Techno-economic assessment of hydrogen offloading systems for offshore wind farms

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Abstract

Offshore wind with H_2 production is an interesting topic being currently explored, offering good capacity factors and low-price electricity for cheap H_2 production. This work studies the competitiveness of different pathways of producing and exporting offshore H_2, by performing a techno-economic assessment of these cases, including H_2 production costs, NPV of the project and their energy efficiency, with special focus on the offloading options to export H_2 for its final use. Among the studied pathways, the use of pipelines to transport H_2 seems to be the best solution, providing a LCOH of 5,35 €/kgH_2 for the baseline case, whereas it has the potential of being as low as 2,17 €/kgH_2 if the EU support to H_2 deployment is successful and achieves its targets. The energy requirement for this pathway is 0,46 MWh/MWhH_2, being one of the less energy intensive methods, due to less conversion steps. Another key insight of this work is that considering the market value of O_2 can improve greatly the economics and viability of the project. Also, a sensitivity analysis is performed to the more influential variables, showing that LCOH is very dependent on the costs of electricity and electrolyzer costs. H_2 has the potential to cut its price to a point in which its application can be competitive in several markets, reaching a H_2 demand of 666 Mt per year, 950% more than the current dedicated production.

1. INTRODUCTION

Green Hydrogen (H_2)[1] arises as one of the main pillars in order to fully decarbonize the energy systems due to its versatility, which allows its use in many different applications, namely as an energy storage medium [1], as fuel for transportation, as an electricity generation fuel or even be used as feedstock for several chemical (e.g. ammonia, methanol, plastics) or metallurgic processes without any associated CO_2 emission [2]. In a decarbonized energy system, H_2 must come from renewable energy sources (RES) in order to guarantee long-term sustainability. Offshore wind energy is one of the most important RES that offers significant synergies with H_2 [3].

H_2 could support the integration of wind energy by avoiding power curtailments, electricity grid congestions and by improving the system reliability in remote areas [4]. Moreover, it offers possibilities

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[1] Green H_2 is used for the production of H_2 from renewable energy sources

for the exploitation of RES in areas where transmission lines do not exist or are saturated [3].

H_2 production costs vary greatly between different countries due to different availability of their resources, in Europe, H_2 produced from natural gas would cost between 1,75–2,3 €/kgH_2 depending on whether Carbon Capture, Utilization and Sequestration (CCUS) is used (Blue H_2[2]) or not (Grey H_2[3]), while in the US these costs would drop to 1-1,5 €/kgH_2 [5].

H_2 dedicated production nowadays goes up to 70 Mt every year. The top four single uses of H_2 today are **oil refining** (33 %), **ammonia production** (27 %), **methanol production** (11 %) and **steel production** (3 %). All this H_2 is produced from fossil fuels, 76 % from natural gas and almost all the rest 23 % from coal [5].

RES irruption in the energy systems and concerns about sustainability are creating new opportunities for H_2 in order to expand into markets. In **transportation**, H_2 has the potential to be competitive in the market associated to heavier vehicles and higher ranges. A complete adoption of H_2 in this market would require around 200 Mt of H_2 by 2030 [6]. For the case of maritime applications, NH_3 or H_2 adoption by 2050 would require 500 Mt of NH_3 or 88 Mt of H_2 [5]. As for aviation, it is expected to require 20 Mt of H_2 by 2040 [7].

Another opportunity arises in **buildings**, by 2030, 12 to 20 Mt of H_2 could be consumed in the main markets [5]. For **industry**, H_2 could play a role in providing **heat** above 100ºC. In the **power sector**, H_2 can contribute to the power sector as an energy storage medium or as a power generator. For power production in peak power plants, H_2 competes with alternatives such as natural gas turbines equipped with CCUS or running on biogas [5].

With such market potential in future decades, the coupling of offshore wind with H_2 production arises as a viable opportunity, these two new technologies have huge potential in helping the decarbonization of society, but these synergies, challenges and potential of their integration need to be assessed. In this context, this work aims to study the coupling of H_2 and offshore wind competitiveness by proposing different pathways of producing and exporting H_2, a techno-economic assessment of these cases is performed, including the H_2 production costs, NPV of the project and their energy efficiency, with special focus on the offloading options to export H_2 for its final use.

2. DATA AND METHODS

The methodology used for the modelling of this work is based on a techno-economic approach to the different alternatives considered for the H_2 production, conversion and transportation from an offshore facility powered by an offshore wind farm. Methodology is schemed in Figure 1.

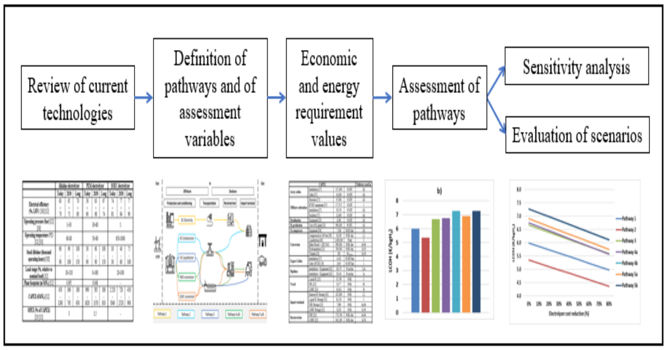

Figure 1 Methodology of the work

2.1 Characterization of technologies

Growing climate concerns pinpoint the need of clean **H_2 production**. Using RES, H_2 production

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[2] Blue H_2 is used for the production of H_2 from fossil fuels with CO_2 emissions reduced by the use of CCUS

[3] Grey H_2 refers to the production of hydrogen from fossil fuels without any kind of CO_2 capture

can be obtained by electrolysis process, providing a sustainable and high purity product [8].

Water electrolysis is an electrochemical process that breaks the water molecules into H_2 and O_2, using electricity in order to induce this process [5]. The theoretical energy needed in order to produce 1 kg of H_2 is 39,699 kWh or 142,1 MJ [9]. Different electrolytic technologies are available to produce H_2. Alkaline electrolysis is a well-known technology and, currently, the one with more installed capacity (MW) for commercial applications worldwide [8]. Another possibility is solid oxide electrolysis (SOE), which is the least developed electrolysis technology. It is mostly under research stage, with no commercial projects running yet [5]. The third technology is proton exchange electrolysis (PEM), this is already at a commercial level and it offers good performance under variable input of RES and the cost reduction possibilities [10].

Regarding the **offloading of H_2**, once produced H_2 has to be transported to its consumers. In this study the focus is to determine what is the best way to do it. For this, three sorts of molecules are considered, which will be explored in this work. **Pure H_2**, which can be transported either in gaseous form (by pipelines) or in liquid form (vessels). **Ammonia (NH_3)** and **Liquid Organic Hydrogen Carriers (LOHC)**.

2.2 Definition of H_2 offloading pathways

Since the main goal of this work is to provide a techno-economic assessment on the different pathways that exist in order to export H_2 from an offshore facility to shore, the focus is in the H_2 production and transportation.

Figure 2 represents the system including physical boundaries and the main scheme of H_2 production and transportation logistics.

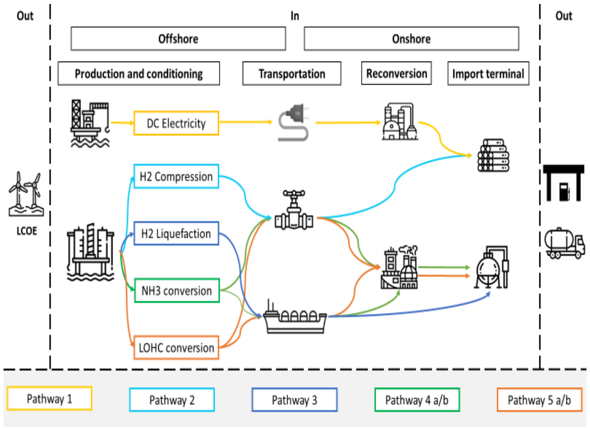

*Figure 2 Explored pathways scheme. *Pathway 1 reconversion stands for inland H2 production. Pathways 4a and 5a explore the transportation by pipeline, while Pathways 4b and 5b assess the vessel exportation.*

Five possible pathways are analyzed, **Pathway 1** (Inland H_2 production) explores a case in which electricity is transported inland, where the H_2 is produced in a dedicated production plant, as seen in yellow in Figure 2. **Pathway 2** explores the offshore production of H_2 and its posterior transportation via pipeline as a compressed gas. As seen in light blue in Figure 2. **Pathway 3** is based in the H_2 offshore production and liquefaction in order to be exported by boat. It is represented by the dark blue line in Figure 2. **Pathway 4** explores the benefits of converting H_2 into NH_3 for an easier and cheaper transportation and storage. Represented in green color in Figure 2. NH_3 transportation towards mainland is explored both by pipeline (**Pathway 4a**) and by boat (**Pathway 4b**), being liquid NH_3 in both cases. Once the NH_3 reaches the import terminal, it is stored as liquid NH_3 and reconverted to H_2. The last configuration is **Pathway 5**, this case explores the benefits of loading H_2 into LOHC for an easier and cheaper transportation and storage. It is represented in orange color in Figure 2. LHOC transportation towards mainland is explored both by pipeline (**Pathway 5a**) and boat (**Pathway 5b**). Once the LHOC reaches the import terminal, it is stored and reconverted to H_2 through the dehydrogenation process in the reconversion plant.

2.3 Definition of economic and energy efficiency considerations

The baseline scenario is projected to be an offshore wind farm placed 50 km from shore, with a nominal capacity of 100 MW and a capacity factor of 0,5. H_2 production technology is always considered to be PEM due to its better features for offshore applications (more compact) and its better performance with variable electricity inputs. The selected electrolyzer system efficiency is 60 % according to literature for current projects [5].

2.4 Sensitivity analysis and definition of scenarios

The analyzed pathways are assessed for a specific offshore wind farm, being the physical and economic configuration explained in Section 2.2. Some of the variables that are observed to influence the final LCOH and NPV are analyzed more in depth by studying their influence carrying out a sensitivity analysis. These factors are summarized in Table 1.

Table 1 Variables included in the sensitivity analysis

Tested variable	Min value	Max value	Units
Electrolyzer system costs	200	990	€/kW$_e$
Electrolyzer efficiency	60	90	%
LCOE	20	70	€/MWh
Distance to shore	50	500	km
Capacity factor	44	64	%
Income Tax Rate	10	34	%

2.5 Definition of scenarios

Two possible futures are studied in order to understand where H_2 can position in the upcoming years.

Scenario 1 is a technology driven case, in which both H_2 and offshore wind development follow the estimations of the already mentioned reports. **Scenario 2** covers a future in which the technology does not only follow a market driven development but also acceleration in innovation and higher cost reductions due to a mass scale adoption boosted by supporting policies such as the European Hydrogen Strategy [11]. These values considered for the different variables are stated in Table 2.

Table 2 Selected values for Scenarios 1 and 2

Scenario	Baseline case	Scenario 1	Scenario 2
LCOE (€/MWh)	50	20	20
Electrolyzer cost (€/kW)	990	585	200
Electrolyzer efficiency	60	68	82

3. RESULTS

The results are shown for the baseline scenario. Energy expenditure, LCOH and NPV are shown. After, the sensitivity analysis results are presented, followed by the results of future possible scenarios (Scenario 1 and 2).

3.1 Assessment of hydrogen offloading pathways

The energy expenditure results (see Figure 3) provides a good vision of how much energy is used, it is easily appreciable that the energy carriers (Pathways 4a/b and 5a/b) represent higher energy losses. This fact is mainly due to the high energy requirements that the reconversion steps require. These numbers compare against the energy expenditure of the state-of-the-art steam reforming plant, which requires around 1,2 MWh/MWhH_2 [12].

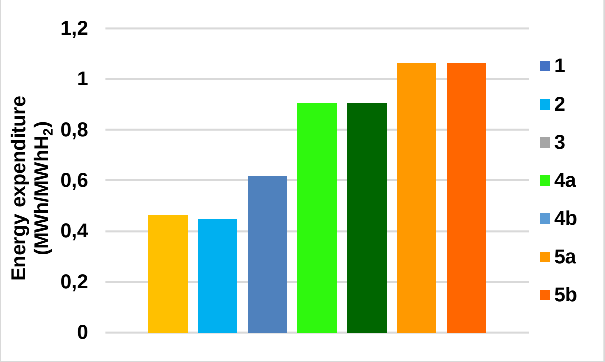

Figure 3 Energy expenditure (MWh/MWhH$_2$) along the process for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H$_2$ Compression; Pathway 3 - H$_2$ Liquefaction; Pathway 4a - NH$_3$ Pipeline; Pathway 4b - NH$_3$ Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

High energy inputs and final product losses in the reconversion units raise the LCOH for NH$_3$ and LOHC pathways. Since these reach costs of 7,27 €/kgH$_2$. Compared to 5,35 €/kgH$_2$ in Pathway 2 (CH$_2$ transportation) (see Figure 4). LCOH can be broken down in order to understand the weight that every factor has on it, as shown in Figure 4, where it is divided into the different steps of the supply chain shown in Figure 2.

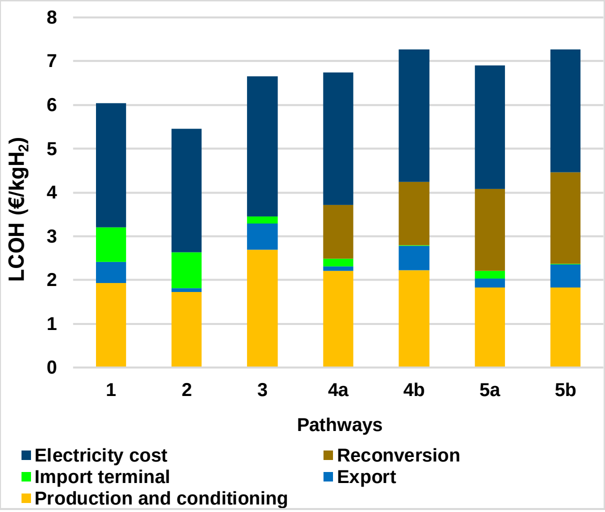

Figure 4 LCOH (€/kgH$_2$) cost breakdown for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H$_2$ Compression; Pathway 3 - H$_2$ Liquefaction; Pathway 4a - NH$_3$ Pipeline; Pathway 4b - NH$_3$ Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

O$_2$ sales are considered in the NPV calculation. These sales effects are analyzed two different selling prices, 100 €/tO$_2$ and 280 €/tO$_2$ [13] [14].

In order to see the O$_2$ sales importance, Figure 5 compares the NPV for three different cases. Showing how the NPV becomes positive thanks to the commercialization of this by-product.

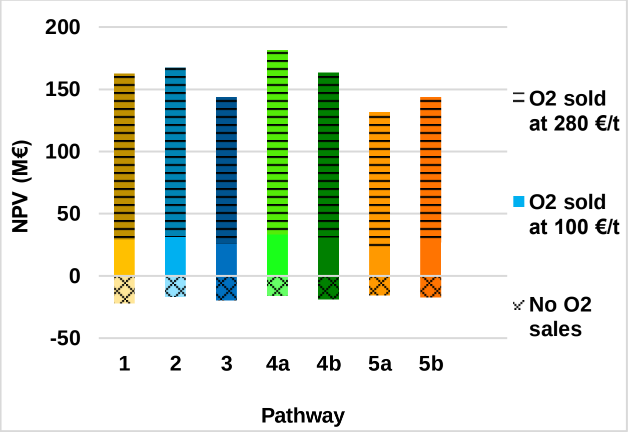

Figure 5 NPV (M€) in the baseline scenario for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H$_2$ Compression; Pathway 3 - H$_2$ Liquefaction; Pathway 4a - NH$_3$ Pipeline; Pathway 4b - NH$_3$ Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

3.2 Sensitivity analysis

Sensitivity analyses are performed on the different variables that may affect the LCOH and NPV.

Electrolyzer cost is the first tested variable in the sensitivity analysis, as presented in Figure 6. In average, the different pathways experience 17,7 % LCOH reduction. This states the importance of electrolyzers as one of the main contributors to H$_2$ costs. However, it also evidences that electrolyzer cost reduction itself may not lead H$_2$ to a point where it is cost competitive with many applications.

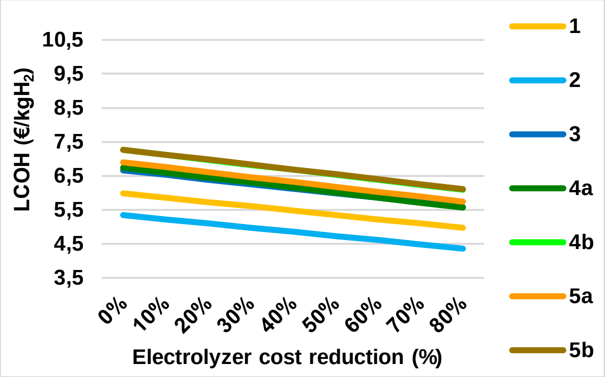

Figure 6 LCOH (€/kgH$_2$) sensitivity on electrolyzer cost reduction (%) for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

The best case is still for CH_2, where LCOH falls down to 4,36 €/kgH$_2$. Some other pathways, such as Pathway 5a offer a slightly steeper decline in LCOH, due to the higher weight of the electrolyzer systems in the CAPEX of the whole system than for example Pathway 3, where high costs of the vessel and the liquefaction system dilute the electrolyzer weight on the CAPEX.

For the **capacity factor** analysis, as presented in Figure 7. Inland production case (Pathway 1) is the most benefited by a capacity factor increase, due to a better utilization of the infrastructure that represents the higher CAPEX of all the possible paths. This one seems to be the factor with major weight in the cost reduction, since the major cuts in the LCOH are for those pathways with more CAPEX such as liquid H_2 transportation and NH_3 transportation by vessel (Pathways 3 and 4b).

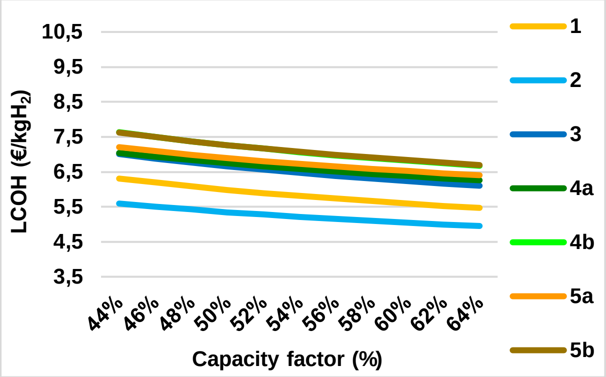

Figure 7 LCOH (€/kgH$_2$) sensitivity on capacity factor (%) for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

LCOE is the largest contributor to LCOH. Cases with lower CAPEX show more sensitivity to price variations in the electricity input (See Figure 8). Cost reductions vary from 27,2-31,5 % in all the cases, reaching levels as low as 3,66 €/kgH$_2$ for Pathway 2.

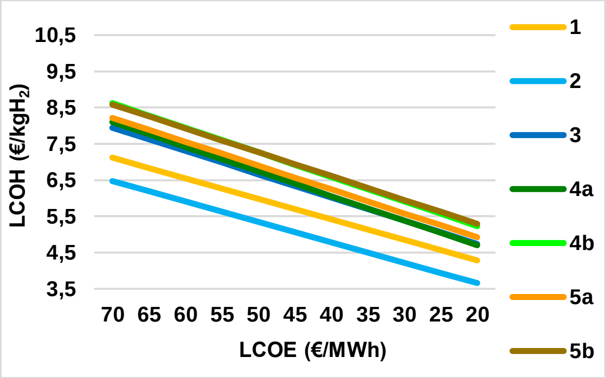

Figure 8 LCOH (€/kgH2) sensitivity on LCOE (€/MWh) for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

Distance to shore is a parameter that affects specially the cases than rely on pipelines or cables, since the material cost influences greatly the final investment. This is easily visible in the Figure 9 where the steeper lines correspond to the inland production method and the LHOC transportation by pipeline. This provides a key insight, which discards these methods when distances are above 100-150 km in comparison with the other alternatives. Also, higher distances represent more complexity in terms of installation. Specially interesting is the case of LOHC transportation by pipeline since, even offering smaller diameters for the same amount of transported hydrogen, it represents huge variations in the prices from 5-500 km. This is due to the already explained fact that this method needs a return pipe to transport the organic carrier back to the platform, doubling therefore the price. The O_2 transportation by pipelines also produces these methods to be less competitive in larger distances, due to more installation and material costs.

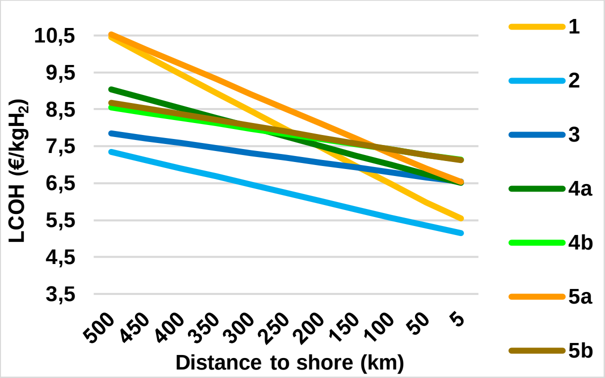

Figure 9 LCOH (€/kgH_2) sensitivity on distance to shore (km) for every pathway. (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

Electrolyzer efficiency improvement has an effect in many areas of the systems, mainly produced by a higher amount of H_2 produced, what incurs into higher sales, but also bigger size of the storage tanks, diameter of the pipelines, size of the boats, etc. (See Figure 10).

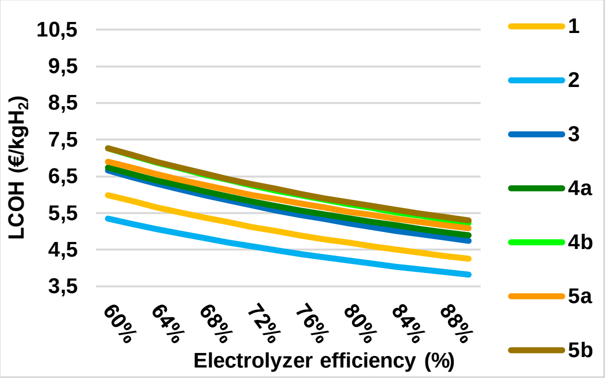

Figure 10 LCOH (€/kgH_2) sensitivity on electrolyzer efficiency (%). (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

However, it is clearly visible that this variable is strongly beneficial for all the cases, achieving cost reductions between 26,3-28,9 % in all the cases.

In terms of the **sensitivity analysis for the NPV**, in the baseline scenario, it was shown how NPV without O_2 sales would be negative because of the influence of **income taxes** on the economics of the project. Figure 11 shows the influence of this tax in the economic viability of the project when the selling cost of H_2 is equal to the LCOH and the O_2 is 100 €/tO_2.

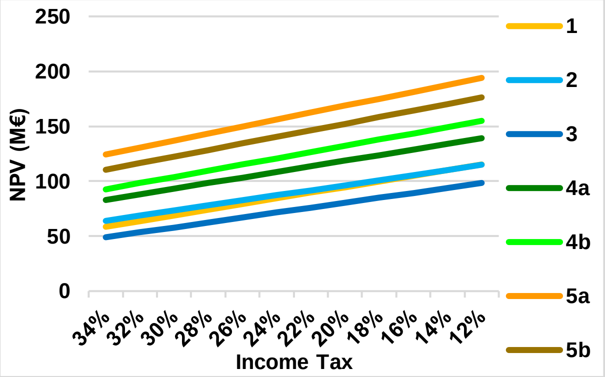

Figure 11 NPV (M€) sensitivity on Income Tax (%). (Pathway 1 - DC Electricity; Pathway 2 - H_2 Compression; Pathway 3 - H_2 Liquefaction; Pathway 4a - NH_3 Pipeline; Pathway 4b - NH_3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

A key insight from this analysis highlights how country-dependent the viability of such a project can be since higher income taxes will incur into higher costs of the H_2 sold or subsidies required.

3.3 Assessment of scenarios

The results for the two scenarios are presented next. **Scenario** results are shown in Figure 12:

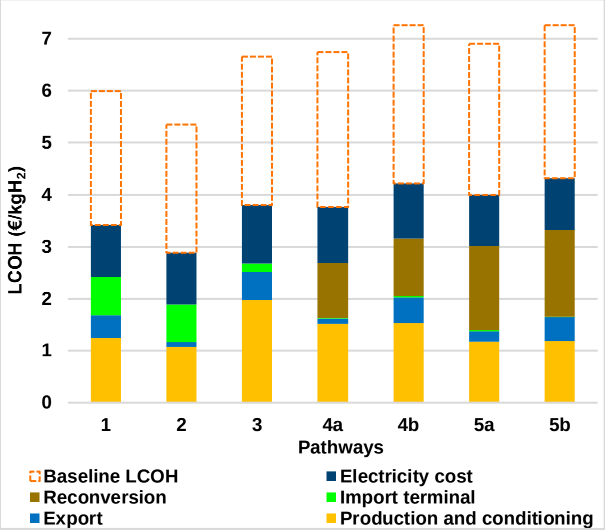

Figure 12 LCOH (€/kgH$_2$) breakdown for Scenario 1. (Pathway 1 - DC Electricity; Pathway 2 - H$_2$ Compression; Pathway 3 - H$_2$ Liquefaction; Pathway 4a - NH$_3$ Pipeline; Pathway 4b - NH$_3$ Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

These new LCOH are much lower than for the baseline case, opening possibilities for the introduction of H$_2$ in newer and bigger markets, as explained in Section 0. There is cost reduction compared to the baseline scenario for every pathway of between 40-46 %. Without consideration of additional costs due to distribution and fueling inland, Pathway 2 could address a demand of between 83-167 Mt of H$_2$ opening up a market of 449 billion € if H$_2$ were to be sold at 2,88 €/kgH$_2$. In all the pathways, current demand of H$_2$ is overpassed.

The complete reduction of the storage cost of 0,73 €/kgH$_2$ of gaseous H$_2$ could bring the prices down in Pathway 2 to 2,13 €/kg, reaching a market potential of around 749 billion €. Generating a market size of 333 Mt of H$_2$. Pathway 1 would drop to 2,69 €/kgH$_2$, a spot in which has a market size of 449 billion €.

Scenario 2 LCOH results are as indicated in Figure 13.

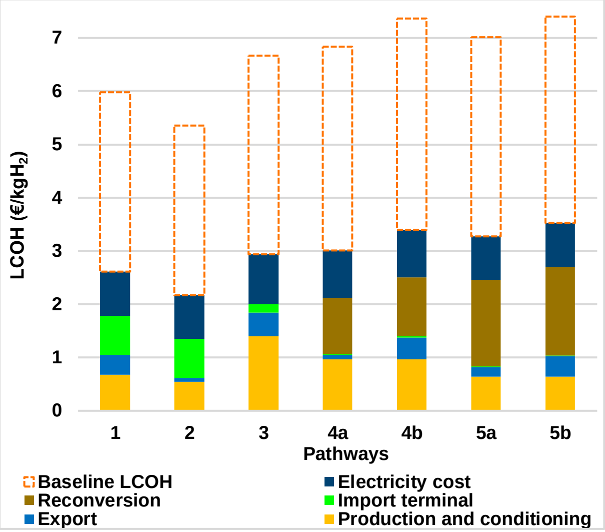

Figure 13 LCOH (€/kgH$_2$) breakdown for Scenario 2. (Pathway 1 - DC Electricity; Pathway 2 - H2 Compression; Pathway 3 - H2 Liquefaction; Pathway 4a - NH3 Pipeline; Pathway 4b - NH3 Vessel; Pathway 5a - LOHC Pipeline; Pathway 5b - LOHC Vessel)

These costs for H$_2$ production allow to envision where this technology can be in the medium term, reaching target costs much sooner than expected, addressing thus more sectors than what previously though. Public support, providing market signals and security for the investments will drive H$_2$ to cost reductions of 53-59 % in all the studied pathways, achieving prices as low as 2,17 €/kgH$_2$ for Pathway 2.

These costs round between 2,17 and 3,40 €/kgH$_2$ being able to address, in the best cases, more than 333 Mt of green H$_2$ demand, generating a market opportunity of 749 billion €. However, significant improvements can be achieved in Pathways 1 and 2. Here, if demand can be co-located nearby the import terminal, as suggested by the EU strategy, the need for gaseous storage would be eliminated. Therefore, cost reductions of around 0,73 €/kgH$_2$ would happen. Lowering the costs to 1,88 and 1,44 €/kgH$_2$ for Pathways 1 and 2 respectively. The achievement of costs lower than 1,8 €/kgH$_2$ would open a market opportunity of 1.199 billion €, by consuming at least 666 Mt of H$_2$ and displacing blue H$_2$ as the cheapest option.

4. CONCLUSIONS

The need of H_2 irruption in the global energy system is significant. H_2 is the only solution for the decarbonization of many sectors, an enabler for the 100 % presence of renewables, storing large quantities of energy over seasonal periods and acting as a feedstock for applications that currently use grey H_2.

Coupling offshore wind with H_2 production can bring several benefits to both technologies. H_2 can be directly coupled to an electricity source that offers good capacity factors without paying grid access feeds or taxes. Moreover, offshore wind potential will be untapped when combined with H_2, reaching areas with vast energy resources that will help to decarbonize the economy.

Among the studied pathways, the use of pipelines to transport H_2 seems to be the best solution, providing a LCOH of 5,35 €/kgH_2 for the baseline case, whereas it has the potential of being as low as 2,17 €/kgH_2 if the EU support is successful and achieves its targets, this pathway represents the lowest H_2 LCOH in all the cases. The energy input in this pathway is 0,46 MWh/MWhH_2, being one of the less energy intensive methods, due to less conversion steps. Inland production is a promising possibility only if the windfarm is relatively close to land, if not, prices increase rapidly due to the high costs of the wires, breaking even with the rest of the pathways, except from Pathway 2 (CH_2 case). Inland production and CH_2 transportation would be of great interest if there was a large consumer close to the import terminal.

Vessel transportation of H_2 or H_2 carriers does not outcompete the pipeline use unless distances are longer than 150-250 km. Liquefaction of H_2 is an interesting option, it offers the lowest costs among all the vessel transportation studied pathways. However, its competitivity could be affected by cost reductions in the reconversion processes of the H_2 carrier pathways since these are more prone to experience cost reductions and efficiency improvements due to their lesser maturity. NH_3 and LOHC for the transportation of H_2 are still under planning stages while liquefaction is a well-known process. Pathway 3 (Liquefied H_2) LCOH in the baseline case is 6,66 €/kgH_2, while it would drop to 2,94 €/kgH_2 in the best case. However, both NH_3 and LOHC vessel transportation cases, (Pathways 4b and 5b) offer better behavior for longer transportation distances, and even if the costs are higher for all the assessed factors, these should be kept in mind due to the aforementioned possibility of cost reductions.

Baseline case costs for NH_3 and LOHC vessel transportation (Pathways 4b and 5b) are higher (7,27 €/kgH_2) while their cost reduction in the EU support scenario makes them more competitive, offering costs of 4,22 and 4,32 €/kgH_2 respectively.

Eventually, NH_3 and LOHC transportation by pipelines (Pathways 4a and 5a) do not outcompete their homologue as pure H_2 and therefore they are not as appealing at first sight. Their costs in the baseline case are 6,74 and 6,90 €/kgH_2 or 2,92 and 3,16 €/kgH_2 in the best scenario, offering the same cost reductions as the vessel transportation case when reconversion is performed by using waste heat.

A key insight of this work is that what could seem a waste product such as O_2 can improve greatly the economics and viability of the project, increasing the NPV by more than 150 M€ without major complexities in the infrastructure.

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