Green Hydrogen and Oxygen Economy developments in Portugal

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ABSTRACT

In order to decarbonize the energy industry, green hydrogen will have a crucial role. However, water electrolysis is still highly capital intensive. Currently, the most predominant and cost-effective process to produce hydrogen is Steam Methane Reforming. The aim of this work is to study the competitiveness of the economic activities that consume oxygen in Portugal, which is co-produced during the electrolysis process. Amongst all these industries, the glass production was reported to be the largest industry in Portugal. Also, given that medical oxygen has a high market value, the consumption of medical oxygen in Portugal and Spain was characterized and quantified. In fact, the hospitals in Portugal with the highest annual oxygen demand have proven to be in Lisbon, Coimbra and Porto. Another key insight of this study is the medical oxygen demand for home care treatments, with an increased market value due to the pressurized cylinders in which oxygen is transported and stored.

Furthermore, the economic activities that consume Hydrogen were characterized, as well as the scenario for future consumption. The most important sector in Portugal is Oil refining, in Sines, having the highest hydrogen demand amongst all other described industries. Another important insight of this work is the comparison between both Alkaline and PEM electrolysers, where Alkaline electrolysers have the highest maturity level with an estimated CAPEX value of 900 €/kW. In fact, all techno-economic calculations presented throughout this work are based on an alkaline electrolyser. Also, this study evaluates in which Portuguese geographical locations would it be more promising to install electrolysers plants, according to both hydrogen and oxygen industry consumers nearby. As it will be shown, the oxygen price will influence significantly the calculations of CAPEX and OPEX, NPV, IRR and payback period of the studied subsystems, contributing ultimately to the economic viability of the electrolysis process.

Although significant financial benefits were observed when selling oxygen as a by-product, government funds and loans are crucial to reduce the green hydrogen selling price, thus rapidly increasing market penetration.

Key-words: *energy; alkaline water electrolysis; oxygen; hydrogen; medical oxygen*

1 INTRODUCTION

The National Energy and Climate Plan (NECP) expects to reach the economy decarbonization by promoting energy transition, in agreement with the European legislation and points to the next decade as decisive to the achievement of these goals.

Portugal targets are extremely ambitious, with their achievement depending substantially on the investment capacity collected by the renewable sector. With respect to the renewable electricity share in Portugal, during 2019, this represented 55.2% of the national demand, led by the wind technology, with 27%, followed by hydro technology with a normalized share of 20 %, solar photovoltaics with 2.2%, bioenergy with 5.7% and geothermal with 0.3% [1]. In 2030, it is estimated that RES will be responsible for more than 28,000 MW installed. In terms of sectors distribution, it is estimated that the solar will account for the largest contribution (9,600 MW, considering centralized, decentralized photovoltaic energy and concentrated thermal solar), followed by wind (9,200 MW) and hydro, which will be responsible for 8,700 MW. Hence, the installed capacity in the Portugal will evolve towards a well-balanced distribution among these renewable energy sources [2].

Therefore, Portugal has the opportunity to become a leading country in terms of renewable energy production. In fact, this study will analyse not only the importance in investing in green hydrogen production from water electrolysis process, but also focus on the possibility of reselling oxygen as by-product. Oxygen is widely used in many industries in Portugal such as chemical, waste and water management, glass, hospital care, metal fabrication, paper bleaching and also petrochemical.

Technological improvements in electrolysis technologies and the continuous cost reduction of renewable energy resources over the years, increase of methane price and increase of CO_2 taxation, could make the production of hydrogen by electrolysis very engaging for the future. For large applications, it is even more imperative oxygen utilization, since also a large amount of hydrogen should be produced from renewable resources via electrolysis process. For instance, a 1MW alkaline electrolyser with 70% efficiency, corresponding to 178 kg/h of H_2O, originates 20 kg/h of hydrogen and 158 kg/h of oxygen with a ratio of 8 kg of O_2/kg of H_2, which is stored as a by-product for sale [3].

In terms of oxygen market price, a recent research estimates oxygen production via PSA and cryogenic separation at 100 to 120 €/tonne of O_2 [4]. Currently, in the majority of the cases, industries tend to use **cryogenic air separation technology** due to its high purity content (oxygen concentration ≥99%) [5]. In fact, amongst all technologies available, only water electrolysis is expected to become competitive with cryogenic air separation for large scale applications. Each year, approximately 100 million tonnes of oxygen are produced every for a variety of industries worldwide [5]. As climate policies regulations become more restrict, renewable energy technologies are expected to increase in the near

future, thus requiring considerable amounts of oxygen as feedstock. In fact, the chemical industry already claims that it will require large quantities of oxygen for **oxyfuel combustion** and **oxygen-blown gasification**, for instance. These processes are used to convert fossil fuels such as coal and methane into synthetic natural gas, which can be later refined to generate electricity or even produce transport fuels.
Besides cryogenic air separation, there are other existing technologies which operate at ambient temperatures, such as **pressure swing adsorption (PSA), or membrane separation process**, where these membranes are normally made of polymers with very specific mechanical properties.
Table 1 presents a comparison between the current air separation techniques available in the market, comprising their maturity, by-product capability and oxygen purity level (in vol.%).

Table 1 - Comparison between air separation techniques for oxygen production

Process	Maturity	By-product capability	Purity level (in vol.%)
Cryogenic	Mature	Excellent	99+
Adsorption	Semi-mature	Poor	95
Polymeric membrane	Semi-mature	Poor	approximately 40
Chemical	Developing	Poor	99+
Ceramic Membrane	Developing	Poor	99+
Water electrolysis	Developing	Excellent	99+

Oxygen-blown combustion can be used in **glass melting industries** in order to reduce the energy consumption of the process. Moreover, when compared to air-blown combustion, oxygen reduces drastically both CO_2 and NO_x emissions into the atmosphere. In fact, a recent study estimated that an oxyfuel furnace consumed 3.4 to 3.6 MJ/kg of glass, which accounts for both preheating the recycled glass and also the energy demand for oxygen production [6]. Comparing these results with conventional air-blown combustion melting process, the energy consumption was around 11 MJ/kg of glass [7], which is significant larger.
Another important application for oxygen is in the **iron and steel fabrication**, in particular for both blast and electrical furnaces. Lawrence Hooey et al. [8] performed a thorough comparative between air blast furnace and oxygen blast furnace, considering a 4 million tonnes hot-rolled coil annual production as reference case. The differences between both processes are noticeable. In fact, in terms of electricity demand, OBF requires 573 kWh/tonne of hot-rolled oil whereas air blast furnace consumed 400 kWh per tonne (about 30% less). Naturally, oxygen blast furnace has considerable larger oxygen demand, around 435 kg per tonne of hot-rolled coil produced. Traditional blast furnace only requires 162 kg of oxygen per tonne. It is also interesting to analyse the fuel demand. OBF requires 311 kg of coke per tonne produced, which represents a reduction of 24% compared to the reference process.
Oxygen is widely used as a reagent to improve **pulp bleaching**. In fact, due to the high oxygen demand, the paper production industry tend to adopt on site production. The main oxygen application is in pulp delignification, which consists in extracting the darkened lignin from the pulp after the cooking process. For this primary step, the oxygen demand varies between 20 and 30 kg of O_2/tonne of pulp [9].
Wastewater treatment also requires oxygen in order to comply with the sanitary conditions imposed by environmental regulators. In fact, the increasing quantities of pollutants and contaminants in treatment plants represents a big concern. The major responsible for such contamination are large scale industry applications, mainly from pulp, textiles, surface treatment plants and the food industry [10]. A study performed by the gas company Linde concluded that 2 mg/l of dissolved oxygen are enough to assure appropriate water treatment [11].
Oxygen demand may vary regarding the process stage as well as the production capacity of the treatment plant. Nevertheless, an oxygen average consumption of 50 kg O_2/tonne is a value widely accepted regarding activated sludge processes, particularly used for processing wastewater from the pulp and paper industry [9].
Lastly, oxygen is widely used for **medical care**, mainly used for the treatment of diseases related to chronic respiratory failure, which results in difficulty in breathing, severe fatigue and accelerate heart rate [12]. Furthermore, relatively to oxygen transportation in cryogenic vessels, three main dimensions are normally used, depending on the medical gas demand. Typically, a 50 Litre cylinder (B50) contains around 10.60 m^3 (14 kg) of oxygen. An intermediate capacity of a 10 Litre cylinder (B10) accommodates 2.12 m^3 (2.8 kg) of oxygen, whereas the minimum size of a 5 Litre cylinder (B5) contains around 1 m^3 (1.3 kg) of oxygen [13]. Overall, medical oxygen represented in 2019 a market size of about €4.25 billion and is expected to rise up to €6.8 billion in oxygen sales by the year of 2026 [48]. For this reason, alternatives to the conventional cryogenic vessels should be properly addressed, with special focus on green hydrogen electrolysis, which assures the required oxygen purity levels.
Hydrogen is a widely used gas in the industrial sector, such as oil refining, steel production and also in the chemical industry, namely ammonia and methanol production. Moreover, hydrogen is also being targeted as a possibility to be mixed with natural gas for building heating purposes [14]. According to IEA [15], **oil refining** is the main hydrogen consumer, representing 33% of the current industrial hydrogen applications (38 Mt H_2/year). Other major consumers also have significant shares, with **ammonia** production representing 27% (31 Mt H_2/year), **methanol** production 11% (12 Mt H_2/year) and **steel production** via Direct Reduced Iron around 3% (4Mt H_2/year).
In this context, this work aims to study the competitiveness of the economic activities that consume oxygen in Portugal, which is produced as a by-product during the electrolysis process. In addition, this study attempts to identify the best locations for installing alkaline electrolysers, based on hydrogen and oxygen consumers nearby. The ultimate goal is to

present an optimistic scenario where these gases were to be delivered via a direct line and consumed in real time by interested industries, thus avoiding compression and storage costs and becoming very cost attractive.

2 DATA AND METHODS

The methodology used in this work includes two different studies. The first one, is based on quantifying oxygen and hydrogen consumption for several industries and understand where geographically are these industries are located, by using Excel´s tool 3D Maps for Portugal. The second part of this section is based on a sensitive analysis for the instalment of a reference 1MW Alkaline electrolyser in one of the locations proposed, including oxygen selling in the revenues. The electrolyser was assumed to be powered by solar electricity, which could be delivered by an already proprietary PV plant or a purchased one, for which extra costs have to be considered.

2.1 Comparative between major industrial oxygen applications in Portugal

In this section, a comparative is made regarding the 4 major industrial oxygen consumers in Portugal, namely glass furnaces, the iron making industry, pulp bleaching and wastewater treatment.

The Portuguese national paper industry reported that the production of pulp for paper production in 2019 was equal to 1.6 million tonnes, with a decrease of 1.9% compared to the year before [16].

For the iron making sector, the Portuguese foundry association was responsible for 90% of iron and steel metal production in Portugal. For calculations purposes, an average value of 140 000 tonnes/year was considered, which accounts for the sum of both grey/nodular iron and steel production for the year of 2017 [17].

Furthermore, Portuguese glass companies which integrate the European Packaging Glass Federation are responsible for the production of around 16 million bottles, flasks and jars, in 6 distinct factories, located in Vila Nova de Gaia, Figueira da Foz, Marinha Grande and Amadora. With 16 furnaces being used for glass melting, a total amount of 1.5 million tonnes of glass is produced annually in these facilities [18].

Lastly, regarding wastewater treatment facilities in Portugal, a total of 560 884 m^3 of wastewater was treated in 2009, which is a significant increase compared to 1991, where only 135 713 m^3 of wastewater have undergone treatment. In terms of untreated wastewater in Portugal, the opposite relation was recorded. In fact, the total amount of unprocessed water decreased from 236 983 m^3 in 1995 to 16 827 m^3 in 2009 [19].

Based on the state of the art discussed in this study regarding the major industrial oxygen consumers, the following assumptions are made:

- For pulp bleaching, an average consumption value of 45 kg O_2/tonne is assumed, which comprises both delignification and bleaching processes [9].
- Consider and oxygen demand for oxygen blast furnaces of 435 kg per tonne of steel produced [8].
- Assume for traditional blast furnaces a consumption of 162 kg of oxygen per tonne of steel [8].
- The oxygen demand for the oxygen combustion furnace is about 400 kg O_2/tonne of glass [7].
- An average oxygen consumption of 50 kg O_2/ tonne of water for oxygen activated sludge processes for wastewater management [9].

In fact, figure 1 underlines a promising demand for the Glass production in Portuguese territory.

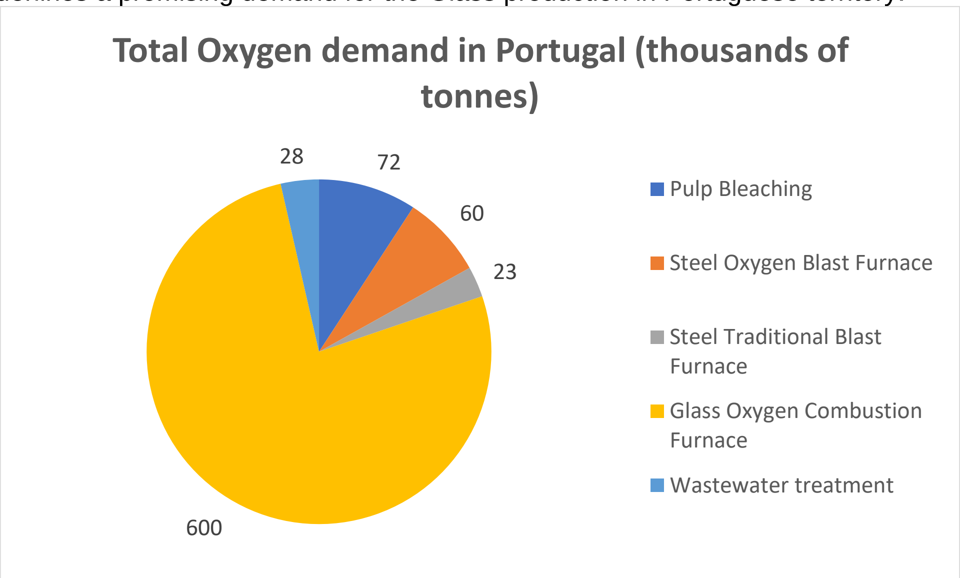

Figure 1 - Estimation of the total oxygen demand (thousands of tonnes) for Portugal

2.2 Medical Oxygen applications in Portugal

According to information provided by Infarmed, Portugal´s health entity regulator, an assessment was made in order to quantify the medical oxygen consumption in the main hospitals in Portugal, as well as to analyse its economic market value [20].

For further calculations regarding oxygen consumption in Portugal, medical oxygen costs were assumed to be very similar to those in Spain. In fact, liquid bulk oxygen was estimated to represent the same cost of 0.68 €/kg [13]. Furthermore, for the case of pressurized oxygen vessels, an average price of 2.38 €/kg was assumed for the B50 size whereas a higher value of 8.8 €/kg was considered for the B05 cylinders. Thus, medical oxygen in Portugal can be assumed to vary from around 680 €/tonne (for the case of bulk liquid oxygen) and 8800 €/tonne (if B05 tanks are considered) [7],[13]. It is noteworthy to underline that such prices are applied to the continental territory. In the archipelagos of Azores and Madeira, liquid bulk oxygen cost can be three times much higher than the values presented in this study.

For calculation purposes, a total value of 8 281 160 euros was assumed, which represents the medical oxygen consumption of the year of 2016, equivalent to around 12 359 940 kg of oxygen consumed, considering liquid bulk oxygen selling price [13].

Figure 2 expresses the medical oxygen expenses considering the national hospitals with the highest oxygen consumption (with a weight percentage of oxygen consumption between 7.1 and 13.3%).

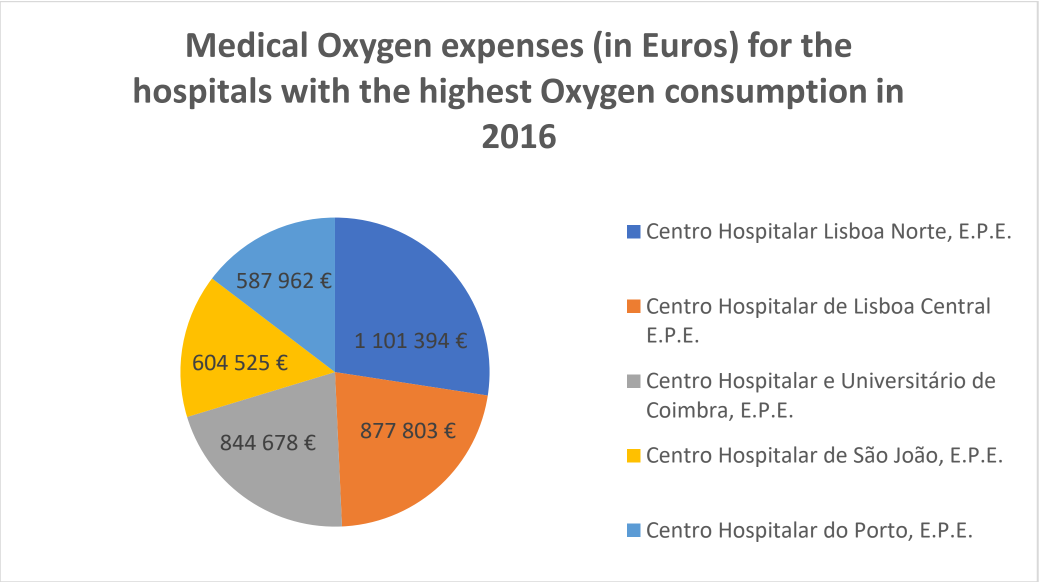

Figure 2 - Medical oxygen expenses (in Euros) for the Portuguese hospitals with the highest oxygen consumption in 2016

For the case study of the Portuguese hospitals with the highest oxygen demand in 2016, the figure below exhibits an estimation for the total oxygen consumption (in tonnes) per hospital.

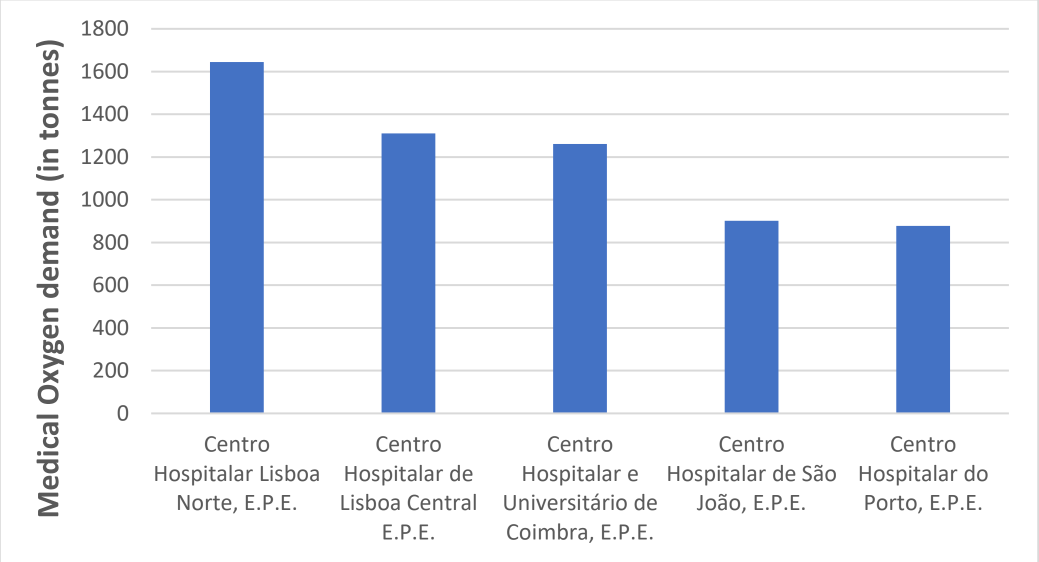

Figure 3 – Estimation of the medical oxygen demand (in tonnes) for the Portuguese hospitals with the highest oxygen consumption in 2016

Another key insight in this study is the oxygen consumed in **home care** applications regarding oxygen therapy. In fact, based on information provided by Infarmed and the Portuguese national institute of statistics, as well as from previous studies regarding medical hospital consumption [7], [20]–[22], this work estimates that Portuguese hospitals only represent around 50% of the total medical oxygen consumed. The other 50% accounts for patients with respiratory diseases which require oxygen therapy at home. Thus, for the year of 2019, which is the last year assumed prior to the Covid pandemic crisis effect in oxygen peak demand, home care oxygen consumption represented a estimation value of 1 326 025 kg, considering and average oxygen selling price of 7.9 €/kg depending on the cylinder size and purpose (stationary or portable application) [20], [21].

In conclusion, medical oxygen is reported to represent a very interesting market value in Europe, and in particular, in Iberian territory.

2.3 Green Hydrogen in Portugal

In this section, current and future hydrogen consumption is estimated for three major industries, namely oil refining, steel production and integrated combined cycle gas turbines.

The oil refining in Portugal is predominantly performed in two refineries owned by the Portuguese oil and gas company Galp, located in Matosinhos and Sines. Nevertheless, hydrogen consumption estimations will only be performed for Sines, since Matosinhos refinery is reported to close until the end of 2021. In fact, in 2014 Matosinhos refinery was reported to produce around 3 500 000 tonnes of refined crude, equivalent to 67% of its total refining capacity. Sines, the biggest refinery in Portugal reported a production of 8 600 000 tonnes of refined crude (around 68% of the plant´s total capacity) in the same year [23]. Assuming an average consumption of 10 kg of H_2 per tonne of refined crude oil [15], an annual demand of 86 000 tonnes of H_2 can be estimated for the case of Sines refinery.

For the steel industry in Portugal, some assumptions were made, based on literature review. It was considered that 1809 million tonnes of steel are produced annually and that Direct Reduced Iron will consume around 8 million tonnes of H_2 per year by 2030, with an expected share of 14% of the total primary steel demand in the world [15]. Thus, assuming an average value of 140 thousand tonnes of steel produced annually in Portugal [17], a demand of 4422 tonnes of H_2 was estimated, for the case of DRI electric arc furnace.

Ultimately, the possibility of blending hydrogen with natural gas in the gas turbines of combined cycle powerplants was analysed. In fact, recent studies show that between 3 a 5% of hydrogen can be used by current gas turbines without significant changes in their operation design [15]. Table 2 exhibits the current natural gas combined cycle powerplants in operation in Portugal, as well as their future hydrogen demand, considering 5% H_2 blend in the gas turbines [15]. Furthermore, according to data provided by the Portuguese Energy and Geology Institute, combined cycle powerplants consumed around 131 471 TJ (36 523 GWh) of natural gas in 2020 [24].

Table 2 – Combined Cycle Powerplants in Portugal and future hydrogen demand (Adapted [15], [25],[24]*)*

Combined Cycle Powerplant	Location	Installed Power Capacity (MW)	Electricity production percentage (%)	Natural Gas consumption (GWh)	Future H_2 consumption (tonnes)
Tapada do Outeiro	Gondomar	990	25,9%	9443,0	14052,2
Lares	Figueira da Foz	826	21,6%	7878,7	11724,4
Pego C.C.	Abrantes	837	21,9%	7983,7	11880,5
Ribatejo	Alenquer	1176	30,7%	11217,2	16692,3
Total	-	3829	100,0%	36522,6	54349,3

In conclusion, integrated combined cycle power plants in Portugal will be a considerable green hydrogen consumer with a total estimation demand of 54 349.3 tonnes per year of hydrogen, considering all 4 existing power stations. In fact, a special emphasis is given to Ribatejo's power plant, with a 1176 MW installed capacity and a future H_2 demand of 16 692.3 tonnes. Moreover, as improvements are made regarding hydrogen blending with natural gas, cost effective retrofitting can be performed in the gas turbines in order to maximize the hydrogen percentage in the fuel gas mixture. For an optimistic case scenario, where gas turbines would operate with 100% hydrogen instead of natural gas, significant changes would have to be addressed in the entire operation design of such infrastructure, which ultimately represent an intensive capital investment.

3. RESULTS

3.1 Geographical Assessment

In this section, a thorough analysis is made with the aim of identifying the regions of Portugal where the highest oxygen and hydrogen consumers are located. In order to do so, the Excel tool 3D Maps was used, where several layers were added.

Firstly, this study starts to identify possible existing renewable energy technologies in Portugal which could be used to power the electrolysers, namely wind and solar PV. In fact, wind energy is mostly located in the northern region, whereas solar has a higher installed capacity in the Southern region, due to larger solar irradiance characteristics. Furthermore, wind energy in Portugal has a total installed capacity of 5,449.38 MW (39.2%), with the highest power capacity districts being Viseu (1,130.40 MW), Coimbra (752.01 MW) and Vila Real (681.10 MW) [26]. On the other hand, the total solar installed capacity in Portugal is 492.79 MW (3.5%), with increased presence in the districts of Beja (165.36 MW), Évora (77.18 MW) and Setúbal (67.51 MW) [26].

After studying the gas consumption for the industries previously mentioned, all the 8 layers above were overlaid, according to geographical location as well as the weight of each industrial sector in Portugal. For instance, the oil refining sector, being the industry with the largest grey hydrogen consumption, was assumed to have a weight of 45%. In fact, green hydrogen electrolysers near oil refineries are crucial to decarbonize such a heavy pollutant sector in the near future. As for the other layers, the average weight assumed can be found in table 3, according to gas consumption and market price for each industry.

Table 3 - Average weight of each layer in the Portuguese Industry

Layer	Weight (%)
Pulp Bleaching (tonnes O2/year)	5
Glass (tonnes O2/year)	10
Medical Oxygen (tonnes O2/year)	20
Wastewater Treatment (tonnes O2/year)	5
Metal (tonnes O2/year)	5
Metal (tonnes H2/year)	5
Oil Refinery (tonnes H2/year)	45
CCGT (tonnes H2/year)	5
Total	100

Figure 4 - Final geographical assessment for electrolysers installation in Portugal

As it can be seen from figure 4, Sines has the highest potential, not only due to geographical factors (namely proximity to a seaport and high solar radiancy levels) but also due to the refining sector importance. Other promising areas are Lisbon (biggest medical oxygen consumer in Portugal) as well as Marinha Grande (largest glass industry location), Figueira da Foz (paper industry sector and combined cycle powerplant), and Porto (second largest medical oxygen consumer and strong steel industry for the oxygen consumption).

3.2 Economic Analysis

A sensitive analysis was performed for the installation of a 1 MW Alkaline Electrolyser, powered by solar electricity (1.25 MW peak power PV Plant). In fact, Alkaline technology was considered for representing the lowest Capex amongst available options, of 900 €/kW [27].

Different scenarios were analysing, considering a proprietary PV plant and the case where both the electrolyser and the solar PV have to be purchased. According to calculations, industrial oxygen was assumed to represent 87% of the Portuguese market share at an average price of 0.15 €/kg, whereas medical oxygen (homecare treatment included) represented only 13% market share at a selling price of 4.3 €/kg. Thus, an average value of 0.7 €/kg of O_2 was chosen to be a representative value for by-product oxygen selling. Hydrogen selling price was assumed at 10 €/kg to reach economic feasibility. In fact, in a highly optimistic future scenario, compression and storage costs could also be largely reduced or even neglected. Sectors like the paper industry, steel, glass and even ceramics, which are heavy oxygen consumers could truly benefit from this, only having the electrolyser operating during the factory production hours, thus consuming oxygen (and for the steel industry both H_2 and O_2) in real time via a direct line with no further costs associated. For this case, calculations were obtained with hydrogen selling price at 8 €/kg. However, note that currently the majority of hydrogen is still obtained by Methane Steam Reforming, where current H_2 market price is around 2 €/kg[27]. Clearly, government funds and tax redemption (due to avoidance of CO_2 emissions) are crucial to make green hydrogen competitive.

A comparison was made regarding the costs and revenues for the two cases considered, the first including compression and storage costs (where H_2 is sold at 10 €/kg) and the second case, which is based on a direct line and real time gases consumption (where H_2 can be sold at 8 €/kg).

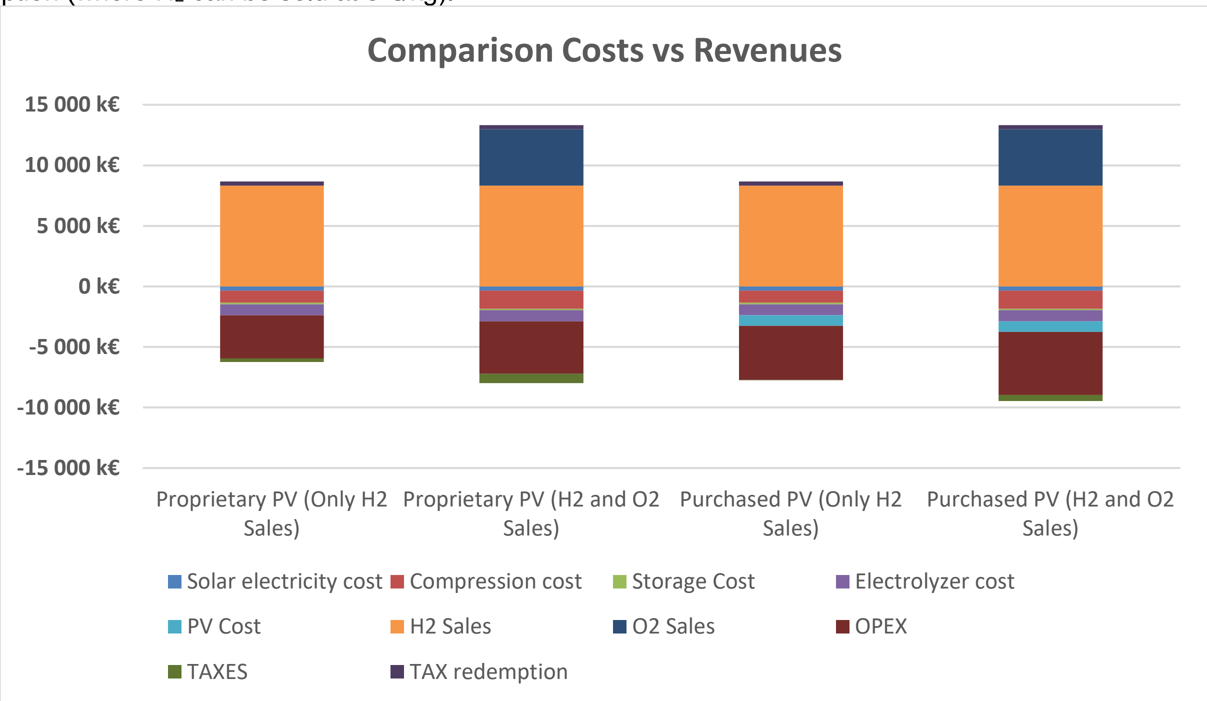

Figure 5 - Costs vs Revenues for several scenarios (considering H_2 selling price 10€/kg)

It is clear from Figure 5 that the main cost parameters are from the compression plant and the electrolyser, followed by the PV instalment cost. Total revenues include constant sales of both hydrogen and oxygen throughout the 20 years plant lifetime, as well as the proposed tax redemption. H_2 revenues account for 8 316 000 €, while oxygen sales represent a revenue of 4 645 200 €. As for the tax redemption, a total value of 349 272€ is proposed for the complete project.
For a more optimistic scenario, where gases are provided via direct line, thus compression and storage costs are neglected, a very interesting financial outcome is obtained. In fact, these two parameters were assumed to represent around 43% of the total CAPEX (considering that both the electrolyser and the PV plant had to be purchased).

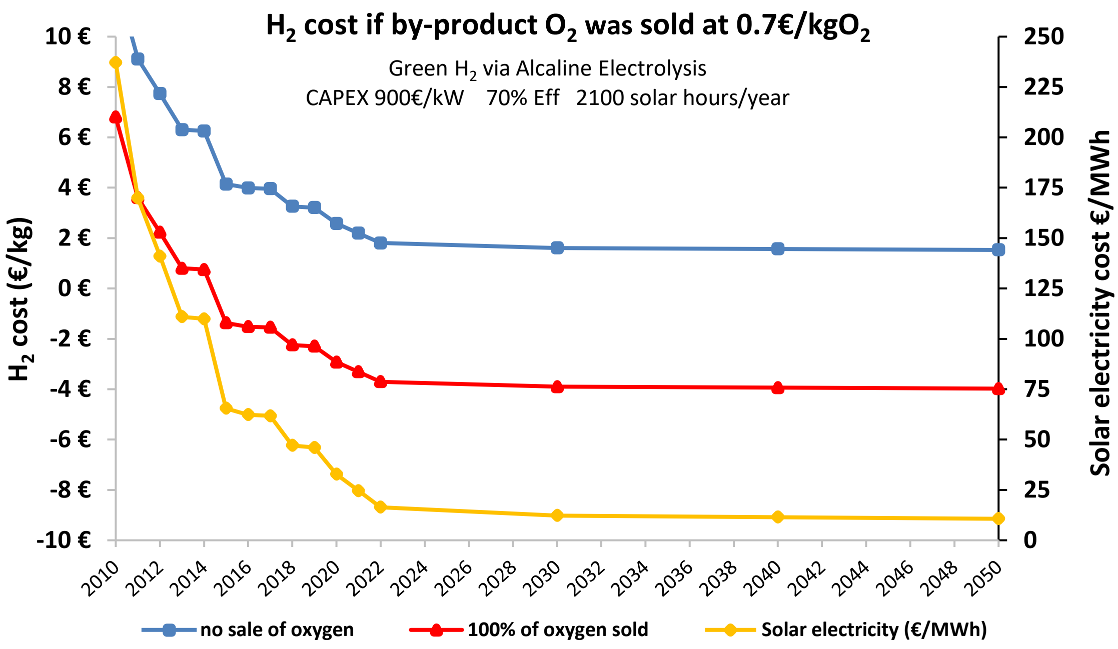

Figure 6 - H_2 cost (€/kg) and Solar electricity cost (€/MWh) forecast [28]

The chart above exhibits the evolution of the H_2 cost over the years, based on a simplified LCH formula, which neglects the compression and storage costs. In fact, it worth noting the profitability of selling the co-produced oxygen for this case, where both gases are consumed in real time. In fact, by supplying H_2 and O_2 via a direct line, not only it is possible to avoid unnecessary costs, but also to avoid electricity usage when the nearby industry consumers are not in operation. For instance, by 2030, H_2 cost considering 100% of oxygen sold would cost around -4€, meaning it would actually be a lucrative business. For the case where no oxygen was to be sold, green hydrogen would still be cost competitive in relation to grey hydrogen, around 2€/kg.
As for the solar electricity cost forecast, historic values were extracted from the international renewable energy agency IRENA [28]. Solar costs suffered a significant drop from 2010 to 2020, and are expected to remain stable around 10 to 12 €/MWh.
NPV and IRR were also calculated for both the conservative and optimistic scenario, considering all different cases regarding PV ownership and H_2 and O_2 sales. In fact, it can be seen that the NPV value of the project for the scenario where gases are consumed in real time is much higher than for the case where compression and storage costs are considered. For the most optimistic case, where the owner already has the PV plant installed and aims to sell both gases, the NPV is 2.3 times higher considering real time gases consumption, in comparison to the previous conservative scenario. If the PV has yet to be purchased, but the owner still intends to sell both gases, the NPV is 7 times larger if gases are delivered via direct line.
For the conservative scenario, the IRR obtained is superior than the equity rate of return considered of 5% for all cases except for the one in which the PV plant is purchased and oxygen sales potential is neglected. The best case obtained is when both gases sales are considered and the owner already operates the PV plant, with the IRR being around 10% and the payback period of 8.4 years. Comparing these values obtained with the scenario where gases are consumed in real time (even considering the hydrogen price 2 € lower), it can be seen a significant difference in the economic feasibility of the project. In fact, for the proprietary PV, with both gases being sold, the IRR is 28% with a payback period of just 3.5 years. Hence, the total investment project reaches a breakeven point in half the time, compared to the same case when considering compression and storage costs. Even for the worst economic case, where only H_2 is being sold and the PV has yet to be purchased, the IRR is around 4.6% and the payback period is 12.8 years, which is a significant improvement compared to the estimated 18 years for the homologous conservative scenario.

4. CONCLUSIONS

In conclusion, the major contributes of this work are not only the feasibility study of a solar powered electrolysis plant but mainly a thorough analysis on the most prominent locations in Portugal for the implementation of such plants. Industrial Hydrogen consumers were quantified, namely the oil refining sector, steel production and its future use in

Integrated Combined Cycle Power plants. In addition, the key insight of this study was to evaluate the main oxygen consumers in the market, as well as the economic impact of reselling by-product oxygen of water electrolysis process.
Industrial oxygen has the highest oxygen demand in Portugal, with special focus in the glass industry, the major oxygen consumer. However, industrial oxygen market prices are considerably low compared to the medical oxygen market. In fact, current industrial oxygen cost might vary from 100 € up to 200 € per tonne, whereas medical oxygen has significant higher values (up to 8800 €/tonne for the B05 cylinders). Liquid bulk medical oxygen was estimated to represent a cost of 0.68 €/kg, with pressurized oxygen vessels reaching an average price of 2.38 €/kg for the B50 size and 8.8 €/kg for the B05 cylinders.
Several locations have shown to be particular promising for the instalment of green hydrogen production plants. Firstly, Sines, has tremendous opportunities for some reasons worth mentioning. The oil refining plant in Sines was estimated to have an annual demand of around 86 000 tonnes of H_2 for hydrotreatment and hydrocracking treatments. Being located in the southern region of Portugal, the solar potential for powering electrolysis is immense. However, future PV panels must be installed in order to reach the target of 2 GW electrolysis capacity by 2030. In fact, the current solar installed capacity in Sines is none, as shown in the 3D Maps obtained. Moreover, the possibility of exporting hydrogen both via maritime or overland routes to Europe is also a major advantage, as well as the current hydrogen consumption in the existing oil refining plant (sector with the highest industrial hydrogen demand). In terms of possible oxygen consumers in such location, the wastewater treatment stands out. In Portugal, a total demand of around 28 044 tonnes of O_2 per year was assumed for sludge treatment processes, with an estimation value of 1.78 tonnes of O_2/year per habitant/km^2 used for calculation purposes. Thus, for the region of Sines, 120 tonnes of O_2 can be consumed each year. For other oxygen consumers to benefit from an electrolysis plant in such location, oxygen transportation costs must be considered.
Other locations worth mentioning for the installation of electrolyzers are Figueira da Foz and Porto, as it can be seen from the 3D maps presented. Being located in the coastline of Portugal, such locations can leverage from maritime products importation and exportation as well as water abundancy for the water electrolysis process. In terms of industrial consumers of hydrogen and by-product oxygen, there is also strong potential in these locations.
Figueira da Foz has the largest papermaking industry in Portugal (total installed production capacity of 1.3 million tonnes of paper annually) and is also a considerable oxygen consumer for the glass industry (1 installed glass factory). Based on calculations, Figueira da Foz would require 61 650 tonnes of O_2/ year for the pulp industry and 100 000 tonnes of O_2/ year for glass production. As for the hydrogen application, the "Lares" natural gas combined cycle powerplant is the most evident future consumer, with an estimative demand of 11 724 tonnes of H_2.
Porto has also considerable medical and industrial oxygen consumption potential. In terms of medical oxygen, Porto is a sizeable consumer (1780 tonnes of O_2/year), only behind Portugal´s capital city, Lisbon (2957 tonnes of O_2/year). As for the industrial oxygen applications, the glass industry (existing factory in Vila Nova de Gaia) is a possible alternative, with a demand for 100 000 tonnes of O_2/year. The steel industry in Porto would also require around 15 000 tonnes of O_2/year in addition to 2 948 tonnes of H_2/year. Besides, Porto is the second district with the highest population density in Portugal, and consequently significant oxygen demand for wastewater treatment industry (9280 tonnes of O_2/year), according to the correlations performed in this study. Furthermore, there are some other relevant future hydrogen consumers worth mentioning. Such location could leverage from CaetanoBus hydrogen fuel cells technology, which is developing buses with 5 hydrogen tanks, with a total maximum capacity of 37.5 kg, and a 60 kW fuel cell. With a targeted annual production of 100 H_2 buses, it would represent a total of 3750 kg of hydrogen base consumption plus investing in recharging points. The combined cycle powerplant "Tapada do Outeiro" can also become a significant hydrogen consumer, reaching a demand of 14 052 tonnes of H_2.
Marinha Grande has also proven to be a promising location, since it has the highest installed capacity in Portugal of glass production (half of the total estimated production capacity, with 3 existing factories), which represent an oxygen consumption of 300 000 tonnes per year.
A continuous focus should be given to research and development in order to achieve feasibility of the capital-intensive alternative technologies for oxygen production, namely ceramic membranes that, together with electrolysis, will definitely play a key role in the near future.

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