Green Hydrogrn and Oxygen Developments in Portuguese Economy in the Context of Refueling Stations

Joana Faria
joana.alexandra@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

This dissertation aims to evaluate the total annual cost of a hydrogen supply network refilling stations, in the Portuguese context and to understand the impact on the economy. Firstly, a selection of 100 freight transportation companies was carried out. Afterwards, it evaluated their fleets and the number of annual kilometres travelled, their need for hydrogen and their respective production and distribution costs. The companies were organized in small clusters, distributed throughout the country (decentralized production). The division between producers and consumers was performed, and finally, the allocation of hydrogen from producers to consumers was performed, obtaining a final total cost of the supply chain. So, 11 viable clusters were obtained, with a total of 32 companies, 11 of them being considered hydrogen producers with a total annual implementation cost equal to 461 646 574€, producing a total of 105 826 tons of hydrogen and 846 609 tons of by-product oxygen, which only 1.3% is able to satisfy the entire hospital oxygen consumption of Portugal. Finally, an economic balance was performed, comparing the hydrogen consumption in a year, with the diesel consumption. It was proved that hydrogen is the most advantageous fuel in the long term, obtaining a return on investment between 2/3 years, in comparison with diesel. It is concluded that implementing a hydrogen supply chain is feasible and advantageous over normal diesel consumption. The sale of oxygen only to the hospital sector, while not harmful, does not have enough positive economic impact to be the driver for this investment.

Keywords: Green hydrogen; Oxygen; Freight transportation; Trucks; Clusters; Optimization;

1. Introduction

The present society is consuming huge amounts of energy and the traditional ways of producing energy are not being enough to produce the amount that is required in the world. Right now, renewable energies are growing and have been gain popularity due to their lower impacts on the environment and environmental awareness has been increasing. There are concerns about the impacts of greenhouse gas (GHG) emissions and how that affects climate change and intensifies global warming.

A study was performed and showed the analyses of the relation between energy consumption and climate change, where some of the author's conclusions were that the "climate change has larger impact on the peak electricity demand that on the average monthly electricity demand" and "climate change affects the geographical pattern of renewable energy supply in the different regions of the world". So, it is possible to verify that climate change and energy consumption are very related. [3]

In 2019, the European Green Deal was presented by the European Commission. The European Green Deal is a set of policy initiatives that aim to reach zero emissions by 2050. One thing that this deal highlight is the role of Hydrogen in this transition, in order to achieve carbon neutrality by 2050.[12]. Hydrogen will affect deeply the energy system, being a flexible energy carrier for industry and transportation, thus, reducing GHG and particle emissions. The European Green Deal sees hydrogen as one of the main keys to achieve EU climate targets and goals that will lead to decarbonization.

Unfortunately, there is no significant amount of hydrogen that is been produced from renewable sources nowadays, and this is the major step forward that the world needs. Hydrogen can be produced from several processes, and depending on the process that it is being used, the amount of emissions that are released varies (influenced by the technology and the energy source considered) but what the world wants to achieve is to produce 100% green hydrogen.

Hydrogen is produced from electrolysis, using renewable electricity (from wind, solar, hydro, etc) corresponds to hydrogen with zero carbon emissions. But this process has a cost, and in the end, the final price of hydrogen will be about $6 per kilogram [14]. However, there is a prediction that states the cost will lower down, achieving a price equal to $2.50 per kilogram until 2030, through the usage of electricity that comes from wind farms[12].

So, here it is possible to see a "window of opportunity". Maybe, we can think about regional hydrogen production, where the regions can be able to auto-sustain their energy consumption by producing their own energy through green hydrogen, where the electricity used can come directly from local Renewable Energy Sources (RES).

Currently, hydrogen is mainly used for oil refineries, as mentioned before, but is also involved in ammonia and methanol production, in Europe. But today's direction is turned to convert hydrogen into electricity (Gas-to-Power). Focusing on green hydrogen and clean electricity generation, the amount of energy consumed during the hydrogen conversion into electricity depends on the type of electrolyser technology that we are using. There are three types of electrolysers, and we are going to see them in more detail further in the work, namely, alkaline electrolyser, proton exchange membrane (PEM), and solid oxide electrolysis (SOE), being their specific consumption's equal to 50-51kWh/kg, 55-58kWh/kg and 40-41kWh/kg, respectively[12].

2. Hydrogen Production

For the H_2 economy to be able to develop and continue to grow, it is important to have economically viable H_2 production, so the type of feedstock and the technology that is used, are the main factors that influence the economic viability of H_2 production.

It is possible to separate H_2 production into two, namely, production from carbon sources and renewable sources, but we can distinguish three types of hydrogen, grey, blue, and green. "Grey hydrogen" corresponds to the one that is produced by carbon sources (eg. fossil fuels), the blue is produced in a similar way that the "grey" but has Carbon Capture and Storage (CCS) technologies, that enable the reduction of CO_2 emissions, meaning lower environmental consequences, and finally, the green, produced from renewables [16].

According to EIA, the most common processes in the world right now are steam methane reforming (SMR) and water electrolysis [7], one method that used carbon sources, producing this way only grey or maybe blue hydrogen, and it is the most used process (being done in refineries) and the other that can use energy from renewable sources, producing the green hydrogen. Since green hydrogen is the key to the future, there will be a focus on that in this work.

2.1. Water Electrolysis

The reason why water electrolysis is considered such a capable hydrogen producer is due to the fact of producing this energy carrier through renewable energy (using solar, wind, among other green energies sources) and using clean feedstock (H_2O) [20]. The origin of the electricity that feeds the reaction influences the type of hydrogen that is being produced and the type of electrolyte that is being used, also influences, being the most known ones the Proton Exchange Membrane (PEM), Alkaline (AE) and solid oxide (SOEC).

Alkaline Electrolysis (AE): the most mature technology. This method consists of using two electrolytes inside an alkaline aqueous solution, usually with a high concentration (30%w/w) of potassium hydroxide. The chemical reaction occurs at the electrode surface. On the cathode, the H_2 molecule splits into H_2 and hydroxyl (OH^-). The OH^- will be attracted by the anode, since it is a negative ion, and will react and form water and oxygen. This process has a lower capital cost, mainly due to the fact of not using precious materials [9].

Proton Exchange Membrane (PEM): is not as mature as AE and uses pure water and also uses a solid polymer between the electrolytes, the membrane. This technology occupies 2,5 less space than AE, which can be attractive for regions with high popular density. The main disadvantages are related to the catalysts used, because they are made from precious materials (platinum, ruthenium and iridium) which turns this method costly and with the fact of its lifetime being shorter than AE [9].

Solid Oxide Electrolysis Cells (SOEC): is not available in the market yet. This technology uses electrolytes made with ceramic material, has a efficiency higher that 81%, works at high temperatures, and can work in reverse mode, in the same way as a fuel cell converting hydrogen into electricity [9]. The limitations of this technology are: durability of the cells, only atmospheric pressure operation, and leakage issues.

3. Hydrogen and Road Transportation Sector?

Hydrogen has a much higher yield per unit of mass when compared to any other fuel and it has a higher ignition temperature than gasoline. Due to its low density, hydrogen dissipates in the air, in opposition to traditional fuels such as diesel and gasoline, which in terms of safety concerns is good and better. However, the lack of studies and experience of hydrogen systems, it is difficult to determine how risky can be hydrogen under certain conditions. With that in mind, some efforts are being done and projects are being conducted to bring hydrogen technologies to usage and understand their performance. In Europe that is not any different [6].

It is possible to think about hydrogen mixed with traditional fuels (petroleum-derived fuels) in internal combustion engines (ICE) [2]. This way it would be possible to decrease the prejudicial emissions because hydrogen does not emit greenhouse gases after combustion. But, despite the direct usage of hydrogen as fuel in internal combustion engines is a possibility, if it is mixed with other fuels, society would still be dependent on fossil fuels and several constraints and risks would appear such as back ignition, early ignition, knock formation, that are not desirable. Besides using hydrogen in ICE with lower conversion efficiency (lower than 25%), it is possible to use it in fuel cell vehicles (FCV) with higher conversion efficiency (50%), called Hydrogen Fuel Cells Vehicles (HFCV).

HFCV's use hydrogen as fuel to produce energy, electricity, that will power the motor. These vehicles are electric, but instead of having a huge battery that stores the electricity and needs to be recharged, has a fuel tank that will store the hydrogen and has a fuel cell that will the reverse reaction of electrolysis, producing energy and water from hydrogen and oxygen. Hydrogen has an energy content equal to 33,33kWh per kilogram (lower heating value), being between the fuels the one with the highest value.

The road freight network is a very important sector and has a major influence on the economics of the world and it has been growing through the years. But, transportation sector is the one that most contributes to GHG, namely road transportation, being the freight transportation's second bigger emitter, following passenger transportation. It is possible to conclude that by decarbonising this sector, which is dominated by traditional fuels (such diesel, gasoline, natural gas), the positive impact that would have on the planet. The question here is how are we going to improve this sector to decrease GHG emissions and consequently achieve also the carbon neutrality target. Electric vehicles technologies are necessary, and currently, the main electric technologies are battery-electric and hydrogen fuel cells that are available for trucks. The major advantage of using hydrogen fuel cell trucks is refuelling. Heavy Fuel Cell Electric Trucks (HFCET) have a refuelling process very similar to the traditional fuels like diesel and gasoline. With batteries that does not happen.

Nowadays, Portuguese society is starting to realize the advantages of introducing hydrogen in the energy sector. Hydrogen is a good energy carrier, that can be produced from a wide range of sources and used in several different ways. Adding to this, besides the reduction of fossil fuel dependency, there will be an improvement in the flexibility of the energy system (eg. energy storage at different scales), and there will be a better and higher energy mix.

Portugal presents impressive conditions to produce green hydrogen on account of its geographic location, its renewable sources that have available (wind, solar, hydro), its capacity of producing renewable energy, already being capable of producing electricity with a very market competitive price (low production costs), with a mean value equal to 20,33€/kWh, ranging between 14,76€/kWh and 31,16€/kWh [5].

Concerning the Portuguese scenario, for the Long-Term Strategy for Carbon The neutrality of the Portuguese Economy by 2050, it is mentioned that "Decarbonisation of the transport sector will be almost total (98% reduction in GHG emissions compared to 2005) and will be based fundamentally on strengthening the role of the public transport system and replacing current fossil fuel vehicles with a mainly electric fleet. The use of hydrogen and advanced biofuels will also play an important role in replacing current fuels" [18]. In Portugal, road transport accounts for 85.9% of the transport of goods and merchandise [8] and this is a very important sector for the Portuguese economy, due to the exportation of goods at the international level.

4. Method

In this work, I intend to create a Hydrogen Supply Chain Network (HSCN), in a Portuguese context, to understand where it would be more interesting to implement hydrogen production sites in the country, namely green hydrogen production sites through water electrolysis. My case study will be freight transportation companies. Being road transportation is one of the biggest emitters, it is my interest to understand the impact this sector will suffer by adopting hydrogen fuel cell technologies into their fleets and having hydrogen refuelling stations infrastructures. One of the goals of this work is to understand if it would be economically attractive or not to start to develop a green hydrogen economy in this sector.

In Portugal, several sectors could be oxygen consumers like pulp and glass industry, metallurgic, hospitals, and water treatment stations but to simplify the network it was decided to choose only one of them. For this study it was selected the hospitals as the oxygen consumers, meaning that they will be the entities to whom it will be sold.

A non-empiric scenario will be created and the hydrogen sites will be inside the transportation companies, where they all agreed to assume a target of decarbonisation of 5%. This means that they assume a commitment to reduce about 5% of their fleet, and consequently decrease their fossil fuel consumption, in a year, replacing them with hydrogen fuel and fuel cell vehicles. the intention is to find strategic points/locals where would make sense to install these stations, by forming clusters of companies and to evaluate where would be feasible to produce the hydrogen fuel in order to supply it in an efficient way to all the companies in the neighbourhood, of each cluster. Some key assumptions are necessary to formulate this model:

- The green hydrogen will be produced inside of each complex of the company using water electrolysis for hydrogen production;
- The water used for the process comes directly from the grid and, if necessary, it is implemented an infrastructure that will purify the water that will feed the production, namely reverse osmosis technology;
- By-products produced from the production facility, such as oxygen, will supply external sectors, namely hospitals.

After the creation of this network, an optimization formulation is solved and the output of the optimization gives:

- The optimal structure of HSCN in Portugal;
- The minimum cost of implementation;
- Which companies will be totally satisfied (and which not);

5. Model

5.1. Objective Function

The hydrogen supply chain network (HSCN) proposed function consists of the following main cost/profit components: the costs are related to hydrogen production, hydrogen transportation, and water supply. The profits considered are associated with oxygen selling. Each of these components will be described in thesis. The purpose of this work is to minimize the cost of HSCN. The equations formulated will give the cost per unit of hydrogen (€/kg H_2). The final objective function will provide the minimum Total Annualized Cost (TAC) for the supply chain:

Objective function:

$$TAC = HP^{Cost} + HT^{Cost} + WSC^{Cost} - BP^{Profit} \tag{1}$$

Where,

- HP^{Cost} is the hydrogen production total cost [€ / y]
- HT^{Cost} is the hydrogen transportation cost [€/y]
- WSC^{Cost} is the water supply cost [€ / y]
- BP^{Profit} is the total oxygen sold to Hospitals [€ / y]

The purpose is to find the optimal combination of these components and to obtain the minimum cost of implementation of hydrogen supply chain.

5.2. Producers and Consumers

This work intends to create a realistic scenario, that would help to understand the cost of implementing hydrogen in Portugal. For that reason, the selection of the transportation companies was made based on their ranking position, where the ranking presents Portuguese companies and is ordered according to the value of their sales, allowing to know the position that a particular company occupies nationally, region, or sectoral

[11]. This ranking contains 7621 companies but only the first 100 companies were selected, being them displayed in figure 1.

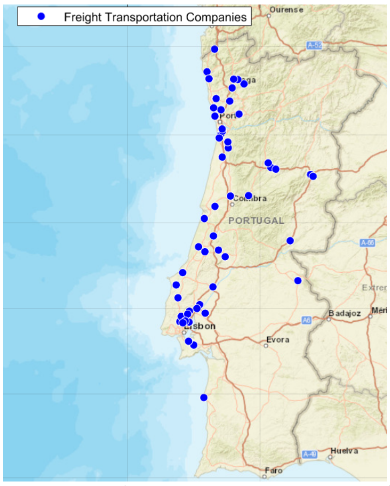

Figure 1: Portuguese freight companies display. Companies analysed.

The next step was to evaluate which of those companies did international transportation because this work is only interested in long distances travels because it is where heavy-duty hydrogen fuel cell trucks will have the advantage in relation to electric heavy-duty vehicles. For that, it was consulted a document of Mobility and Transportation Institute (also called IMT - Instituto de Mobilidade e dos Transportes), where I could find every freight company that is present in Portugal and discriminates the type of transportation that each company does, if national, international or both [4].

The final selection of companies was done based on 2 factors and it was given priority to the ones with available data: the number of vehicles in the fleet and the number of kilometres travelled in a year. With this selection, the number of companies suitable for the study decreased to 56.

To be able to determine the amount of hydrogen that each company needs, to agree with the 5% decarbonisation target, it was necessary to search for the average kilometres that each company does per year. With this information would be possible to know the average kilometres that each truck does for a specific company.

Based on some hydrogen heavy truck vehicle brands available, considering their tank capacity in kilograms (kg) and the kilometres (km) that they were capable to travel, it was calculated a hydrogen consumption factor per kilometer (kg H_2/km). This way it was obtained the total amount of hydrogen necessary to supply to each company, considering the kilometres that it does per year.

Since this technology is currently expensive, it wouldn't make sense to all companies to acquire it, **plus acquiring the fuel cell vehicles** and each of them to implement the infrastructure necessary for the production. With this in mind, it was necessary to decide which of the companies were better ones to produce hydrogen. For this, two approaches were study but at the end only one of them was suitable for the work. Instead of taking into account the mean distance from one company to all others, first approach, the decision was to evaluate as groups. Considering all companies, clusters were formed with them and, per each cluster, there would be one producer. The clusters were determined based on the position of companies with help of MATLAB Software.

With this new approach other factors require to take into consideration such as the number of clusters that will be formed, the minimum number of elements that each cluster must have, the maximum distance between the two furthest points in the cluster,and a if every company will participate on the supply chain. For a company that does not follow every requirement, it will be excluded from the clusters.

The function used in MATLAB finds clusters in a set of spatial points expressed in XY coordinates [1]. So, the geographic coordinates (latitude and longitude) of each company were transformed into Cartesian coordinates and they were displayed into an XY graphic. To obtain a realistic result, and to be possible to work with distances and preserve the companies characteristics, it was used a simple equirectangular projection, and the data of the companies were converted into distances to Earth's referential origin, namely, Equator (Latitude) and Greenwich Meridian (Longitude).

In the end, it is obtained a graphic similar to the one in figure 2.

5.3. Oxygen Demand

For the water electrolysis, it is necessary water as well as electricity, as previously mentioned. In terms of numbers, it requires about 9L of water to produce 1kg of H_2 and around 8kg of O_2, as by-product[9].

The O_2 generated from water electrolysis has a very high level of purity. In literature, it is already mentioned that this oxygen can be sold to health care units or the industrial sector [13]. Taking this

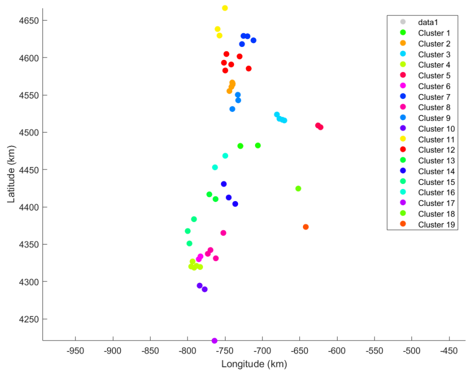

Figure 2: Clustering process. Clusters with a min. of 1 element and with a max. distance of 50 km.

information into consideration, for this model, was considered that the oxygen produced from water electrolysis is sold to hospitals until their demand is fully satisfied.

It was necessary to look for some Portugal databases about hospitals. In the year 2019, and according to Pordata, a total of 10766292 kg of O_2 was consumed by a total of 238 hospitals.

Oxygen Revenue:

$$BP^{Profit} = BP_0 \times UOSP \quad (2)$$

- BP_0 is the total by-product (oxygen) Hospital demand [kg / y];
- UOSP is the unit of oxygen selling price [€ / kg];

5.4. Hydrogen Production Cost

Water electrolysis is simply the separation of water molecules (H_2O) into hydrogen and oxygen (O_2). In order to realize this separation, it is necessary to give energy to the process to the molecule to break, and due to the fact of being an endothermic process, an amount of energy, namely electricity, is required.

Here we can see one of the things that affect the hydrogen production cost is the price/cost of the electricity that is consumed during the reaction. Water electrolysis can be defined by the source of electricity that uses (fossil fuels, wind, solar, nuclear, etc) and by the type of electrolyte that is being used. In this model it will be considered that all production sites will be using the AE because is a mature technology and can achieve an efficiency of production of 70%.

Hydrogen Production Total cost:

$$HP^{Cost} = \frac{ELCTR}{1000} + \frac{CAPEX}{10} \times \frac{1}{HPY} \times \frac{33.33}{EFF} \quad (3)$$

- The equation 5.6 was adapted from [19].
- HP^{Cost} is the hydrogen production total cost [€/y]
- ELCTR is the electricity price consumed during the electrolysis [€/MWh]
- CAPEX is the total investment in the Alkaline electrolysis technology [€/kW]
- The 10 years is considering the life-time of the technology;
- EFF is the efficiency of the Alkaline electrolyser;
- 33,33 is the theoretical minimum power consumption [kWh/kg] if the electrolyser was 100% efficient.

5.5. Water Supply Cost

to produce one kilogram of hydrogen it is necessary to use 9kg of water. This way, knowing the total amount of hydrogen that will be produced, it is possible to know the total annual amount of water that will be used for the process.

Water Total Cost:

$$W_{Supply} = UWS_G \times WD_T \quad (4)$$

Where,

- WD_T= 9 $\times H_{produced}$
- UWS_G is the unit price of water supply from the grid per kilogram of hydrogen [€ / kg H_2]
- WD_T is the water total demand for the hydrogen production [kg]
- $H_{produced}$ is the total amount of hydrogen, kg, that each producer will produce.

5.6. Hydrogen Transportation Cost

It is being considered a decentralized production, where some production sites will produce the hydrogen to other companies. Decentralized production has the advantage of being distributed for several regions, facilitating the consumer to access the product and avoiding traveling long distances to reach it.

One thing that affects the transportation of H_2 is the form under with it will be transported. There are two possible ways of transporting hydrogen, in liquid form or gaseous form. For smaller distances, hydrogen can easily be transported in gaseous form.

Transportation Cost:

$$HT^{Cost} = Dist \times GHD_{Cost} \times HD_{Cost} \quad (5)$$

Where,

- Dist is the distance of each producer to each consumer [km];
- GHD_{Cost} is the gaseous hydrogen delivery cost to specific industry per km [€ / km / kg]
- HD_{Cost} is the amount of hydrogen to be deliver in each consumer per year [kg H_2 / y]

6. Results and Discussion

6.1. Geographical Assessment

The clustering method was selected for the companies in this study and this way several producers are distributed along with the territory, that get in line with the Portugal's goal of having a decentralized green hydrogen production. After the method selection, it was conducted a sensitivity analysis in order to understand how the number of clusters vary and how the elements of each cluster were affected, by varying the minimum number of elements from 2 to 5. With distance variation, it was decided to vary the distance from 20 kilometres to 50 kilometres, changing 15 kilometres per case, meaning that the distances in consideration were 20 kilometres, 35 kilometres, and 50 kilometres. The results showed that to distance equal to 35km and distance equal to 50km, nothing changes. Due to that, it was only considered the distances equal to 20 and 50 kilometres. Figure represents one of the scenarios obtained, with the constrains of minimum elements equal to 2 and a maximum distance of 50km, overlapping with Portugal geographic map.

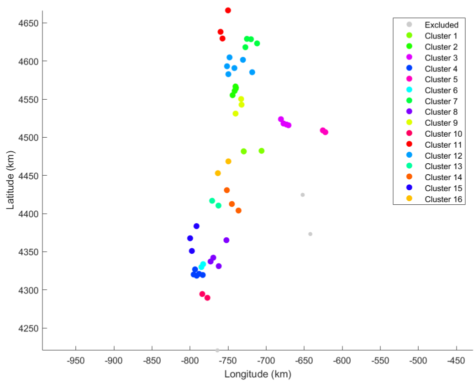

Figure 3: Clustering process. Minimum elements equal to 2 and a maximum distance of 50km

6.2. Supply chain - Economic analysis

The second main goal of this work was to try to evaluate the distribution of hydrogen from the producers to the consumers. After the clusters were formed, a study of distribution based on the capacity of the producer and the demand of each consumer was performed. With this, it was possible to obtain the total cost of hydrogen grid implementation per scenario and the implementation cost associated with each cluster. To do it so, a Transportation Assignment method was used in this work, using Excel Solver tool.

Running all case studies, it is obtained the total cost of implementation of a hydrogen supply network per each. The cost of implementation is represented in figure 4.

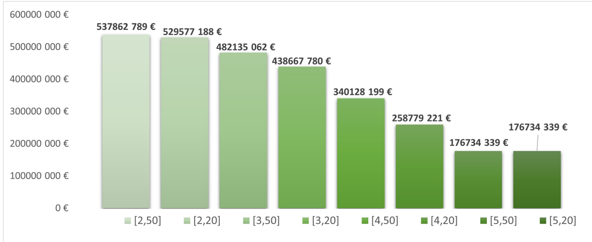

Figure 4: Total cost of implementation of hydrogen supply chain for the different scenarios.

6.3. Discussion

Due to the results obtained, it was necessary to select the ones where it would be the most advantageous sites to implement the technology and would be the most efficient clusters, allowing to development of an efficient network supply. The criteria used for the selection of the cluster were simple. Only clusters that had their elements being supplied (completely or partially) were chosen. If any element of the clusters was not supplied at all, that group was not considered. This has the purpose of trying to pick the best sites for a first implementation, where all the elements are being supplied with hydrogen. With this, it is obtained the final selection of eleven clusters being them 1, 3, 4, 5, 6, 8, 9, 10, 13, 15, and 16. They can be found marked in the map represented in figure 5.

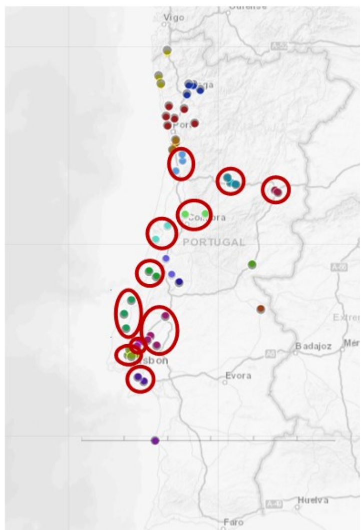

Figure 5: Best sites for refuelling stations.

Taking into consideration those sites, table 1 shows the clusters characteristics, namely it cost of hydrogen implementation and the amount of oxygen, as by-product, that is produced.

Table 1: Clusters information.

Cluster	Implementation Cost (€)	Oxygen Produced (kg)
1	21 214 343 €	39099
3	59 712 469 €	118957
4	140 966 445 €	256000
5	14 480 632 €	28928
6	14 336 269 €	28253
8	79 965 952 €	140276
9	47 087 080 €	82639
10	19 467 658 €	39111
13	10 465 326 €	18879
15	28 486 279 €	48947
16	25 464 121 €	45519
Total	461 646 574 €	846609

Another analysis that is crucial for this work is the study of how oxygen selling affects the costs of hydrogen implementation. Unfortunately, the amount of oxygen produced is massive compared with what the real demand is. In 2019 the total oxygen consumption in the hospital sector was equal to 10766 tons, and according to Infarmed reports, there was a total expense equal to 10 409 294€ [10], which give a cost of around 0.97€/kg of oxygen.

Comparing the perspective of the amount of oxygen that will be produced, 846609 tons, with the amount that is consumed by this sector, it corresponds only to a 1.3% of the total production of the by-product. It is important to have a market competitive price to guarantee that the sector will prefer the oxygen that is produced in Portugal. By decreasing the unit price of oxygen by 0.17€/kg, that will give revenue of 8 613 034€. However, this only saves 1,9% of the entire implementation cost, which would not make the companies invest in the business.

Most heavy-duty trucks work with an internal combustion engine running with diesel fuel. So, assuming that all trucks that are being replaced in this work, in each of the companies, run with diesel fuel, it is possible to compare the diesel consumption in a year and its costs with the hydrogen. A work developed in association with a transportation company, where the consumption of the vehicles was evaluated, it is referred that the desired consumption for a truck is 30L/100km [15]. Knowing the number of trucks that would be replaced and the total number of kilometres they do in a year, it was obtained the total diesel consumption (in a year), for that same amount of vehicles. Assuming the average value of road diesel price given in Pordata, equal to 1.30€/L [17], the total cost of that fuel consumption was obtained. In the same study mentioned it is also presented the costs of acquiring a heavy-duty truck with hydrogen fuel cell technology with a price around 160 000€ [15].

A good tool that helps to understand if this investment is good or not is the Net Present Value (NPV). NPV is calculated through the difference between the present value of cash inflows and outflows, for a while. Can be calculated using the expression with a discount rate equal to 5%.

$$NPV = \sum_{n=1}^{N} \frac{Inflows - Outflows}{(1+r)^n} - I_0 \quad (6)$$

Considering the investment that is necessary to do to acquire all the vehicles and the annual costs of producing and distributing hydrogen, it takes between 3 to 4 years to have some return on that investment. After the 4th year, the companies start to see the financial advantage of changing to hydrogen fuel. The addition of oxygen selling, with the conservative unit cost of 0,80€, will help to down the price. This oxygen selling is considered as an inflow, that is constant per year.

This works focus its attention on 11 production sites (where they can also be considered refuelling stations because they serve other companies) and will provide economic analysis for 10 years.

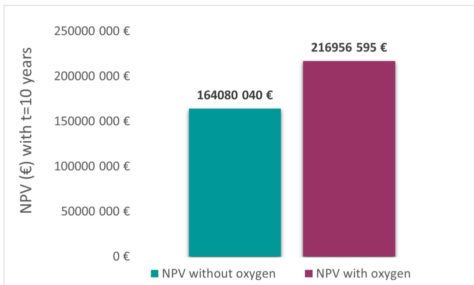

Figure 6: NPV of the project for 10 years, considering and not considering the oxygen selling.

As is possible to verify by the figure 6, the NPV is positive for both scenarios, considering the selling (in dark purple) or not (in green), which indicates that both scenarios are viable cases for a profitable investments.

The Internal Rate of Return (IRR) and the payback time were also analysed.

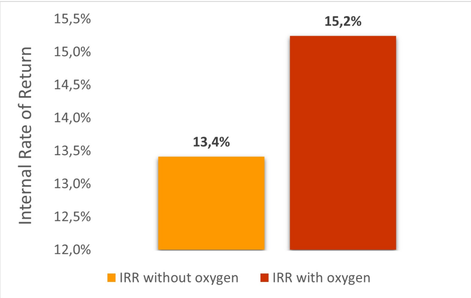

Figure 7: Internal Rate of Return (IRR), considering and not considering the oxygen selling.

For both cases, presented in figure 7, IRR is higher than the rate of return used to calculate the NPV (5% <13,4% and 5% <15,2%), which means that for both cases, selling or not the oxygen, the implementation of the hydrogen network is a good project to invest.

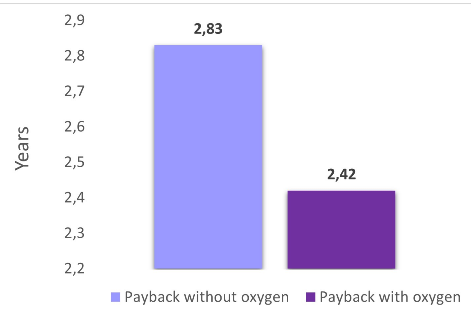

Figure 8: Payback time, considering and not considering the oxygen selling.

As expected, and possible to confirm in figure 8, by selling the oxygen produced as a by-product, the amount of time that is necessary to recover the investment is lower because the selling helps to depreciate the costs.

7. Conclusions

This work intends to help to visualize the economical investment that it would be feasible to implement a green hydrogen decentralized supply grid in Portugal and where would be more advantageous to implement. It is a rough estimation because it is a very simple model but even so, is possible to see that even with the best scenario, where oxygen demand of all hospitals would be satisfied, the hydrogen integration in Portugal would be very costly, and it was only considered a scenario of 56 transport companies, being with a maximum number of producers equal to 11, creating 11 clusters with 2, 3, 4 and 5 elements located in Lisbon (3 clusters), in Santarém (1 cluster), in Leiria (2 clusters), in Coimbra (2 clusters), in Aveiro (1 cluster), in Viseu (1 cluster) and Guarda (1 cluster).

The amount of oxygen produced can easily supply the oxygen demand of all hospitals in Portugal. This would affect other sectors, like gaseous sector, where their main market is selling gas, being oxygen one of them. The market competitiveness would be huge and due to that a competitive price of 0.80€ per kilogram of O_2 was considered, to prioritize the by-product, without needing to appeal to imports, allowing to obtain a revenue equal to 8 613 034 €. Hydrogen is required and Portugal can produce it but the question is what to do with the excess of oxygen. It is necessary to reach new markets and consumers like water treatment stations, pulp industry, glass industry, metallurgic industry. It is also indispensable to reach international markets to be able to leak the excess product that Portugal has.

The savings visualized in diesel costs, having a total value of 511 370 348€ and considering the acquisition of hydrogen fuel cell trucks, can easily transform this project attractive. Looking at NPV results, even not considering the oxygen selling, it was possible to conclude that this was a viable project that would generate profit and with a payback time lower than 3 years (2.83 years). The results obtained for the IRR were also positive (13.4% without selling oxygen and 15.2% by selling it), being higher than the return rate used (5%) for NPV calculations, which helped confirm once again the viability of the network (NPV >0).

The oxygen selling alone is not enough to make the companies adapt the technology but adding the diesel savings, it helps to decrease the costs and decrease the payback time to lower than 2 and a half years (2.42 years). It is important to highlight also the unitary price of hydrogen production that was obtained in this model, assuming the value equal to 3.81€/kg, which is a very competitive price considering the world's average price mentioned previously.

In conclusion, it is possible to see that the implementation of a hydrogen supply chain network is possible and more important, economically attractive in Portugal. Unfortunately, due to the lack of data, and the missing collaboration of Portuguese companies, it was not possible to develop a greater grid and correspond to Portugal intentions of building 50-100 refuelling stations by 2050, which would give about 2 stations per year until 2050 (considering that are still missing 28 years). But, besides being a simple model and a rough approximation, building a network with 11 production sites for the next 10 years showed to be achievable and attractive.

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