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Economic impact assessment of Hydrogen generated from Offshore Wind: A case study for Belgium

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Abstract. Green hydrogen is increasingly cited as a solution to the decarbonisation of industry. Its large-scale production is still a recent topic with uncertainties. In this paper, an economic impact assessment (EIA) method is explained. A modular and flexible cost model is generated, which estimates the LCOE (Levelized Cost of Energy) of an offshore wind farm and the LCOH (Levelized Cost of Hydrogen) of a hydrogen generation plant either as a hybrid renewable energy system (HRES) or independent from each other. The costs are estimated using a schedule-based approach, which considers the reliability, maintenance operations as well as production of both the offshore wind farm and the hydrogen generation plant. Developed EIA is demonstrated for Belgium using Mermaid Offshore Wind Farm.

1. Introduction

Green hydrogen, which is generated by using electricity from renewable energy sources, is being investigated as a potential energy source to reach the decarbonisation goals of the EU. Green hydrogen is normally produced by water electrolysis using electrolysers, and the electrolyser capacity needs to grow to 350GW by 2030 according to [1]. Although currently, blue hydrogen (a combination of fossil fuels and carbon capture and storage) is still cheaper than green hydrogen, with both the cost reductions of renewable energy, especially offshore wind and the development of electrolyser technologies, it is predicted that the green hydrogen will become cost competitive by 2030 [2] and further reduction is expected beyond [3], [4], [5], [6], [7]. The understanding of costs involved in hydrogen production needs to be properly studied to ensure financial profitability in comparison to other means of production to realize these goals.

LCOH, together with other economic metrics such as net present value (NPV), is commonly used for the economical assessment of different technologies. There are various models and approaches used to estimate LCOH in the literature. Although most methods focus on the assessment of a specific hydrogen generation technology, other methods also exist, comparing different technologies to find the optimum. Here, we provide an overview of the most recent literature on these methods to cover this rapidly developing landscape of studies analysing hydrogen generation with its LCOH implications.

[8] and [9] reviewed techno-economic analysis approaches to evaluate different hydrogen generation methods. [10] assessed hydrogen storage in combination with renewable energy sources by analysing 15 different projects. [11] proposed integrated systems for the use of

large-scale floating wind farms dedicated to hydrogen generation. [12] developed an eco-techno-economical analysis approach to evaluate hydrogen generation using solid oxide electrolysis cells (SOECs), including their long-term degradation. They showed that LCOH from SOECs are in the range \$2.78/kg to \$11.67/kg compared to grey hydrogen, where LCOH varies between \$1.03/kg and \$2.16/kg, and they furthermore concluded that the electricity price was more dominant than the capital costs in these results. Similarly, [13], [14], [15] looked at Polymer Electrolyte Membrane (PEM) electrolysis, including degradation of efficiency, system modelling, optimisation and economical evaluation. [4] proposed a model to investigate integrated offshore wind and hydrogen generation infrastructure comparing onshore, offshore or in-turbine electrolysis with the goal of reducing LCOH. This study estimated an LCOH value of 2€/kg for green hydrogen generated offshore. [5] modelled and compared green hydrogen generation systems via electrolysis from offshore wind power, taking the hourly wind speeds into account. They found that LCOH from offshore wind electrolysis could drop to \$2.09/kg compared to the conventional way of obtaining offshore wind-generated electricity from the grid, which ends up at \$3.86/kg. A parametric model is proposed by [16] to compare the LCOH from Photovoltaic solar energy (PV), onshore and offshore wind energy. A range from €2.1/kg to €5.05/kg for LCOH for different scenarios was predicted. Other available models [17], [18], [19], [20] and [21] provided detailed modelling frameworks to assess several hydrogen generation options with usage of renewables or other sources. In [18], there is also a multi-criteria analysis (MCA) tool included to help with the decision-making process, which is elaborated in [17]. In most of the tools found in the literature, a significant effort has been put into the hydrogen generation system modelling however offshore wind farm modelling part has been included with less fidelity by focusing on the hourly power based on the wind speeds in the most detailed ones or grid infrastructure.

The EIA approach proposed in this paper models both the hydrogen and the electricity generation with similar fidelity to provide the same developmental and operational flexibility for both hydrogen and electricity generation plants assessing both LCOH and LCOE. This is done by using the existing models available to estimate LCOE of offshore wind farms in [23] and extend these models with the hydrogen generation capability with PEM electrolysis located onshore as this is the most commonly implemented technology currently [22], [9]. As a case study, an offshore wind farm is used to generate electricity and a part of this electricity is used to produce hydrogen in an onshore plant. Most of the costs involved are taken into account using a schedule-based cost model applied to this Hybrid Renewable Energy System (HRES) (Figure 1).

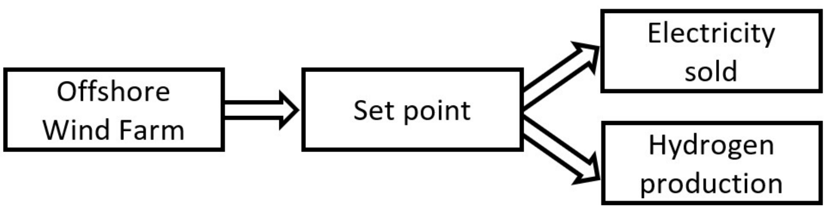

Figure 1. HRES model

2. Cost Model

The Economic Impact Assessment of the HRES is executed using a cost model which consists of two different modules to cover most of the involved costs of setting up and operating an offshore wind farm and an onshore hydrogen generation plant. These modules include the construction part of the systems, called the CAPEX Module, and a schedule-based module assessing the operational costs as well as the production of the representative systems, called the OPEX and Revenue Module.

2.1. CAPEX Module

First, the cost of setting up both systems, the wind farm and the hydrogen plant, is assessed in a CAPEX module. This part only involves the pre-operational period of both systems and is therefore not time-dependent.

The CAPEX of an offshore wind farm can be divided into two parts: the Balance of Plant (BoP) and the cost of installation. The cost of the BoP is the cost of procuring the equipment and the necessary material to build the wind farm, while the installation costs deal with the cost of constructing the wind farm.
CAPEX installation costs and the BoP of the offshore wind farm are mainly based on the ORBIT model of NREL [24]. Based on ORBIT, different stages of the installation activities are modelled by taking the vessel spread, the vessel rates, and the necessary timing into account. BoP is modelled by summing the cost of monopiles, cables, wind turbines, and other miscellaneous costs.
The cost of monopiles is calculated by entering the dimensions of the monopile, the cost of steel, and the cost of manufacturing using the ORBIT [24]. The cable costs are estimated using the cost of the cables per length and the total length of the cables. The cost of wind turbines is estimated using the empirical formula provided by the Romeo project [26]:

$$Cost_{Turbines} = ((3 * 10^6)ln(MW) - 662400) * 1.16 \tag{1}$$

Where MW is the rating of the turbine in Megawatt, and 1.16 is used to convert from pounds to euros.

Concerning the hydrogen generation plant, the approach to calculating the CAPEX is similar. CAPEX costs are divided into three main parts: the BoP cost, the electrolyser cost, and the installation cost. BoP of the hydrogen generation plant is estimated by summing up the costs of compression, rectifier, gas holder, and ancillary, which are individually obtained or modelled using the approaches in [4] and [20]. The cost of the electrolyser (PEM-electrolysis) is estimated as in [4].

$$Cost_{Electrolyser} = P_{elec}RC_{elec}(\frac{P_{elec}.10^3}{RP_{elec}})^{SF_{elec}} \tag{2}$$

Where P_{elec} is the electrolyser capacity, RC_{elec} is the reference cost for PEM electrolysis assumed to be 600€/kW, RP_{elec} is the reference power, and SF_{elec} is the scale factor assumed to be -0.14. Since there is not yet much data on the installation costs, it is used as 20% of the CAPEX as recommended in [21].

2.2. OPEX and Revenue Module

In this part, the OPEX and Revenue module is described. This schedule-based module simulates every hour of the HRES operational life to calculate the operational costs and the production of both the offshore wind farm and the hydrogen generation plant. The basic principle of the model can be described in Figure 2.

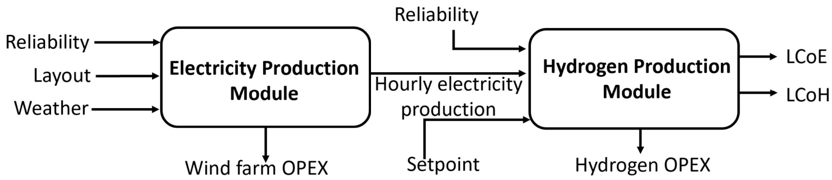

Figure 2. OPEX and Revenue Module principle

OPEX costs of the wind farm are estimated by modelling the failures of 21 subsystems composing a wind turbine. Five damage categories based on their estimated severity are implemented. Each of these failure possibilities leads to repair costs and an associated downtime where the turbine involved is not available and can therefore not produce any electricity. To evaluate when these failures happen, a Monte Carlo loop is used following the principles of the NOWIcob model in [25] where a homogeneous Poisson's process (HPP) is used to randomize the component failures for each hour of the offshore wind farm's lifetime. The principle of the failure analysis and the associated downtime for a turbine is summarized in Figure 3.

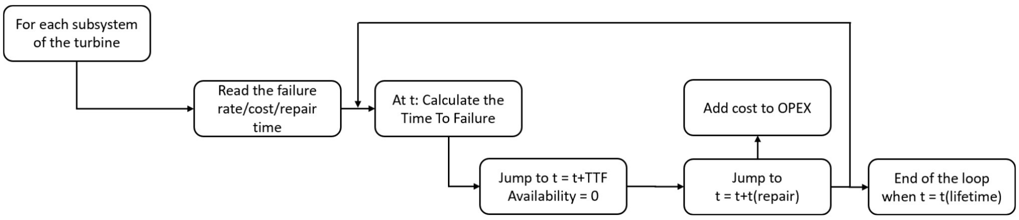

Figure 3. Failure and downtime principle

The OPEX cost of every failure is summed to obtain the total OPEX cost of the wind farm over the entire lifetime. Furthermore, the hourly availability of one turbine is calculated and summarized in a matrix where the black tiles represent an unavailability period. This matrix is represented in Figure 4. Once the availability of every turbine is obtained, electricity production of the wind farm is calculated using the historical wind speed, and wind rose information at the wind farm location. The wake losses have also been implemented as a percentage of production.

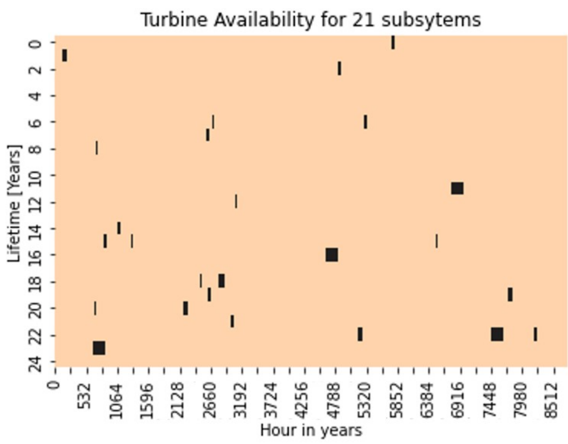

Figure 4. Availability matrix of a wind turbine

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A percentage of the electricity produced is used to generate green hydrogen, while the other part is sold to the grid. This percentage is chosen based on a set point between 0 and 100%.

Concerning the hydrogen generation plant, a similar approach is used to calculate the failure cost and estimate the availability throughout the lifetime of the plant. Furthermore, part of the electricity sent to this system is used for the compression and for the demineralization of the water used for the electrolysis. The formula 3 is used where the stack efficiency is time-dependent because of the linear degradation of the stack. Additionally, the Lower Heating Value (LHV = 33.3 kWh/kg) of the hydrogen is taken into account to convert the energy into the mass of hydrogen produced [20].

$$m_{H_2}(t) = \frac{(SetPoint * E_{WF}(t) - E_{comp}(t) - E_{demin}(t))\eta_{stack}(t)}{LHV} \quad (3)$$

The cost of replacing the stack every 85000 operating hours is evaluated, as well as the cost of buying the water needed for the electrolysis at the local market price. Furthermore, 14 Liters of water are necessary to produce 1kg of hydrogen.

Finally, the value obtained using this cost model is compared to a case where the electricity is now bought from the local grid at the market price. The LCoE of the offshore wind farm, the LCoH of the hybrid system, and the LCoH considering the grid electricity as input are evaluated with the formulas in Table 1:

Table 1. LCoE and LCoH formulas

LCoE	**LCoH1 (from HRES)**	**LCoH2 (from grid electricity)**
$\frac{\sum_{t=0}^{Lifetime} \frac{(I_{WF,t}+O_{WF,t})}{(1+r)^t}}{\sum_{t=0}^{Lifetime} \frac{AEP_t}{(1+r)^t}}$	$\frac{\sum_{t=0}^{Lifetime} \frac{(I_{WF,t}+O_{WF,t}+I_{H_2,t}+O_{H_2,t})}{(1+r)^t}}{\sum_{t=0}^{Lifetime} \frac{M_{H_2,t}}{(1+r)^t}}$	$\frac{\sum_{t=0}^{Lifetime} \frac{(MarketPrice*E_{used}+I_{H_2,t}+O_{H_2,t})}{(1+r)^t}}{\sum_{t=0}^{Lifetime} \frac{M_{H_2,t}}{(1+r)^t}}$

Where r is the discount rate considered as 6%, I is the CAPEX costs, O is the OPEX costs of the different systems, and AEP is the annual energy production of the offshore wind farm.

3. Study Case

The economic impact of hydrogen generation is mainly quantified by estimating the LCOH of the hydrogen generation plant using the electricity generated by an offshore wind farm. In order to have precise and representative values for the different costs involved, the Mermaid Offshore Wind Farm in Belgium developed and operated by Otary, is chosen in this study, with the following parameters:

Table 2. Representative Offshore Wind Farm parameters

Parameters	
Number of Turbines	28
Turbines Type	SG 8.0-167
Farm Capacity	235MW
Foundation Type	Monopile
Hub Height	107.5 meters
Distance to Shore	54km
Operator	Otary RS N.V.

The representative hydrogen generation plant for this study is a virtual plant located in the Belgian city of Zeebrugge, with the following characteristics:

Table 3. Representative onshore hydrogen plant parameters

Parameters	
Location	Zeebrugge
Electrolyzer Capacity	235MW
Type of Electrolysis	PEM
Distance to Wind Farm	54km
Compression	700 kW
Lifetime	25 years

Several technology types can be used to perform water electrolysis, such as the AEL-electrolysis, the PEM-electrolysis, or the SOEC-electrolysis. All these technologies have different advantages (efficiency, operating time, dynamic response). For this study, the technology used is the Polymer Electrolyte Membrane electrolysis (PEM), as it is appropriate for renewable energy sources such as offshore wind. The stack, which is the component converting the electricity into hydrogen, is supposed to need a replacement every 85,000 working hours. Furthermore, an initial efficiency of 62% is considered with a linear degradation of 0.1% every 1,000 operating hours. The operating temperature is 85°C, and the pressure is 55 bar. Finally, a demineralizer is implemented with an electricity consumption of 1.5 kWh/m^3 to ensure that the water bought from the Belgian network is pure.

The values obtained by using the cost model in this study case are also compared with an LCoH estimation when the electricity is coming from the Belgian grid using the 2022 market prices as in [29]. In this case, the studied hydrogen generation plant is considered as decoupled from the offshore wind farm.

4. Results and discussion

CAPEX share of different components for wind farm and the hydrogen plant in Figures 5 and 6 shows that the largest costs are the wind turbines and the electrolyser. A CAPEX cost of 619 k€/MW is found for the hydrogen generation plant, which is within the expectation for such a project based on [31].

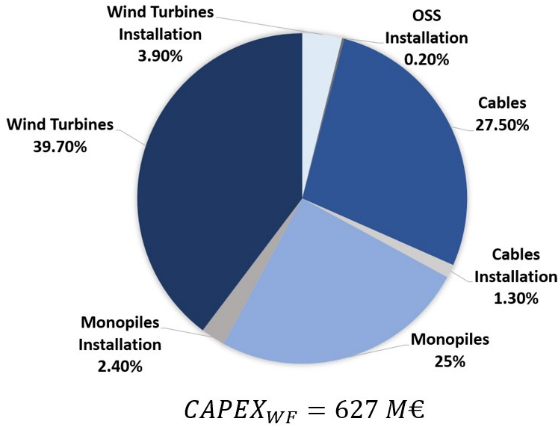

Figure 5. Breakdown of the wind farm CAPEX

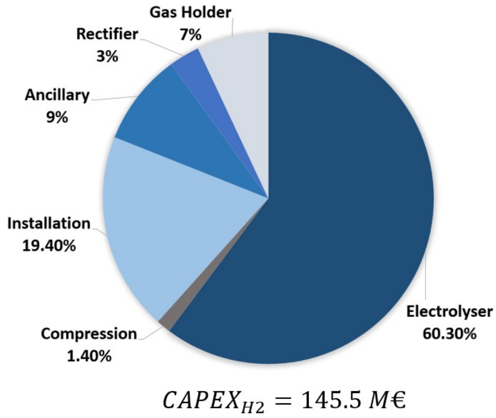

Figure 6. Breakdown of the hydrogen plant CAPEX

An OPEX cost of 1,300k€/Turbine/year is found for the wind farm (910.16M€ over the lifetime of Mermaid Wind Farm) with a time availability of 96%. Although the actual availability of this wind farm is not published to our knowledge, [32] estimates an average of 95% for an offshore wind farm which is close to this prediction. The hydrogen generation plant has a lower OPEX cost with 2,921k€/year (73.1M€ over the lifetime). Two different versions of OPEX costs are shown for the hydrogen generation; in Figure 7 using the electricity from the offshore wind farm and in Figure 8 from the grid (bought at Belgian market price) as input.

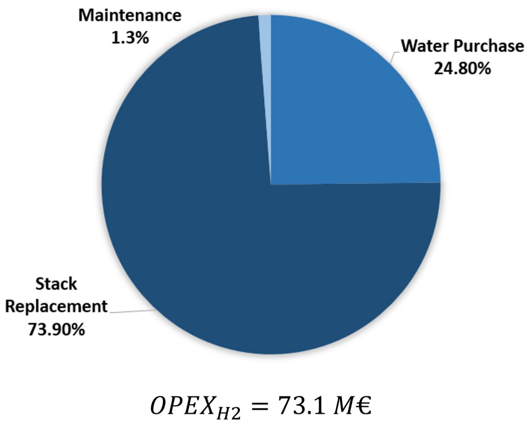

Figure 7. Breakdown of the hydrogen generation OPEX (wind farm electricity)

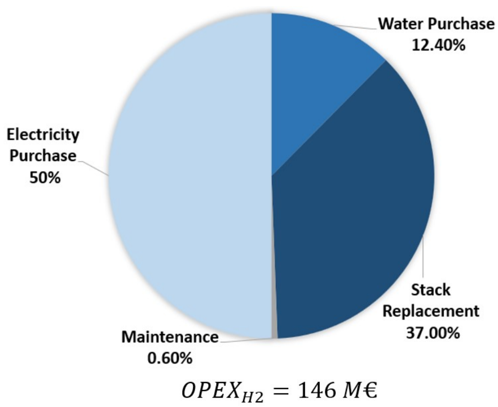

Figure 8. Breakdown of the hydrogen generation OPEX (grid electricity)

When the entire HRES is studied, the most significant cost is the stack replacement which happens two times in the entire lifetime of the plant that is modelled in this study (every 85,000 operating hours, which is taken from [4]). Replacing the stack is a very expensive action due to the cost of the stack which is composed of several rare materials such as titanium, platinium, iridium, as explained in [27]. 14L of water is necessary to produce 1kg of hydrogen, and as a result, purchasing the water has a significant share in OPEX. The maintenance costs are less than 2% of the whole OPEX, which is expected due to the fact that the hydrogen plant is located onshore and no delay in repair actions of failures is modelled. When the electricity is bought from the grid, a massive OPEX cost for hydrogen generation is seen, representing half of the OPEX cost.

Finally, the production of both systems is also evaluated. Average hourly electricity production of 96.3 MWh is found for Mermaid wind farm over its lifetime and, when 100% of the electricity is used for hydrogen production, 1555 kg per hour of hydrogen is generated on average.

Table 4. LCoE and LCoH results

LCoE	LCoH1 (from HRES)	LCoH2 (from grid electricity)
101.3 €/MWh	6.76 €/kg	9.26 €/kg

The values of LCoE and LCoH obtained are summarized in Table 4. The LCoE found is higher than the published value of 79€/MWh [33]. The difference can be explained by the uncertainty of some assumptions (different turbines, failure rates, wake loss). Government subsidies are also not taken into account in this model. The LCoH1, representing the cost of producing hydrogen from the HRES, is in the range of what was found in [15], which is significantly more expansive than the current cost of grey hydrogen found in [15] (between 0.97€/kg and 2.04€/kg). [30] found a value of approximately 6€/kg which is close to our prediction. However, [28] shows an average LCOH value of 5.3€/kg for Belgium in 2022 for green hydrogen which is lower than our prediction. Since this reference value was obtained for an AEL-electrolysis with better efficiency, a lower LCOH value is expected. LCoH2, when electricity is bought from the grid at market price with the same amount of hydrogen, is also included here for comparison.

To better understand the different cash flows at stake during the lifetime of the HRES, Figure 9 illustrates that the OPEX of the hydrogen plant is most of the time minor. However, every 85,000 operating hours, the stack replacement makes this visible since it leads to a significant operational cost.

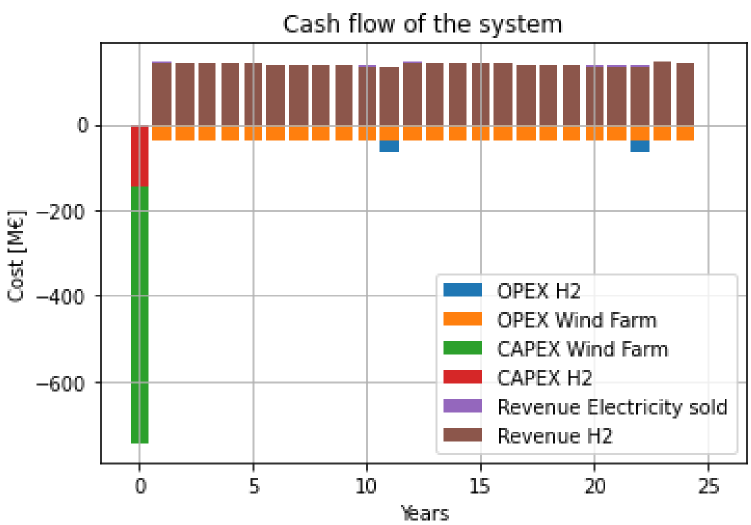

Figure 9. Cash flow of the HRES

Linear degradation of the stack efficiency is seen with a decrease in the hydrogen production, and therefore revenue, before a stack replacement. Additionally, the annual OPEX of the wind farm remains regular throughout the lifetime of the system. If the hydrogen is sold at a higher price than the LCoH, the system becomes profitable. Here, a value of 10€/kg is used, which is the hydrogen sale price of the fuel stations in Belgium [34]. With these values, the NPV of the system is 565M€. On the other hand, if all of the wind farm's electricity is sold to the grid at 25c/kWh [29], NPV is calculated to be around 1.5B€. This comparison shows that, for this study, hydrogen generation is less profitable compared to selling electricity to the grid.

As explained before, a setpoint was implemented regulating the quantity of electricity sent from the offshore wind farm to the hydrogen generation plant. By varying the value of this setpoint, the two different LCoH also vary, and Figure 10 illustrates these variations.

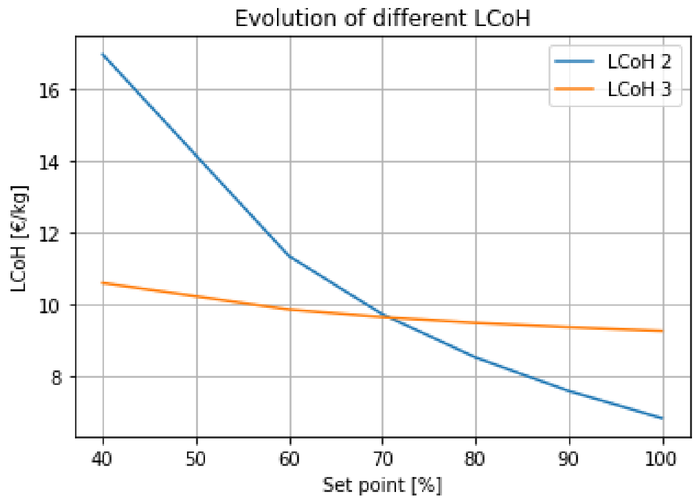

Figure 10. Effect of the setpoint on LCoH

LCoH1 corresponds to the LCoH of the total system with electricity from the offshore wind farm production, while LCoH2 is when electricity is bought from the grid at market price with the same amount of hydrogen generated. Figure 10 shows that using more than 71% of the wind farm electricity for hydrogen production is needed to produce cheaper hydrogen than with a grid electricity electrolysis for the study case.

A sensitivity analysis has also been realised to assess the impact of the different assumptions and to estimate the main parameters that can optimize the cost of the hydrogen generated from an offshore wind farm. This analysis is shown in Table 5.

This analysis shows that the stack efficiency and discount rate have the highest impact on the LCoH, whereas water cost seems to have the least impact. Furthermore, a change of 10% of the total CAPEX leads to a change of 6% in the final LCoH. With improved electrolysis technology for better efficiency, the cost of producing green hydrogen could be significantly reduced in the future.

Criterion	Base Case	New Scenario	Effect on LCoH1	New LCoH1 [€/kg]
Basic LCoH				6.76
Discount rate	6%	3%	-14.35%	5.79
Discount rate	6%	9%	+15.5%	7.81
Total CAPEX	772.5M	695.25M	-6.1%	6.35
Total CAPEX	772.5M	849.75M	+6.1%	7.17
Stack Efficiency	62%	52%	+19.1%	8.05
Stack Efficiency	62%	72%	-13.8%	5.83
Stack Degradation	0.1%/1000h	0.05%/1000h	-1.8%	6.64
Stack Degradation	0.1%/1000h	0.2%/1000h	+3.55%	7.00
Water Cost	3.7 €/m^3	3.4 €/m^3	-0.15%	6.75
Water Cost	3.7 €/m^3	4 €/m^3	+0.15%	6.77
Failure Rate H2	Base Case	Base Case * 10	+5.3%	7.12

Table 5. Sensitivity analysis results

5. Conclusions

An economic impact assessment method for an HRES, which consist of an offshore wind farm and a hydrogen generation plant, is developed. This method has been demonstrated using the Mermaid offshore wind farm in Belgium and a virtual onshore hydrogen generation facility. From the study, the following conclusions can be drawn:

- Developed approach can be used to compare hydrogen generation strategies coupled or decoupled with an offshore wind farm
- Both offshore wind farm and the hydrogen generation plants are modelled with similar detail including failure rates of various components, hourly wind speeds, weather availability, downtimes, etc. This allows the evaluation and optimisation of many options on the LCOH and LCOE or both at the same time.
- If electricity purchase is not included, the stack replacement is the major cost for the OPEX of the modelled onshore hydrogen plant.
- Estimated LCOH values are slightly higher than the values found in the literature.
- LCOH is shown to be dependent on the electricity source.
- Set point approach makes it possible to identify the amount of electricity from an offshore wind more profitable compared to obtaining it from the grid.

The methodology developed here is quite flexible, allowing various parametrisation possibilities for optimizing LCoH and LCoE values at the same time. However, it also has limitations. The main ones are listed below:

- Hydrogen generation plant is located onshore so the assessments cannot include distance to shore for the hydrogen plant.
- The electrolyser is assumed to respond to the variable energy generation perfectly. And the size of the electrolyser is not evaluated as a parameter in this study although it is possible.
- Variable electricity price is not taken into account.

Although the predicted LCOH values are close to the values found in the literature, the model will need validation when more data from a similar real HRES will be available.

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