

Assessment of the potential consumption of green hydrogen in the Portuguese industrial sector as a direct feedstock for high heat applications

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 dissertation 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 [1].

This thesis focuses on the industrial sector, which is the second-largest energy-consuming sector in Portugal, following transport. Despite transport holding the highest overall consumption [2], 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.

1 Furthermore, industrial processes that require high-temperature heat, above
2 200 °C, present a particular challenge for decarbonization. At present, there are
3 no widely available alternatives to fossil fuels for such applications, aside from
4 carbon-free hydrogen or carbon-free synthetic fuels, which typically require
5 hydrogen to be produced. This positions hydrogen as a critical enabler in
6 reducing industrial emissions while ensuring continuity in energy-intensive
7 processes.

10 **Hydrogen Overview**

12 *Hydrogen production*

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

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

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

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

36 *Hydrogen transport and storage*

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

43 Having established that hydrogen's low volumetric energy density
44 represents the principal economic challenge in its transport, it is useful to briefly
45 outline the main transport pathways available. Broadly, hydrogen can be moved

1 as compressed gas, as liquefied hydrogen, or in the form of chemical carriers
2 such as ammonia or liquid organic hydrogen carriers (LOHCs) [3].

3 For compressed or liquefied hydrogen, the gas is stored either in pressurised
4 cylinders or in cryogenic tanks and transported via truck, ship, or rail [4]. The
5 choice between compression and liquefaction is strongly context-dependent and
6 hinges on factors such as the quantity of hydrogen to be transported, the transport
7 distance, and the trade-off between processing costs (compression or
8 liquefaction energy requirements and costs) and the logistics of additional
9 transport capacity (more trucks, ships, or tanks).

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

19 However, an alternative approach is the injection of hydrogen into existing
20 natural gas networks, where blends of up to 20% hydrogen by volume are
21 considered technically feasible without major modifications [5]. This strategy
22 can provide an immediate, lower-cost pathway for integrating hydrogen into
23 energy systems and probably the best method to jumpstart the hydrogen supply
24 chain.

25 26 *Current hydrogen demand and main consumption sectors*

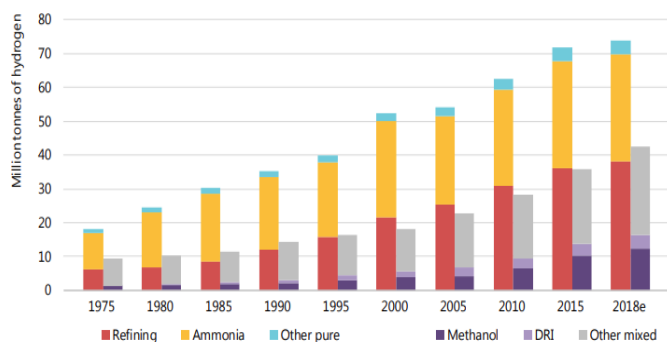
27
28 Having discussed how hydrogen is produced, transported, and stored, this
29 section now turns to hydrogen's current demand, major consumption sectors,
30 and use cases.

31 From a global perspective, hydrogen demand has historically been used
32 primarily in intermediate processes to produce higher-value compounds,
33 materials, and products. On average, around 70 Mt of pure hydrogen are
34 consumed annually, primarily in oil refining and ammonia production. In
35 addition, approximately 45 Mt of hydrogen are used without prior separation
36 from other gases in industrial processes such as direct reduced iron (DRI)
37 production, methanol synthesis, and other chemical transformations [6].

38 **Error! Reference source not found.** illustrates the historical evolution of
39 global hydrogen demand between 1975 and 2018. The data show a clear upward
40 trend in hydrogen consumption within these established sectors. Considering the
41 growing momentum of global decarbonization policies, as well as energy
42 security strategies, it is likely that hydrogen consumption will continue to expand
43 beyond these established applications in the years ahead.

1

2 **Figure 1.** *Global Hydrogen demand - pure hydrogen on the left column,*
 3 *hydrogen mixed with other gases on the right column [6]*



4

5

6 The graph in **Error! Reference source not found.** also provides insight into
 7 the global sectoral distribution of hydrogen consumption, with oil refineries
 8 representing the largest share. In refineries, hydrogen is primarily used in
 9 processes that upgrade heavy residual fractions from crude oil distillation into
 10 higher-value products, thereby improving overall refinery yields. These
 11 processes will be described in more detail in the subsequent sections. While
 12 global decarbonization policies suggest a gradual reduction in oil refining
 13 activities, hydrogen demand in this sector is expected to remain relatively stable
 14 in the near term. Given its existing large-scale infrastructure and hydrogen use,
 15 the refining sector is strategically positioned to play a significant role in
 16 supporting the transition towards a green hydrogen economy.

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

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

32 The steel sector likewise represents a major consumer of hydrogen,
 33 primarily through the Direct Reduced Iron (DRI) process. This method reduces
 34 iron oxides ("iron ores") to metallic iron using a reducing agent [5], which can
 35 be coke or a syngas mixture containing hydrogen. This process will be further
 36 discussed in subsequent sections.

37 These processes and sectors are particularly relevant for scaling up the green
 38 hydrogen economy, as the actors already integrated into the existing hydrogen

1 value chain are best positioned to drive its transition. By adapting their
2 operations, these established players can play a pivotal role in steering the
3 hydrogen value chain towards green hydrogen.

4 5 *Hydrogen value chain and future use cases*

6
7 While the current hydrogen value chain remains carbon-intensive [6],
8 hydrogen is well positioned to become a key enabler of global decarbonization.
9 A first and immediate step would be the transition from grey or black/brown
10 hydrogen to green hydrogen.

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

15 Starting with heat, hydrogen is expected to play a central role in the
16 decarbonization of high-temperature industrial processes, where direct
17 electrification is either technically unfeasible or economically prohibitive [5]. In
18 this context, hydrogen could replace coal and natural gas, contributing not only
19 to emissions reduction but also to energy sovereignty. However, such a transition
20 would require substantial infrastructure investments, significant changes in
21 national energy mixes, and the adaptation or replacement of equipment currently
22 designed for coal or natural gas. A more cautious perspective suggests that this
23 transformation will be gradual. However, as previously noted, the blending of
24 hydrogen into existing natural gas infrastructure represents should be feasible in
25 the near-term.

26 In the mobility sector, hydrogen also presents compelling opportunities,
27 particularly for the decarbonization of heavy transport [5]. Although hydrogen
28 technologies generally display lower energy efficiency compared to direct
29 electrification, hydrogen possesses a higher gravimetric energy density than
30 currently available battery solutions. This advantage is particularly relevant in
31 shipping, aviation, and long-haul trucking, where minimizing weight and
32 maximizing cargo space are critical for economic viability.

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

39

1 **Methodology**

3 *Data and Methodology*

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

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

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

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

- 29 • Verified carbon emissions per industrial unit in Portugal, made available
30 by the European Emissions Trading System (ETS)
- 31 • Sabi Informa, for any financial information deemed relevant to determine
32 each player's market relevance, as well as location and other data points

33
34 Once the sectors and their key players are characterized, the subsequent step
35 involves mapping the locations of their industrial units and compiling their
36 annual carbon emissions (made available by ETS). Building on this, the analysis
37 then identifies the main industrial processes that either currently consume
38 hydrogen directly or could potentially do so through high-temperature energy
39 requirements.

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

- 44 1. Directly using data on annual hydrogen consumption when such
45 information was made available by companies

1 2. Estimating hydrogen demand potential through the use of other data
2 points and derived equations

3
4 The outcome of this stage is the calculation of hydrogen demand potential
5 per player and per district within each industrial subsector.

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

12
13 *Hydrogen consumption potential for high heat applications based on carbon*
14 *emissions*

15
16 As previously discussed, blending hydrogen into the natural gas grid
17 represents one of the most practical entry points for introducing hydrogen into
18 the industrial sector. Accordingly, this section begins by outlining the
19 methodology used to estimate the potential hydrogen consumption in a natural
20 gas–hydrogen blend, compared to the exclusive use of natural gas.

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

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

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

31 Where Q refers to heat in kWh.

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

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

36
37 Where LHV is the low heating value in kWh/kg and m is mass in kg.

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

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

The mass fraction of hydrogen (w_{H_2}) is derived from the density (ρ) in kg/Nm³ 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%.

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

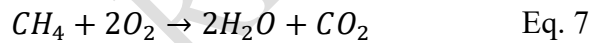
Once the hydrogen mass fraction is determined, the total mixture mass (m_{mix}) can be computed, as shown in Eq. 5.

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

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

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

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.



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

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

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)	15,50	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

1 free emission allowances. When emissions exceed this allowance, companies
2 must purchase additional credits [7].

3 *Industrial sectors overview and methodology*

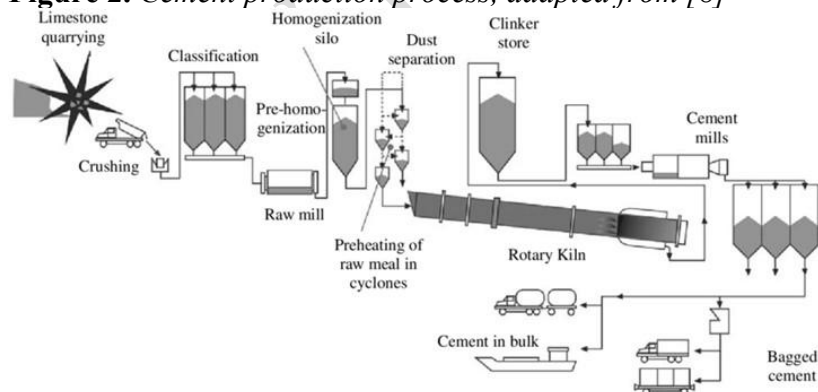
5 Cement and Lime methodology

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

13 The cement manufacturing process is broadly similar across these players.
14 It begins with the preparation of a raw material mixture composed predominantly
15 of limestone, which is crushed and ground into a fine powder. This mixture is
16 then processed in a rotary kiln at very high temperatures, where it is transformed
17 into clinker, the key intermediate in cement production. Clinker is primarily
18 composed of quicklime (calcium oxide), silica, alumina, iron oxides, and minor
19 constituents. After cooling, clinker is blended with gypsum and other additives
20 such as limestone filler, fly ash, slag, or calcined clay, before being ground into
21 the final cement powder. **Error! Reference source not found.** illustrates the
22 main stages of this process.

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

28 **Figure 2.** *Cement production process, adapted from [8]*



29
30
31 Within the cement and lime production process, the rotary kiln stage
32 represents the primary opportunity for hydrogen integration. This stage is highly
33 energy-intensive, requiring temperatures of approximately 1 450°C [9].
34 Traditionally, these kilns are fired using coke or petroleum coke, which are
35 preferred due to their high flame emissivity [10]. Nonetheless, rotary kilns are
36 known for their flexibility in fuel usage, and many companies have already

1 begun incorporating alternative fuels into their energy mix to reduce overall
2 carbon emissions, such as natural gas, biomass, and other substitutes.

3 For the purposes of this work, the fuel considered for kiln operation is
4 assumed to be a mixture of coke combined with natural gas and hydrogen.
5 Specifically, the model adopts a fuel blend consisting of 70% coke and 30%
6 natural gas, with hydrogen introduced into the natural gas stream at blending
7 levels of 5%, 10%, and 20%, as described previously. This approach is informed
8 by findings published in the IEEE Transactions on Industry Applications journal
9 [10], which indicate that natural gas can replace powdered coal (or coke) at a
10 thermal substitution rate of up to 30% without compromising kiln performance.
11 Furthermore, it is assumed that blending hydrogen into the natural gas stream at
12 concentrations of up to 20% does not significantly alter flame characteristics,
13 thus maintaining process stability.

14 To estimate the potential hydrogen consumption in cement and lime plants,
15 the first step is to determine the production mass of clinker or quicklime. This is
16 achieved using Eq. 9, which divides the total reported CO₂ emissions, in tons,
17 (m_{CO_2}) by the specific emissions of CO₂ per ton of product (t CO₂/t product).
18 Emissions data are available through the ETS database, while company annual
19 reports provide the specific emissions factors.

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

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

$$Q_{mix} = \text{Production mass} \times \text{Specific thermal energy} \times 0,3 \quad \text{Eq. 10}$$

26 These metrics are made available by each companies' annual reports.

27 The blending methodology described in Section 3.2 enables the calculation
28 of potential hydrogen demand for each plant. The results are expressed as
29 hydrogen consumption potential at both the company and district level within
30 the cement and lime sector.
31

32 Ceramics methodology

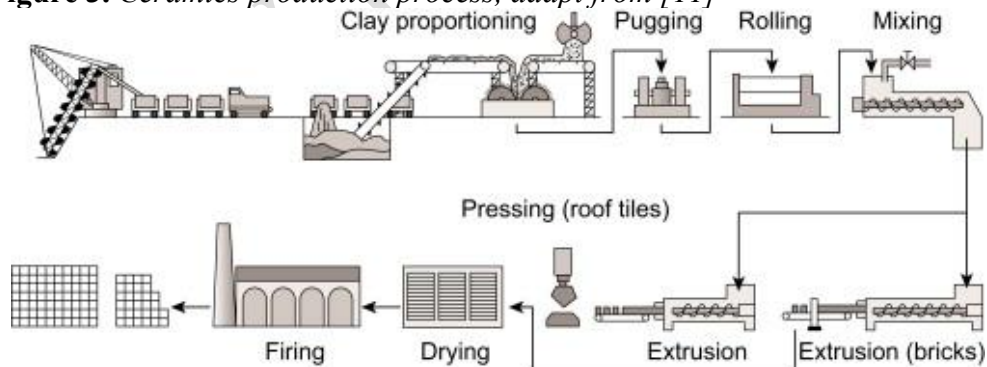
33 Portugal has a long-standing tradition in the production of ceramics, with an
34 established industrial ecosystem that includes major players such as the Pavigrés
35 Group, Preceram Group, Cinca Group, and Roca. In addition, globally
36 recognized high-end brands such as Vista Alegre and Bordalo Pinheiro
37 contribute to the country's reputation in this field. The sector is characterized by
38 a high granularity of companies and production units, with a strong
39 concentration along the western coast of Portugal, particularly in the districts of
40 Leiria and Aveiro.
41

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

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

20 While the general sequence of steps is consistent across the sector, the
 21 specific production scheme varies depending on the type of ceramic
 22 manufactured. **Error! Reference source not found.** illustrates this by
 23 presenting an example of roof tile production, where additional processes such
 24 as pugging and rolling are applied. These steps remove air from the clay mixture,
 25 ensuring homogeneity and an even texture, thereby offering a representative
 26 visual aid of a typical industrial production process.

27
 28 **Figure 3.** *Ceramics production process, adapt from [11]*



29
 30
 31
 32 In the Portuguese ceramics industry, natural gas is the dominant energy
 33 source, followed by electricity, which accounts for a comparatively small share
 34 of total consumption [12], [2]. The firing stage represents the most energy-
 35 intensive step in the production process, where ceramic products are exposed to
 36 temperatures ranging from 800 °C to 1 400 °C [13]. This step is critical to

1 hardening the material into its final form and, therefore, presents the greatest
2 potential for hydrogen integration as a substitute fuel, blended with natural gas.

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

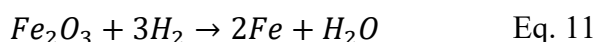
12 It is worth noting that the use of oxygen, a by-product of hydrogen
13 electrolysis, could also contribute to efficiency improvements in furnaces by
14 enhancing combustion. However, this was not considered for the scope of this
15 work.

16 Metallurgy methodology

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

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

28 Beginning on the DRI process, iron is typically extracted in its natural form
29 as forms of iron oxides (or “iron ore”), which in turn needs to be turned into
30 metallic iron to be melted, and formed into the various products, structures and
31 others, that has shaped the economies and society’s evolution for millenniums.
32 This means that the iron ore requires a reduction process to be turned into
33 metallic iron, through the use of a reduction agent. This reduction agent, as
34 previously mentioned is typically coke or a syngas mixture containing hydrogen,
35 carbon monoxide and others. However, this agent can be solely hydrogen, which
36 makes the base for green steel production, Eq.11 shows the DRI reaction
37 equation.
38



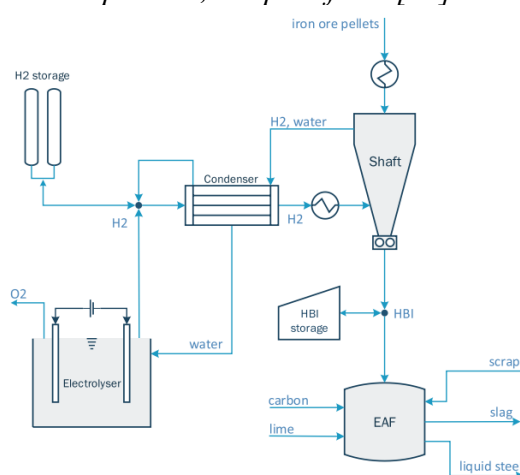
40 Stoichiometric analysis shows that approximately 51.5 kg of hydrogen are
41 required per ton of steel produced.

42 Historically, Portugal operated a DRI process at Siderurgia Nacional do
43 Seixal (now part of Megasa), which was decommissioned in 2001 [14].
44 Although the DRI process is not currently in use, its inclusion here is relevant,
45 as domestic steel demand cannot be met solely with recycled feedstock. The

1 sector therefore retains significant potential for future hydrogen adoption, should
 2 DRI production be reintroduced. However, due to economic and operational
 3 constraints, this scenario is not considered within the scope of this work.

4 After the DRI the metallic iron is moved to an Electric Arc Furnace, which
 5 uses a high voltage powered electric arc to melt steel before it is formed into its
 6 final shape. This process makes use of steel's electric conductive properties to
 7 melt iron using solely with electricity, the alternative being natural gas or coke
 8 powered blast furnaces at high temperatures. **Error! Reference source not
 9 found.** provides a simple scheme of green iron production process, DRI
 10 followed by EAF.

11 **Figure 4. Iron production process, adapted from [15]**



13
 14
 15 Currently, Megasa's Portuguese steel plants (Siderurgia Nacional do Seixal
 16 and Siderurgia Nacional de Maia) operate using Electric Arc Furnace (EAF)
 17 technology, primarily by melting recycled steel scrap.

18 Though DRI presents a large potential for the use of hydrogen, this process
 19 is no longer used in Portuguese steel production units, with metallic steel and
 20 recycled steel used directly in the Electric Arc Furnace, before shaping the steel
 21 into its final form. Furthermore, since the vast majority of steel produced in
 22 Portugal comes from recycled steel (84%-91%), the hydrogen consumption
 23 potential within DRI would be limited to the smaller share of non-recycled steel.
 24 Nonetheless, these industrial units continue to rely on natural gas furnaces for
 25 steel reheating processes [16], which opens an opportunity for hydrogen
 26 blending.

27 As such, to estimate hydrogen consumption potential, the methodology
 28 outlined in Section 3.2 is applied, using emissions data from Megasa's annual
 29 reports and the European Emissions Trading System (ETS) tables. Based on the
 30 reported CO₂ emissions and considering that natural gas is the primary fuel
 31 source, it is possible to infer natural gas consumption and, consequently,
 32 hydrogen demand under different blending scenarios.

33 Lastly, in the case of Lusosider, hydrogen potential lies primarily within its
 34 annealing furnace, which operates on natural gas. Therefore, similar to Megasa,

1 hydrogen will be considered as a blended fuel substitute in this stage of
2 production.

3 4 Chemical and polymers methodology

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

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

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

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

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

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

36 37 Refineries methodology

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

42 Galp is also positioning itself as a key player in the green hydrogen sector,
43 as it is currently leading one of the country's largest projects by integrating a 100
44 MW electrolyser into its Sines refinery, which will cover roughly 20% of the
45 Refineries yearly production of grey hydrogen [17]. This initiative aims to
46 enhancing the amount of green hydrogen used in its production process.

1 Additionally, given that refineries are one of the biggest hydrogen consuming
2 sectors globally, as stated previously in this work, players such as Galp can take
3 a substantial part in driving the green hydrogen market.

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

11 To maximize yield, the heavier residues from the atmospheric distillation
12 unit undergo further treatment in a vacuum distillation unit. This process
13 operates under reduced pressure, allowing the separation of heavier
14 hydrocarbons at lower temperatures, thereby preventing thermal cracking and
15 degradation of valuable molecules [51]. The vacuum distillation process
16 produces vacuum gas oil and vacuum residues, which, depending on their
17 characteristics, are further processed in the following conversion units:

- 18
- 19 • Fluid Catalytic Cracking (FCC)
- 20 • Visbreaking
- 21 • Hydrocracking
- 22

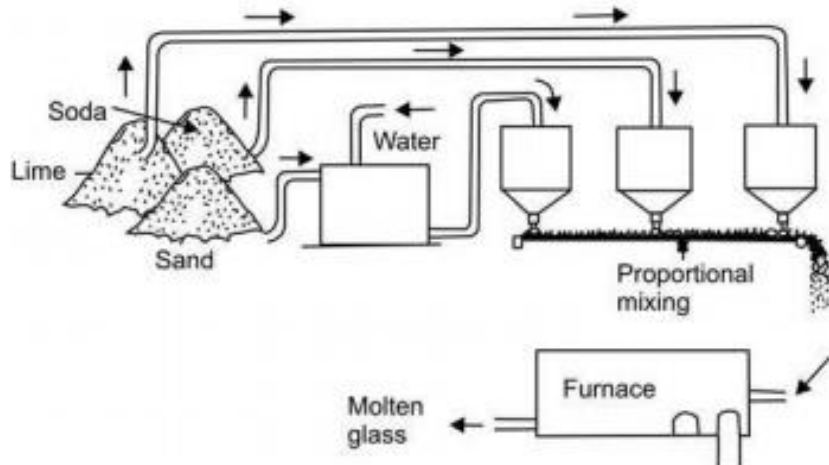
23 The greatest potential for hydrogen consumption within the refining process
24 lies in the hydrocracking unit, given its direct reliance on hydrogen as a key
25 input. Other processes, such as heating, are largely supplied through the use of
26 the refinery's own fuel products, and therefore hydrogen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

30 Glass methodology

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

37 The glass production process begins with raw materials, primarily silica
38 (sand), coming from Rio Maior Mine, limestone, soda ash, and other substances,
39 that are combined as the base components. These inputs are introduced into a
40 furnace where they undergo a high temperature melting process, typically
41 ranging between 1400 °C and 1700 °C [18]. This stage, commonly referred to as
42 the melting process, is the most energy-intensive, as it transforms the raw
43 mixture into molten glass. Once liquefied, the molten glass is shaped using
44 molds to form the desired products. Within this process, the highest potential for
45 hydrogen substitution lies in the melting stage, given its extreme heat
46

1 requirements and reliance on fossil fuels, namely natural gas that burns inside
 2 the furnace through a diffusion flame. **Error! Reference source not found.**
 3 provides a simplified scheme of the glass production process.
 4 **Figure 5.** *Glass production process, adapt from [19]*



5
6

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

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

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

24
25

26 **Results and discussion**

27

28 *Map of Hydrogen Consumption Potential in Different Scenarios*

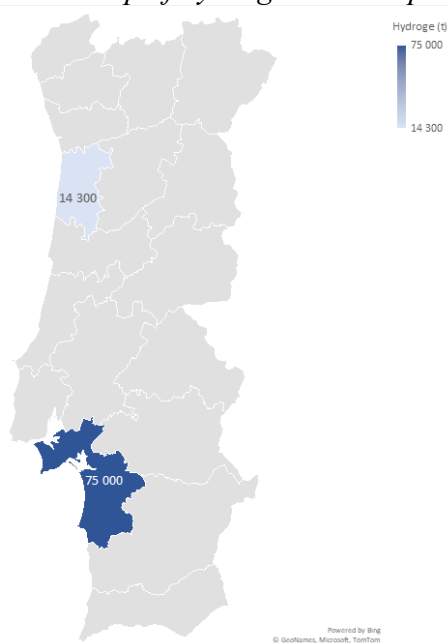
29

30 To provide greater clarity and analytical depth, the following sections will
 31 present two separate consumption maps, one dedicated to direct feedstock use

1 and another to hydrogen for high heat applications (at a 20% hydrogen mixture
2 scenario).

3 **Error! Reference source not found.** presents a heat map illustrating
4 Portugal's hydrogen consumption potential for direct feedstock applications.
5 The districts of Setúbal and Aveiro emerge as the only regions currently
6 displaying measurable potential, primarily due to the presence of Galp's Sines
7 refinery and Bondalti's chemical production unit in Estarreja, respectively. Both
8 industrial facilities already rely on hydrogen as a key feedstock in their
9 production processes, as detailed in the previous section. Consequently, these
10 two players stand out as strategic enablers of Portugal's future hydrogen
11 economy, particularly given their ongoing initiatives to integrate green hydrogen
12 production units within their operations.

13
14 **Figure 6.** Heat map of hydrogen consumption potential for heat applications



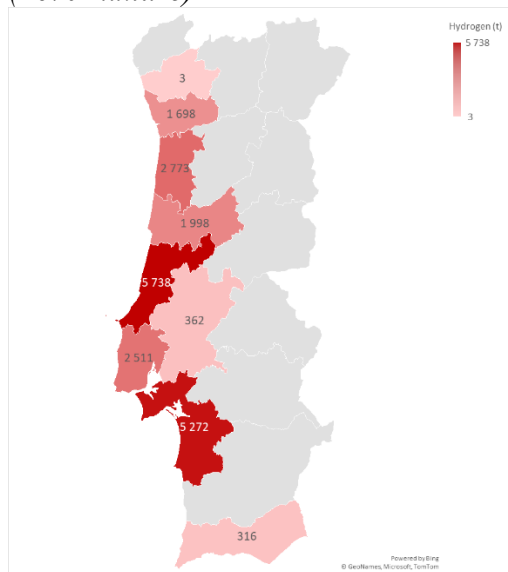
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16
17 **Error! Reference source not found.** shifts the analysis from direct
18 feedstock use to heat applications, modelled as a 20% hydrogen mixture with
19 natural gas. In this context, the district of Leiria emerges as the most significant
20 contributor, with an estimated potential of 5.7 thousand tons of hydrogen per
21 year. This dominance is largely attributed to its strong industrial base,
22 particularly the glass production cluster, comprising two Vidrala units and one
23 BA Glass facility, each accounting for roughly 1 thousand tons annually,
24 alongside several ceramic manufacturers jointly representing approximately 1.3
25 thousand tons. In addition, the presence of three SECIL cement plants,
26 collectively contributing around 700 tons, further reinforces Leiria's position as
27 the leading district for hydrogen consumption in heat applications.

28 Setúbal follows closely with an estimated 4.4 thousand tons per year. Unlike
29 Leiria, where consumption is spread across multiple industries, Setúbal's
30 potential is more concentrated, primarily driven by Repsol Polímeros, with about

1 2.8 thousand tons, and a SECIL cement plant, contributing approximately 1.1
2 thousand tons annually.

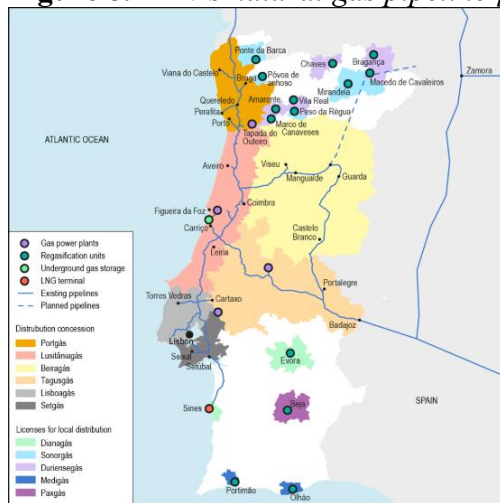
3 In Aveiro, the potential reaches 2.8 thousand tons per year, reflecting a
4 combination of smaller ceramics facilities and the influence of the Estarreja
5 chemical cluster, as previously discussed. Similarly, Lisbon (2.5 thousand tons)
6 and Coimbra (1.9 thousand tons) exhibit comparable demand structures,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

11
12 **Figure 7.** Heat map of hydrogen consumption potential for heat applications
13 (20% mixture)



14
15
16 An important aspect regarding heat applications lies in the geographical
17 alignment of industrial demand with existing energy infrastructure. As shown in
18 **Error! Reference source not found.**, the main industrial consumers identified
19 in this analysis are located along REN's natural gas transmission pipeline. This
20 spatial correspondence suggests that, with limited infrastructure adaptation,
21 hydrogen blending (up to 20% by volume) could be progressively introduced
22 into the existing network, thereby facilitating a smoother transition towards
23 hydrogen-based heat generation.

24

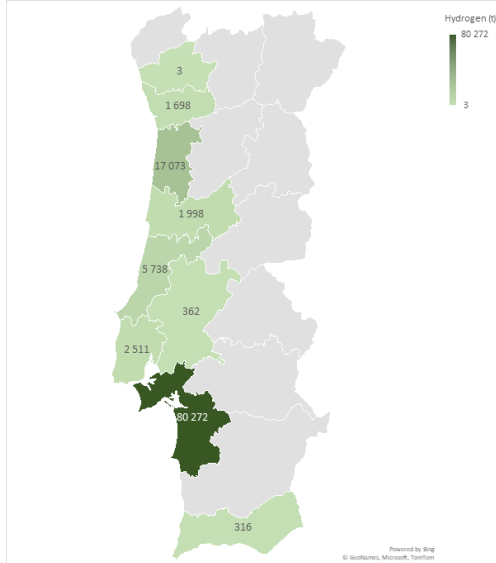
1 **Figure 8. REN's natural gas pipeline [20]**

2

3

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

10 To conclude this section, **Error! Reference source not found.** presents a
 11 combined heat map integrating both direct feedstock and heat applications,
 12 providing a comprehensive overview of Portugal's hydrogen consumption
 13 potential across the industrial landscape. The results indicate that, in the early
 14 stages of deployment, hydrogen demand should be primarily driven by Galp's
 15 refinery in Sines and Bondalti's chemical complex in Estarreja, both of which
 16 already rely on hydrogen as a key feedstock in their industrial processes. These
 17 existing hydrogen users represent natural starting points for the introduction of
 18 green hydrogen into the Portuguese industrial system.

1 **Figure 9.** Heat map of hydrogen consumption potential.

2
3
4
5 Together, these two demand profiles define the initial framework for the
6 emergence of a Portuguese green hydrogen economy within the industrial sector,
7 balancing technological readiness with gradual infrastructure adaptation.

8
9 **Table 2.** Hydrogen consumption potential (tonnes) in Portugal considering
10 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

11
12
13 As summarized in Table 2, direct feedstock applications represent the
14 largest potential source of hydrogen demand, highlighting their pivotal role in
15 driving the first phase of green hydrogen integration in Portugal.

16 17 18 **Conclusions**

19
20 At an early stage, the introduction of green hydrogen into the Portuguese
21 industrial sector could build upon two complementary demand paths, direct
22 feedstock applications, estimated at around 89 thousand tons of hydrogen per
23 year, concentrated mainly in two key industrial players (Galp and Bondalti), and
24 heat applications, ranging from 4.5 to 20.6 thousand tons per year when blended
25 with natural gas. Together, these two routes represent the foundation for
26 hydrogen integration within Portugal's industrial landscape.

27 These findings suggest two viable implementation strategies. The first is a
28 centralized approach, achieved through the injection of hydrogen into the
29 national natural gas grid, enabling its gradual adoption across multiple sectors.
30 The second is a decentralized approach, based on on-site hydrogen production

1 and consumption by major industrial players, particularly those already
2 identified in this study.

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

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

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

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

26 27 28 **References** 29

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