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Production and transportation costs for green hydrogen from an offshore wind farm to an industrial end–user onshore

umlaut: Patrick Wienert, Petja Stöver, Philipp Wiener
KONGSTEIN: Thore Schreiber, Bonke Jensen

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1. Introduction

One of the biggest challenges of today's society is to prevent the global warming. To achieve this target, 196 Nations including Germany, signed the **Paris Agreement**[1] in 2015 to limit the global warming by 2°C compared to pre–industrial levels. Each country is responsible for the compliance and the establishment of individual carbon reduction strategies. For example, Germany aims to become climate neutral by the year of 2050[2]. Therefore, Germany already plans to implement 20 GW of offshore wind capacity[3] and 5 GW of hydrogen capacity[4] until 2030.

Green hydrogen plays an important role in decarbonization of multiple sectors e.g. mobility, energy and industry. For industrial production sites, green hydrogen can reduce greenhouse gas emission significantly and make it traceable, e.g. by replacing the fossil fuels used in heat generation. On the other hand, the demand of centralized industrial production sites for the long–term, secured supply of hydrogen can be covered by large offshore wind farms (OWF). Consequently, green hydrogen and offshore wind power can be considered as key factors to assist Germany achieve the climate goals. The **Windenergie–auf–See–Gesetz**[3] (Wind Energy at Sea Law) and the **National Wasserstoffstrategie**[4] (National Hydrogen Strategy) paves the way for the alternative technologies in offshore energy converting and transportation.

Therefore, information regarding the cost of production and transportation of green hydrogen to the centralized industrial production sites is necessary.

[1] Paris Agreement: https://unfccc.int/sites/default/files/english_paris_agreement.pdf
[2] Bundes–Klimaschutzgesetz: https://www.gesetze–im–internet.de/ksg/BJNR251310019.html
[3] Windenergie–auf–See–Gesetz: https://www.gesetze–im–internet.de/windseeg/BJNR231000016.html
[4] Nationale Wasserstoffstrategie: https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die–nationale–wasserstoffstrategie.pdf?__blob=publicationFile&v=20

2. Objectives

In order to gain a better understanding of the production and transportation costs of green hydrogen, a cost assessment is conducted with following purpose:

"Determining the cost implications of the Levelized Cost of Hydrogen for end-to-end transportation scenarios of green hydrogen generated in the North Sea and transported to a major industrial consumer in Germany."

Two offshore wind farms in the German Exclusive Economic Zone (EEZ) will be examined for their production capacity and several different transport scenarios via two seaports will be calculated.

Figure 1: Overview of hydrogen production, seaports and industrial end-consumer

3. Transportation Scenarios

The two aforementioned offshore wind farms are He Dreiht and Nemo both with an estimated power generation of 900 MW. He Dreiht is located approx. 85 km north of the island Borkum and approx. 104 km west of the island Heligoland. The offshore wind park Nemo is located approx. 183 km from the shore and north–western in the German Exclusive Economic Zone. The two seaports are Brunsbüttel in the north–west of Germany and Rotterdam in the Netherlands.

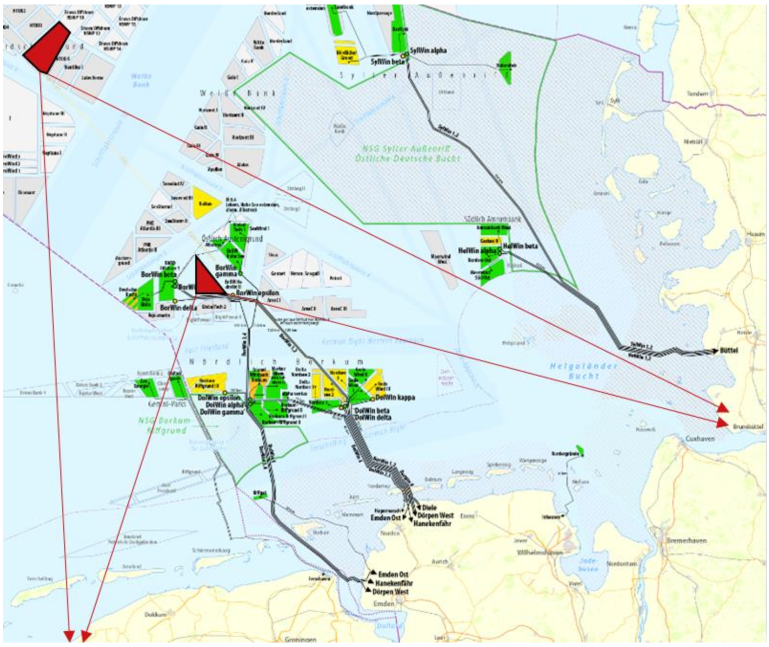

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Figure 2: Two reference wind farms in the German bight

To identify the most economically attractive end–to–end transportation setup, a close investigation is required, and hence multiple transportation scenarios are being taken into account. Starting point for such a transportation arrangement is the offshore substation at which the hydrogen is produced. For this cost assessment the starting point and offshore substation is located at the OWF He Dreiht or Nemo. The distance to shore changes respectively and may have a huge impact on CAPEX and OPEX.

Both of the OWF are considering a direct transportation strategy via pipeline to the industrial end–client in the first scenario. The other scenarios are dependent on the seaport, as transportation vessels will be utilized for shipping the hydrogen to shore on a regular basis. Either the German seaport Brunsbüttel, which is already investigating the hydrogen infrastructure, or the Dutch seaport Rotterdam are being taken into consideration. Upon arrival at Brunsbüttel, the hydrogen will be offloaded and transported via truck, train, or onshore–pipelines to the end–client. For Rotterdam the hydrogen will be transported via inland ship, train or truck. **Figure 3** shows the considered transportation scenarios for each OWP to an industrial end consumer in Duisburg.

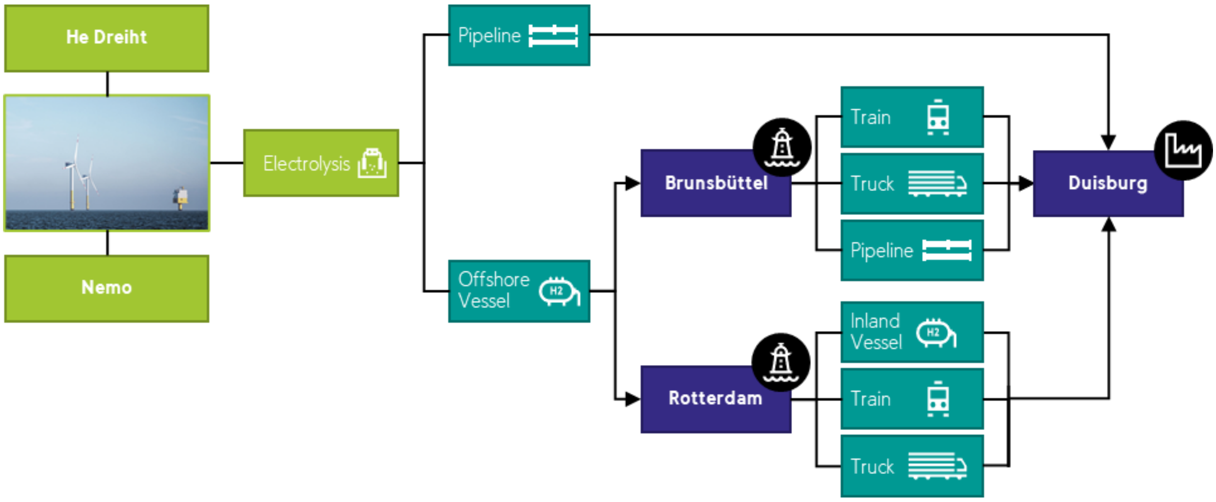


Figure 3: Transportation scenarios from the OWF He Dreiht and Nemo to an industrial end–consumer in Duisburg

4. Cost Assessment

The current estimation for all transportation scenarios is split up into Capital Expenditures (CAPEX) and respective annual Operational Expenditures (OPEX) for every single component depending on the operational lifetime. The single components include the offshore wind farm, electrolysis and transportation arrangement. In the aftermath the Levelized Costs of Hydrogen (LCOH) is calculated by dividing the individual CAPEX through their perspective lifetimes. The resulting annual CAPEX and OPEX are divided through the produced annual amount of hydrogen. The results of the cost estimation for each scenario are shown in **Table 1**.

Table 1: Cost comparison of the transportation scenarios

Scenario	CAPEX [M€]	OPEX [M€/a]	LCOH [€/kg]
Offshore Wind Farm He Dreiht			
Direct export via pipeline to end–consumer	5,128	177	**6.81**
Ship transport to Brunsbüttel & transport via train	3,475	288	**8.76**
Ship transport to Brunsbüttel & transport via truck	3,475	297	**8.93**
Ship transport to Brunsbüttel & export via pipeline	4,615	203	**7.43**
Ship transport to Rotterdam & transport via inland ship	3,475	254	**8.05**
Ship transport to Rotterdam & transport via train	3,475	240	**7.77**
Ship transport to Rotterdam & transport via truck	3,475	247	**7.91**
Offshore Wind Farm Nemo			
Direct export via pipeline to end–consumer	5,739	189	**7.31**
Ship transport to Brunsbüttel & transport via train	3,475	290	**8.79**
Ship transport to Brunsbüttel & transport via truck	3,475	298	**8.96**
Ship transport to Brunsbüttel & export via pipeline	4,615	205	**7.46**
Ship transport to Rotterdam & transport via inland ship	3,475	255	**8.06**
Ship transport to Rotterdam & transport via train	3,475	241	**7.79**
Ship transport to Rotterdam & transport via truck	3,475	248	**7.93**

Figure 4 illustrates the results of the LCOH assessment in **Table 1** for transporting hydrogen from the OWFs He Dreiht and Nemo for each transport scenario to the industrial end–consumer in Duisburg.

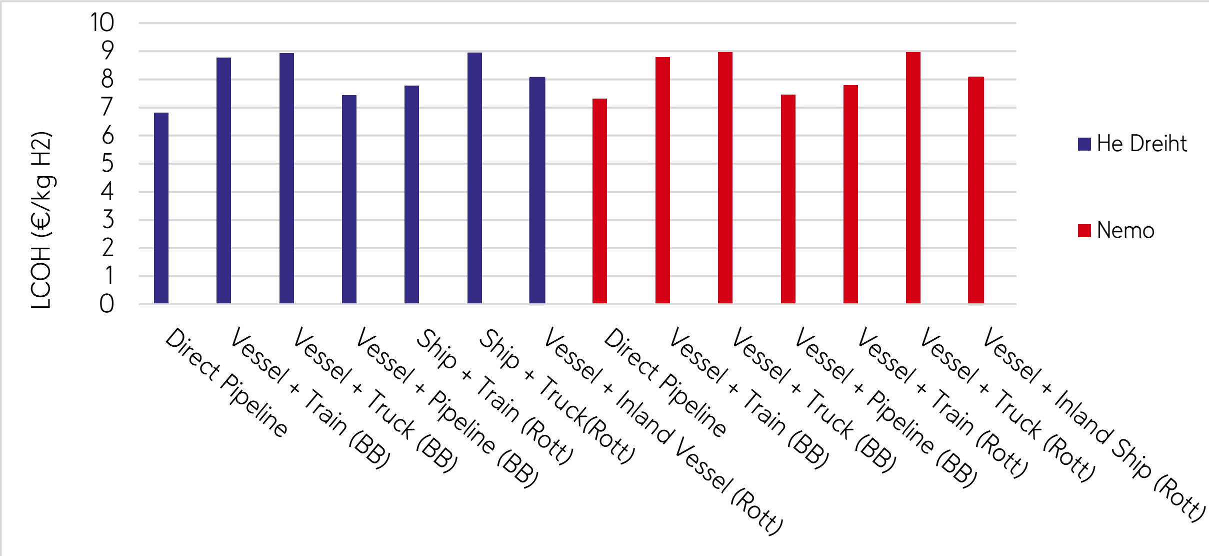


Figure 4: LCOH for each transportation scenario

Figure 5 compares two transport scenarios of the OWF He Dreiht and their different cost components. The transport scenario with an offshore vessel via the seaport Brunsbüttel and a train transport is compared with the scenario of a direct pipeline. It's worth mentioning that the costs for the offshore components is approx. 58 % of the total cost of the transport scenario with an offshore vessel via the seaport Brunsbüttel and a train transport. For a direct pipeline transport scenario, the cost of the offshore components is approx. 80 %. The cost for offshore components contains all cost regarding **Energy Generation** and **Hydrogen Production**.

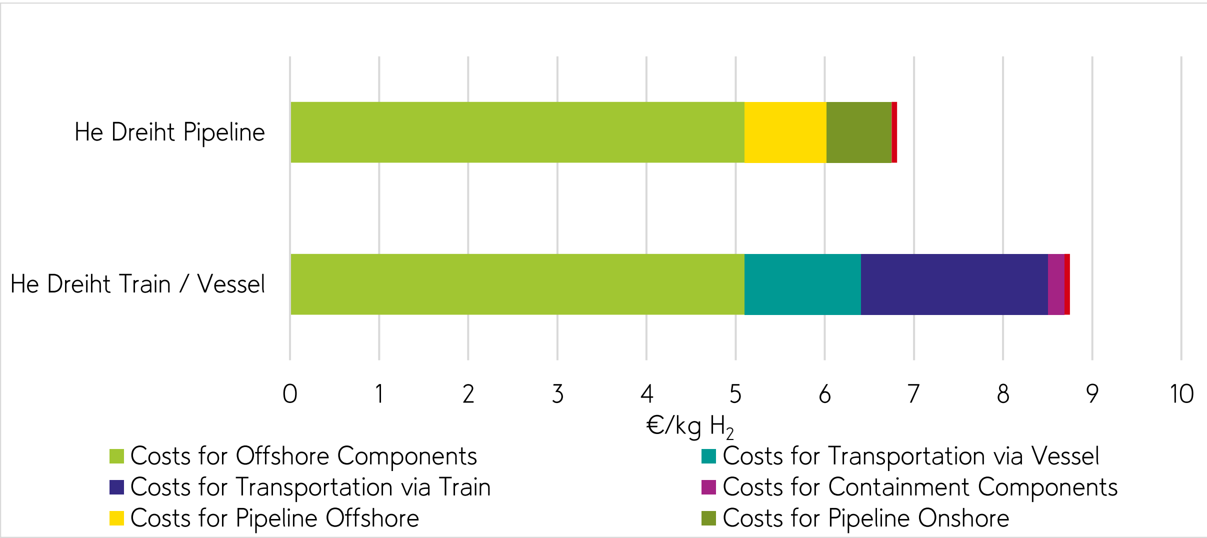


Figure 5: Cost comparison of two transport scenarios of the OWP He Dreiht

Different breakeven points for transport scenarios of the OWF He Dreiht are illustrated in **Figure** . For each illustrated transport scenario, the initial CAPEX with the respective annual OPEX is compared over a time period of 25 years in operations.

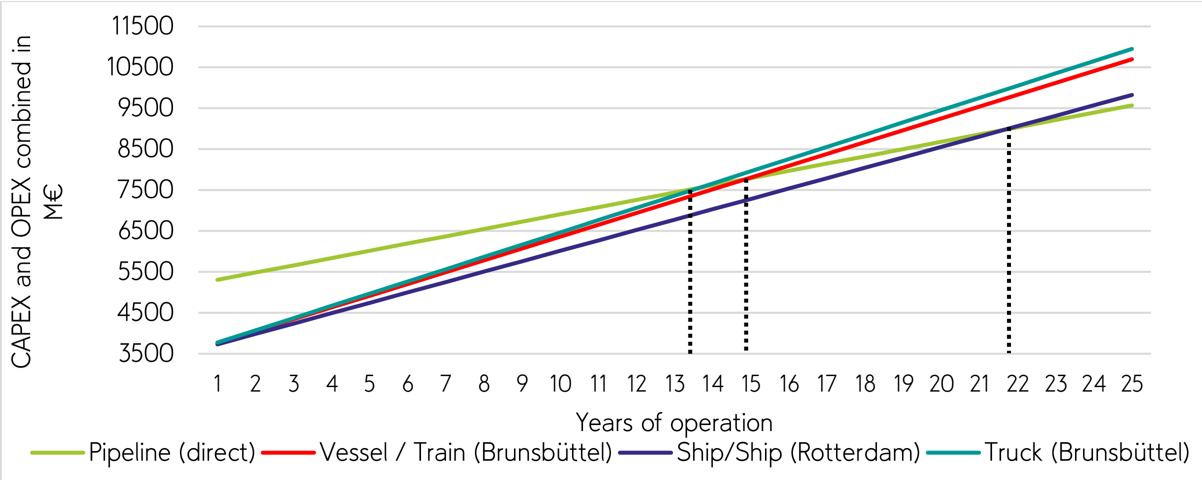


Figure 6: Breakeven costs for transportation scenarios of the OWF He Dreith

Before a transportation scenario can go into operation, a governmental or regulatory clearance and a construction phase must be considered. The respective timelines for the first 25 years of the different transportation scenarios are shown in **Figure** . The timelines include the years for governmental clearance, the construction phase and operational phase. The timeline of the windfarm, offshore substation or electrolysis is not included, because it is the same for all transportation scenarios.

Current approval procedures suggest that governmental clearance for a pipeline takes up to 10 years and the construction phase another 7 years. On the other hand, the construction of a specific offshore vessel requires up to 18 months. For inland vessel, train and truck no construction time is calculated, due to rental or shipping options.

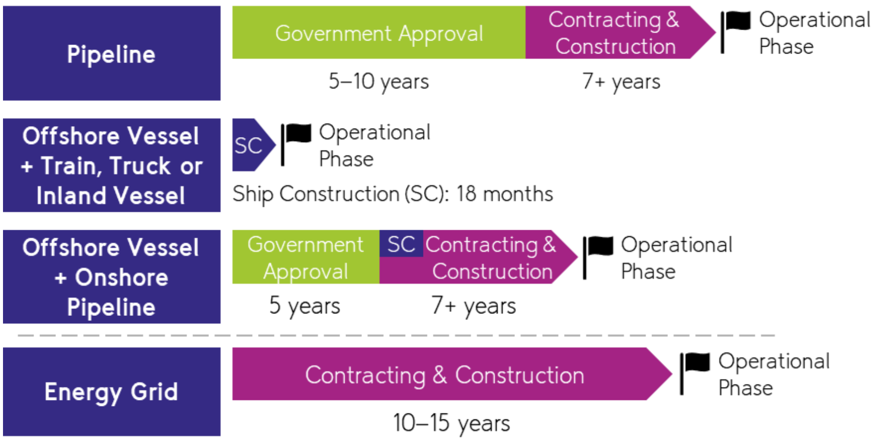


Figure 7: Expected implementation timeline for transportation scenarios

5. Evaluation

For the OWF He Dreiht the most economically attractive transportation method is to construct a pipeline which transports the H_2 directly to the industrial end customer. With CAPEX costs of 5,128.56 M€ it is among the most cost intensive investments; however, the operational expenditures are the lowest of all use cases. The Levelized costs of Hydrogen throughout its operational lifetime (30 years) sum up 6.81 €/kg H_2 which represents the lowest calculated LCOH among all examined use cases.

The second most attractive scenario is to transport the H_2 via vessel to the offshore port Brunsbüttel and from there further to its end customer via a pipeline connection. CAPEX estimation for this scenario sums up to 4,615 M€ while the OPEX costs are calculated to reach 203 M€. The resulting LCOH is at 7.46 €/kg H_2 for a combination of shipping and pipeline connection.

A non–pipeline connection to transport the H_2 for instance via vessel and train includes CAPEX attractive investment costs of approximately 3,475 M€. However, the OPEX costs are compared to a purely pipeline based transportation scenario up to 50 % higher and approximate to respectively 288 M€ (vessel transportation to Brunsbüttel, train to end customer) and 240 M€ (vessel transportation to Rotterdam, train to end customer). The respective LCOH accumulate to 8.76 €/kg with Brunsbüttel as base port and 7.77 €/kg for a scenario with Rotterdam as base port.

For the OWF Nemo, the most feasible non–pipeline transportation scenario would be to implement a combination of shipping the produced H_2 to the offshore port Rotterdam, followed by a transportation via train to its destined end customer. CAPEX costs for this scenario result in 3,475 M€ as well as OPEX costs of approx. 241 M€. The LCOH sums up to 7.79 EUR/kg H_2. Whereas a purely pipeline connection from Nemo to its end customer incorporates CAPEX costs of approximately 5,739 M€, and Operational Expenditures of approximately 189 M€, ending in LCOH of 7.31 €/kg which makes it currently the most attractive transportation scenario for the OWF Nemo.

Yet by efficiently utilizing vessels, this option could become economically very attractive. Implementing a shipping cycle with either 3 or 4 vessels and increasing the storage capacity could decrease the LCOH even further.

However, all transportation scenarios result in a respective LCOH in close range. Only the transportation scenarios vessel to truck is an outlier as the least attractive option for both of the OWF. The CAPEX and OPEX costs for these scenarios result in a higher LCOH of approximately +28 % compared to other scenarios. Additionally, utilising trucks for the transportation of green hydrogen has a negative impact on the CO_2 footprint of the industrial sectors.

Figure 5 shows exemplary the allocation of cost components for the pipeline transportation method from the OWF He Dreiht to the industrial end customer as well as the vessel and train solution. CAPEX and OPEX costs for the offshore components make up for more than 70 % of the overall cost while the cost for the transportation make up for approximately 25 % of the overall LCOH.

For the transportation scenario via vessel and train as shown in **Figure 5**, the cost for offshore components accumulate to approximate to 60 % while the costs for the transportation via vessel and train result in around 38 % of the total LCOH.

Due to several uncertainties, limitations must be assumed. For instance, the timeline assessment for a pipeline connection off– and onshore is rather uncertain due to time consuming approvals and regulatory uncertainties (see **Figure**). Additionally, the costs for a pipeline connection are uncertain since current cost estimations are based on oil and gas pipelines. Costs for an adapted H_2 may vary significantly.

For the purpose of this study the pipeline is currently planned as a straight line to the industrial end customer. However, the costs for the onshore pipelines to allow for an assumed additional 15 to 20 % in costs for the pipeline distance, since the pipeline will not be constructed as a straight line onshore.

As stated, a vessel–based solution not only offers LCOH which range in the same area as a pipeline–based transportation method but offers more flexibility in terms of shipping the H_2 to an offshore port from where it is distributed. The same argument applies for onshore based vessels.

A widespread perception is that a purely shipping based solution would run into the risk of supply chain interruption in case weather conditions do not allow for an offshore offloading of H_2 onto the vessel. However, with current ship designs and suitable technology, a safe offshore offloading procedure can be guaranteed at up to 7 m significant wave height "H_s". With an accessibility of >99% the risk of supply chain interruptions can be kept at an absolute minimum.

6. Methodology & Assumption

Energy Generation

The cost for energy generation has been calculated bottom–up, based on current industry values for offshore substation, wind turbine, wind turbine foundation and inter–array cabling. For He Dreiht and Nemo one substation is assumed. For both wind farms the following assumption were made:

- Wind farm capacity: 900 MW
- Lifetime: 30 years
- Values for full load hours and OPEX were conservatively chosen

For a better comparison of the transport scenarios, both wind farms are investigated under similar assumptions. For a more realistic scenario evaluation, further adjustments for different settings e.g., specific wind turbines or multiple substations can also be calculated.

Hydrogen Production

Regarding the hydrogen production process, several assumptions and initial parameters need to be made and determined. The most relevant ones which are crucial to understanding of the offshore production price €/kg H_2 are described below. Major input parameters are:

- Capacity of the electrolysis is set to 80 % or 720 MW of the wind park nominal power
- CAPEX assumption for the large–scale electrolysis considered at the lower end of the currently realized market prices
- Electrolysis technology assumed to be Proton–Exchange Membrane (PEM) whereas Alkaline Electrolysis (AEL) would also be feasible
- Lifetime of the electrolysis set to 50% of the lifetime expectations for all other parts
- OPEX set to 3 % of CAPEX invest per year considering large scale installation advantages but also offshore condition disadvantages
- Desalination has been considered in CAPEX and OPEX calculation
- Output pressure level assumed to be atmospheric pressure

Maritime Logistics

In order to transport the hydrogen to shore, two main methodologies are considered. Firstly, an offshore pipeline, for which no experience is available. Derived from the oil and gas industry, a mean value of 6,5 M/km is assumed for manufacturing, transport and installation. A low one–digit percentage of the CAPEX forms the basis for the annual OPEX determination. Even though the wind farm is presumed at 30 years of operational lifetime, pipelines have a significantly longer lifetime expectancy, which was considered in the form of 50 years.

Instead of a pipeline, a shuttle–vessel based transportation can be implemented, which is commonly used in the oil & gas industry. Based on previous project experience, the transportation vessel will utilize low–pressure of up to 100 bar at a capacity of 160 t. With a mean daily hydrogen production of approx. 130 t and a cruise speed of 12 knots, a total amount of three transportation vessels is required for both He Dreiht and Nemo when operating in a shuttle approach with limited offshore storage capacity. The vessel is fitted with adequate offloading technology, which is commonly used in the oil & gas industry. Such technology combined with sufficient seakeeping capabilities of the vessel allow operations in wave conditions of up to 7 m H_s.

Onshore Logistics

If a direct pipeline connection from the offshore wind farm to the industrial end–client can be established, no onshore processing facility is required. However, due to simpler transport and installation, lower CAPEX is considered. The operational costs are decreasing accordingly.

Independent of the offloading location and the onshore logistics, a sophisticated port infrastructure is required for the vessel–based transportation. A cumulated value of approx. 30 M€ is considered for such infrastructure with an operating time of 30 years. This infrastructure comprises compression, which enables and accelerates the transfer from the vessel to the port, loading systems, pipes & valves as well as safety and surveillance equipment.

An additional compressor in the port perimeters is used to compress the hydrogen, as the onshore transport is much more subject to a high volumetric energy density to reduce overall transport costs. This allows the transportation in standardized 20 ft containers via truck, train or inland vessel. The amount of required containers was considered with a purchase price of approx. 247,000 €.

For transportation via truck, train or inland vessel, it is presumed that the companies will be contracted for the transport. Hence, transportation costs of 1.25 €/km per container for trains, 1.50 €/km per container for trucks and 1.30 €/km per container for inland vessels formed the basis.

7. Conclusion & Outlook

Producing green hydrogen far out in the North Sea, utilizing large–scale offshore wind parks offers tremendous potential to decarbonize whole industries onshore. This scenario also offers an independent and reliable solution for energy intensive industries such as steel production. However, future green hydrogen costs must not threaten competitiveness of local products. Therefore, this evaluation aims at providing an overview of potential end–to–end costs for green hydrogen and its transport vectors to large–scale onshore industries.

Four major value creation steps are assessed and added up to a LCOH result for every selected scenario. Those steps are energy generation, hydrogen production, maritime logistics and onshore logistics. The energy generation cost calculation leads to 55.60 € per MWh and is significantly lower compared to current installations, due to the missing grid connection. The hydrogen generation costs calculation leads to approximately 5 €/kg hydrogen, for today. Those costs will significantly decrease during the next 30 years by decreasing CAPEX costs for offshore wind and electrolysis installations. Also increasing full load hours for wind parks located in the far North–West corner of the German Exclusive Economic Zone will play an important role and would be reflected by the second park scenario Nemo. Regardless of the positive outlook for the first two value creation steps, it must be mentioned that photovoltaic–based green hydrogen from regions like Morocco, Saudi–Arabia or Oman will most likely always outperform regional offshore wind–based hydrogen. But value chain stability and shorter transport vectors leading to lower transport costs might mitigate this fact and make evaluations like this highly relevant.

Regarding the transport vector related value creation steps two major results can be derived:

Firstly, the evaluation shows that the implementation and construction of a pipeline linking the offshore platform and the industrial end customer far in the country results in the economically best scenario. The LCOH result for this end–to end chain is 6.81 €/kg H_2 for the wind park closer to the coastline and 7.31 €/kg H_2 for the park Nemo. The second–best price is for a vessel–based transport to Brunsbüttel and an onshore transport via pipeline to the end user resulting in 7.43 € (He Dreiht) respectively 7.64 €/kg H_2 (Nemo).

Secondly, the transport solutions, that do not require the construction of a dedicated pipeline are vessel transports, using Brunsbüttel or Rotterdam as base port and onwards train transport to the end user. These solutions are commercially more attractive via Rotterdam resulting in prices of 7.77 € for the windfarm closer to shore (He Dreiht) and 7.79 €/kg H_2 for Nemo.

Nevertheless, these costs reflect the view across the total time of pipeline utilization. A simple break–even analysis shows that approx. 15 years are required to pay off the huge CAPEX and outperform a transport scenario without a direct end–to–end pipeline connection. Additionally, current timeline assumptions show that the construction and the regulatory framework for pipeline takes a minimum of 12 years up to 17 years. On the flipside a combination of transportation vessels and onshore transportation offers a much quicker implementation with the advantage of being more flexible compared to a pipeline.

To project these conclusions to a more global level, the LCOH figures have been compared with the results derived from a more global study provided by umlaut and research partners in 2020 (Link to Study). This study provides LCOH values for liquid hydrogen imported from abroad to a harbor located in Germany. The predicted cost range lies between 3.5 and 5 €/kg H_2, projected to the year 2050. With a cost implication of roughly 1 € /kg H_2 for the inland transport, the costs of offshore–produced H_2 lies in the range between 5.80 €/kg and 7.00 €/kg and therefore, the delta between imported and domestic hydrogen from offshore is only approx. 1.00 €/kg H_2.

Considering further cost reductions in offshore wind within the next 20 years, green hydrogen from European offshore windfarms can be a reliable and competitive supplementary to a high amount of imported green hydrogen.

Impressum

Publisher

umlaut energy GmbH
Am Kraftversorgungsturm 3
52070 Aachen
Germany

www.umlaut.com
beyond@umlaut.com

Kongstein GmbH
Baumwall 7
20459 Hamburg
Germany

www.kongstein.com
info@kongstein.com

Authors

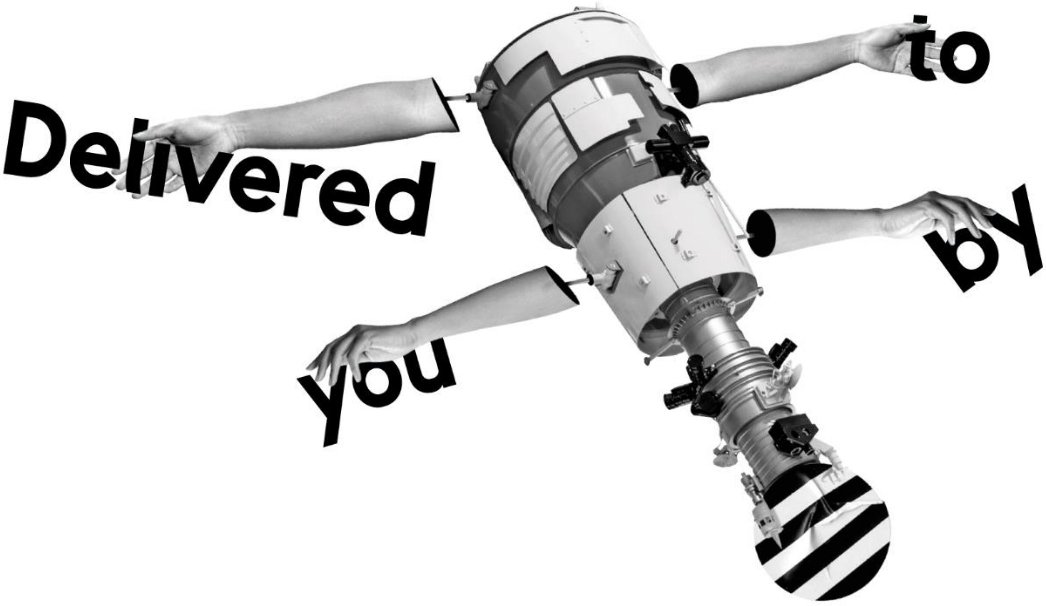
Patrick Wienert
Head of Hydrogen
Patrick.wienert@umlaut.com

Petja Stöver
Head of Wind Power
Petja.stoever@umlaut.com

Philipp Wiener
Consultant
philipp.wiener@umlaut.com

Thore Schreiber
Senior Project Manager
ths@kongstein.com

Bonke Jensen
Project Engineer
bj@kongstein.com



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