

Novel approach to location planning of hydrogen refueling stations: How market drivers and existing infrastructure impact the hydrogen economy

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ARTICLE INFO

Keywords:

Hydrogen refueling station
Hydrogen infrastructure planning
HRS networks
Geospatial analysis
Levelized cost of hydrogen

ABSTRACT

This study aims to present a novel methodology to assess future potential location of hydrogen refueling stations (HRS), involving geospatial and levelized costs of hydrogen (LCOH) analyses. This methodology entails five stages and was developed and applied to mainland Portugal. It can be used in other regions or countries. In this study, a total of 708 potential locations for different HRS were identified and studied for five scenarios. The results indicate that LCOH varies between a minimum of 6.5 €/kg H₂ and a maximum of 11.2 €/kg H₂. Moreover, 3 574 routes were analyzed considering four hydrogen production sites and the five scenarios, of which 2 395, or 67% of the routes, have a LCOH of between 6–9 €/kg H₂. The main conclusions of the study indicate that there are significant regional disparities in Portugal and that the adoption of hydrogen as an alternative fuel still presents challenges, especially in regions with limited hydrogen refueling infrastructure. The uneven distribution of hydrogen infrastructure and the high associated costs are likely to further exacerbate these economic and technological disparities. Addressing these imbalances requires the development of regional strategies that encourage, for example, hydrogen production in remote and underserved regions.

1. Introduction

Green hydrogen stands out as a strategic element within the Portuguese and European Union (EU) energy and climate policy context. This resource can be used as a feedstock, fuel, or energy carrier. Hydrogen can be stored as compressed gas (350–700 bar), liquefied hydrogen (–253°C), or in solid-state materials to increase gravimetric density. Compressed gas storage, commonly used at refueling stations, involves high-pressure tanks that store hydrogen efficiently but require significant space and pose safety risks due to potential leaks and material embrittlement [1,2]. Liquefied hydrogen storage, operating at cryogenic temperatures, offers high storage efficiency but involves substantial energy demand and high costs [3]. Green hydrogen is emerging as a key solution to decarbonize hard-to-abate sectors like heavy-duty transport and industry, where emissions remain a major challenge [4]. This view aligns with the Joint Research Centre (JRC) work for EU [5], which found that most scenario analyses identify transport and industry as the two key sectors in which hydrogen will play an important role.

Therefore, hydrogen plays a crucial role in the EU energy and climate mitigation targets. The 2030 target includes a reduction of at least 55% in net greenhouse gas (GHG) emissions compared to 1990 [6], a renewable energy share of at least 42.5%, and improvements in energy

efficiency [7]. Additionally, an intermediate target for 2040 proposes a net reduction of 90% in GHG emissions relative to 1990 levels [8]. By 2050, the EU's goal will be to achieve carbon neutrality [6]. The EU's hydrogen strategy [9] follows the Fit-for-55 policy package and the REPowerEU, which aims for 10 Mt of domestic renewable hydrogen and 10 Mt of imported renewable hydrogen by 2030 [10]. These targets exceed by far the previous objectives of the 2020 Hydrogen Strategy [11]. In the recent 2040 Climate Target Impact Assessment study it is found that in some of the scenarios the transport sector is responsible for most of the final hydrogen consumption in EU [12].

The Alternative Fuels Infrastructure Regulation (AFIR) was launched as part of the 'Fit for 55' package [9]. To ensure that all Member States (MS) have adequate refueling infrastructure to support the decarbonization of the transport sector. AFIR requires MS to locate hydrogen refueling stations (HRS) for light- and heavy-duty vehicles along the Trans-European Transport Network (TEN-T) within 200 km of each other by 2030. It also requires HRS at each urban node of the TEN-T network. Minimum pressure for these stations should be 700 bars, and there should be a daily fueling capacity of one ton [9].

Portugal has also committed to move towards a hydrogen economy namely through its National Hydrogen Strategy (EN-H₂) [13], which sets hydrogen deployment goals for 2030 and for 2050 for the gas grid,

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<https://doi.org/10.1016/j.ijhydene.2026.153603>

Received 1 October 2025; Received in revised form 14 January 2026; Accepted 17 January 2026

Available online 20 February 2026

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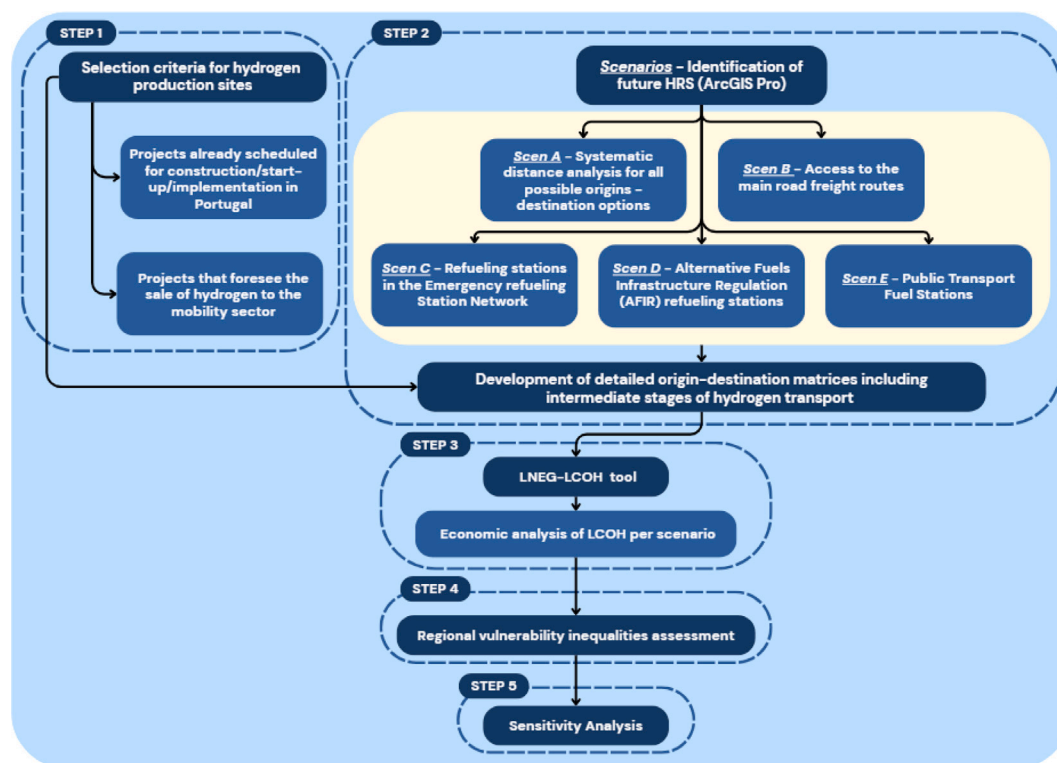


Fig. 1. Methodology approach.

Source: LNEG.

power transport and industrial sectors, using only hydrogen produced from electrolysis supplied with renewable electricity. Among the 2030 targets are 2–2.5 GW of installed capacity of electrolyzers, 50–100 HRS, 1%–5% of hydrogen in final energy consumption of transport and 400–500/750 heavy-duty freight trucks/buses running on hydrogen [13]. Several hydrogen infrastructure initiatives are also developing, such as the “Portuguese Hydrogen Backbone” and “H₂Med/CelZa” that have been designated as European Important Projects of Common European Interest (IPCEI). The first entails the adaptation of the national gas network to be able to transport blended hydrogen, while “H₂Med” includes 248 km of dedicated hydrogen pipelines (162 km in Portugal), creating a Mediterranean hydrogen corridor with a capacity to transport 0.75 million tons per year by 2030 [14]. On the hydrogen production side, 34 projects are being deployed in Portugal [15]. Some of these are part of the Recovery and Resilience Plan Mobilizing Agendas initiative, including, for example, H₂ Green Valley, SinesH₂GValley and Moving2Neutrality [15]. It should be mentioned that the 2024 revised National Energy and Climate Plan 2030 (NECP) does not set explicit quantitative targets for HRS or hydrogen vehicles, although it mentions amounts of hydrogen required for mobility [16].

Despite the ambitious hydrogen policy targets, there are challenges in implementing the hydrogen economy, partially due to the lack of distribution and transport infrastructure [17]. This aligns with findings in the literature, which highlight key barriers such as insufficient government support, limited infrastructure, and high investment and operating costs [18]. Road transport and pipeline distribution are critical components of the distribution infrastructure. Compressed hydrogen gas is transported in high-pressure tanks, while pipelines offer a continuous supply but require significant investment and maintenance. Each method has advantages and disadvantages, with the choice depending on specific energy conversion applications and end-use requirements [19,20].

As hydrogen distribution technologies develop, it is imperative to consider refueling infrastructure, since HRS act as both a hydrogen hub for storing hydrogen and refueling vehicles [21]. Therefore, HRS

are key infrastructure, and their location planning is vital due to the complexities of hydrogen transport and distribution [22]. The most frequently used criteria for planning HRS location are construction costs, hydrogen demand, and proximity to consumers [23–28]. Other used criteria are proximity to hydrogen production plants, supply volumes, and existing refueling stations that could incorporate hydrogen options [25,28]. Kuvvetli [24] also accounted for risks associated with HRS, such as operational and seismic risks. Tafakkori et al. [26] included social welfare criteria, such as employment rates and local development. Current literature does not consider value chain levelized cost of hydrogen (i.e. from production until HRS), nor implications of HRS locations and hydrogen costs for regional planning and equitable access to hydrogen.

Inequal geographical access to climate change mitigation practices (as hydrogen for transport) is a relevant topic that has been studied [29]. Related to this, there is the important concept of “climate change justice” that refers to “fair availability and accessibility of clean and affordable energy for all population groups” [30]. Nonetheless, there is a lack of studies addressing these inequalities, especially at national and sub-national level [31]. To be noted that the EU has established the “Just Transition Fund” to mitigate the negative impacts of its climate transition by supporting the most affected territories and workers [32].

This paper aims to present a novel methodology to assess future potential location of HRS to support AFIR, carbon neutrality and green hydrogen policy goals. The approach considers value chain levelized costs of hydrogen supply and focuses on the near-term context and is implemented for Portugal, addressing regional inequalities. It can be applied to other countries and regions.

2. Material and methods

This section presents an overview of the methodology explaining the approach and assumptions structured in the following blocks: (i) for hydrogen production sites; (ii) as scenarios and routes for potential

HRS location; (iii) LCOH estimate; (iv) regional analysis of vulnerability and (v) sensitivity analysis.

2.1. General overview of the adopted methodology

A five-step approach was adopted: Step 1 consisted of, selecting hydrogen production sites that could supply HRS (i.e. hydrogen for the mobility sector); Step 2 involved developing five scenarios to identify potential sites for future refueling stations, and detailed origin–destination matrices from the production sites to the HRS, including intermediate stages of H₂ transport routest; Step 3 focused on calculating the LCOH and cost structure for each scenario; Step 4 developed a regional vulnerability index on hydrogen availability for transport and Step 5 conducted a sensitivity analysis. The developed methodological approach is systematically presented in Fig. 1. This study focuses on mainland Portugal (i.e. it does not consider the island regions of Azores and Madeira) and its time frame is 2030.

The selection criteria in Step 1 were to consider projects that are likely to be operational by 2030 in Portugal and that will be delivering hydrogen to the mobility sector. In Step 2, the five potential HRS location scenarios developed consider the following possible future mobility market segments. HRS will be located near the main H₂ suppliers (Scenario A), HRS will be near points of interest for heavy freight consumers (Scenario B), HRS will serve all types of transport consumers by adapting the existing conventional fuel stations in the National Emergency Fuel Station Network (Scenario C), the HRS required under the AFIR regulation (Scenario D) and finally, HRS located near points of interest for public transport bus companies (Scenario E). All suppliers and potential HRS locations were mapped and origin–destination matrices from the production sites to the HRS were developed using ArcGIS software. Step 3 entailed the calculation of the whole value chain LCOH using the volumes of produced hydrogen from each considered producer in Step 1 and the routes mapped in Step 2 which were input in the LNEG-LCOH tool [33].

To analyze regional inequalities, the results were organized at the NUTS III level. NUTS is an EU-wide common classification of territorial units for statistics that considers three levels of division (NUTS I, NUTS II and NUTS III) (European Parliament, 2025). Mainland Portugal has 26 NUTS III regions, which were found sufficient to carry out the analysis.

Each of the steps in the figure is described in more detail in the following sections.

2.2. Step 1: Hydrogen production sites

Hydrogen production sites were selected based on the following cumulative criteria: (i) hydrogen production projects located in mainland Portugal; (ii) for which implementation in on-going assessed by the fact that there is an on-going permitting process or construction has started, and (iii) there is a stated intention by the producer to supply all/a fraction of the produced hydrogen to the mobility sector (thus, excluding those projects intended for industrial or non-mobility applications). The information for project selection was obtained through literature reviews, expert consultations (Portuguese representatives in the Clean Hydrogen Joint Undertaking, academia, hydrogen producers association, etc.) and gray literature (media, technical publications, hydrogen websites, etc.) from march till the end of 2024. This ensures the selected sample aligns with market reality and development trends regarding hydrogen supply. By taking a concrete and planned approach, rather than relying solely on theoretical scenarios, the results can be applied to the planning of future H₂ infrastructure in Portugal. A total of 30 H₂ production projects were initially identified, of which only four sites were selected based on the mentioned criteria. The projects considered were: Galileu Green H₂ Valley; GalpH₂Park; H₂Enable; and Hyperion H₂ Setúbal. The characteristics of the production sites can be seen in Table 1.

It should be noted that the quantities produced by these four sites are insufficient to supply the estimated amounts required for mobility under the revised NECP. It is assumed, however, that these suppliers will contribute to the supply of hydrogen to the transportation sector, even if not all hydrogen is sold in the country. Furthermore, other hydrogen sources will likely play a role, though they are not yet mapped.

2.3. Step 2: Scenarios and routes for potential HRS location

To identify potential locations for future HRS, five different scenarios (A, B, C, D, and E) were considered, trying to represent different business models where hydrogen is sold either to different transport consumer segments or simply in proximity to production sites:

- Scenario A considers that HRS will be located near the main H₂ producers and thus the potential future HRS location entailed a systematic distance analysis for all possible origin–destination options by applying buffers around each producer point of 10 km, 25 km and 50 km;
- Scenario B considers that HRS will be near points of interest for heavy freight transport consumers was thus based on access to major freight transport routes, as identified by the National Association of Road Freight Transport (ANTRAM);
- Scenario C considers that HRS will serve all types of transport consumers by adapting the existing conventional fuel stations within the National Emergency Fuel Station Network (REPA);
- Scenario D considers the HRS required under the EU AFIR Regulation based on the minimum regulatory requirements of 200 km buffers and urban nodes (Porto, Barcelos, Guimarães, Braga, Vila Nova de Famalicão, Coimbra, Leiria, Viseu, Lisbon, Setúbal, Évora, and Faro) along the TEN-T core network;
- Scenario E considers that HRS will be located near points of interest for public transport bus companies considering the current network of public transport terminals as potential HRS locations, as obtained from the Portuguese Mobility and Transport Institute (IMT).

Each of the potential HRS location points in each of the five scenarios was mapped.

It is important to note that the selection of distances of 10 km, 25 km, and 50 km for scenario A was inspired by the study presented by Kuvvetli [24] for HRS planning. In this study, the author considers the range of hydrogen vehicles (400–500 km) and applies a margin of approximately 10% to ensure safe initial coverage, maximize accessibility and minimize risk of unavailability [24]. The selection of the three distances for this study reflects a logic of balanced territorial coverage based on proximity. The 10 km represents a minimum distance to ensure high density in the areas surrounding production stations where transportation costs will be minimal. The 25 km represents an average value that optimizes the relationship between greater coverage and costs. Finally, 50 km represents a maximum distance that ensures accessibility in less dense areas and greater coverage.

For all the scenarios, only road transport of hydrogen via tanker trucks was considered, excluding the natural gas network due to the complexity of blending hydrogen with natural gas for injection and subsequent separation before use. Moreover, the natural gas infrastructure is limited to certain areas, requiring additional transport steps that complicate logistics and increase costs. Gaseous hydrogen was chosen over liquefied hydrogen to avoid significantly higher costs and additional technical challenges associated with liquefaction and cryogenic storage.

To determine the logistical routes between production points and HRS, it was necessary to calculate the distance between these locations. Geographic Information Systems (GIS) tools were utilized to map and organize the previously collected data. Esri's ArcGIS Pro 3.4.3 was used

Table 1
Relevant information on production sites.

Parameters	Galileu	Hyperion	Galp	Enable
Electrolyzer capacity (MW)	300	7.5	100	40
H ₂ production ^a (kg/day)	116 510	3240	41 096	15 069
Production allocated to mobility ^b (%)	20	50	25	10
H ₂ produced for transportation (kg/day)	23 302	1620	10 274	1507
Main offtakers considered by the companies	Mobility sector	Mobility sector	Mobility sector ^c	Mobility sector
	H ₂ blending into the natural gas grid	H ₂ blending into the natural gas grid	Sines refinery	H ₂ blending into the natural gas grid
	Cement industry		Galp biofuel plant H ₂ consumers and/or nearby Industrial facilities	Aniline production
Geographical coordinates	38.923210	38.559951	37.977433	40.777609
	-9.009399	-8.861132	-8.818059	-8.574436

^a Due to the lack of information on the type of electrolyzer used in the project, the calculation of H₂ produced (kg/day) is based on an average for an ALK and PEM electrolyzer.

^b As there is no information on the % for each offtaker, an equal distribution was considered in most cases.

^c To supply HRS from Galp.

to perform these analyses. In this software, the “Closest Facility” tool in the “Network Analysis” module was used to calculate the shortest distance between points, considering existing roads. This functionality is based on “Network Dataset”, a set of data that represents the national roads network.

2.4. Step 3: Estimate of LCOH

The information from Steps 1 and 2 was used to calculate the LCOH for each potential HRS.

The formula used to estimate the Levelized Cost of Hydrogen (LCOH) was:

$$\text{LCOH} = \frac{\text{CAPEX} + \sum \frac{\text{OPEX}_{\text{fix}} + \text{OPEX}_{\text{var}}}{(1+r)^n}}{\sum \frac{\text{AHP}}{(1+r)^n}} \quad (1)$$

The variables in the formula include fixed operational and maintenance costs (OPEX_{fix}) for expenses such as labor and administrative costs, variable operational and maintenance costs (OPEX_{var}) for expenses such as electricity and electrolyzer stack replacements, the discount rate (r), the year of expenditure or production (n), and the annual hydrogen production (AHP) or the equivalent amount of hydrogen (stored, transported, distributed). Additionally, the LCOH definition aligns with the Levelized Cost of Energy/Electricity (LCOE), allowing direct conversion from €/kg H₂ to €/MWh, and facilitating comparisons between energy projects beyond hydrogen.

The cost analysis conducted in this study adopted “LNEG-LCOH - Levelized Cost of Hydrogen Calculator” tool, developed by the National Laboratory of Energy and Geology (LNEG) [33]. This tool is available online and comes with a methodological report. The LNEG-LCOH tool includes six optional modules: H₂ Production, H₂ Liquefaction, H₂ Storage, H₂ Road Transport, H₂ Pipeline Distribution, and H₂ Refueling Stations (HRS). These modules represent components of the hydrogen value chain and can be used individually or in combination. However, the high volume of calculated routes made it impractical to manually determine the LCOH for each route using the online LNEG-LCOH tool. Therefore, to optimize the calculation process, an adaptation of the tool’s base code was used, allowing for automatic LCOH calculations for all routes associated with each production station. Table 2 presents selected the parameters used in the computation of the LCOH, a complete list of parameters can be found in Appendix B.

It is important to note that the default values applied in this study were used because the tool is relatively recent (2025) and its default values were defined to reflect the most updated values and representative practiced in the market. These values were estimated through consultation of a variety of robust sources both public (scientific literature, publications from relevant companies in the field and reports

from relevant organizations as International Energy Agency) and semi-confidential consultations with companies operating in the sector in Portugal. All parameters are adapted to the Portuguese context, which ensures relevance and methodological consistency.

2.5. Step 4: Regional vulnerability inequalities assessment

To assess the vulnerability of the 26 NUTS III different regions to hydrogen costs and availability for transport, a regional index was developed that considered, per NUTS III, two sub-indexes: (i) HRS sub-index that considers the number of HRS in each region and (ii) LCOH sub-index that considers how much more the value of the LCOH in a certain region differs (in %) from the lowest absolute LCOH in the country (see Table 3).

Each of the sub-indexes was classified in six classes, ranging from very low to very high. In the case of the number of HRS sub-index, very low reflects poor scoring and very high is the best possible performance. The opposite holds true for the LCOH sub-index.

As stated, a normalization procedure was applied to the LCOH data to ensure comparability between regions. The LCOH was normalized using a min–max approach, in which each value was rescaled based on its difference from the minimum LCOH observed in all regions.

Subsequently, both classifications were adapted to the distribution of the actual data values through the statistical method of natural breaks (jenks). This approach was chosen because the data exhibited significant nonuniformity. By tailoring the class boundaries to the empirical distribution, the resulting classification ensured a more representative segmentation of the data, thereby enhancing the interpretability and robustness of the final vulnerability assessment table.

2.6. Steps 5: Sensitivity analysis

A sensitivity analysis was performed to study the effect of the variability of the most significant variables in the LCOH results. The main variables considered were the CAPEX of the production unit, the electricity costs, the hydrogen production load factor, and the discount rate. OPEX was considered as a function of CAPEX, and it was set as 2% of the CAPEX. As the computations of the LCOH were applied to each potential node and route, distances are intrinsically considered in the analysis. This was done for each one of the five scenarios.

A second sensitivity analysis was conducted using a series of heatmaps to evaluate the combined effect of (a) CAPEX and electricity costs, (b) CAPEX and load factor of the hydrogen production unit, (c) CAPEX and OPEX, and (d) CAPEX and discount rate on the LCOH. Each

Table 2
Selected parameters for H₂ production and road transport.

Parameters	Galileu	Galp	Enable	Hyperion
H₂ production				
Electrolyzer capacity ^a [MW]	60	25	4	3.75
Lifetime of the electrolyzer [years]			25	
Water input type	Waste water			
Electrolyzer type ^b	ALK			
H₂ road transport				
Transport of H ₂ as	Gas			
Truck/trailer capacity [kg/H ₂]	1000			
Number of dispatch per day ^c [travel/day]	$\frac{2 \times (\frac{No. \text{ of km}}{50}) + 8}{12}$			

Note: For all other parameters, the tool’s “default values” were used.

^a To calculate the capacity of the electrolyzers, the assumptions and characteristics of the production stations for each project were used, which can be seen in Table 1.

^b Due to the lack of information on the majority of the electrolyzers used in the projects, it was assumed that all of them used alkaline electrolyzers (ALK).

^c This number was calculated for each route in the origin–destination matrices using the following equation (It should be noted that this no. is rounded up so that only entire numbers are calculated). Main assumptions are: (i) The truck has an average speed of 50 km/h; (ii) round trip is always made; (iii) 12 h of work; (iv) 4 h to charge/discharge.

Table 3
Classes considered for the subindexes for the regional vulnerability inequalities assessment.

Classes	HRS sub-index Number of HRS in the region	LCOH sub-index % Variation between LCOH in the region and minimum LCOH across all regions
Very low	1–10 (worst case)	0–5%
Low	11–20	6–30%
Low-Medium	21–35	31–40%
Medium-High	36–49	41–50%
High	50–80	51–60%
Very high	81–10	61–100% (worst case)

heatmap represents the simultaneous variation of these two parameters, with color intensity representing the resulting LCOH.

For the second sensitivity analysis, only one representative location (corresponding to the AFIR potential HRS with a distance from the Galileu production unit of about 20 km) was selected from the 12 considered in the AFIR scenario. The production unit with the highest capacity and consequently the lowest LCOH values was considered. This choice aimed to simplify the analysis while maintaining relevance by using a point considered typical in terms of infrastructure and operational conditions. However, this approach introduces certain implications: the results reflect the specific characteristics of the selected point and may not capture the variability present across the entire network. Consequently, the calculated LCOH values are influenced by local parameters such as the distance between the HRS and the production site, which could differ in other locations. Although the LCOH values for this production unit do not vary significantly, there is a limitation in terms of generalizing the results, so this method should be interpreted as indicative and not exhaustive. Nevertheless, this method provides useful information on the sensitivity of the parameters.

3. Results and discussion

This section presents the results regarding the potential locations of HRS and the respective LCOH per scenario and location. It also presented the results of the sensitivity analysis and a discussion of the applicability of the developed approach to other cases.

3.1. Potential location of HRS

Regarding the number of HRS considered for each scenario, there is a substantial variation. Scenario A (Proximity from producers) results

Table 4
Number of HRS.

	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
No. of HRS per scenario	694	229	358	12	121
Total no. of HRS ^a	708 ^a				

^a The total number of HRS ignores duplicated HRS across scenarios. The HRS in scenarios A and D are also present in scenarios B, C and E. For the total number of HRS, they were not considered.

Table 5
Total number of routes per scenario and maximum, minimum, mean, and median distances.

Scenario	Number of routes	Max. (km)	Min. (km)	Mean (km)	Median (km)
Scenario A	694	92	1	33	29
Scenario B	916	537	6	235	264
Scenario C	1432	558	1	217	204
Scenario D	48	504	5	237	250
Scenario E	484	550	5	217	185
Total	3574^a	558	2	186	153

^a This value may include duplicate routes in different scenarios.

in 694 HRS, Scenario B (road freight) 229, Scenario C (conversion of existing fuel stations) features 358, Scenario E (bus companies) comprises 121, and Scenario D (AFIR) includes only 12 HRS. This variation reflects the diversity of possible options considered in the scenario design. This will have impacts on H₂ supply logistics and associated costs. In total, 708 different HRS were obtained. Table 4 presents the total number of HRS across scenarios.

A total of 3574 routes connecting the HRS to the four considered production sites were obtained, with distances calculated between these points (see Table 5). The total number of identified routes, by scenario, and the average, maximum, and minimum distances are presented in the table. Route distances ranged from only 1 km to 558 km, with an average of 186 km and a median of 153 km. Notably, Scenario C has 1432 routes, while Scenario D has only 48 routes reflecting the assumed number of HRS.

Regarding distances per scenario, Scenario C has the maximum distance and one of the shortest minimum distances, due to having the most stations, resulting in more routes and a higher likelihood of distant

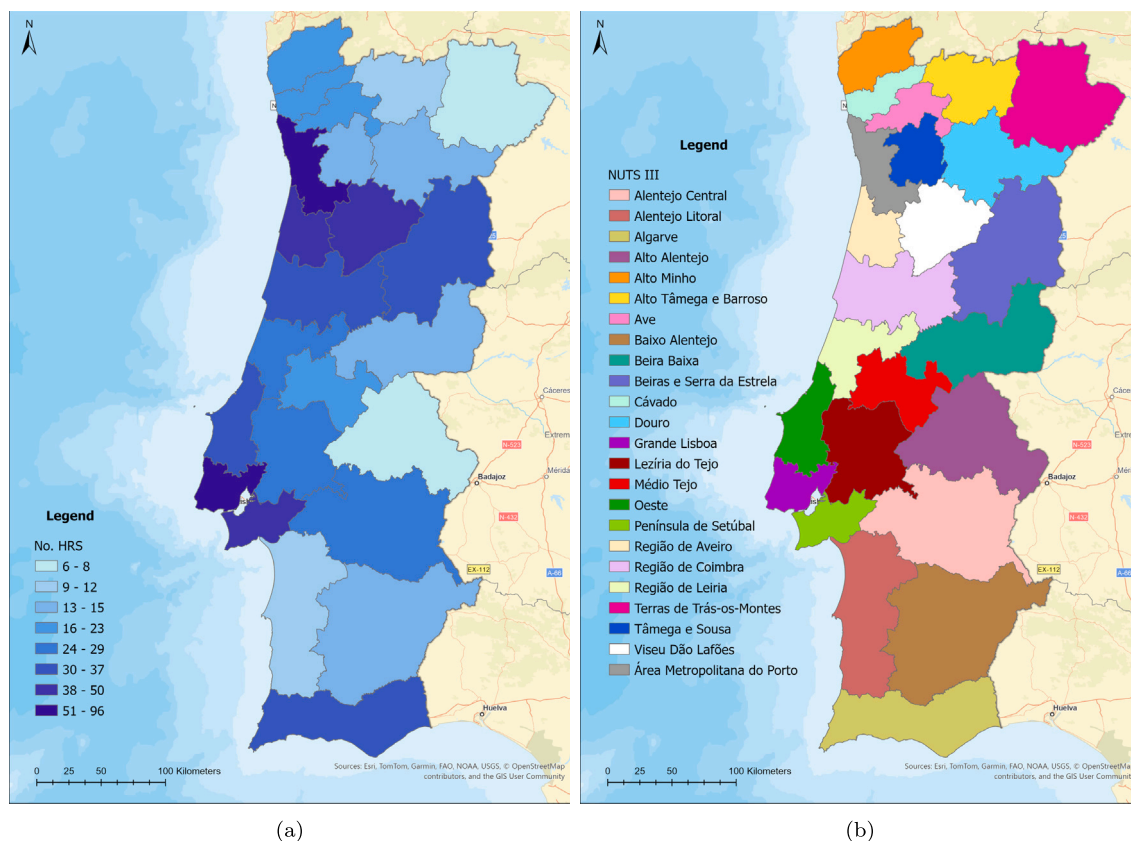


Fig. 2. Overview of potential total number of HRS (left) and of regional administrative areas NUTS III names (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Source: LNEG.

or nearby points. Moreover, Scenario A has shorter maximum, minimum, average, and median distances, due to the buffer area restrictions considered.

The geographic distribution of potential HRS is shown in Fig. 2. The figure shows the distribution of HRS per NUTS III, revealing significant regional concentration differences. The Grande Lisboa and Área Metropolitana do Porto have the highest numbers of HRS, highlighted in darker blue, with Área Metropolitana do Porto having 96 HRS and Grande Lisboa 78. In contrast, Alto Alentejo and Terras Trás-os-Montes, marked in lighter blue, have significantly fewer HRS, with only 6 and 8, respectively. Industrial hubs and logistical corridors likely explain higher concentrations in certain regions, while more isolated areas have fewer HRS, highlighting territorial asymmetries that pose challenges for hydrogen accessibility.

3.2. LCOH for future HRS evidenced regional inequalities

This section presents the estimated LCOH per scenario and location. Results are presented in Fig. 3. Total LCOH (e.g. considering production of hydrogen, storage, distribution and HRS costs) varies across potential future HRS and scenarios between 6.5 and 11.2 €/kg H₂. It is important to note that the computation of the latter also considers water costs for the electrolysis process, electricity, CAPEX, OPEX, fuel costs for the distribution through road transport, and all other costs involved in the value chain from production to the construction and operation of the HRS.

Analyzing the data from scenarios A, B, C, D, and E reveals significant differences in the distribution and dispersion of total LCOH values. Each scenario's median is relatively close, with most values concentrated between 6.6 and 9.7 €/kg H₂. Scenario A shows the least dispersion, as expected, since in this scenario the distances were shorter

and less varied due to the buffers. Scenarios B, C, and E show higher variability in LCOH, with some routes showing considerably higher costs. These three scenarios also present the highest maximum LCOH value (11.2 €/kg H₂). Scenario D shows a dispersion very similar to that of scenarios B, C, and E, with some routes having higher costs compared to scenario A.

Fig. 4 shows the LCOH for all HRS, aggregated per production site, highlighting variations between different production sites and per costs components of the total LCOH. The orange bar represents the total LCOH, summing the various components of the hydrogen value chain. Galileu production site has the lowest average LCOH across all 708 potential future HRS at 6.5 €/kg H₂ and the Hyperion station the highest at 9.6 €/kg H₂. Additionally, the Galileu and Galp sites generally have the lowest LCOH values, due to their larger project sizes and higher hydrogen production volumes. The graph also illustrates the shares of the LCOH estimated from the different value chain phases, including production, storage, transport, and distribution, with production having the greatest impact on total LCOH.

Fig. 5 shows the spatial variation in LCOH for each potential HRS locations for each of the four considered production sites across all five scenarios. Fig. 5a shows that Galileu is the project that can deliver H₂ with a lower LCOH across all country, with LCOH values that vary only between 6.5 and 6.6 €/kg H₂. Galileu benefits from its location in the Lisbon area, providing robust infrastructure and proximity to a large number of HRS, with lower LCOH due to higher hydrogen production volumes. If this site would be the main supplier, the delivery of hydrogen to HRS across the country would be cheaper and more homogeneous cost wise.

Galp, while still producing a significant amount of hydrogen, has fewer nearby HRS, necessitating longer travel distances. It is possible to observe that regions like Grande Lisboa or Península de Setúbal

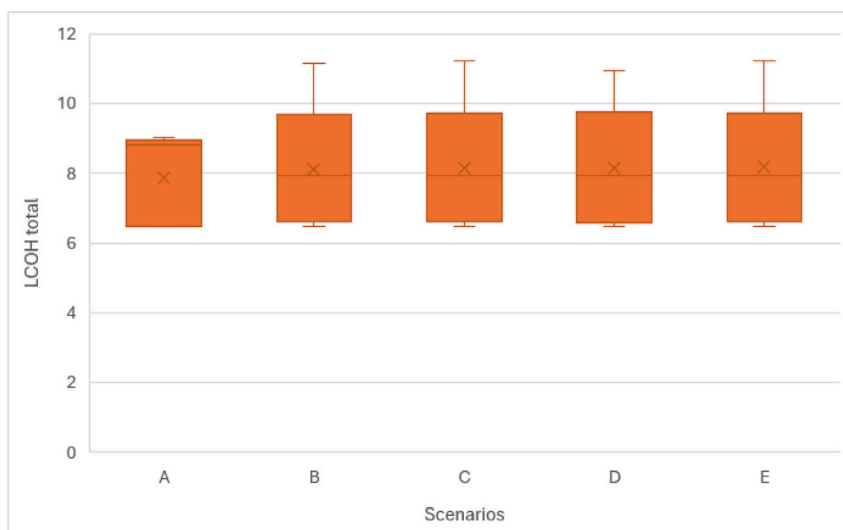


Fig. 3. LCOH results per scenario. Source: LNEG.

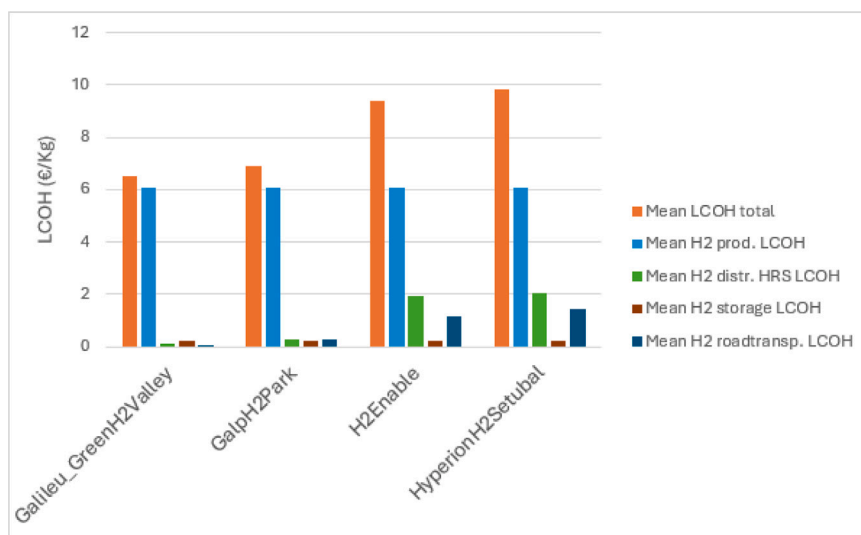


Fig. 4. LCOH results per production site. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) Source: LNEG.

are more privileged both in terms of costs and infrastructure. Fig. 5b shows that the highest concentration of lower LCOH HRS, ranging from 6.7 to 6.9 €/kg H₂, is in the south/central region, closer to where the Galp production site is located. Higher LCOH HRS values are located essentially across the Northern region and have LCOH values around 7.0 €/kg H₂.

For the Enable site, Fig. 5c shows that the lowest LCOH values, ranging from 8.8 to 8.9 €/kg H₂, are concentrated around the production plant in Aveiro and Porto regions. In contrast, the southern regions exhibit higher LCOH values, reaching 10.0 €/kg H₂ to 11.0 €/kg H₂. For the Hyperion site, Fig. 5d shows that the lowest LCOH values, ranging from 9.0 to 10.0 €/kg H₂, are found in the region of Grande Lisboa and Peninsula de Setubal. The highest LCOH values follow the same pattern and are in the northern regions of Portugal, where LCOH can reach 11.2 €/kg H₂.

These four maps illustrate the increasing trend of higher LCOH with greater distances between production and HRS points. Consequently, projects as Enable and Hyperion that are smaller in scale, result in more heterogeneous LCOH distributions across the country. Due to

their limited hydrogen production capacity, these projects are primarily able to supply local demand, restricting their impact on broader regional distribution. This localized supply is particularly evident in more vulnerable areas to regional inequalities, such as the northern and southern extremities of the country, where there are less potential future HRS available and transport distances are greater.

3.3. Regional vulnerability on hydrogen for transport

Fig. 6 shows the results obtained by applying the developed regional vulnerability index for each of the 26 NUTS III regions of mainland Portugal. Some regions have a low number of potential HRS and higher LCOH values, depending on the production site, such as the case of Baixo Alentejo, if supplied by either Hyperion or H₂Enable or Alto Tâmega e Barroso or Terras Trás-os-Montes, if supplied by Hyperion. Many of these regions can also present logistical challenges, such as less dense road infrastructure than in other regions. In addition, hydrogen adoption as an alternative fuel may be more difficult in these regions with fewer HRS, especially for long-distance transportation

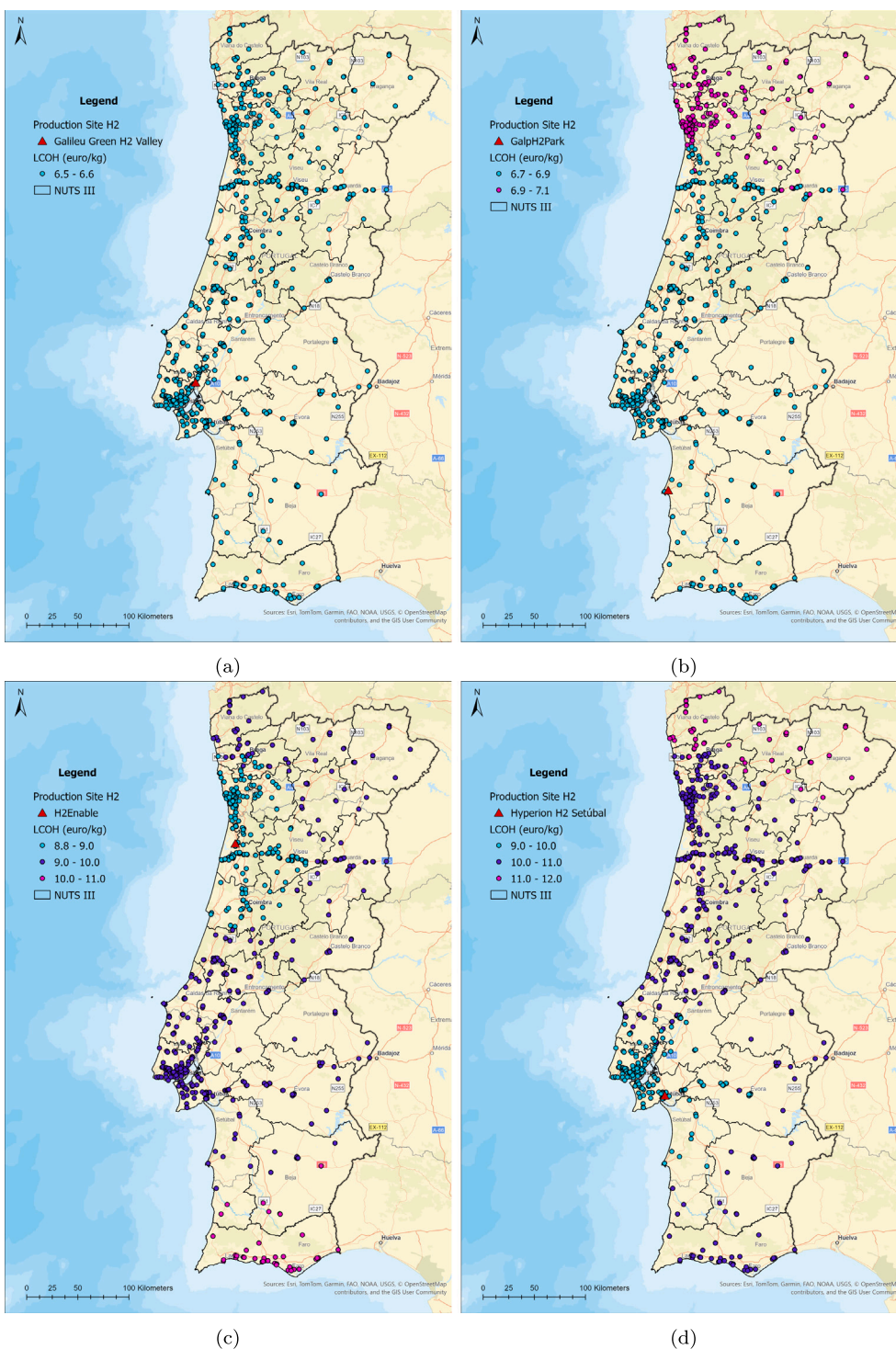


Fig. 5. Potential location of HRS per production site and LCOH distribution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Source: LNEG.

fleets, which may compromise equity in accessing more sustainable energy solutions. Thus, economic and technological disparities between regions are likely to increase because of the lack of infrastructure and high costs.

In this sense, identifying vulnerable regions that are not considered priority areas for immediate investment is essential to guide public policies that promote territorial equity. The lack of infrastructure in these areas and high costs should not be interpreted solely as a limitation but also as an indication of the need for medium- and long-term strategic

planning. This highlights the need for such projects to be in strategic locations, as well as reinforcing the need for policies that encourage the installation of infrastructure in vulnerable areas to promote regional development. Intervention in these areas may involve structural actions that prepare the territory for future energy and logistic opportunities and/or challenges.

In addition, developing HRS in remote or vulnerable areas faces some other major challenges such as investment risks and demand uncertainty that discourage private financing. According to IRENA &

NUTS III	No. HRS per NUTS III	Normalized LCOH difference with regard to the minimum LCOH			
		Galileu	Galp	Enable	Hyperion
Algarve					
Alentejo Central					
Alentejo Litoral					
Alto Alentejo					
Baixo Alentejo					
Península de Setúbal					
Grande Lisboa					
Lezíria do Tejo					
Médio Tejo					
Oeste					
Beira Baixa					
Beiras e Serra da Estrela					
Região de Aveiro					
Região de Coimbra					
Região de Leiria					
Viseu Dão Lafões					
Alto Minho					
Alto Tâmega e Barroso					
Área Metropolitana do Porto					
Ave					
Cávado					
Douro					
Tâmega e Sousa					
Terras de Trás-os-Montes					

HRS sub-index		
Class	Range	Level
Very Low	1-10	
Low	11-20	
Low - Medium	21-35	
Medium - High	36-49	
High	50-80	
Very High	81-100	

LCOH sub-index		
Class	Range	Level
Very Low	0%-5%	
Low	6%-30%	
Low - Medium	31%-40%	
Medium - High	41%-50%	
High	51%-60%	
Very High	61%-100%	

Fig. 6. Regional Vulnerability index for hydrogen use in the transport sector per NUTS III. Source: LNEG.

CPI [34], securing private investment for green hydrogen infrastructure is significantly limited by high perceived risk [34]. The sector faces significant economic barriers, such as high production and upfront costs, which make the cost of capital particularly critical [34,35]. Uncertainty about demand and the difficulty in obtaining long-term off-take agreements is the main market risk, exposing projects to the risk of underutilization and unviability [34]. The instability of policies, incentives, and legal frameworks, with fragmented permitting processes, causing delays and increasing compliance costs is an additional risk perceived by developers and financial institutions, which is crucial for the long-term commercial viability of this type of sector [34,35].

Therefore, to overcome these deployment challenges in vulnerable areas, policy interventions must reduce investment risk and simplify regulatory processes. Risk sharing and targeted incentives are one way to achieve this [36–38]. Lessons learned from renewable energy show that mechanisms such as feed-in tariffs and contracts for difference have stabilized early markets [36,37]. For hydrogen, a similar approach (e.g., minimum revenue guaranties, strike prices, or usage-based subsidies) can reduce project risks and attract private investment in regions with uncertain demand [36,38]. Second, standardization and simplification of licensing can significantly reduce delays and costs. Harmonized safety codes, fast-track licensing frameworks and measures such as the streamlined licensing provided for in the EU’s Net Zero Industry Act aim to ensure regulatory clarity and accelerate project implementation [39].

3.4. Sensitivity analysis

Results of the sensitivity analysis are presented in Figs. 7 and 8. As aforementioned, the sensitivity analysis considered five variables: the hydrogen production unit’s CAPEX; electricity costs; the H₂ plant’s load factor; the discount rate; and the OPEX. According to Fig. 7, the cost of electricity and the load factor were the parameters that had the greatest effect on LCOH variability at the four production sites. Both

parameters displayed substantial variability in their results. In contrast, parameters such as CAPEX or the discount rate have smaller value dispersion between the 25th and the 75th percentiles (smaller boxes), thereby having a less significant effect on the LCOH.

The results in Fig. 8 show once again that the cost of electricity is the main determining factors (with the highest sensitivity). These results correspond to a selected potential HRS AFIR location, as explained in the methodology. It is important to note that the variation of the LCOH between the 12 potential HRS AFIR locations for the base cases is less than 2%. It can be observed from Fig. 8 that for a CAPEX of 2500 €/kW, an increase in the cost of electricity from 40 to 80 €/MWh leads to an increase in LCOH from around 6.19 to 9.01 €/kg H₂, while comparable variations in CAPEX result in changes of around 1.3 €/kg H₂ (Fig. 8a). The load factor also emerges as a critical parameter, particularly for high CAPEX. For example, for a CAPEX of 2500 €/kW, increasing the load factor from 0.6 to 0.9 reduces the LCOH from approximately 6.74 to 5.52 €/kg H₂ (Fig. 8b). The discount rate has a secondary but relevant impact in high investment scenarios, increasing the LCOH by around 0.86 €/kg H₂ when the discount rate rises from 0.06 to 0.09 (Fig. 8d). In contrast, OPEX is set as a fixed part of CAPEX, which means it is not a separate variable in the sensitivity analysis. This means that as CAPEX increases, the related OPEX also has a bigger impact on the total LCOH cost (Fig. 8c).

In other words, the LCOH is highly sensitive to fluctuations in electricity costs and the load factor, suggesting that small changes in their values could significantly increase or decrease the LCOH in volatile market conditions. Therefore, mitigation mechanisms, such as fixed supply contracts for electricity or investment in more efficient technologies, are recommended. Results are similar for all hydrogen production sites.

4. Conclusions

A key component of ensuring accessibility and affordability is the transport and distribution of hydrogen to HRS. It is therefore essential

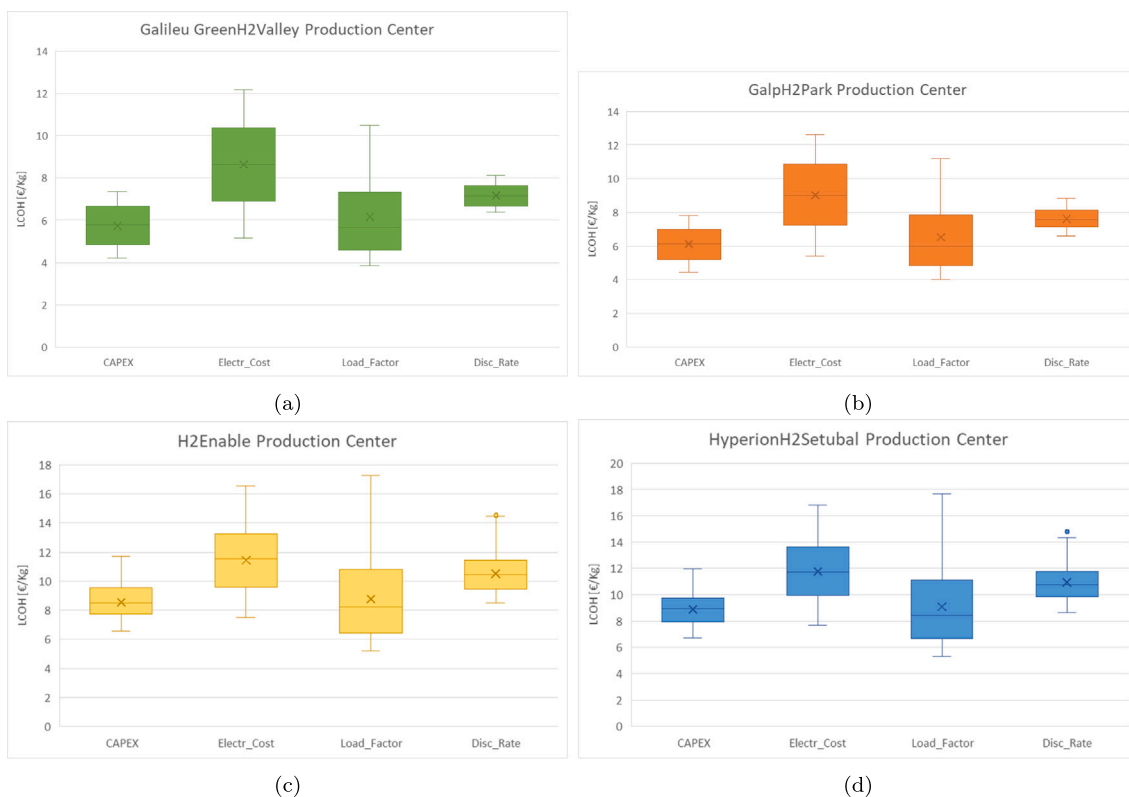


Fig. 7. Sensitivity analysis results per production site. Source: LNEG.

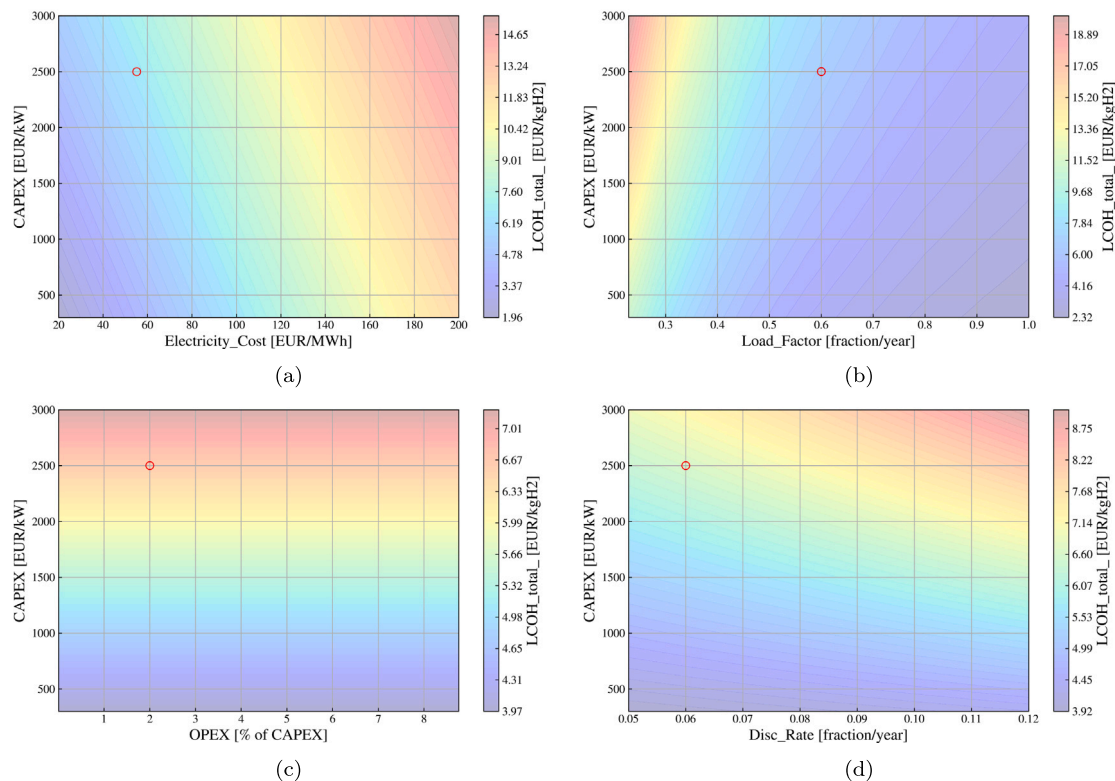


Fig. 8. Sensitivity analysis results of the LCOH considering the variation of (a) CAPEX and electricity costs, (b) CAPEX and load factor of the hydrogen production unit, (c) CAPEX and OPEX, and (d) CAPEX and discount rate. The red circle represent the base case for the selected HRS AFIR location. These results correspond to the AFIR potential HRS with a distance from the Galileu production unit of about 20 km. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Source: LNEG.

to plan HRS locations effectively, as this directly impacts the cost and feasibility of supplying hydrogen to different regions.

This study presented a new methodology that involves geospatial and cost analyses for hydrogen refueling station location planning. The methodology involved five steps, which started with the criteria definition for selecting hydrogen production sites (Step 1), the design of various scenarios and the geospatial analysis of nodes and routes for HRSs (Step 2), the computation of the levelized cost of hydrogen (Step 3) that served as the main indicator for comparing HRS location alternatives, an analysis of regional inequalities in costs and number of potential future HRS (Step 4), followed by a sensitivity analysis (Step 5).

Four hydrogen production sites were identified within the project portfolio for Portugal, suitable for analysis, which served for the HRS location planning for 2030. Five scenarios were designed replicated different business models to sell these hydrogen to different consumer segments of the transport sector (heavy road freight, bus transport companies, all of the previous and any other consumer) or based on proximity to production sites. Based on the five scenarios, a total of 708 potential locations for HRS were identified in mainland Portugal, which translates to 3 574 possible routes from the H₂ production sites to each of these potential HRS locations. An aggregated analysis shows that most levelized cost of hydrogen median values are concentrated between 6.6 and 9.7 €/kgH₂. However, some scenarios present a larger dispersion in LCOH, mainly due to a greater number of potential HRS locations and a larger variation of route distances from the H₂ production sites to the HRS. The sensitivity analysis showed that the parameters that affect the LCOH the most are the electricity cost, the load factor of the hydrogen production units, i.e. the annual production per installed capacity, and the CAPEX, named in decreasing order of importance.

Results at the production plant level showed that the HRS costs supplied by the larger production plants, i.e., Galileu and Galp, present the lowest LCOH with lower variability across HRS locations (between 6.5 and 7.1 €/kgH₂). In contrast, HRS costs supplied by the smaller H₂ production sites, i.e., Hyperion and H₂Enable, led to LCOH of 8 to 12 €/kgH₂. This is due to the lower operational efficiency in terms of the number of HRS that these sites are capable of supplying and logistical challenges, such as less dense road infrastructure compared to other regions, which translates into inefficient or sub-optimal fleet operations. Only “nearby” HRS locations would be feasible to supply by these sites. In any case, the LCOH will be higher compared to Galileu and GALP stations. These decentralized hubs of production and distribution are expected to reflect a high hydrogen selling cost due to the lack of economies of scale.

The adoption of hydrogen as an alternative fuel presents significant challenges in regions with limited hydrogen refueling infrastructure, particularly for long-distance transportation fleets. These challenges are exacerbated when the hydrogen supply is dependent on small-scale producers, potentially hindering access to more sustainable energy solutions. Across the 26 NUTS III regions of mainland Portugal. It was found that regions located in Baixo Alentejo or Northeast Portugal (Alto Tâmega e Barroso or Terras Trás-os-Montes) will have not only a low number of potential HRS, but also higher LCOH values. Consequently, economic and technological disparities between regions are likely to deepen due to the uneven distribution of hydrogen infrastructure and the associated high costs. This underscores the necessity of locating hydrogen production projects in strategically advantageous locations while simultaneously emphasizing the importance of policy measures that support infrastructure development in underserved areas to foster regional equity and a broader adoption of hydrogen fuel.

Moreover, the current disparities in hydrogen availability and pricing further reflect and reinforce existing regional inequalities. Addressing these imbalances requires the implementation of targeted incentives aimed at stimulating hydrogen production in remote and poorly served regions. By encouraging decentralized production, it

Table A.6

LCOE computation input values [40,41].

Description [Unit]	PV	Onshore wind
LCOE [€/MWh] ^a	35.66	74.77
Discount rate [%] ^b	8.00	8.00
DECEX as percentage of CAPEX ^b [%]	5.00	5.00
CAPEX [€/kW] ^c	500	1100
Capacity factor of the farm [%] ^d	20	26
Insurance costs [% of CAPEX per year] ^c	1.50	1.50
O&M cost [€/kW-year] ^c	5	50
Lifetime of projects [years] ^c	25	25

^a Values obtained for this study based on the parameters listed in table.

^b Assumed for this study.

^c MIBGAS [40] (2025).

^d Simões et al. [41] (2023).

becomes possible to reduce transportation distances, lower distribution costs, and mitigate regional disparities in hydrogen access. Therefore, regional development strategies must incorporate the establishment of complementary projects in proximity to these underserved areas, ensuring a more equitable and efficient transition to hydrogen-based transport systems.

The methodology developed and applied to continental Portugal is deemed to be replicable and with applicability to other countries or regions, especially in the early stages of HRS planning. In more advanced stages of infrastructure development, the consideration of additional factors beyond those considered in this study is expected. This study only considered hydrogen gas as the commodity for distribution via road transport; other means of transport might be considered, like hydrogen pipelines. Note that safety and positioning constraints, like safety/exclusion zones were not considered.

CRediT authorship contribution statement

Maria Espinha: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juan C.C. Portillo:** Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Sofia G. Simoes:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Juliana Barbosa:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research work was supported by the Portuguese Programme of Recovery and Resilience (02/C05-i01/2022) through the Moving2Neutrality Mobilizing Agenda (Project 32), WP3 P3.3.

Appendix A. Parameters used to estimate the LCOE of renewable sources for hydrogen production

This appendix presents the main assumptions and computed the LCOE used in this study. It was assumed that the renewable electricity used in the electrolysis process was composed of 50% PV and 50% wind onshore sources. Typical production units have been considered to be 100 MW (see Table A.6).

Table B.7Input values for the LNEG-LCOHtool - H₂ Production module [33,42–45].

Variable name [Unit]	Value
Electrolyzer capacity [MW]	Variable according to production center
Lifetime of electrolysis plant [years]	25
Annual discount rate [%/year]	6
Water input type	WasteWater
Electrolyzer type	ALK
Electrolyzer stack replacement period [h]	80 000
Mean annual load factor [fraction/year]	0.6
H ₂ production capacity [kgH ₂ /h/MW]	18
Stack annual degradation rate [%/year]	1.5
CAPEX of electrolysis plant [€/kW]	2500
Stack cost [% CAPEX]	15
OPEX fixed annual [% CAPEX/year]	2
Electricity consumption per kgH ₂ [kWh/kgH ₂]	52.14
Water consumption per kgH ₂ [L/kgH ₂]	18
Wastewater unit cost [€/m ³]	3.79
PV Solar electricity supply [%]	50
Onshore wind electricity supply [%]	50
Network electricity supply [%]	0
PV Solar electricity unit cost [€/MWh]	35.66
Onshore wind electricity unit cost [€/MWh]	74.77

Table B.8Input values for the LNEG-LCOHtool - H₂ Storage module [46,47].

Variable name [Unit]	Value
Storage capacity [t]	Variable according to production center
Location of storage	Aboveground
Storage method	Tank
CAPEX of storage system - tanks, pipes and compressors [€/t]	100 000
OPEX fixed annual - Tanks [% CAPEX]	2
Annual discount rate [%/year]	6
Lifetime of storage system - Tanks [years]	30

Table B.9Input values for the LNEG-LCOHtool - H₂ Road Transport module [47].

Variable name [Unit]	Value
CAPEX of truck/trailer [€/kg H ₂]	1140
Number of dispatch per day [travel/day]	See Table 2
OPEX fixed annual [€/kg H ₂]	0.06
Fuel consumption [€/km]	0.6125
Daily mean distance per truck/trailer [km]	Variable value
Mean number of truck/trailer per HRS [unit/HRS]	1.0
Annual discount rate [%/year]	6
Lifetime of truck/trailer [years]	10

Table B.10Input values for the LNEG-LCOHtool - H₂ Refueling module^a.

Variable name [Unit]	Value
CAPEX of one HRS [€/HRS]	5 000 000
CAPEX of compression system [€/kW]	0
Electricity consumption [kWh/kgH ₂]	3.25
OPEX fixed annual [€/kg H ₂]	0.5
HRS actual mean dispatch capacity [kgH ₂ /day]	1000
HRS number for analysis [unit]	1
HRS annual availability [%]	98
Annual discount rate [%/year]	6
Compressor number per HRS [unit/HRS]	2
Lifetime of HRS [years]	20

^a Values from companies consultation and internal market assessment.

Appendix B. Parameters used to compute the LCOH (complementary to the ones in Table 2)

This appendix presents the main data used to compute the LCOH. The next tables present the input data to the LNEG-LCOHtool for the modules considered and main sources of values (see Tables B.7–B.10).

Appendix C. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2026.153603>.

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