Analysing the competitiveness of offshore hydrogen-wind production models

Javier Pollos Ezquerra
javierpollosezquerra@gmail.com
Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Extended Abstract

Green hydrogen (H_2, obtained from renewable energies) production is gaining a lot of popularity in 2020. Its contributions to the energy systems have been recognised by every stakeholder in the field of energy systems. Both governments and companies have announced in the last months massive support to this technology. The combination of offshore wind and H_2 plants for large-scale production of this gas is a field worth to be studied and with tremendous potential for development since both technologies present synergies that can leverage the deployment of offshore wind farms (OWFs) and green H_2 plants. This paper analyses the main options when connecting an OWF to a H_2 production plant and assesses the results based on economic indicators and technical needs. Four cases are defined and compared. The results for the studied cases indicate that, the addition of oxygen (O_2) in the gases sales strategy is necessary to achieve a positive Net Present Value (NPV) with a potential representation of almost 65% of the gases sales. As a result, the case selected as the best option is the production of H_2 in an offshore, dedicated and centralized way with a Levelized Cost of Hydrogen (LCOH) of 5.98 €/kg. Additionally, with the aim of broadening the assessment, a sensitivity analysis is performed regarding the more influential variables that affect the project. Lastly, a potential case study is shown, covering the factors that may arise in the future when H_2 plays a relevant role in the field of energy systems.

1. INTRODUCTION

Being the energy sector as a whole a focus of innovation in recent years, this thesis rises as a response to the numerous movements and expressions of interests that individuals, companies and governments have shown for H_2 since last year. The new H_2 trend started in 2019 on a worldwide scale (Australia, South Korea, China, Japan), but only arrived to Europe in 2020 confirmed through the publication of several roadmaps at country-level. Such interest has been spurred by the EU Hydrogen Strategy announced in July 8th 2020 [1], which aims to use green H_2 to fulfil up to 14 % of its final energy demand by 2050. Many countries have included H_2 targets and roadmaps in their climate plans or stated clear intentions to do so. Moreover, some of the largest energy companies worldwide have made public their intentions to enter in the H_2 market. This fact is especially visible in the growth of the number of associated members to institutions such as Hydrogen Council or Hydrogen Europe have experienced in the last year. As an example, the former has increased its members from 59 to 92, including not only enterprises but also academia and national organizations in only 6 months [2].

This strong momentum for H_2 comes at a time in which this energy carrier is not yet competitive either with fossil fuel or sustainable alternatives, especially for the case of green H_2, where costs need to be drastically reduced to fulfil the above-mentioned EU expectations in a competitive way.

Therefore, even when H_2 is still recognized by the different players to have a long path ahead for cost reduction, most of the stakeholders in the energy sector have aligned in the last months to push for the H_2 development, led by the International Energy Agency (IEA). This lies on the fact that H_2 is the only alternative for the decarbonization of the so-called "hard-to-abate sectors", such as the steel production, high heat production, long-haul transport, or the chemical industry. Here, the reach of electrification is limited, both technically and economically. Hence, these H_2 green molecules can provide a solution for decarbonizing all these sectors [3].

Currently, and as stated by the IEA, there is a clear opportunity to limit the global CO_2 emissions after the COVID-19 pandemic shock [4] and to point these towards the Paris Agreement goals which aim to limit the temperature increase up to 2 ºC above pre-industrial levels while pursuing efforts to limit it even further to 1.5 ºC. In order to achieve this 1.5 ºC target, the Intergovernmental Panel on Climate Change (IPCC) published in its report "Global Warming of 1.5 ºC" that CO_2 emissions should be cut down to zero by 2050 by providing measures to carry it out [5].

Governments have shown disposition to take this chance and turn the COVID pandemic into a shift to a cleaner future.

Once the importance of H_2 as a decarbonization agent to achieve a sustainable energy system is recognised, it is crucial to determine the possible renewable energy sources (RES) that can be coupled to it, offering abundant energy amounts at low prices in order to produce competitive H_2. Both solar PV and onshore wind are among the considered RES that can power the electrolysers [4]. Another technology that is expanding at fast pace and can couple with H_2 is offshore wind. This is a fast-growing industry with the potential of producing 36,000 TWh/year in installations less than 60 m deep and in a range closer than 60 km from shore [6]. Plus, it is expected that the development of floating wind turbines can take this potential even further to 253,000 TWh/year [6].

Levelized Cost of Electricity (LCOE) is projected to decline by nearly 60 % by 2040, to around 50 €/MWh [6], from which half of it would belong to the electricity transmission assets, such as substation or cables. This low price combined with its high value to the system (it is considered as a pseudo-baseload source) will make offshore wind one of the most competitive sources of electricity systems of the future [6].

Therefore, offshore wind shall be considered as one of the main RES to produce the large amounts of H_2 that will be needed to achieve the sustainable future that all nations are looking for. The synergies of these two technologies lie on the high-capacity factors with relatively low prices that Offshore Wind farms (OWFs) could offer to produce H_2.

Hence, the study of OWFs and H_2 production combination arises as an important topic to study. This work aims to explore different configurations of the coupling of these two technologies and provides insights about the possible benefits of these, both in economic and technical terms.

2. THEORY

Offshore wind energy production

Wind energy is one of the fastest growing renewable energy sectors along with solar energy and can make similar contributions to the energy system as coal or gas power plants do (but in a sustainable and cleaner way) due to similar LCOEs and relative high capacity factors, particularly in the offshore wind case [7].

Despite deeper knowledge and experience in the onshore wind sector, offshore is expected to experience a greater rollout in the upcoming years for a total capacity of 560 GW in the sustainable scenario of offshore wind by 2040, compared to 28 GW in 2019 [15].

One of the factors with the highest impact on costs and complexity in the design and construction of OWFs is the water depth. To date, most OWFs have been built in shallow water with no more than 20 meters deep [6]. But as mentioned above, going into deeper waters provides the opportunity of benefiting from a vast resource. Therefore, the possibility of doing so in a cost-effective and technically possible way is being explored.

As it can be observed in Figure 1, the North Sea region and China represent most of the wind offshore capacity added from 2010 to 2018 [6], while they are expected to cope with the highest share of the market in the upcoming years too [8].

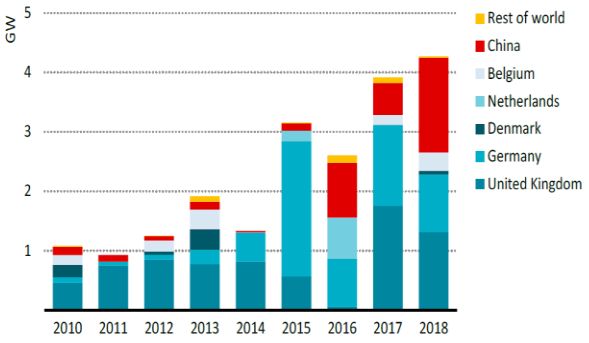

Figure 1 – Annual offshore wind capacity additions by region [6].

The fast development expected for this sector relies not only on the technology improvement, but also in the vast resource it can take advantage of at this stage.

Wind capacity factors above 50 % are available in areas closer than 60 km from shore and wind´s technical potential in these areas is around 36,000 TWh, which is x1.5 the current electricity demand [6].

The wind turbine capacity and the size of the wind farm are immersed is an increasing trend. OWFs size doubled in a decade from 313 MW in 2010 to 621 MW in 2019 and the trend seems to continue in the short term with floating structures which are especially competitive at large water depths where the depth makes the conventional bottom- supported structures non-competitive

H_2

There have been peaks of inflated expectations regarding the H_2 economy in the past. The first demonstrations of water electrolysis and fuel cells took place in the 1800s [3].

The demand for H_2 in its pure form is approximately 70 million tons per year (MtH_2 / year) and it is obtained almost entirely from fossil fuels (6 % of the world's natural gas and 2 % of the world's coal are used to produce H_2) while only 2 % of it is obtained from electrolysis [3]. As a consequence, H_2 production is responsible for the emission of about 830 million tonnes of CO_2 and, in terms of energy, the total annual demand for H_2 worldwide is about 330 Million Tonnes of Oil Equivalent (Mtoe) [3].

H_2 main benefit to the energy systems is its high versatility, which supports a deep integration of RES and the possibility of tackling emissions in several applications. Green H_2 is especially interesting in the so-called hard-to-abate sectors [3], such as chemical industry, long-haul transportation and, among others, steel manufacturing. Nevertheless, its role is different for each case, in the chemical reaction it is used as a feedstock, while in the high-heat production it is used as a fuel [9]. H_2 versatility particularly stands out in the transportation case, where it is expected it will be powering road vehicles and trucks in its pure form (H_2) by its application in fuel cells, or it can combine with other compounds to form synthetic fuels such as kerosene or ammonia (NH_3) to be used in different air and sea transportation methods.

H_2 can be produced using a variety of energy sources and technologies. Global H_2 production today is dominated by the use of fossil fuels. Electrolytic H_2, that is, H_2 produced from water and renewable electricity, plays only a minor role, with 0.1 % of the dedicated H_2 production globally [3].

Electrolysis consists on the separation of the elements of a compound by applying a voltage differential. Therefore, water electrolysis is an electrochemical process that splits water (H_2O) into H_2 and oxygen (O_2). As shown in Equation 1

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1}$$

The main water electrolysis technologies are Alkaline Electrolysis (AEL), Polymer Electrolyte Membrane Electrolysis (PEMEL) and Solid Oxide Electrolysis (SOEL).

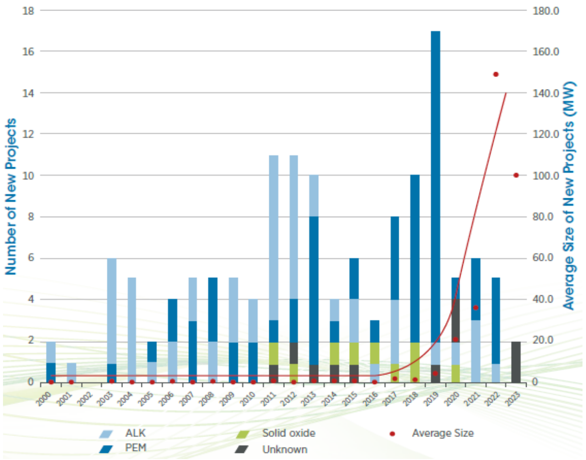

Figure 2 – Timeline of power-to-H_2 projects by electrolyser technology and project scale [11].

When H_2 is produced by water electrolysis process, O_2 is also produced simultaneously as a by-product of H_2 and 1 kg of H_2 implies the production of 8 kg of O_2. Although the main driver of this report is the H_2 production, the potential of selling O_2 is also assessed, paying special attention to its effect on the overall economics of the project [10].

Markets for H_2 / O_2

Nowadays, the majority of the H_2 (pure and mixed) is used in only three industrial sectors: oil refining (33 %), chemicals (NH_3 production 27 %, methanol production 11 %) and metals (iron and steel 3 %). However, the H_2 used in these sectors comes mostly from fossil fuels, having a negative impact in the environment providing a potential market for H_2 coming from cleaner pathways such as blue or green H_2 coming from electrolysis [12]. H_2 irruption in the future energy systems will open up new markets for this molecule.

O_2 is a colourless and odourless gas essential for living, it accounts around 21 % of the earth's atmosphere and is the most abundant element in the earth's crust [13]. It has the ability to optimise the performance of several industrial applications, such as combustion processes, also it can help to reduce costs and carbon footprint for many different applications [13].

One important characteristic of this project and a significant differentiation with similar studies consists on the addition of the O_2 as a value product of the process. It is important to mention that 8 kg of O_2 are produced per kg of H_2.

Although some previous works have shown that the sales of O_2 produced during electrolysis can reduce the O_2 sales prices, it is not considered that the produced volumes would saturate most markets, but in fact the reality is that the O_2 has multiple applications and the demand will increase in the upcoming years [14].

3. METHODOLOGY AND DATA

In order to analyse and optimize the offshore wind-to-hydrogen system, this project´s objective is to obtain H_2 from wind energy (coupling concept), based on three main systems as follows:

- System 1: Electricity generation
- System 2: H_2 production
- System 3: Transportation and storage of H_2 and electricity transmission.

Firstly, prior to the analysis of each system, its general conditions and the assumptions made are described for every scenario.

The reference date considered as the starting point of the project is year 2020. In this sense, it shall be noted that both the data and its treatment have not taken into account the Covid-19 crisis and its consequences in the short and medium term. Legal issues, delays or other external factors are not considered at this stage, being these additional factors that could be considered in further studies.

The North Sea, off the UK coast, has been selected for the location of the project. This election has been motivated by the privileged environmental conditions that it offers, such as its good wind resource, its shallow sea depth and the UK intention of supporting renewable projects in the next years [15].

The studied cases are presented below (Figure 3, Figure 4, Figure 5, and Figure 6):

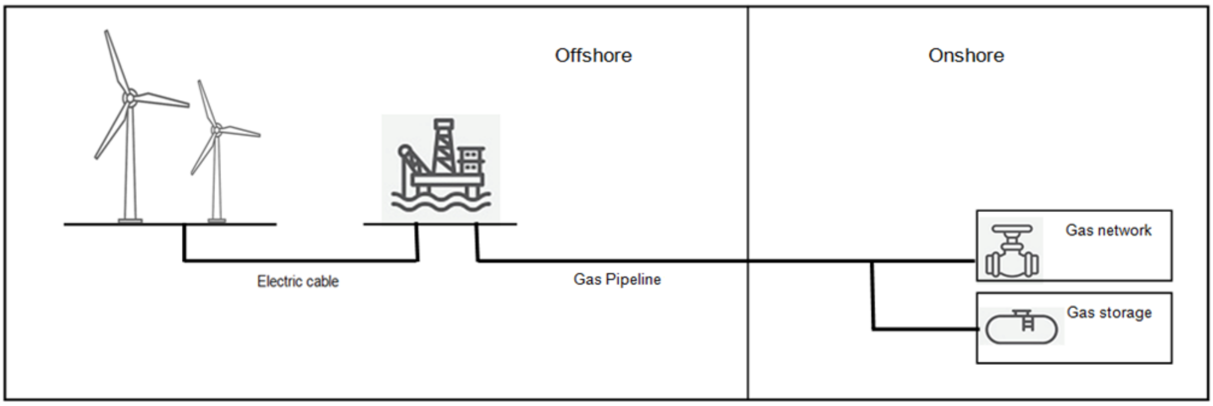

Figure 3 – Case scenario 0 diagram: Centralised and dedicated H_2 production on an offshore platform.

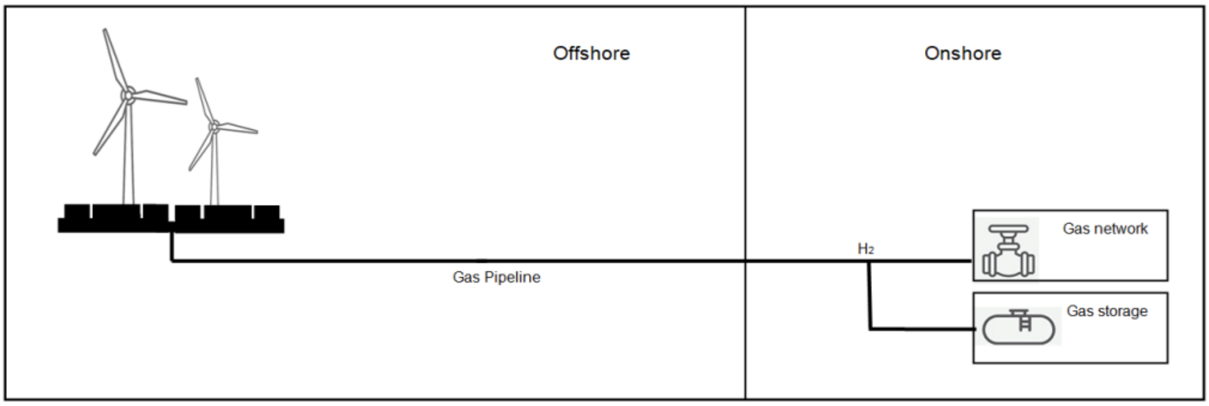

Figure 4 – Case scenario 1 diagram: Decentralized and dedicated H_2 production on wind turbines.

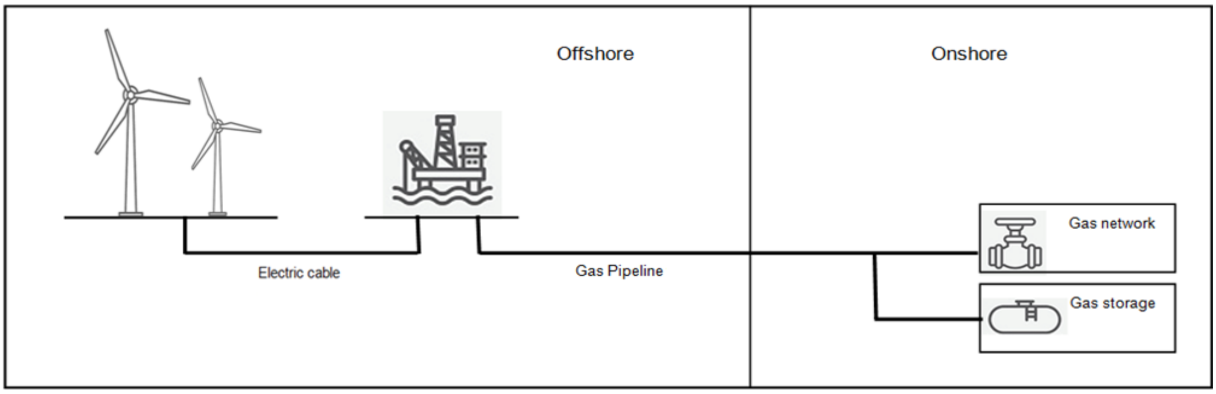

Figure 5 – Case scenario 2 diagram: Centralised and curtailed H_2 production on an offshore platform.

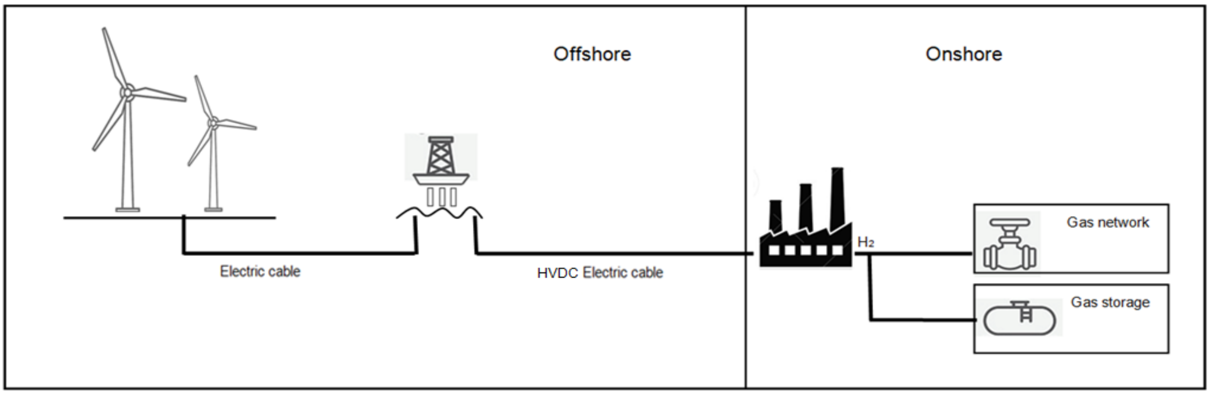

Figure 6 – Case scenario 3 diagram: Centralised and dedicated H_2 production onshore.

4. RESULTS

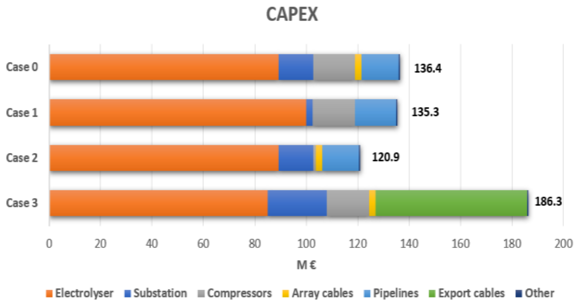

Figure 7 – CAPEX Breakdown results.

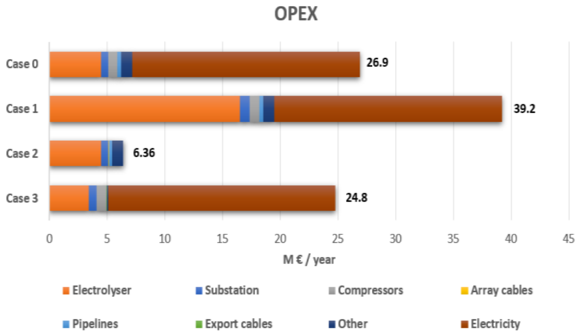

Figure 8 – OPEX Breakdown results.

Figure 7 shows that the case with the highest CAPEX is Case 3 (186.3 M€) and the lowest one is Case 2 (120.9 M€), while Case 1 and Case 2 are very similar (136.4 M€ & 135.3 M€). This is principally due to the fact that in Case 3 the inclusion of export cables for electricity plus the need to maintain an electrical offshore substation anyways makes the costs soar.

Figure 8 summarises the annual OPEX for every case. It can be observed how Case 1 has the highest annual OPEX (39.2 M€/year) while, again, as it occurs with CAPEX, Case 2 offers the lowest costs (7.2 M€/year) and both Case 0 and Case 3 are similar (26.9 M€/year & 24.8 M€/year). The reason for Case 1 to have such high costs is due to the fact that most of the systems are distributed in the different wind turbines making it more expensive, while again Case 2 has lower CAPEX due to a smaller system and much lesser electricity consumption.

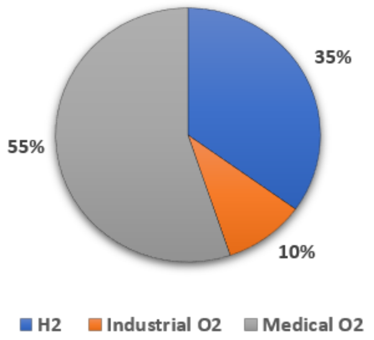

Figure 9 – Gases repercussion on sales (%).

Figure 9 presents the effect on the sales of the different gases produced. Although, O_2 is produced 7.9 times more than H_2, it does not have the same impact on the sales. On the O_2 side, medical O_2, due to its higher price, dominates the sales, while the industrial one sold in a 9:1 ratio represent just a discrete 10%. Finally, H_2 shows a relevant 35% over the total.

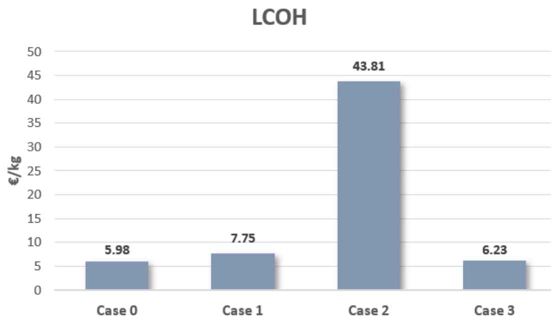

Figure 10 – LCOH results.

Figure 10 presents the LCOH results for each of the cases. On the one hand, Case 2 has the highest cost per kg of H_2 production, being above 43 €/kg H_2 and being up to 5 times more expensive than the rest of the cases. It is important to remark that LCOH is not a fair comparison for Case 2, because it also relies on the sales of electricity. Although it is the case that has the lowest CAPEX and OPEX, it is the one with the lowest production too. Therefore, it is concluded that a project of these characteristics has certain fixed costs that are very high and just by taking advantage of free electricity the fixed costs do not dilute.

On the other hand, Case 0 has the lowest LCOH being 5.98 €/kg, less than Case 1 and Case 3 with 7.75 €/kg and 6.23 €/kg, respectively. Case 1 is particularly interesting, since OPEX affects heavily the final LCOH. However, Case 0 is even more interesting than the others in terms of LCOH, including additionally more reliability due to its centralised configuration.

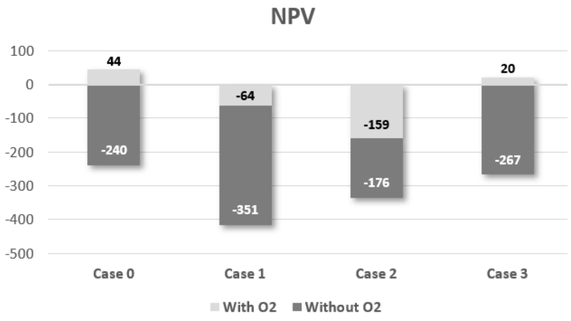

Figure 11 – NPV results.

Figure 11 presents the NPV results of the different cases, differentiating between the option of selling H_2 only and the option of combining it with O_2, in order to emphasize the importance that the incorporation of O_2 can have in the economic results.

At first glance the results show that none of the cases present a positive NPV with the sales of H_2, however H_2 together with O_2 allows the NPV to become positive.

For cases 0, 1 and 3 adding the O_2 to the sales is determinant to make the NPV turn into positive and therefore making the project viable under the assumptions presented. Amongst these three mentioned cases, Case 0 and Case 3 are the most attractive projects. On the other hand, Case 2 does not lead to a positive NPV, not even with the addition of the O_2, making it a non-recommended investing project from a NPV point of view

Table 1 – IRR results.

	Gas production (ton/year)			
	Case 0	**Case 1**	**Case 2**	**Case 3**
IRR	10.62 %	0.10 %	-	8.20 %

As regards the IRR, Table 1 shows the estimated values for each project. The only case with a non-possible IRR value is Case 2. In this option, by definition, the IRR does not exist since the NPV does not equal zero but is always negative. Table 1 shows that for market interest rates below 10.62 % Case 0 would be a suitable investment as the NPV would result positive, in the same sense Case 3 would present a positive NPV when the market interest rate is below 8.2 %. Finally, Case 1 would only present positive NPV with interest rates below 0.1%.

5. ANALYSIS

Once the different cases have been analysed and compared, it is concluded that Case 0 is the most advantageous option, while Case 2 is a possibility that does not make sense from an economic perspective. This is particularly interesting since it is heard many times that H_2 could store the curtailed electricity of a system/country while the results shown in this work prove that this is not viable at this stage.

From an economic point of view, Case 0 has acceptable OPEX and CAPEX as compared to the other alternatives, the production of gases is similar to the other options and lastly and most importantly, the indicators of LCOH and NPV places Case 0 as the best option among the ones presented. Its LCOH is in line with the best current indications for the cost of producing H_2 from OWFs in Europe REF.

Moreover, Case 0 offers several advantages that are welcome in new concepts with high uncertainties, such as the topic under discussion in this paper. For instance, a centralised location may ease all the maintenance activities.

<u>Case improvement</u>

An optimization of the electrolyser capacity is highly recommendable, since this work considers a direct relation of 1 MW of this capacity per 1 MW of wind capacity. In order to be more efficient, the ideal would be to have a lower capacity electrolyser since, in addition to the losses in electricity transmission and the electrical substation, most of the time the wind turbines are not operating at their maximum power, so a reduction of electrolyser would lead to savings without significantly affecting the production of gases.

The choice of a more specific location than the one chosen in Case 0 could lead to improvement and lower costs in some of the structures or their best use. A greater distance to the coast would make the pipes even more economically attractive than the cables, while selecting a shorter distance to the coast would have the opposite effect. In addition, placing the H_2 production plant in areas with existing oil rigs can save up costs both in pipelines and structures, by reusing already existing infrastructures.

Better integration of the systems is needed in order to further optimise the overall project. If the production is centralised, different systems that are actually accounted as independent units can offer synergies such as use of waste heat to keep the stack in stand-by mode or a centralised power conditioning unit for all the equipment. This needs further study in all the processes and the requirements shall be set for each unit.

Finally, it is fundamental to take advantage of the high quality of the gases that are produced via electrolysis. These gases, with a very high purity, are demanded in more specialized markets such as electronics or healthcare systems, where in exchange of purity the prices are increased considerably, and therefore this fact would multiply the revenues.

<u>Alternative scenario (Case Z)</u>

The following is intended to show the results of a possible scenario that takes into account some factors that are expected to change in the coming years and that would require a new study with the new variables. Meanwhile, the intention with an invented scenario (Case Z) is to predict what could be the context of a project with the same characteristics. In Case Z, the cost of electricity from the OWF 35 €/MWh, it is assumed that a reduction in the price of the electrolyser of 40 % occurs, the price of all gases is reduced by 50% and the sales of O_2 are divided equally between medicinal use and industrial use. Table 2 shows the comparison between the new scenario and Case 0, previously analysed.

Table 2 – Alternative scenario results. Case 0 vs Case Z

	Case 0	Case Z	Units
LCOH	5.98	4.33	€/kg
NPV	44	405	
Payback	6.90	1.85	years
CAPEX	136.39	100.74	M€
OPEX	26.88	19.19	M€/year

The results show how the combination of cost reductions and optimization of the sales can boost the profitability of these projects, with special focus on the O_2 sales as a main contributor to this new competitiveness.

6. CONCLUSIONS & SUGGESTIONS FOR FURTHER RESEARCH

OWFs and H_2 production constitute an area within the energy sector which is extremely worthy to be studied. Taking advantage of the vast offshore wind resource for H_2 production can provide economies with abundant and price-competitive resources, and the potential contributions the two sectors may offer to the energy systems go far beyond the constraints and challenges that they present in the short term.

Special consideration must be given to the synergies of these two technologies. For instance, the possibility of linking both factors in DC current would lower the costs for both applications. Moreover, technologies such as PEM are well suited for electricity input variations such as the ones experienced from wind supply. There are concepts such as the decentralised production that are very prone to experience further cost reductions as Original Equipment Manufacturers (OEMs) of both technologies develop joint projects. Both from erasing redundant systems and by proving that the equipment works properly in an offshore environment.

Additionally, another interesting insight is how important O_2 is for the H_2 projects to be feasible. O_2 is a valuable gas both for industry and health, which are markets that currently belong to few operators who are reticent to share the selling costs of this gas due to the high margins they obtain. However, O_2 production from electrolysis offers high qualities at “low” production costs, being therefore O_2 highlighted as one key enabler for the rollout of H_2 projects.

In this project, as conclusions drawn, centralised production arises as the most promising technology for the current state-of-the-art, since it allows for cheaper maintenance and enables development of economies of scale. Decentralised production incurs into higher OPEX due to manned labour hours but nonetheless, it is argued that remote control of the equipment and predictive maintenance shall play a key role in these activities, rising the competitiveness of this method.

Conversely, curtailed production from OWFs is shown as a not a feasible option. Moreover, the increasing presence of smart grids is expected to reduce the hours of free electricity. H_2 is not an option for excess electricity at small scale.

While production in land is competitive in the current context, as time goes by, OWFs LCOE is expected to be greatly reduced, overall by the fact that WACCs are expected to shrink and the technologies are believed to be improved and produced more cheaply. Transmission assets, by contrast, are not prone to experience these cost reductions. Therefore, by 2040, almost half of the LCOE from an OWF will be related to the transmission assets. This will incur into a loss of competitiveness from this method.

As additional remarks and next steps, it must be noted that data used in the report are requested for the calculations and refer to the minimum requirements for the project, this is, that assuming better resources would lead to better results. For this report, the following hypothesis have been considered: commissioning and decommissioning periods have not been taken into account, no faults or delays throughout the project lifetime are considered, the gases produced are totally sold and the market value stable throughout the project lifetime and no other alternative incomes or debt effects are considered. Hence, to carry out a more detailed analysis of this baseline project as a next step or of any of the scenarios and systems that are presented, it is necessary to update the data used and understand its meaning and assumptions, since the project is developed in a conditioned environment, due to the continuous change of technologies and their rapid evolution as well as to the influence external factors such as political and social reasons.

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