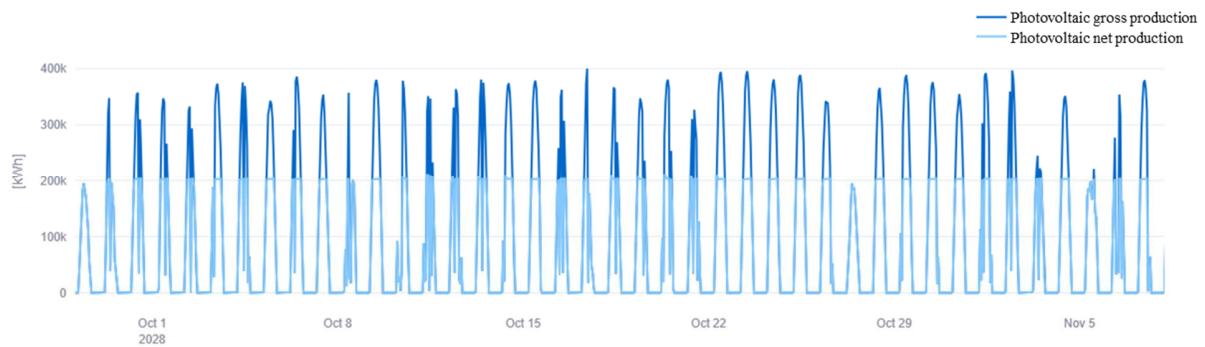


Figura 3 – Electrolyser efficiency



When comparing the tool's outcomes to other studies in the literature, the results fall within a credible range. For instance, a study focusing on a renewable hydrogen hub in Pecém port estimated LCOH values between €2.72 and €4.44/kg (Feitosa; Costa, 2025). Another analysis reported LCOH values between USD 2.50 and 6.80/kg depending on technology assumptions and regional contexts across Brazil (Da Silva et al., 2025). The slightly higher values in this study (€6.08–6.33/kg) can be attributed to conservative assumptions, such as not yet incorporating economies of scale or Brazil-specific cost adjustments. Therefore, the tool's outputs should be interpreted as cautious estimates, with room for refinement as more location-specific and large-scale cost data become available.

Overall, the pre-optimization process effectively identified plant configurations that deliver higher hydrogen output resulting in a better demand coverage, and lower production costs. These findings underline the importance of simultaneously considering production, storage, and demand profiles in early-stage techno-economic assessments of renewable hydrogen systems.



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4 CONCLUSIONS

This study demonstrated the application of a pre-optimization tool to support the design of renewable hydrogen production plants. The tool identified two configurations of interest: one minimizing the levelized cost of hydrogen (LCOH), and another balancing cost with demand fulfillment.

Compared to the base scenario, the optimized configurations significantly improved plant performance, increasing hydrogen production by up to 85% and demand coverage from 50% to over 92%, while reducing LCOH by approximately 20%. These results were achieved by increasing the photovoltaic and electrolyser capacities and downsizing storage tanks, highlighting the importance of aligning system components to the demand profile.

The outcomes underline the tool's potential to guide early-stage planning and decision-making, helping plant promoters explore trade-offs between cost and reliability. Future work will focus on extending the tool to improve the optimization method, guaranteeing more refined scenarios, develop a more complete economic analysis that can support a full techno-economical study, as well as applying it to diverse geographical contexts.

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