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Assessment of the Potential Consumption of Green Hydrogen in the Portuguese Industrial Sector as a Direct Feedstock for High Heat Applications

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The global need to decarbonize energy systems has intensified the search for alternative production, storage, and transport solutions. Among these, green hydrogen has emerged as a promising energy vector capable of supporting industrial and energy sector decarbonization. However, its large-scale deployment still faces significant technical, economic, and infrastructural challenges. This paper assesses the potential for green hydrogen consumption within the Portuguese industrial sector, with a particular focus on high-temperature heat applications and direct feedstock use. Through a geographically detailed approach, the analysis identifies major industrial players, their potential hydrogen demand under different blending scenarios (5%, 10%, and 20% with natural gas), and their spatial distribution across the country. The study further distinguishes between hydrogen used as a feedstock, currently concentrated in key facilities such as Galp's Sines refinery and Bondalti's Estarreja chemical complex, and hydrogen used for heat applications, notably in sectors like cement, glass, and ceramics. This mapping provides insight into how green hydrogen infrastructure could be implemented, either through centralized blending within the existing gas network or through decentralized supply to major industrial consumers. By combining industrial, geographical, and infrastructural perspectives, this work contributes to understanding how hydrogen demand could emerge regionally and identifies potential synergies to support the development of a sustainable green hydrogen economy in Portugal.

Keywords: *green hydrogen, high heat industrial processes, Portuguese industry, industrial processes, value chain, geographical analysis*

Introduction

Recent developments in climate policy have progressively intensified global concern for environmental sustainability, resulting in international agreements and strategic initiatives such as the Paris Agreement and the European Green Deal, both of which set the path toward achieving a net-zero carbon society. Within this framework, green hydrogen has emerged as a key solution for decarbonizing sectors that are difficult to abate, owing to its versatile applications and its potential contribution to strengthening energy security (IEA 2023).

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This paper focuses on the industrial sector, which is the second-largest energy-consuming sector in Portugal, following transport. Despite transport holding the highest overall consumption (DGEG 2021), industry is expected to be amongst the first sectors to adopt green hydrogen, as hydrogen is already used within certain processes, such as feedstock in chemicals and refining. This existing integration provides a foundation for broader deployment across other industrial activities.

Furthermore, industrial processes that require high-temperature heat, above 200 ºC, present a particular challenge for decarbonization. At present, there are no widely available alternatives to fossil fuels for such applications, aside from carbon-free hydrogen or carbon-free synthetic fuels, which typically require hydrogen to be produced. This positions hydrogen as a critical enabler in reducing industrial emissions while ensuring continuity in energy-intensive processes.

Hydrogen Overview

Hydrogen Production

There is a wide range of technologies available for hydrogen production, each relying on different feedstocks and processes, and resulting in distinct levels of associated emissions.

Electricity-based methods, primarily water electrolysis, do not generate direct greenhouse gas (GHG) emissions since they rely on splitting water into hydrogen and oxygen (green hydrogen). Nevertheless, their indirect emissions depend heavily on the carbon intensity of the electricity mix used to power the processes.

By contrast, fossil-based methods tend to have the highest direct emissions, as they rely on the reforming or breakdown of carbon-containing compounds. An exception is methane pyrolysis, which produces solid carbon rather than greenhouse gases (GHG), thereby avoiding direct emissions (grey hydrogen). Moreover, the integration of carbon capture and storage (CCS) with some of these fossil-fuel based processes has the theoretical potential to significantly reduce, or even eliminate, carbon emissions (blue hydrogen). However, these technologies remain at a low technology readiness level, as do most alternative hydrogen production methods currently under consideration.

Given that this work is centred on decarbonisation pathways, particular emphasis will be placed on green hydrogen produced via electrolysis, as it currently represents the most mature and readily deployable technology for large-scale low-carbon hydrogen production worldwide.

Hydrogen Transport and Storage

The primary challenge in hydrogen transport arises from its very low volumetric energy density. In practical terms, this means that to move the same amount of energy as natural gas, hydrogen requires either much larger storage volumes or pipelines capable of handling substantially 3 times higher volumetric flows.

Having established that hydrogen's low volumetric energy density represents the principal economic challenge in its transport, it is useful to briefly outline the main transport pathways available. Broadly, hydrogen can be moved as compressed gas, as liquefied hydrogen, or in the form of chemical carriers such as ammonia or liquid organic hydrogen carriers (LOHCs) (European Commission 2021).

For compressed or liquefied hydrogen, the gas is stored either in pressurised cylinders or in cryogenic tanks and transported via truck, ship, or rail (Hydrogen Europe 2017). The choice between compression and liquefaction is strongly context-dependent and hinges on factors such as the quantity of hydrogen to be transported, the transport distance, and the trade-off between processing costs (compression or liquefaction energy requirements and costs) and the logistics of additional transport capacity (more trucks, ships, or tanks).

Pipeline transport is regarded as a very effective option for delivering hydrogen, offering efficiency and scalability once the infrastructure is in place. With two main approaches in play, the construction of dedicated hydrogen pipelines or the retrofitting of existing natural gas infrastructure, both do involve substantial upfront investment costs, making them unfeasible short term. As a side note, due to its lower volumetric energy density, hydrogen requires roughly three times the volumetric flow of natural gas to deliver the same amount of energy. This has important implications for pipeline design and capacity planning in the longer term, as well as for retrofitting existing pipelines.

However, an alternative approach is the injection of hydrogen into existing natural gas networks, where blends of up to 20% hydrogen by volume are considered technically feasible without major modifications (DNV 2022). This strategy can provide an immediate, lower-cost pathway for integrating hydrogen into energy systems and probably the best method to jumpstart the hydrogen supply chain.

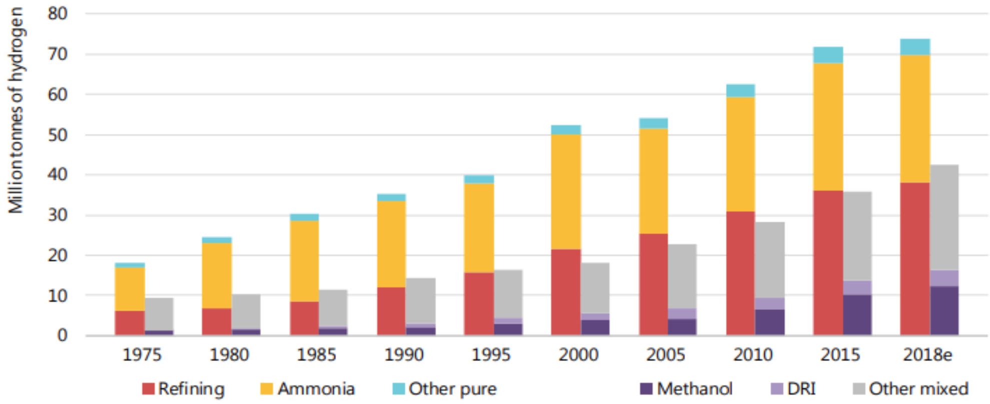
Current Hydrogen Demand and Main Consumption Sectors

Having discussed how hydrogen is produced, transported, and stored, this section now turns to hydrogen's current demand, major consumption sectors, and use cases.

From a global perspective, hydrogen demand has historically been used primarily in intermediate processes to produce higher-value compounds, materials, and products. On average, around 70 Mt of pure hydrogen are consumed annually, primarily in oil refining and ammonia production. In addition, approximately 45 Mt of hydrogen are used without prior separation from other gases in industrial processes such as direct reduced iron (DRI) production, methanol synthesis, and other chemical transformations (IEA 2019).

Figure 1 illustrates the historical evolution of global hydrogen demand between 1975 and 2018. The data show a clear upward trend in hydrogen consumption within these established sectors. Considering the growing momentum of global decarbonization policies, as well as energy security strategies, it is likely that hydrogen consumption will continue to expand beyond these established applications in the years ahead.

Figure 1. *Global Hydrogen Demand - Pure Hydrogen on the Left Column, Hydrogen Mixed with Other Gases on the Right Column (IEA 2019)*



The graph in Figure 1 also provides insight into the global sectoral distribution of hydrogen consumption, with oil refineries representing the largest share. In refineries, hydrogen is primarily used in processes that upgrade heavy residual fractions from crude oil distillation into higher-value products, thereby improving overall refinery yields. These processes will be described in more detail in the subsequent sections. While global decarbonization policies suggest a gradual reduction in oil refining activities, hydrogen demand in this sector is expected to remain relatively stable in the near term. Given its existing large-scale infrastructure and hydrogen use, the refining sector is strategically positioned to play a significant role in supporting the transition towards a green hydrogen economy.

Following oil refining, ammonia production constitutes the second largest global consumer of hydrogen. Ammonia is produced by combining hydrogen and nitrogen, and it plays a critical role in several industrial value chains. Its primary use is in the manufacture of fertilizers for agriculture, but it is also an essential precursor for the synthesis of various chemical compounds and is employed in the production of cleaning products and agents. This wide range of applications underscores ammonia's strategic importance to both global industry and the broader economy.

Methanol also accounts for a significant share of global hydrogen consumption. As a simple alcohol, methanol is a critical intermediate in the chemical industry. It serves as the primary feedstock to produce formaldehyde, which in turn underpins the manufacture of plastics, paints, coatings, adhesives, and polymer fibres used in textiles. In addition, methanol is a precursor for a range of pharmaceuticals, including antibiotics and vitamins, as well as certain agrichemicals, highlighting its broad industrial relevance.

The steel sector likewise represents a major consumer of hydrogen, primarily through the Direct Reduced Iron (DRI) process. This method reduces iron oxides ("iron ores") to metallic iron using a reducing agent (DNV 2022), which can be coke or a syngas mixture containing hydrogen. This process will be further discussed in subsequent sections.

These processes and sectors are particularly relevant for scaling up the green hydrogen economy, as the actors already integrated into the existing hydrogen value chain are best positioned to drive its transition. By adapting their operations, these established players can play a pivotal role in steering the hydrogen value chain towards green hydrogen.

Hydrogen Value Chain and Future Use Cases

While the current hydrogen value chain remains carbon-intensive (IEA 2019) hydrogen is well positioned to become a key enabler of global decarbonization. A first and immediate step would be the transition from grey or black/brown hydrogen to green hydrogen.

Beyond production, hydrogen also presents opportunities to address other hard-to-abate sectors, including high-temperature industrial processes and segments of the transport sector, where alternative decarbonization solutions are limited.

Starting with heat, hydrogen is expected to play a central role in the decarbonization of high-temperature industrial processes, where direct electrification is either technically unfeasible or economically prohibitive (DNV 2022). In this context, hydrogen could replace coal and natural gas, contributing not only to emissions reduction but also to energy sovereignty. However, such a transition would require substantial infrastructure investments, significant changes in national energy mixes, and the adaptation or replacement of equipment currently designed for coal or natural gas. A more cautious perspective suggests that this transformation will be gradual. However, as previously noted, the blending of hydrogen into existing natural gas infrastructure represents should be feasible in the near-term.

In the mobility sector, hydrogen also presents compelling opportunities, particularly for the decarbonization of heavy transport (DNV 2022). Although hydrogen technologies generally display lower energy efficiency compared to direct electrification, hydrogen possesses a higher gravimetric energy density than currently available battery solutions. This advantage is particularly relevant in shipping, aviation, and long-haul trucking, where minimizing weight and maximizing cargo space are critical for economic viability.

There is a considerable potential for hydrogen in the decarbonization process of the economy. Nevertheless, it is clear that the initial steps should prioritize applications where hydrogen is already in use, thereby enabling a smoother substitution of fossil-based hydrogen with its green counterpart, as well as the introduction of it in current natural infrastructures in concentrations that will only require minimal or no rectifications.

Methodology

Data and Methodology

Having established that the first steps for the implementation of green hydrogen in the economy involve (i) the substitution of fossil fuel–derived hydrogen with its green counterpart and (ii) the blending of hydrogen into the natural gas grid for high-temperature industrial applications, this forms the starting point for the present paper. Accordingly, this section outlines the data sources and methodological framework adopted for the analysis.

Since the focus of this work is the Portuguese industrial sector, the initial step was to identify the subsectors most relevant for assessment. These were defined either by (i) their direct use of hydrogen, or the presence of players that could adopt hydrogen as feedstock in production processes, or (ii) their reliance on high-temperature heat inputs that cannot be easily substituted through electrification. Based on these criteria, the following subsectors were selected: Cement and lime, Ceramics, Metallurgy, Chemicals and polymers, Refineries and Glass.

Other subsectors, including pulp and paper, food, tobacco, and textiles, are also of considerable importance within the Portuguese industrial landscape. However, their processes generally lack direct applications for hydrogen, and their heat requirements remain below 200 °C, making electrification a more suitable and cost-effective decarbonization solution.

With the industrial subsectors of interest defined, the next step is to conduct a detailed analysis of each sector. This begins with a brief characterization of the sector within Portugal, followed by the identification of the largest and most influential players. To achieve this, two primary databases were consulted:

Verified carbon emissions per industrial unit in Portugal, made available by the European Emissions Trading System (ETS).

Sabi Informa, for any financial information deemed relevant to determine each player's market relevance, as well as location and other data points.

Once the sectors and their key players are characterized, the subsequent step involves mapping the locations of their industrial units and compiling their annual carbon emissions (made available by ETS). Building on this, the analysis then identifies the main industrial processes that either currently consume hydrogen directly or could potentially do so through high-temperature energy requirements.

Having identified both existing and potential hydrogen-consuming players, their annual hydrogen demand potential was estimated through two complementary approaches:

1. Directly using data on annual hydrogen consumption when such information was made available by companies.
2. Estimating hydrogen demand potential through the use of other data points and derived equations.

The outcome of this stage is the calculation of hydrogen demand potential per player and per district within each industrial subsector.

Finally, the results from all subsectors are aggregated to construct a comprehensive spatial mapping of hydrogen demand potential across the Portuguese industrial sector. This geographical representation provides a visual understanding of regional variations in hydrogen consumption and their implications for the siting of hydrogen production facilities, as well as for the broader hydrogen value chain and its potential synergies.

Hydrogen Consumption Potential for High Heat Applications Based on Carbon Emissions

As previously discussed, blending hydrogen into the natural gas grid represents one of the most practical entry points for introducing hydrogen into the industrial sector. Accordingly, this section begins by outlining the methodology used to estimate the potential hydrogen consumption in a natural gas–hydrogen blend, compared to the exclusive use of natural gas.

Building on the upper limit of a 20% hydrogen admixture by volume (as noted earlier), three blending scenarios are considered in this work: 5%, 10%, and 20%. These scenarios allow for the assessment of how different blending ratios influence the potential hydrogen demand across the industrial subsectors under analysis. It is important to emphasize that many of the industrial processes considered in subsequent sections rely on natural gas combustion, and thus the methodology presented here is broadly applicable.

To begin, the heat generated by burning natural gas (NG) must be equal to the heat generated by burning the natural gas–hydrogen mixture (mix), as stated in Eq. 1.

$$Q_{NG} = Q_{mix} \qquad \text{Eq. 1}$$

where Q refers to heat in kWh.

Heat is determined by the product of the lower heating value (LHV) of each fuel and its respective mass, as shown in Eq. 2. The LHV is used instead of the higher heating value (HHV), as the industrial processes under consideration cannot recover the latent heat of water condensation.

$$LHV_{NG} \times m_{NG} = LHV_{mix} \times m_{mix} \qquad \text{Eq. 2}$$

where LHV is the low heating value in kWh/kg and m is mass in kg.

The low heating value of the mixture (LHV_{mix}) is determined by the mass fraction of each component, as given in Eq. 3.

$$LHV_{mix} = LHV_{H_2} \times w_{H_2} + LHV_{NG} \times w_{NG} \qquad \text{Eq. 3}$$

The mass fraction of hydrogen (w_{H_2}) is derived from the density (ρ) in kg/Nm^3 and the volume fraction (X) of each component, as expressed in Eq. 4. The hydrogen volume fractions considered in this work are 5%, 10%, and 20%.

$$w_{H_2} = \frac{\rho_{H_2} X_{H_2}}{\rho_{H_2} X_{H_2} + \rho_{NG} X_{NG}} \qquad \text{Eq. 4}$$

Once the hydrogen mass fraction is determined, the total mixture mass (m_{mix}) can be computed, as shown in Eq. 5.

$$m_{mix} = \frac{m_{H_2}}{w_{H_2}} \qquad \text{Eq. 5}$$

By reverting to Equation 1, the potential hydrogen mass can then be determined using Eq. 6.

$$m_{H_2} = \frac{LHV_{NG}}{LHV_{mix}} m_{NG} \times w_{H_2} \qquad \text{Eq. 6}$$

Up to this stage, the method determines the hydrogen mass in a mixture relative to the total mass of natural gas. However, it became evident during this research that few industrial players disclose their yearly natural gas consumption. Instead, the European Emissions Trading System (ETS) provides verified annual carbon emissions per industrial unit, which can be used to estimate natural gas consumption through stoichiometric analysis, assuming natural gas properties correspond to methane (which constitutes approximately 90% of natural gas in Portugal), Eq. 7.

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \qquad \text{Eq. 7}$$

From Eq. 7, the natural gas mass can be estimated as shown in Eq. 8.

$$m_{NG} = m_{CH_4} = \frac{M_{CH_4}}{M_{CO_2}} \times m_{CO_2} \qquad \text{Eq. 8}$$

where M_{CH_4} is the molar mass of methane in (kg/mol), M_{CO_2} is the molar mass of carbon dioxide in (kg/mol), m_{CO_2} is the carbon dioxide emissions in kg.

Table 1 includes the considered values for the methodology explained above.

Table 1. *Natural Gas, Hydrogen and Carbon Dioxide Properties*

	LHV (kWh/kg)	ρ (kg/Nm^3)	M (kg/mol)
Natural gas (CH_4)	13.19	0.66	16.05
Hydrogen	33.33	0.089	-
Carbon dioxide	-	-	44.01

The methodology outlined above provides the basis for estimating hydrogen consumption potential in natural gas–hydrogen blends across natural gas combustion-based industrial processes, under the different blending scenarios considered.

As a side note, the European Emissions Trading System (ETS) is a carbon trading mechanism under which industrial players receive a limited number of free emission allowances. When emissions exceed this allowance, companies must purchase additional credits (European Commission n.d.).

Industrial Sectors Overview and Methodology

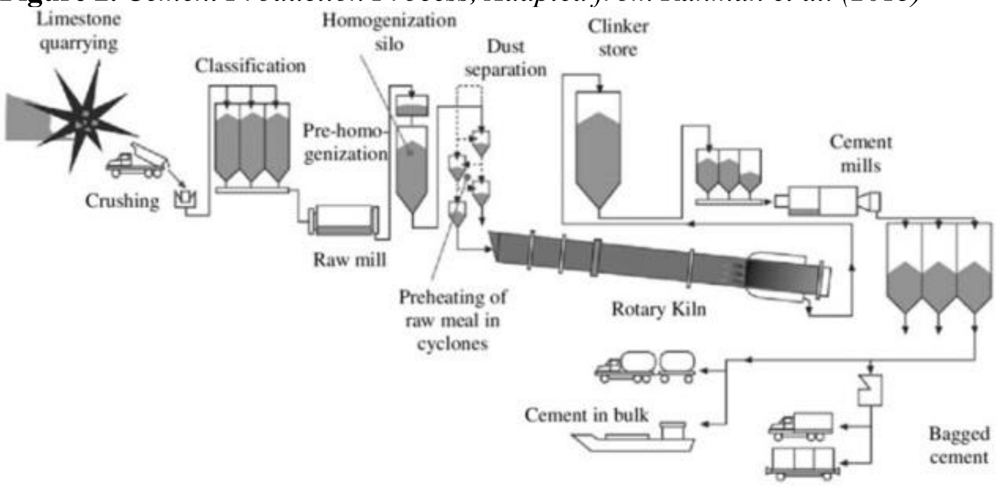
Cement and Lime Methodology

The Portuguese cement and lime sector is characterised by a high level of market concentration, with two major groups, Cimpor and SECIL, dominating production and sales. Their portfolios encompass a wide array of products, though cement production remains the main focus. Beyond these two groups, Lusical (a subsidiary from Lhoist Group) and Calcidrata also hold a degree of relevance, particularly in more specialised niches of quicklime and other similar products.

The cement manufacturing process is broadly similar across these players. It begins with the preparation of a raw material mixture composed predominantly of limestone, which is crushed and ground into a fine powder. This mixture is then processed in a rotary kiln at very high temperatures, where it is transformed into clinker, the key intermediate in cement production. Clinker is primarily composed of quicklime (calcium oxide), silica, alumina, iron oxides, and minor constituents. After cooling, clinker is blended with gypsum and other additives such as limestone filler, fly ash, slag, or calcined clay, before being ground into the final cement powder. Figure 2 illustrates the main stages of this process.

Although Calcidrata does not directly produce cement, its production of quicklime and related derivatives follows a broadly similar process, whereby raw materials are ground and subsequently processed in rotary kilns under high-temperature conditions.

Figure 2. *Cement Production Process, Adapted from Rahman et al. (2013)*



Within the cement and lime production process, the rotary kiln stage represents the primary opportunity for hydrogen integration. This stage is highly energy-intensive, requiring temperatures of approximately 1 450°C (Cimpor 2023). Traditionally, these kilns are fired using coke or petroleum coke, which are preferred due to their high flame emissivity (Akhtar et al. 2016). Nonetheless, rotary kilns are known for their flexibility in fuel usage, and many companies have already begun incorporating alternative fuels into their energy mix to reduce overall carbon emissions, such as natural gas, biomass, and other substitutes.

For the purposes of this work, the fuel considered for kiln operation is assumed to be a mixture of coke combined with natural gas and hydrogen. Specifically, the model adopts a fuel blend consisting of 70% coke and 30% natural gas, with hydrogen introduced into the natural gas stream at blending levels of 5%, 10%, and 20%, as described previously. This approach is informed by findings published in the IEEE Transactions on Industry Applications journal (Akhtar et al. 2016), which indicate that natural gas can replace powdered coal (or coke) at a thermal substitution rate of up to 30% without compromising kiln performance. Furthermore, it is assumed that blending hydrogen into the natural gas stream at concentrations of up to 20% does not significantly alter flame characteristics, thus maintaining process stability.

To estimate the potential hydrogen consumption in cement and lime plants, the first step is to determine the production mass of clinker or quicklime. This is achieved using Eq. 9, which divides the total reported CO_2 emissions, in tons, (m_{CO_2}) by the specific emissions of CO_2 per ton of product (t CO_2/t product). Emissions data are available through the ETS database, while company annual reports provide the specific emissions factors.

$$\frac{m_{CO_2}}{Specific\ emissions} = Production\ mass \qquad \text{Eq. 9}$$

Annual reports also supply the specific thermal energy required per ton of product. Given the earlier assumption that the natural gas and hydrogen blend accounts for 30% of total kiln energy requirements, the corresponding heat demand (Q_mix) can be estimated using Eq. 10.

$$Q_{mix} = Production\ mass\ X\ Specific\ thermal\ energy\ X\ 0{,}3 \qquad \text{q. 0}$$

These metrics are made available by each companies' annual reports. Blending methodology, enables the calculation of potential hydrogen demand for each plant. The results are expressed as hydrogen consumption potential at both the company and district level within the cement and lime sector. It was applied sector-specific emissions benchmarks (following EU ETS guidelines and WBCSD/CSI protocols) to isolate process emissions ($CaCO_3 \rightarrow CaO + CO_2$, accounting for ~60% to 65% of raw cement plant emissions) from thermal energy emissions resulting from fuel combustion (~35% and 40%). Regarding to fuel mix adjustments, it was accounted for the existing fuel share (e.g., petcoke, coal, alternative waste fuels vs. natural gas) used in kiln burners to isolate direct natural gas replacement potential.

Ceramics Methodology

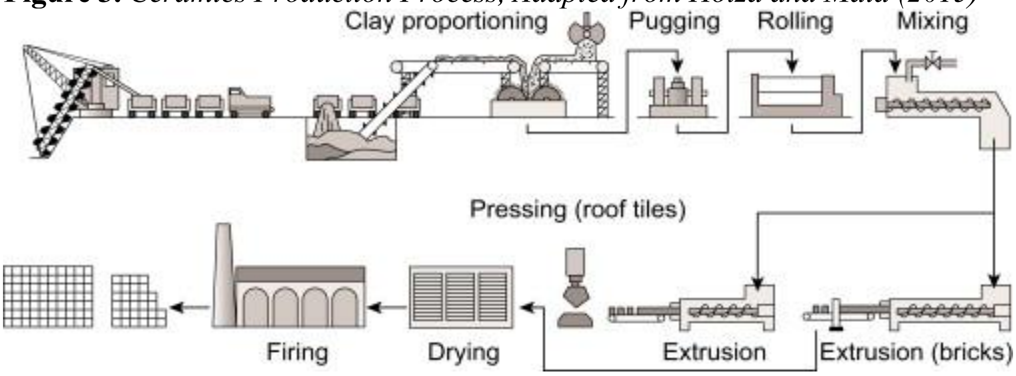
Portugal has a long-standing tradition in the production of ceramics, with an established industrial ecosystem that includes major players such as the Pavigrés Group, Preceram Group, Cinca Group, and Roca. In addition, globally recognized high-end brands such as Vista Alegre and Bordalo Pinheiro contribute to the country's reputation in this field. The sector is characterized by a high granularity of companies and production units, with a strong concentration along the western coast of Portugal, particularly in the districts of Leiria and Aveiro.

As in the cement and lime industry, the production processes within the ceramics sector are largely standardized, though variations exist in the final stages depending on the type of product. Distinctions arise from whether vitrification is required, the production is geared toward industrial applications at scale, or the focus is on smaller-batch, high-end goods for home décor and specialized markets.

In general terms, ceramic production begins with milling, where raw materials such as clay, feldspar, and silica are finely ground to achieve uniform particle size and consistency. This is followed by mixing, in which the raw materials are blended—often with water and additives like binders or plasticizers—to improve workability. The forming stage then shapes the ceramic body into its intended form, using methods such as pressing, extrusion, or slip casting and thermal treatment to dry the paste. The paste thermal consumption can achieve 60% of the total gas invested in the total process. Depending on the product, glazing may follow, coating the surface with a glassy layer that enhances both visual appeal and functional properties such as durability and water resistance. Finally, firing in a kiln at high temperatures sinters and densifies the material, imparting the strength, hardness, and mechanical properties required for end use.

While the general sequence of steps is consistent across the sector, the specific production scheme varies depending on the type of ceramic manufactured. Figure 3 illustrates this by presenting an example of roof tile production, where additional processes such as pugging and rolling are applied. These steps remove air from the clay mixture, ensuring homogeneity and an even texture, thereby offering a representative visual aid of a typical industrial production process.

Figure 3. *Ceramics Production Process, Adapted from Hotza and Maia (2015)*



In the Portuguese ceramics industry, natural gas is the dominant energy source, followed by electricity, which accounts for a comparatively small share of total consumption (DGEG 2021, APICER 2024). The firing stage represents the most energy-intensive step in the production process, where ceramic products are exposed to temperatures ranging from 800 ºC to 1 400 ºC (ISQ & APICER 2022). This step is critical to hardening the material into its final form and, therefore, presents the greatest potential for hydrogen integration as a substitute fuel, blended with natural gas.

Although detailed company-specific data on energy use was limited for the identified players, the European Emissions Trading System (ETS) database provided the information on carbon emissions for each industrial unit. Based on this dataset, the methodology outlined in Section 3.2 is applied to estimate hydrogen consumption potential. By starting from the reported emissions of each player and given that natural gas is the predominant energy source in the sector, it is possible to infer the corresponding natural gas consumption and, in turn, determine the hydrogen demand potential under different blending scenarios, using the eq. 8 and eq. 6 from the section 3.2.

It is worth noting that the use of oxygen, a by-product of hydrogen electrolysis, could also contribute to efficiency improvements in furnaces by enhancing combustion. However, this was not considered for the scope of this work.

Metallurgy Methodology

The Portuguese metallurgy sector is characterized by a high level of concentration, particularly in steel production. The country currently hosts only two steelmaking units, both operated by the Megasa Group, located in Seixal (Setúbal) and Gaia (Porto). Additionally, the Lusosider facility, situated in Seixal and owned by the Brazilian Companhia Siderúrgica Nacional (CSN), plays a significant role in flat steel production.

Green steel has emerged as a key driver for green hydrogen adoption worldwide. It is produced through Direct Reduced Iron (DRI) technology, which uses hydrogen as a reducing agent and an Electric Arc Furnace (EAF) for melting, thereby eliminating direct carbon emissions and relying solely on electricity and renewable hydrogen.

Beginning on the DRI process, iron is typically extracted in its natural form as forms of iron oxides (or "iron ore"), which in turn needs to be turned into metallic iron to be melted, and formed into the various products, structures and others, that has shaped the economies and society's evolution for millenniums. This means that the iron ore requires a reduction process to be turned into metallic iron, through the use of a reduction agent. This reduction agent, as previously mentioned is typically coke or a syngas mixture containing hydrogen, carbon monoxide and others. However, this agent can be solely hydrogen, which makes the base for green steel production, Eq. 11 shows the DRI reaction equation.

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \quad \text{Eq. 11}$$

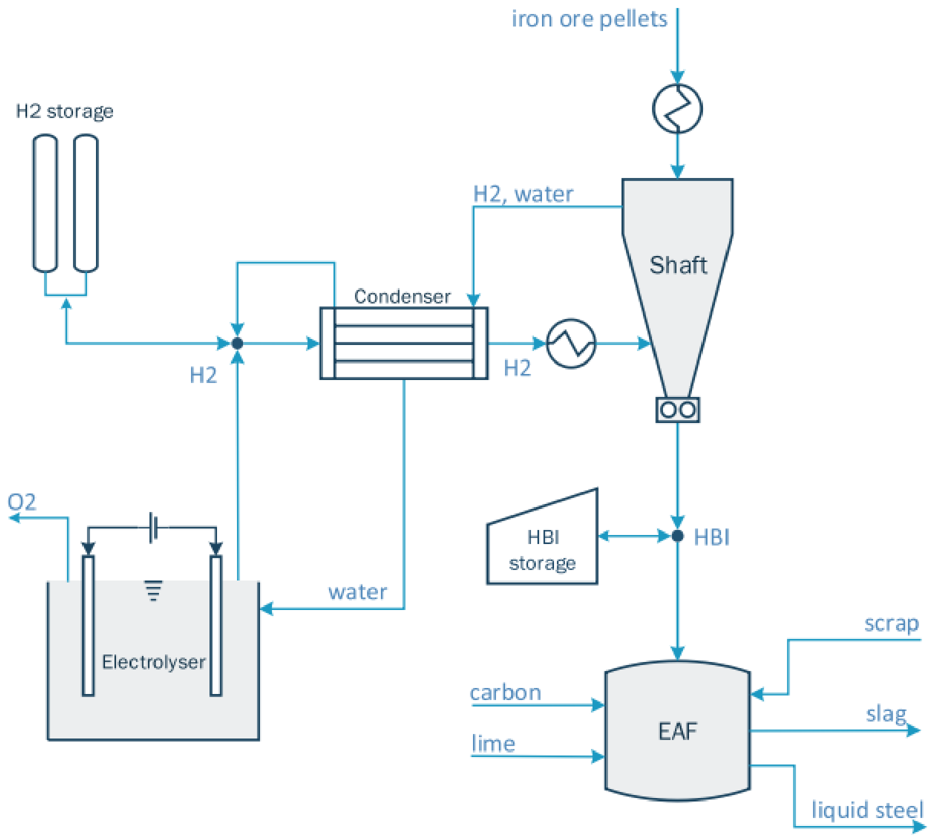
Stoichiometric analysis shows that approximately 54.2 kg of hydrogen are required per ton of steel produced.

Historically, Portugal operated a DRI process at Siderurgia Nacional do Seixal (now part of Megasa), which was decommissioned in 2001 (Machado 2012). Although the DRI process is not currently in use, its inclusion here is relevant, as domestic steel demand cannot be met solely with feedstock. The sector therefore retains significant potential for future hydrogen adoption, should DRI production be reintroduced. However, due to economic and operational constraints, this scenario is not considered within the scope of this work.

After the DRI the metallic iron is moved to an Electric Arc Furnace, which uses a high voltage powered electric arc to melt steel before it is formed into its final shape. This process makes use of steel's electric conductive properties to melt iron using solely with electricity, the alternative being natural gas or coke powered blast furnaces at high temperatures.

Figure **4** 4 provides a simple scheme of green iron production process, DRI followed by EAF.

Figure 4. *Iron Production Process, Adapted from Vogl et al. (2018)*



Currently, Megasa's Portuguese steel plants (Siderurgia Nacional do Seixal and Siderurgia Nacional de Maia) operate using Electric Arc Furnace (EAF) technology, primarily by melting recycled steel scrap.

Though DRI presents a large potential for the use of hydrogen, this process is no longer used in Portuguese steel production units, with metallic steel and recycled steel used directly in the Electric Arc Furnace, before shaping the steel into its final form. Furthermore, since the vast majority of steel produced in Portugal comes from recycled steel (84%-91%), the hydrogen consumption potential within DRI would be limited to the smaller share of non-recycled steel. Nonetheless, these industrial units continue to rely on natural gas furnaces for steel reheating processes (Megasa 2020), which opens an opportunity for hydrogen blending.

As such, to estimate hydrogen consumption potential, the methodology outlined in Section 3.2 is applied, using emissions data from Megasa's annual reports and the European Emissions Trading System (ETS) tables. Based on the reported CO_2 emissions and considering that natural gas is the primary fuel source, it is possible to infer natural gas consumption and, consequently, hydrogen demand under different blending scenarios.

Lastly, in the case of Lusosider, hydrogen potential lies primarily within its annealing furnace, which operates on natural gas. Therefore, similar to Megasa, hydrogen will be considered as a blended fuel substitute in this stage of production.

Chemical and Polymers Methodology

The chemical sector in Portugal is mainly focused on petrochemicals and fertilizers, with most of its players based on two major industrial clusters in Setúbal (Sines) and Aveiro (Estarreja). These clusters represent the backbone of the national chemical sector, hosting key players involved in the production of base chemicals, polymers, fertilizers, and related derivative products.

These clusters are strategically located near the country's largest shipping ports, such as the Aveiro port and the Sines deep-water port, ensuring efficient access to raw materials and global trade. Furthermore, these clusters are positioned not only for logistical advantages but also to maximize synergies between industry players that comprise them, as explained below in further detail.

Although on a smaller scale, Lisbon and Setúbal also host notable chemical production facilities, including ADP Fertilizantes and Solvay's soda ash plant. While these units are not part of a dedicated chemical cluster, they nonetheless benefit from proximity to other heavy industrial operations, such as Cimpor in Lisbon and Siderurgia Nacional (Megasa) in Seixal, enabling local synergies in energy use and logistics.

Unlike the other sectors analysed in this study, the chemical and polymers sector is characterized by a high degree of process and product diversity, encompassing a wide array of industrial operations. Due to this complexity, the analysis will focus specifically on the direct utilization of hydrogen as a feedstock, as well as on its potential mixture with natural gas for high-temperature heat applications exceeding 200 °C, as previously outlined.

Considering these criteria, five key industrial players have been identified for this assessment, either due to their direct hydrogen consumption or their relevant high-temperature heat demand within the Portuguese chemical and polymers sector: ADP Fertilizantes, Dow Portugal, Bondalti, Foresa (Bresfor) and Repsol Polímeros.

Given the high temperature ranges involved in the industrial processes used within these players facilities, the method explained in Section 3.2. will be used to determine the hydrogen consumption potential.

Refineries Methodology

Galp is the sole oil refining company in Portugal, operating the country's sole active refinery, in Sines. Also, it is the owner of another refinery in Leça da Palmeira, which ceased production in 2021 and is currently going through a dismantling process.

Galp is also positioning itself as a key player in the green hydrogen sector, as it is currently leading one of the country's largest projects by integrating a 100 MW electrolyser into its Sines refinery, which will cover roughly 20% of the Refineries yearly production of grey hydrogen (Galp 2023). This initiative aims to enhancing the amount of green hydrogen used in its production process. Additionally, given that refineries are one of the biggest hydrogen consuming sectors globally, as stated previously in this work, players such as Galp can take a substantial part in driving the green hydrogen market.

The refining process transforms crude oil into various valuable hydrocarbons such as gasoline, naphtha, diesel, jet fuel, and lubricants, among others. Galp specifically begins this process in an atmospheric distillation unit, where crude oil is heated and separated into different fractions based on their boiling points. In this initial step, lighter fractions like gasoline and naphtha rise to the top of the distillation column, while heavier fractions such as diesel and residual oils settle at lower levels.

To maximize yield, the heavier residues from the atmospheric distillation unit undergo further treatment in a vacuum distillation unit. This process operates under reduced pressure, allowing the separation of heavier hydrocarbons at lower temperatures, thereby preventing thermal cracking and degradation of valuable molecules. The vacuum distillation process produces vacuum gas oil and vacuum residues, which, depending on their characteristics, are further processed in the following conversion units:

- Fluid Catalytic Cracking (FCC)
- Visbreaking
- Hydrocracking

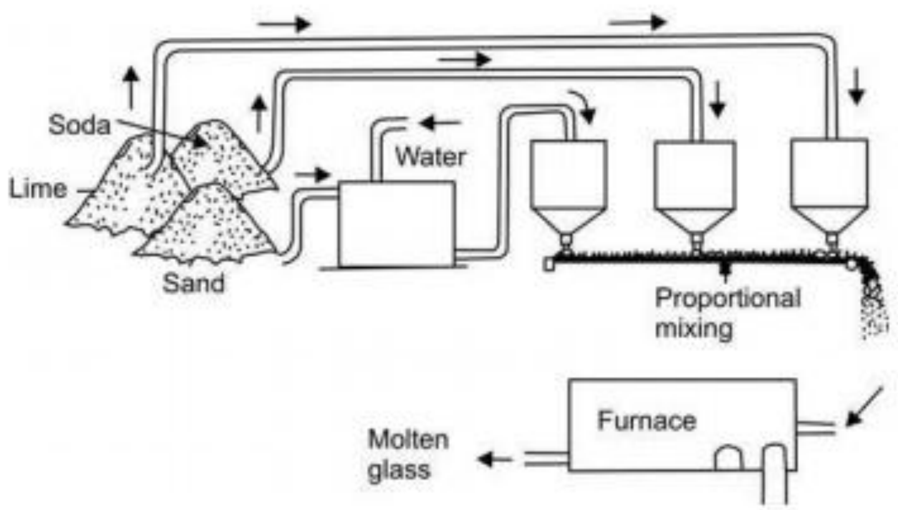
The greatest potential for hydrogen consumption within the refining process lies in the hydrocracking unit, given its direct reliance on hydrogen as a key input. Other processes, such as heating, are largely supplied through the use of the refinery’s own fuel products, and therefore hydrogen demand for heating is not considered in this work. Accordingly, the potential for hydrogen consumption in the refinery sector is determined through a direct approach based on data provided by the company consumption potential.

Glass Methodology

In Portugal, Marinha Grande stands out as the primary hub for glass production, concentrating leading industrial players such as BA Glass, Vidrala, and Crisal, alongside several smaller units. This industrial cluster brings together some of the sector's most significant operators and therefore represents strong potential for synergies in the development of hydrogen production and consumption strategies.

The glass production process begins with raw materials, primarily silica (sand), coming from Rio Maior Mine, limestone, soda ash, and other substances, that are combined as the base components. These inputs are introduced into a furnace where they undergo a high temperature melting process, typically ranging between 1400 °C and 1700 °C (D'Antonio et al. 2003). This stage, commonly referred to as the melting process, is the most energy-intensive, as it transforms the raw mixture into molten glass. Once liquefied, the molten glass is shaped using molds to form the desired products. Within this process, the highest potential for hydrogen substitution lies in the melting stage, given its extreme heat requirements and reliance on fossil fuels, namely natural gas that burns inside the furnace through a diffusion flame. Figure 5 provides a simplified scheme of the glass production process.

Figure 5. *Glass Production Process, Adapted from Rahman et al. (2013)*



Since hydrogen is not currently used directly in glass production processes, its potential integration is considered through its substitution of natural gas as a fuel in the melting stage. The use of pure oxygen and pure hydrogen are use um Crisal as a cutting premixture flame that allow the cutting of rotating glasses into the production process. This approach aligns with the sector's most energy-intensive step, where extremely high heat is required.

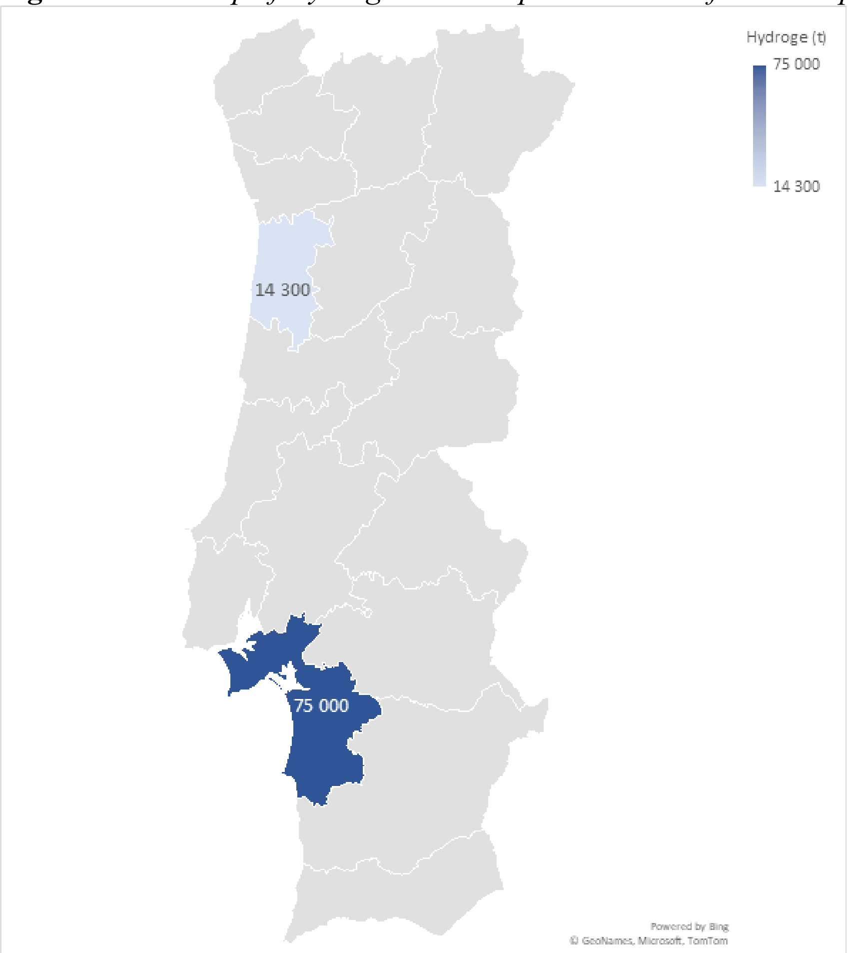
For this analysis, the emissions data of each industrial unit were collected through the EU ETS database. These values were then used to estimate the heat consumption of each player, following the methodology outlined in Section 3.2. By translating emissions into energy demand and applying the conversion factors previously described, the corresponding hydrogen consumption potential was determined.

It is important to note that the analysis focuses solely on the substitution of natural gas for hydrogen in the melting process. Other potential synergies, such as the use of oxygen (a by-product of hydrogen electrolysis) to enhance furnace efficiency, are acknowledged but remain outside the scope of this work, as mentioned is previous sections.

Uncertainty Analysis

We explicitly account for variations in the typical Portuguese natural gas grid composition (which contains between 88% and 95% methane, alongside ethane, propane, nitrogen, and CO_2). Through sensitivity analysis that approximating natural gas as pure methane introduces an estimated margin of error of less than ±3.5% in overall hydrogen replacement volumes, which falls well within the accepted bounds for macro-level sector screening studies.

Figure 6. *Heat Map of Hydrogen Consumption Potential for Heat Applications*



Results and Discussion

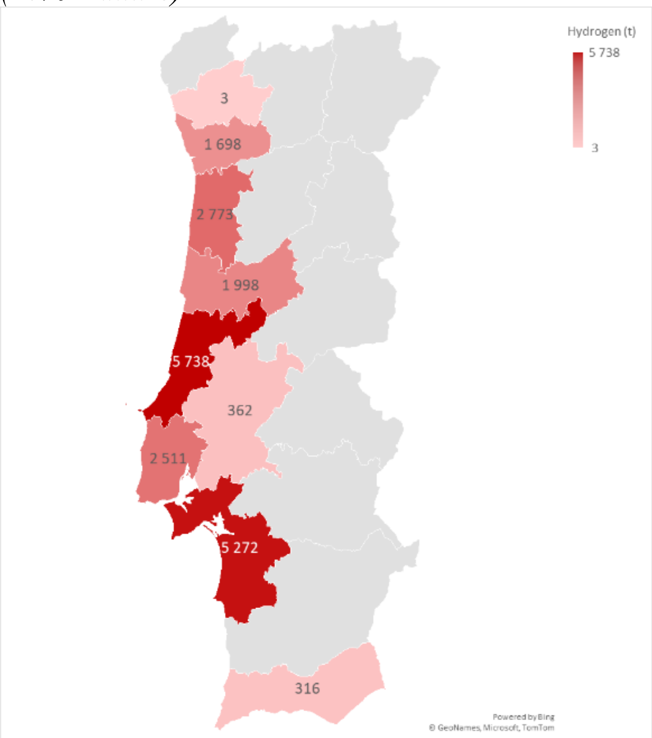
Map of Hydrogen Consumption Potential in Different Scenarios

To provide greater clarity and analytical depth, the following sections will present two separate consumption maps, one dedicated to direct feedstock use and another to hydrogen for high heat applications (at a 20% hydrogen mixture scenario).

Figure 6 presents a heat map illustrating Portugal's hydrogen consumption potential for direct feedstock applications. The districts of Setúbal and Aveiro emerge as the only regions currently displaying measurable potential, primarily due to the presence of Galp's Sines refinery and Bondalti's chemical production unit in Estarreja, respectively. Both industrial facilities already rely on hydrogen as a key feedstock in their production processes, as detailed in the previous section. Consequently, these two players stand out as strategic enablers of Portugal's future hydrogen economy, particularly given their ongoing initiatives to integrate green hydrogen production units within their operations.

Figure 7 shifts the analysis from direct feedstock use to heat applications, modelled as a 20% hydrogen mixture with natural gas. In this context, the district of Leiria emerges as the most significant contributor, with an estimated potential of 5.7 thousand tons of hydrogen per year. This dominance is largely attributed to its strong industrial base, particularly the glass production cluster, comprising two Vidrala units and one BA Glass facility, each accounting for roughly 1 thousand tons annually, alongside several ceramic manufacturers jointly representing approximately 1.3 thousand tons. In addition, the presence of three SECIL cement plants, collectively contributing around 700 tons, further reinforces Leiria's position as the leading district for hydrogen consumption in heat applications.

Figure 7. *Heat Map of Hydrogen Consumption Potential for Heat Applications (20% Mixture)*



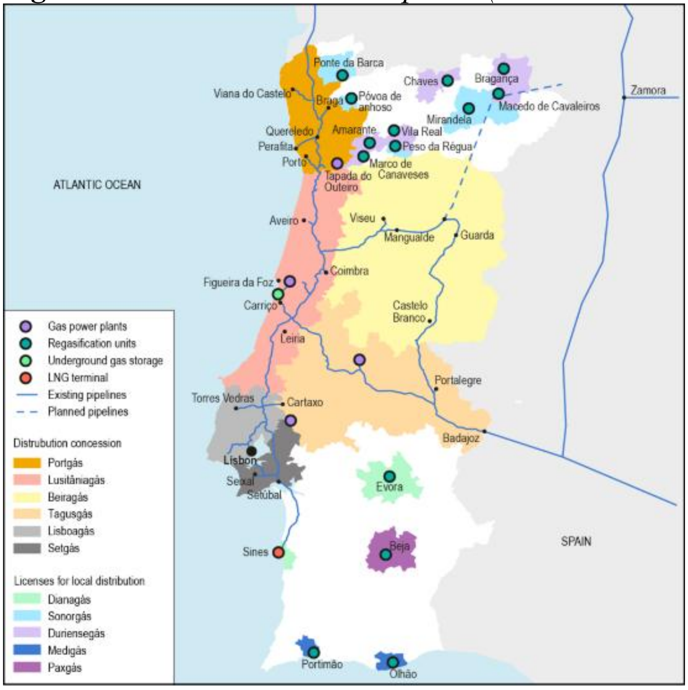
Setúbal follows closely with an estimated 4.4 thousand tons per year. Unlike Leiria, where consumption is spread across multiple industries, Setúbal's potential is more concentrated, primarily driven by Repsol Polímeros, with about 2.8 thousand tons, and a SECIL cement plant, contributing approximately 1.1 thousand tons annually.

In Aveiro, the potential reaches 2.8 thousand tons per year, reflecting a combination of smaller ceramics facilities and the influence of the Estarreja chemical cluster, as previously discussed. Similarly, Lisbon (2.5 thousand tons) and Coimbra (1.9 thousand tons) exhibit comparable demand structures, each characterized by a cement plant and a major glass production unit. In Lisbon, this corresponds to Cimpor's cement plant (1.2 thousand tons) and a BA Glass facility (0.9 thousand tons), whereas in Coimbra, demand arises from another Cimpor plant (1.1 thousand tons) and a Verallia glass unit (0.7 thousand tons).

An important aspect regarding heat applications lies in the geographical alignment of industrial demand with existing energy infrastructure. As shown in Figure 8, the main industrial consumers identified in this analysis are located along REN's natural gas transmission pipeline. This spatial correspondence suggests that, with limited infrastructure adaptation, hydrogen blending (up to 20% by volume) could be progressively introduced into the existing network, thereby facilitating a smoother transition towards hydrogen-based heat generation.

It is also important to note that blending up to 20 per cent hydrogen may present significant challenges in terms of adapting the infrastructure; issues relating to combustion dynamics, NOx emissions, and aspects associated with safety and the materials used in burners are beyond the scope of this article. However, it is important to note that methane blends containing 20% hydrogen, increase in laminar burning velocity and its potential to induce flashback in standard atmospheric burners (Zhang et al. 2009, Yang et al. 2025, Schefer et al. 2002). The elevated flame temperatures resulting from hydrogen addition and the corresponding need for low-NOx burner designs or flue gas recirculation (Glarbord et al. 2018, Nemitallah et al. 2024, Schwarz et al. 2024). Hydrogen embrittlement in pipelines, seal degradation, purging protocols, and lower explosive limit (LEL) shifts (Melaina et al. 2013, Briottet et al. 2012, De Vries et al. 2017, Lowesmith et al. 2009).

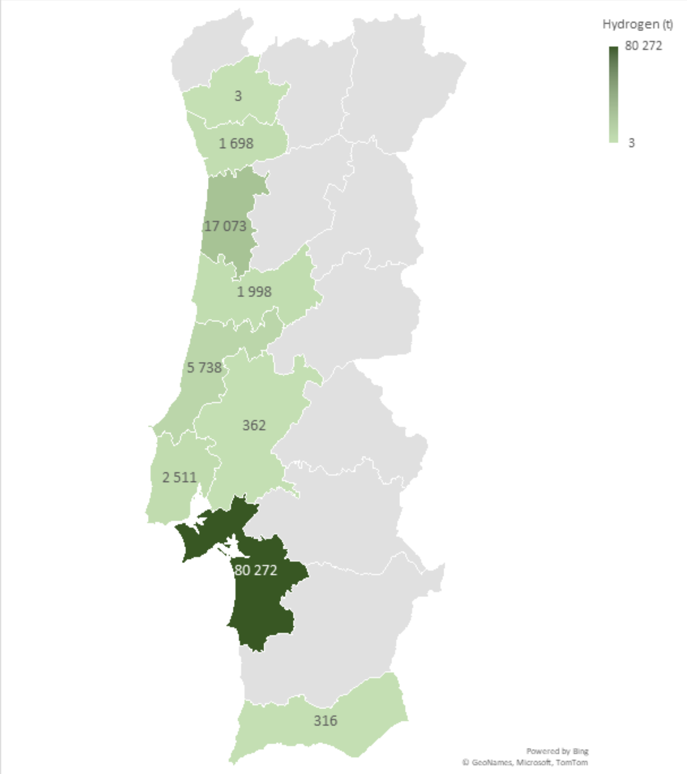
Figure 8. *REN's Natural Gas Pipeline (Gás é Andar Para Trás (n.d.))*



Nevertheless, several technical and economic challenges persist. Factors such as the cost of hydrogen, its effects on combustion processes and material integrity, and the operational implications for the natural gas grid require careful consideration. Despite these challenges, the geographical overlap between hydrogen demand and existing gas infrastructure represents a solid foundation for the development of an integrated green hydrogen economy in Portugal.

To conclude this section, Figure 9 presents a combined heat map integrating both direct feedstock and heat applications, providing a comprehensive overview of Portugal's hydrogen consumption potential across the industrial landscape. The results indicate that, in the early stages of deployment, hydrogen demand should be primarily driven by Galp's refinery in Sines and Bondalti's chemical complex in Estarreja, both of which already rely on hydrogen as a key feedstock in their industrial processes. These existing hydrogen users represent natural starting points for the introduction of green hydrogen into the Portuguese industrial system.

Figure 9. *Heat Map of Hydrogen Consumption Potential*



Together, these two demand profiles define the initial framework for the emergence of a Portuguese green hydrogen economy within the industrial sector, balancing technological readiness with gradual infrastructure adaptation.

Table 2. *Hydrogen Consumption Potential (Tonnes) in Portugal Considering Different Hydrogen Mixing Scenarios*

	H_2 Potential 5%	H_2 Potential 10%	H_2 Potential 20%	Direct feedstock
Hydrogen (t)	4 584	9 527	20 671	89 300

As summarized in Table 2, direct feedstock applications represent the largest potential source of hydrogen demand, highlighting their pivotal role in driving the first phase of green hydrogen integration in Portugal.

Conclusions

At an early stage, the introduction of green hydrogen into the Portuguese industrial sector could build upon two complementary demand paths, direct feedstock applications, estimated at around 89 thousand tons of hydrogen per year, concentrated mainly in two key industrial players (Galp and Bondalti), and heat applications, ranging from 4.5 to 20.6 thousand tons per year when blended with natural gas. Together, these two routes represent the foundation for hydrogen integration within Portugal's industrial landscape.

These findings suggest two viable implementation strategies. The first is a centralized approach, achieved through the injection of hydrogen into the national natural gas grid, enabling its gradual adoption across multiple sectors. The second is a decentralized approach, based on on-site hydrogen production and consumption by major industrial players, particularly those already identified in this study.

Among these, Galp and Bondalti stand out as the main early adopters. Both companies have initiated green hydrogen projects, yet these currently address only a fraction of their total hydrogen requirements, as large-scale investments remain contingent on economic feasibility and global market competitiveness. Nonetheless, these initiatives mark essential steps toward reducing fossil fuel dependence and enhancing Portugal's energy sovereignty.

Given that industrial transformation requires significant time and process adaptation, coordination among major industrial stakeholders will be crucial. Fortunately, the Portuguese industrial structure, characterized by high concentration and a limited number of large players, could facilitate such alignment, promoting collaborative progress toward hydrogen-based decarbonization.

For heat applications, the existing natural gas infrastructure provides a technical foundation for hydrogen blending, although economic and operational challenges, including blending limits, process compatibility, and cost competitiveness, must still be addressed.

Overall, the gradual implementation of green hydrogen offers a realistic and strategic pathway for industrial decarbonization in Portugal. As hydrogen demand scales up, production volumes could help reduce total hydrogen costs, fostering wider adoption. However, this progress will depend heavily on the availability and affordability of renewable electricity, since electrolysis remains an energy-intensive process. Strengthening renewable generation capacity, therefore, is a prerequisite for achieving a sustainable and economically viable green hydrogen economy.

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