Proceedings of 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

Using a Design Exploration Model to Assess the Global Techno-Economic Feasibility of Far Offshore Green Hydrogen Production Towards 2050

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ABSTRACT

With space constraints onshore, strong renewable resources available far offshore and growing green hydrogen demand, far offshore green hydrogen production may be an attractive option. To assess this potential, a mixed integer quadratically constraint programming (MIQCP) optimization model was developed to find the cost per kilogram of far offshore green hydrogen in specific scenarios. The design of the far offshore green hydrogen supply chain was optimized with this model for six high potential scenarios in varying locations and the results were analyzed. It was found that far offshore green hydrogen costs are in the same order of magnitude as the costs of its alternatives. Far offshore green hydrogen may be considered marginally competitive with these alternatives from 2035 onwards in the analyzed scenarios when taking into account the considerable advantages of far offshore production, such as avoidance of scarce land usage in crowded areas and certain geopolitical considerations.

KEY WORDS

Far offshore; Green hydrogen; Green FPSO; LCoH; Optimization

INTRODUCTION

As the world attempts to slow down and eventually stop climate change, sustainability becomes increasingly important. According to Lapides et al. (2020), around 80% of the economy is relatively easy to decarbonize by electrification, with costs being reasonable and technologies already (widely) available. The other 20% consists of peak power generation, heavy duty transport (buses, trucks and ships) and industrial processes requiring combustion of a fuel to create high temperatures. For this last 20%, also referred to as the ‘last mile’ of decarbonization or hard-to-abate, hydrogen may play a key role in the path towards sustainability.

Hydrogen produced without any emissions using renewable energy is called green hydrogen. The production of green hydrogen occurs in a process called electrolysis, where electricity and water are used to produce hydrogen and oxygen. When renewable energy is used in this process, the hydrogen can be regarded as zero-emission and green. Since the production of green hydrogen will require large amounts of energy, a lot of additional renewable energy is needed. (Hague, 2021)

The demand for hydrogen is expected to rise strongly towards 2050 in many parts of the world (The Hydrogen Council & McKinsey & Company, 2021). Looking at the net-zero goals set by various countries (United Nations, n.d.), the demand

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Submitted: 23 February 2024, Revised: 30 April 2024, Accepted: 1 May 2024, Published: 27 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.913 e-ISSN: 3050-4864

for green hydrogen and renewable energy in general will grow significantly, which means space restrictions onshore and near offshore may present problems. In addition, the development of floating energy generation, and the strong and steady wind resources available in many (far) offshore locations may make far offshore renewable energy generation attractive. To transport large amounts of energy over long distances, transport in the form of hydrogen is more economic than transport through electrical cables (d'Amore-Domenech et al., 2021). Therefore, far offshore green hydrogen production could be even more beneficial, as it will make long distance transport to shore more economic and therefore the distance to shore of the production location less important.

The actual techno-economic feasibility of far offshore green hydrogen production is however still largely unknown. Therefore, the main objective of this research is to create a first idea of the worldwide technological and economic feasibility of far offshore green hydrogen production over time, identifying the technologies to be used in its supply chains, looking at which factors influence its price, comparing it to its alternatives and showing the role it may play in a net-zero economy in and towards 2050. In this research, 'far offshore production' is defined as production in areas with water depths over 50 meters, where floating production is necessary (ESMAP, 2019).

Many factors can influence the far offshore green hydrogen supply chain and therefore the costs of far offshore green hydrogen. The right combination of energy generation devices, electrolyzers, conversion devices, storage size, FPSO size and hydrogen carrier must be determined in every scenario. In order to solve this design challenge and find the optimal combination of all these aspects leading to the lowest far offshore green hydrogen costs, an optimization model is needed when analyzing the scenarios to be considered. How to best set up the model for this research will be discussed in the literature review. In this literature review, the method of the literature retrieval and the technologies that were considered in this research will be discussed as well. Next, the methodology will show the model developed in this research and the scenarios that were analyzed. After this, the results will be analyzed, followed by a short discussion and the conclusions.

LITERATURE REVIEW

An extensive literature review was conducted to map the available knowledge regarding far offshore green hydrogen production and related topics. In this section, it will be discussed how the relevant literature was retrieved, how a suitable modelling method was found and which technologies were included in the model.

Literature Retrieval

For the literature retrieval, mainly SCOPUS was used. Eight combinations of search terms were used, which are shown in Figure 1. On the search results, a title scan and subsequently a quick abstract scan were performed which resulted in a list of possibly interesting references. Next, the selected references were analysed further by doing an extensive abstract scan and a quick scan of the rest of the paper. This lead to a further selection and structuring of the papers. In Figure 1, the literature retrieval process is shown visually and the amount of references is indicated for each part of the process. As can be seen, the initial scan resulted in a total of 247 references, which was brought down to 180 after the second scan. These references were then placed in four different categories (A, B, C and D), with categories A and B containing the literature with relevant general information on the various topics of interest (for example on the techno-economic feasibility of possibly interesting technologies) and categories C and D containing the literature describing possibly relevant methods. Furthermore, categories A and C contain the references that were expected to be relevant in their entirety, whereas categories B and D contain the references that are not relevant in their entirety, but contain relevant aspects, such as one or several specific input data values or a method for a specific (small) part of the model. Eventually, a total of 57 references were identified as most relevant (categories A and C). The literature review has been set up primarily based on these references. In all of the reviewed literature, only one reference was found describing a solution approach with a similar scope, which was used as a base for the modelling approach developed in this research, as will be explained below.

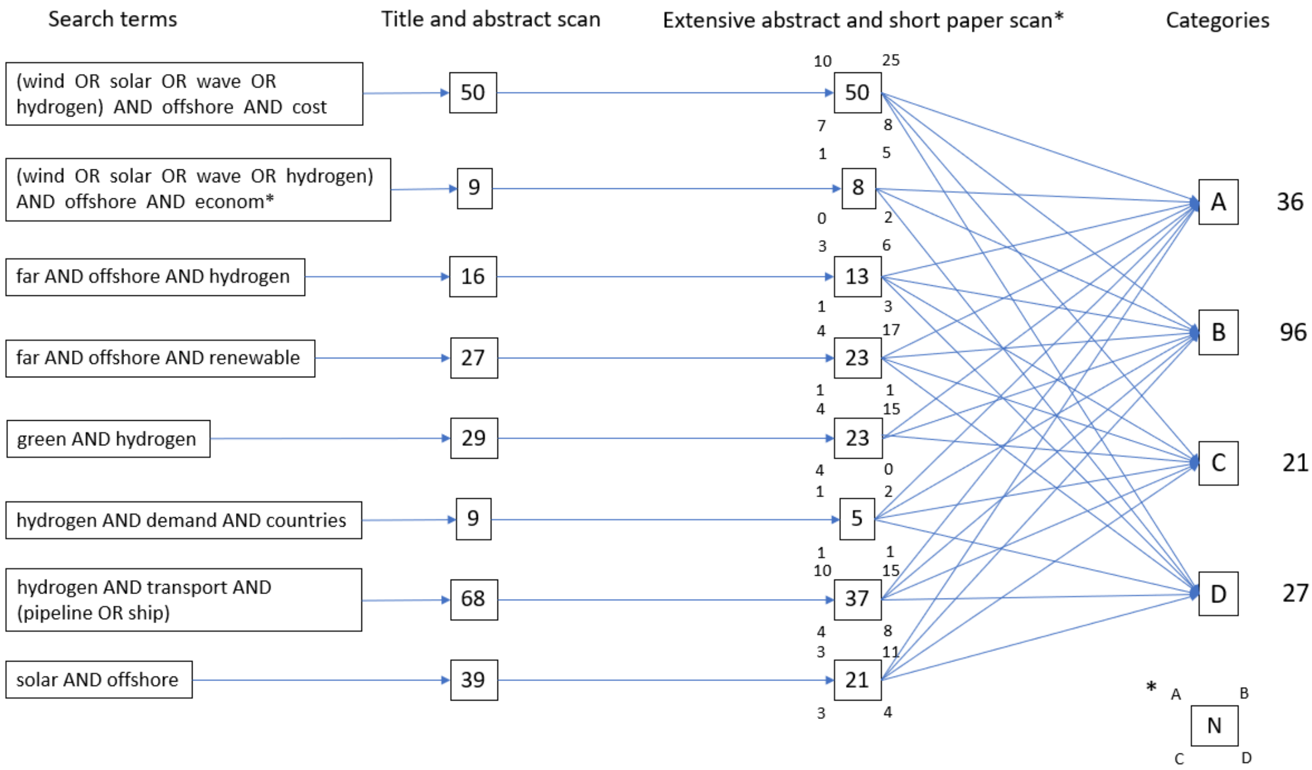

Figure 1: Flow chart literature retrieval (please note that the small numbers in the third column indicate how many references were placed into each category, as shown in the legend in the bottom right corner of the figure)

Suitable Modelling Method

During the reviewing, only one reference describing a solution approach with a similar scope to this research has been found. In this paper, Salmon and Bañares-Alcántara (2022) look at the worldwide feasibility of (far) offshore green ammonia production in 2030. Their main analysis is done on a global level, directly comparing the best onshore with the best offshore locations. This may however not show the full potential of far offshore production of green hydrogen and its derivatives. For example, if we directly compare an onshore production location in Morocco and an offshore production location off the coast of New Zealand to each other, the production costs of the onshore location in Morocco might be lower. However, if the demand is located in New Zealand, the delivered costs of the green hydrogen may still be lower from the offshore location when taking into account the conversion and transport costs. For this reason, comparing green ammonia production costs on a global level directly as done by Salmon and Bañares-Alcántara (2022) in their main analysis does not lead to a realistic comparison and approaches the potential of far offshore green ammonia from a very conservative side. This is a major limitation to their research and was therefore taken into account when setting up the modelling method for this research.

In order to assess the effect of infrastructure costs on the potential of far offshore green ammonia, Salmon and Bañares-Alcántara (2022) shortly look at its potential in two scenarios with usage in Germany and Japan (including transport). They conclude that far offshore green ammonia will be beneficial in Japan and not in Germany, with which they illustrate themselves that the specific scenario is highly important, which means an analysis based on specific scenarios is needed to make a realistic analysis. Therefore, the global potential of far offshore green hydrogen should be assessed 'bottom-up', where a representative set of specific scenarios is analyzed, from which conclusions are drawn about the global potential of far offshore green hydrogen. This means the main gap in literature to be filled by this research is an evaluation of the global potential of far offshore green hydrogen over time using local comparisons with specific scenarios. In addition to this, Salmon and Bañares-Alcántara (2022) only made predictions for 2030 and only considered ammonia. These shortcomings were addressed in this research as well. When defining the scenarios to be analyzed in this research, the highest potential scenarios were selected first, as it was still unknown whether far offshore green hydrogen production will become feasible at all. In the methodology, the scenarios considered in this research will be discussed in more detail.

In Figure 2, the modelling approach used by Salmon and Bañares-Alcántara (2022) is shown with the main adjustments as described in the previous paragraph (green blocks). This was used as a base for the model developed in this research. As can be seen, transport costs and technical data, several hydrogen carriers, and the period until 2050 are included. Also, the potential of far offshore green hydrogen is evaluated with local comparisons, shown by the fact that local demand and green hydrogen alternatives are used.

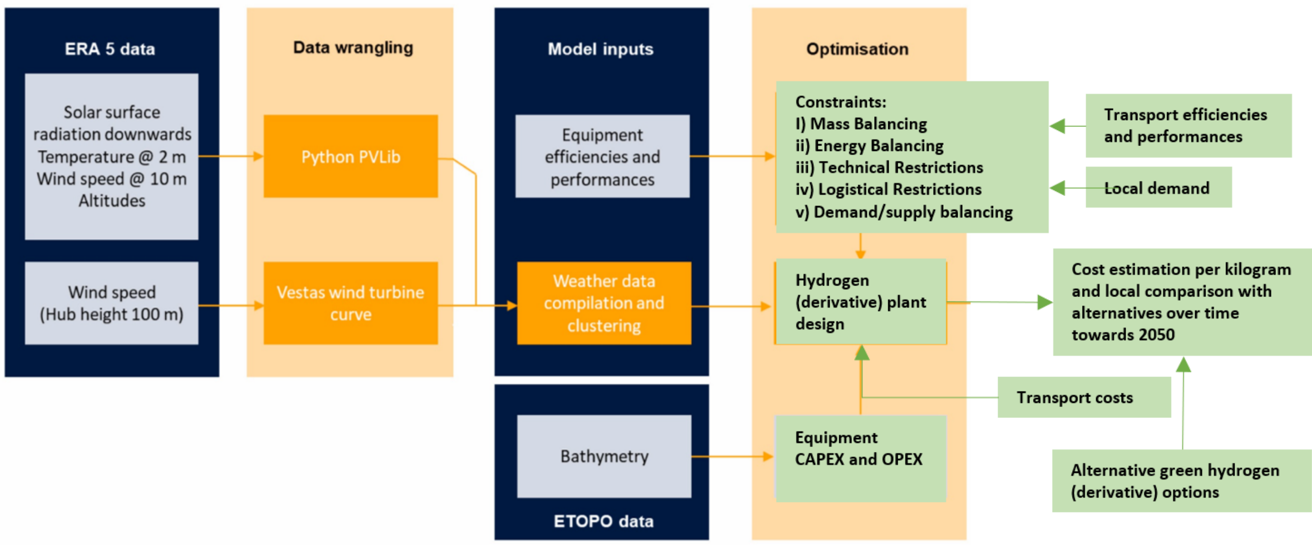

Figure 2: Basis for the modelling approach as adjusted from Salmon and Bañares-Alcántara (2022) (only main adjustments)

When following a modelling approach similar to the one shown in Figure 2, the focus is put on the optimization of the far offshore green hydrogen supply chain. The alternative would be to put the focus on a higher level supply/demand interaction in a global network of production and usage locations, and simplify the far offshore green hydrogen supply chain modelling. It is expected that putting the focus on the optimization of the far offshore green hydrogen supply chain will have a more direct practical relevance for the choices to be made in the development of far offshore green hydrogen production at this moment in time. In addition, it is expected that it will result in more complete and reliable insights into what technologies may become part of far offshore green hydrogen supply chains and how the potential will develop. Furthermore, when focusing on the optimization of the supply and demand interaction, too large uncertainties are expected to be introduced. More research must be performed to be used as a base for a research with such a focus. Therefore, the focus was put on the optimization of the far offshore green hydrogen supply chain in this research. Within this supply chain, the main optimization challenges included in the model developed in this research are (1) the optimization of the combination of various renewable energy generation devices with the electrolyzers, and (2) the choice between several hydrogen carriers as transport medium. Both of these optimizations integrate various parts of the far offshore green hydrogen supply chain. The outcome therefore depends on many different factors and the two optimizations are connected as well when solved simultaneously. How the model was set up to solve the two main optimization challenges and design the rest of the supply chain too will be discussed in more detail in the methodology.

Next to the focus of the model, the method to be used is of great importance. Salmon and Bañares-Alcántara (2022) applied an optimization model with mixed integer linear programming (MILP). MILP is preferred over genetic algorithms as it guarantees the optimality of the solution (EMD International, 2020). In addition, optimization is preferred over simulation, because the optimal supply chain must be designed by the model to assess the full potential of far offshore green hydrogen and it is expected to be difficult to predefine a set of simulations due to the limited knowledge available on far offshore green hydrogen supply chains. So far, the approach of Salmon and Bañares-Alcántara (2022) is followed. However, because several hydrogen carriers were considered in this research, it was expected that not all constraints would be linear, since the value of certain variables would depend on which hydrogen carrier is used, which is defined in the model through a constraint. When those variables are then used in other constraints, quadratic constraints can arise. For the same reason, quadratic objective terms could also arise. Therefore, MILP cannot be applied in this research and mixed integer quadratically constraint programming (MIQCP) is used instead to deal with the quadratic constraints and objective terms. Lastly, the model is implemented in Python and the Gurobi optimization solver is used, which is freely available through an academic license.

Technologies to Be Included

The next step was to decide what exactly to include in the model, which was needed to be able to expand the general modelling approach presented in Figure 2 to a more detailed one. To do this, the retrieved literature was reviewed to assess what is already known about the techno-economic feasibility of the various aspects of a far offshore green hydrogen supply chain. An overview of the technologies included in the model is given in Table 1.

For the far offshore renewable energy generation, moored floating wind and solar energy production seem to be coming close to techno-economic feasibility (De Vries et al., 2021; Jan De Nul, 2023; SolarDuck, n.d.) and are therefore considered. The technological and especially cost development of wave energy converters is deemed too uncertain (Kasiulis et al., 2022; Rehman et al., 2022) and therefore, wave energy is left outside of the scope of the intended research.

With regards to the hydrogen production, it was found that PEM electrolyzers are expected to be most suitable for far offshore green hydrogen production due to their compact stacking possibilities and ability to handle the dynamic power input associated with renewable energy production (Jang et al., 2022). Furthermore, the focus of this research was put on centralized hydrogen production in an FPSO, leaving the option of decentralized hydrogen production out of the scope. Offshore hydrogen production with PEM electrolyzers will require a desalination plant as well (Jang et al., 2022).

Looking at the transport of hydrogen produced far offshore, the transport over sea seems most feasible from a techno-economic perspective if it is done by ship in the form of ammonia or liquid hydrogen. Whether ammonia or liquid hydrogen is more beneficial depends on the distance to be traveled and the quantity of hydrogen to be transported (International Renewable Energy Agency, 2022). Both options have therefore been included in the model. Methanol and compressed hydrogen are not considered in the model, since their costs are expected to be higher for most far offshore green hydrogen production scenarios (Cebolla et al., 2022). Other liquid organic hydrogen carriers (LOHCs) are also left out of the scope because there are multiple challenges that can limit their potential role in the global hydrogen trade, including limited availability, high costs, low hydrogen density, losses during recycling and high energy usage to recover the hydrogen from the carrier (International Renewable Energy Agency, 2022). Transport over land is assumed to be done with pipelines as gaseous hydrogen, since this seems to receive most attention at the moment. Long term storage onshore is not included in the model, but storage in the FPSO is. This storage may be done in the form of ammonia or liquid hydrogen, depending on which medium is used for transport.

Table 1: Technologies included in the model for each step of the far offshore green hydrogen supply chain

Step	**Technologies included in the model**
Power generation	Floating wind turbines Floating solar platforms
Electrolysis	PEM electrolyzers (with desalination) Centralized production on FPSO
Conversion and storage on FPSO	Ammonia Liquid hydrogen
Sea transport	Ammonia (by ship) Liquid hydrogen (by ship)
Land transport	Gaseous hydrogen (through pipelines)

METHODOLOGY

In this section, the model will be shown and its general outline will be discussed. In addition, the scenarios to be analyzed will be presented. In the report this paper was based on, a more detailed explanation of the model is given.

Model Overview

A schematic overview of the calculations belonging to an optimization of a far offshore green hydrogen supply chain, which forms the core of the developed model, is shown in Figure 3. It should be noted that only one optimization is visualized here, while a normal run of the model will include several optimizations for the chosen scenario in different years, meaning the visualized optimization will be run multiple times with changing input data. When looking at the input data for these optimizations belonging to different years, only the cost data will change, which is represented by the cell in the bottom right of Figure 3. This could lead to a different optimal far offshore green hydrogen supply chain for every considered year.

Next to the time domain included in the model by simulating several years, a second time domain is included within each optimization. From ERA5, hourly weather data is imported for a reference period of 10 months, which enters the model at the very left of Figure 3. From this hourly weather data, the hourly power production, the hourly power available for and used by the electrolyzers, and the hourly hydrogen production are determined over the reference period. Using these hourly production figures, the supply chain is optimized for production over a longer period of time, leading to more realistic results.

In Figure 3, the cells with yellow background color are 'normal', numeric input data or based on calculations with solely numeric data. The cells with red background color are variables, which are to be varied directly by the used optimization solver when finding the optimum. The cells with blue background color are based on calculations including other variables, meaning their value also changes while the optimization runs. Furthermore, the black arrows connecting cells represent 'regular' calculations, whereas the orange arrows represent constraints. Finally, the colors of the borders of the cells show to which part of the model they belong, as discussed further later in this section.

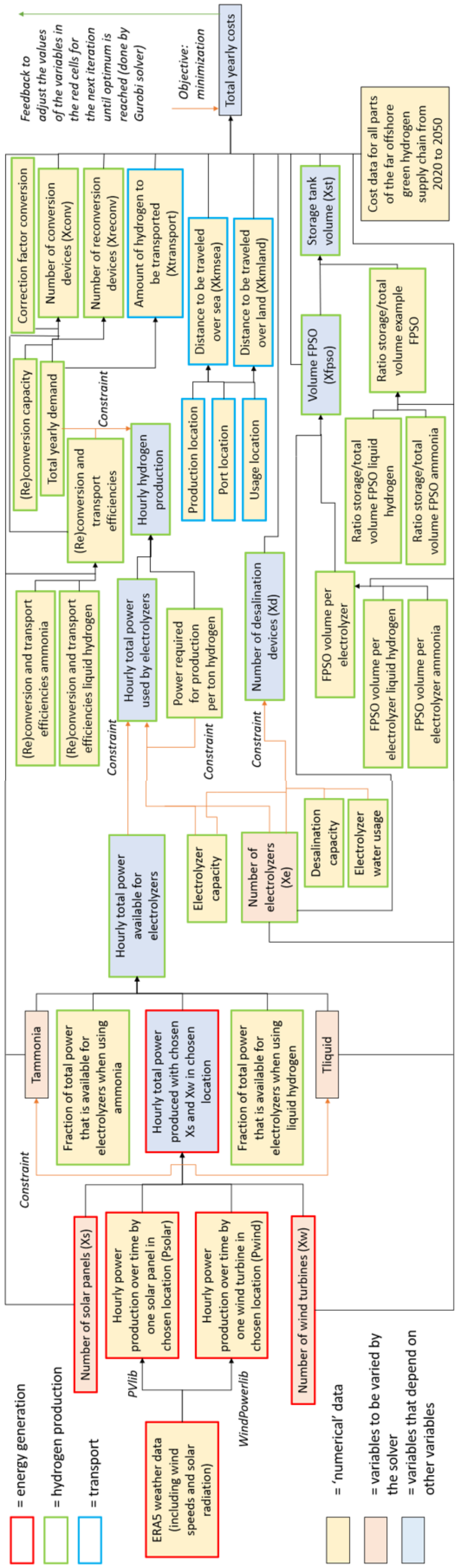

Figure 3: Model visualization

As can be seen in the figures, most calculations in the model eventually lead back to the calculation of the total yearly costs. As the yearly hydrogen production is given as a (constant) input to the optimization, these total yearly costs are directly related to the costs per kg of hydrogen. This means minimizing the total yearly costs is equal to minimizing the costs per kg of hydrogen for the analyzed supply chain. Therefore, the objective function to be minimized in the model is formulated as shown in Equation (1), where ‘i’ indicates the components of vectors x and C. Vectors x and C represent the number of units and the cost per unit respectively.

$$MIN(\sum_i x[i] * C[i]) \tag{1}$$

This means the sum that is minimized in the objective function is equal to the total costs for the far offshore green hydrogen supply chain in the defined scenario in the selected year. The elements of vectors x and C can be split up into three different groups: energy generation (X_{energy} and C_{energy}), hydrogen production ($X_{\text{production}}$ and $C_{\text{production}}$) and transport ($X_{\text{transport}}$ and $C_{\text{transport}}$). This gives the split shown in Equation (2). In Figure 3, it has been indicated which part of the model belongs to each group through the color of the borders of the cells. The meaning of these colors is given in the legend. The cells with T_{ammonia}, T_{liquid} and the cost data do not have a colored border, because the calculations in which they are used belong to multiple groups.

$$x * C = X_{\text{energy}} * C_{\text{energy}} + X_{\text{production}} * C_{\text{production}} + X_{\text{transport}} * C_{\text{transport}} \tag{2}$$

The three categories shown in Equation (2) can each be split up further, as shown in Equations (3) to (5). In Table 2, the variables and parameters used in these equations are explained. As indicated in the table, most of the equipment types are restricted to integer values.

$$X_{\text{energy}} * C_{\text{energy}} = X_{\text{w}} * C_{\text{w}} + X_{\text{s}} * C_{\text{s}} \tag{3}$$

$$\begin{aligned} X_{\text{production}} * C_{\text{production}} = {} & X_{\text{e}} * C_{\text{e}} + X_{\text{d}} * C_{\text{d}} + X_{\text{st}} * C_{\text{st}} + X_{\text{fpso}} * C_{\text{fpso}} \\ & + T_{\text{ammonia}} * X_{\text{convammonia}} * C_{\text{convammonia}} + T_{\text{liquid}} * X_{\text{convliquid}} * C_{\text{convliquid}} \\ & + T_{\text{ammonia}} * X_{\text{reconvammonia}} * C_{\text{reconvammonia}} + T_{\text{liquid}} * X_{\text{reconvliquid}} * C_{\text{reconvliquid}} \end{aligned} \tag{4}$$

$$X_{\text{transport}} * C_{\text{transport}} = X_{\text{basetransport}} * C_{\text{basetransport}} + X_{\text{kmsea}} * C_{\text{kmsea}} + X_{\text{kmland}} * C_{\text{kmland}} \tag{5}$$

Table 2: Meaning variables and parameters

Component	Meaning	Unit
X_w	Number of wind turbines (integer)	*dmnl*
X_s	Number of solar platforms (integer)	*dmnl*
X_e	Number of electrolyzers (integer)	*dmnl*
X_d	Number of desalination devices (integer)	*dmnl*
X_{st}	Volume of the storage tank on the FPSO	m^3
X_{fpso}	Volume of the FPSO	m^3
X_{kmsea}	Distance to be traveled over sea	*km*
$X_{basetransport}$	Amount of hydrogen to be transported	*tons*
X_{kmland}	Distance to be traveled over land	*km*
$X_{convammonia}$	Amount of conversion devices in case of transport as ammonia (integer)	*dmnl*
$X_{convliquid}$	Amount of conversion devices in case of transport as liquid hydrogen (integer)	*dmnl*
$X_{reconvammonia}$	Amount of reconversion devices in case of transport as ammonia (integer)	*dmnl*
$X_{reconvliquid}$	Amount of reconversion devices in case of transport as liquid hydrogen (integer)	*dmnl*
$T_{ammonia}$	Binary variable that indicates transport is done with ammonia when equal to 1	*dmnl*
T_{liquid}	Binary variable that indicates transport is done with liquid hydrogen when equal to 1	*dmnl*
C_w	Yearly costs of one wind turbine	*euros/year/unit*
C_s	Yearly costs of one solar platform	*euros/year/unit*
C_e	Yearly costs of one electrolyzer	*euros/year/unit*
C_d	Yearly costs of one desalination device	*euros/year/unit*
C_{st}	Yearly costs of one m^3 of storage tank	*euros/year/$m3$*
C_{fpso}	Yearly costs of one m^3 of FPSO	*euros/year/$m3$*
C_{kmsea}	Costs of ammonia or liquid hydrogen transport over sea for one tonkm hydrogen	*euros/ton of hydrogen/km*
$C_{basetransport}$	Base sea transport costs of ammonia or liquid hydrogen for one ton of hydrogen	*euros/ton of hydrogen*
C_{kmland}	Costs of gaseous hydrogen transport over land through pipelines per tonkm hydrogen	*euros/ton of hydrogen/km*
$C_{convammonia}$	Yearly costs of one ammonia conversion device	*euros/year/unit*
$C_{convliquid}$	Yearly costs of one liquid hydrogen conversion device	*euros/year/unit*
$C_{reconvammonia}$	Yearly costs of one ammonia reconversion device	*euros/year/unit*
$C_{reconvliquid}$	Yearly costs of one liquid hydrogen reconversion device	*euros/year/unit*

In Equations (3) to (5) and in some of the other calculations in the developed model, $T_{ammonia}$ and T_{liquid} are used, which are also mentioned in Table 2. $T_{ammonia}$ and T_{liquid} are binary variables used to include the choice between transporting with ammonia or liquid hydrogen in the optimization. To force the optimization solver to choose between the two, the constraint in Equation (6) has been implemented, which is also shown in Figure 3.

$$T_{\text{ammonia}} + T_{\text{liquid}} = 1 \tag{6}$$

In this section, the central cost calculation for the objective function as done by the developed model was shown. However, many related calculations and constraints are included in the model as well. As mentioned before, those are discussed in more detail in the report this paper was based on.

Scenario Definition

As explained before, the global potential of far offshore green hydrogen was assessed through the analysis of a representative set of high potential scenarios. To find these scenarios, usage locations were identified with high local production costs, as shown in Figure 4. In addition production locations were selected with strong wind resources and limited water depths, as shown in Figure 5.

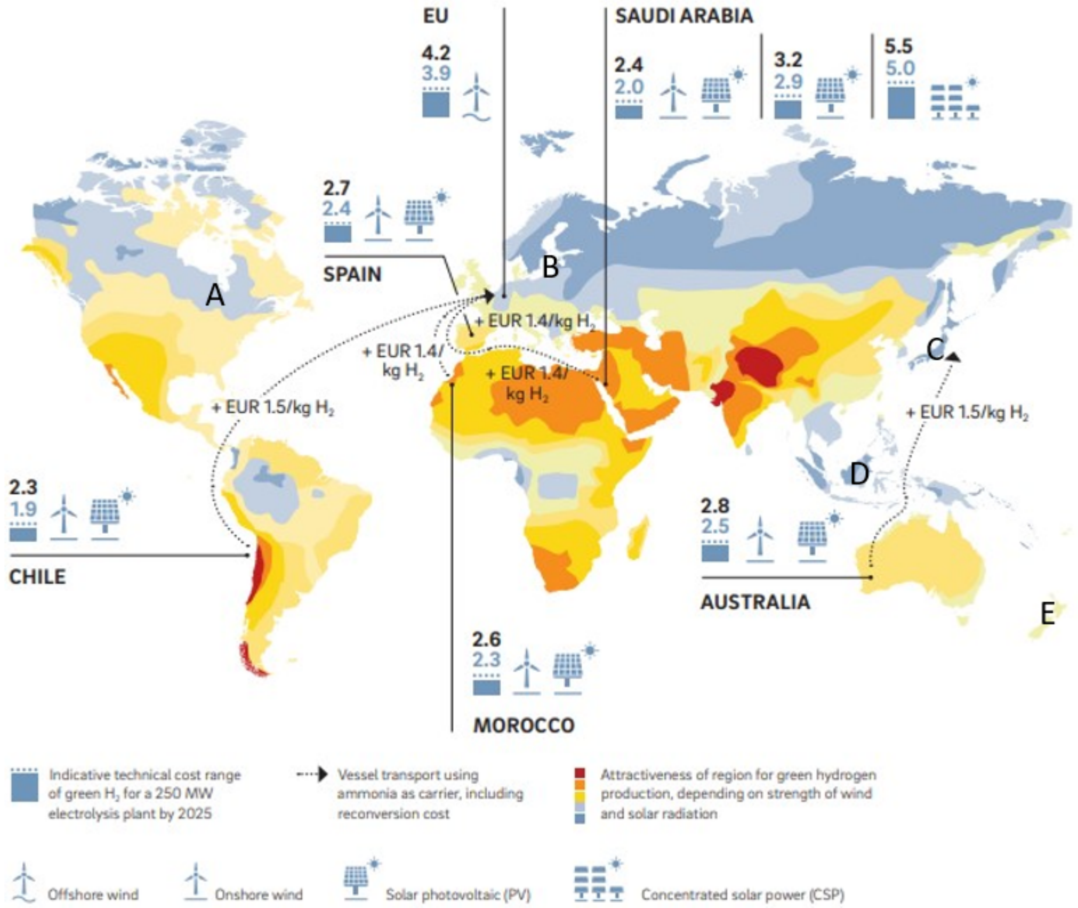

Figure 4: High potential far offshore green hydrogen usage locations A to E (modified from (De Vries et al., 2021))

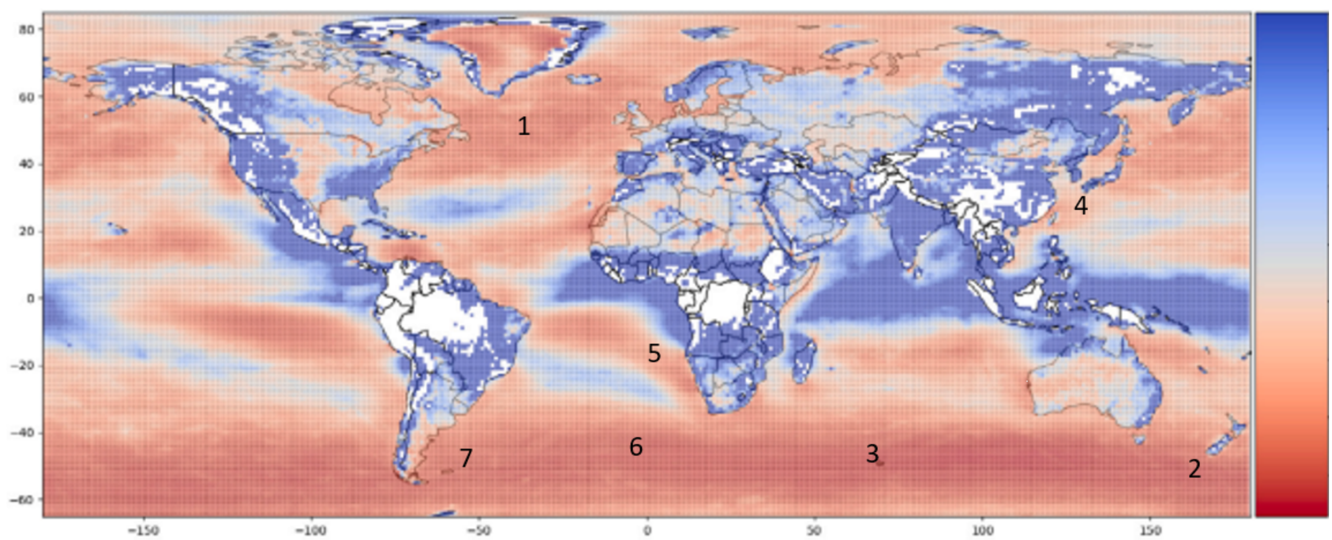

Figure 5: High potential far offshore production locations 1 to 7 (modified from (Salmon & Bañares-Alcántara, 2022))

The potential usage locations were combined with the closest production location to create the scenarios to be analyzed. For usage location D (Singapore), this could have been production location 2 (in the Southern Pacific Ocean), 3 (in the Indian Ocean) or 4 (in the East Chinese Sea). In this case, location 2 was chosen due to the strong renewable resource potential and relatively large area with limited water depth. The selection as described here lead to the selected scenarios shown in Table 3.

Table 3: High potential far offshore green hydrogen scenarios to be analyzed further in this research

	Production location	**Usage location**
Scenario 1	East Chinese Sea (4)	Tokyo, Japan (C)
Scenario 2	East Chinese Sea (4)	Seoul, South Korea (C)
Scenario 3	Northern Atlantic Ocean (1)	Cologne, Germany (B)
Scenario 4	Northern Atlantic Ocean (1)	New York, USA (A)
Scenario 5	Southern Pacific Ocean (2)	Singapore (D)
Scenario 6	Southern Pacific Ocean (2)	Christchurch, New Zealand (E)

RESULTS

After having formulated the model and defined a representative set of scenarios, the chosen scenarios could now be analyzed. The far offshore green hydrogen supply chain was optimized for all scenarios using the developed model and the accompanying costs per kilogram of hydrogen produced far offshore were compared to the costs of local green hydrogen production and green hydrogen import. The latter were determined primarily with the model made publicly available by Brändle et al. (2021). In the report this paper was based on, the general input data for the model (which stays the same across scenarios) and the scenario-specific input data can be found. In Figures 6 to 11, the results of the scenarios are presented, where the orange lines represent the far offshore green hydrogen costs.

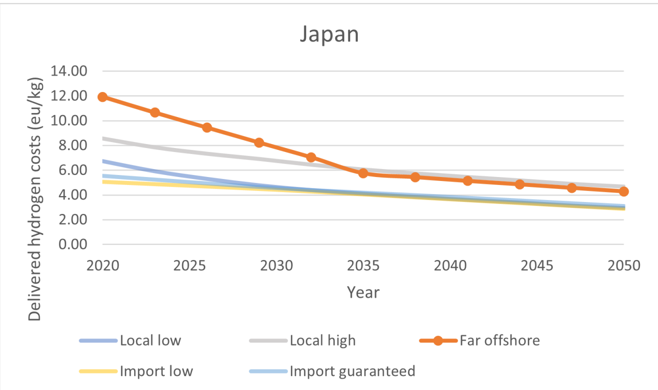

Figure 6: Results scenario 1

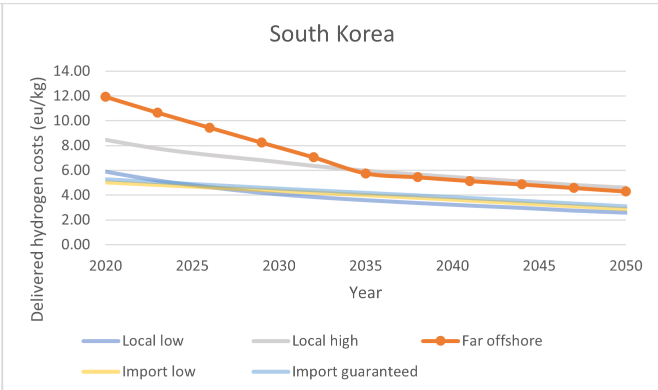

Figure 7: Results scenario 2

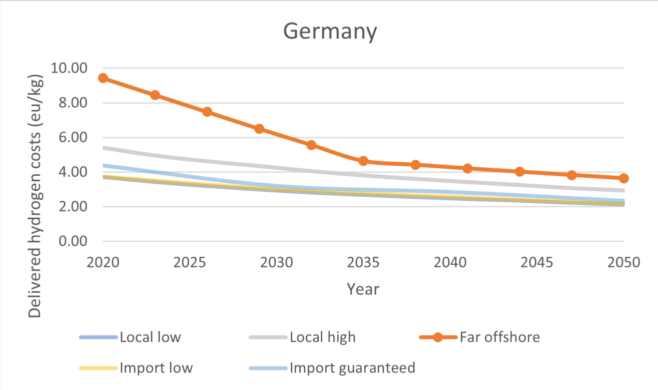

Figure 8: Results scenario 3

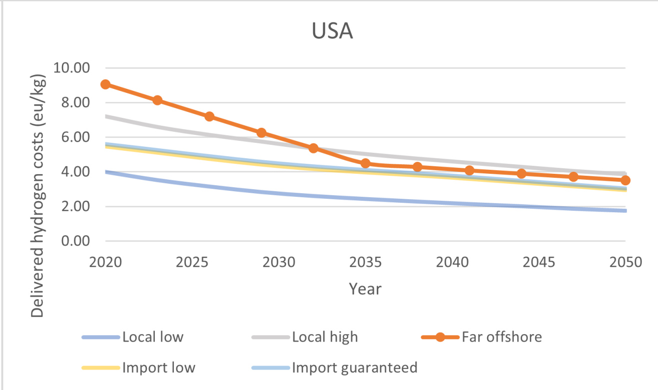

Figure 9: Results scenario 4

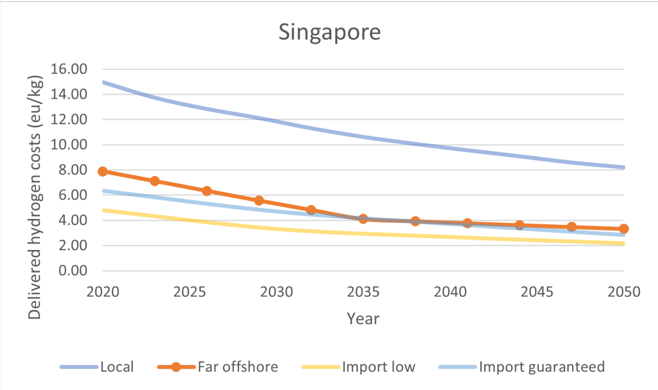

Figure 10: Results scenario 5

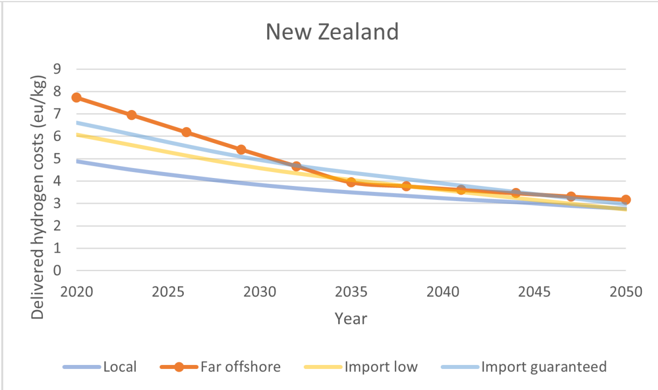

Figure 11: Results scenario 6

The results differ greatly between scenarios. In scenarios 1 and 2 (Figures 6 and 7), the far offshore green hydrogen costs are similar to the highest local production costs between 2035 and 2050. Green hydrogen import costs are clearly lower, which means far offshore green hydrogen does not have the preference from a purely techno-economic standpoint in these scenarios. However, since the cheap green hydrogen import options for Japan are mostly represented by China, Russia, Iran, Saudi Arabia and Oman, geopolitical factors may play in favour of far offshore green hydrogen. Based on the local production capacity of Japan (Brändle et al., 2021) and the expected demand in 2050 (The Hydrogen Council & McKinsey & Company, 2021), Japan is not expected to be able to be self-sufficient with onshore production, which means far offshore production will be necessary if Japan aims to be self-sufficient. The situation for South Korea is similar, although the onshore production capacity is higher there (Brändle et al., 2021).

When looking at scenario 3 (Figure8), it can be seen that far offshore green hydrogen is less economic than its alternatives over the entire period, but especially before 2035. The import options for Germany in this scenario include Spain, Italy, France, Norway and Morocco. It is therefore expected that the influence of geopolitical factors will be limited here. For scenario 4 (Figure 9), the far offshore green hydrogen costs are lower than the highest local production costs and similar to the import costs. However, the onshore green hydrogen production capacity in the USA is very large (Brändle et al., 2021), which means the local demand can be filled without any import. In scenarios 3 and 4, far offshore green hydrogen is not expected to be feasible from a purely techno-economic perspective based on these results. Societal factors such as the willingness to install renewable energy production onshore may however have an influence.

Finally, scenarios 5 and 6 (Figures 10 and 11) show relatively low far offshore green hydrogen costs, which can be attributed to the production location in the Southern Pacific Ocean, where very strong and steady winds can be found. From 2032 to

2050, the far offshore green hydrogen costs are similar to the import costs and also before 2032, the difference is relatively small. In Singapore (scenario 5), the local production costs are very high and the capacity is very small, so import is expected to be essential, either from a different country (in this case China) or from far offshore. Both options could share the market or the Singaporean government could choose between the two. In New Zealand, local onshore production is also relatively economic. It may depend on the capacity of this onshore production whether import from China or far offshore production is necessary. If one of these is necessary, again no strong preference can be given based on the costs.

Next to the scenario analysis based on the final costs, some additional analysis was done. It was found that combining wind turbines and solar platforms to create a more steady energy production is beneficial in most scenarios and that in every scenario, a different combination of wind turbines, solar platforms and electrolyzers is optimal. Figure 12 shows the installed wind and solar power generation capacity over the years for scenario 1 to illustrate this. In scenarios 1 and 2, a relatively large amount of solar power is used in the beginning, but this decreases over the years since the floating wind costs develop faster than the floating solar costs under the assumptions taken. After 2035, the model still uses some solar power in most years, but the capacity is small compared to the installed wind power capacity. The latter is the case for the entire period between 2020 and 2050 in scenarios 3 and 4. In scenarios 5 and 6, no solar power is used, indicating a relatively strong wind resource in the production location used in those scenarios.

Next, it was found that energy generation represents the biggest share of the total far offshore green hydrogen costs in 2020, but this decreases over the years. The percentage taken up by ammonia conversion, ammonia transport and the FPSO on the other hand grow because their costs stay constant while all other costs are decreasing over the years. This can be seen in Figure 13, which shows the development over the years of the far offshore green hydrogen costs and its distribution for scenario 1 as an example. In 2050, the ammonia (re)conversion costs are expected to be the biggest cost contributor, closely followed by the energy generation

Furthermore, ammonia is found to be the preferred transport medium for far offshore green hydrogen until at least 2050 in the analyzed scenarios. The choice between ammonia and liquid hydrogen based on the distance to be traveled over sea and the storage volume on the FPSO is illustrated in Figure 14 for scenario 1 in 2050. In this figure, it can be seen clearly that lower transport distances and lower storage volumes favor liquid hydrogen. The effect of reducing the liquid hydrogen transport, storage and (re)conversion costs by 10% is also shown.

Finally, in order to gain further insight in the influence of different input parameters on the costs per kilogram of far offshore green hydrogen, a sensitivity analysis was performed. In this analysis, it was found that the interest rate, floating wind costs, floating solar costs, ammonia (re)conversion costs, FPSO costs and large changes in water depth can have significant influence on the costs per kilogram of hydrogen. In addition, it was found that dampening and enhancing effects can be seen when changing the costs of floating wind, floating solar and the electrolyzers. Furthermore, it was found that the desalination costs, liquid hydrogen and ammonia transport costs, electrolyzer costs, distance to shore and size of the hydrogen demand have a relatively small influence within the variations performed. The small influence of the last one was however attributed to model simplifications.

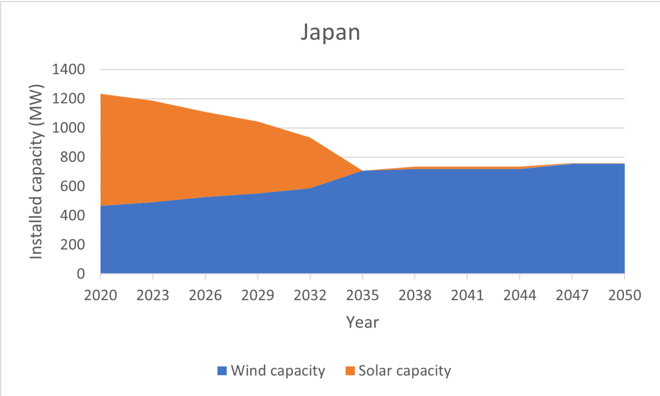

Figure 12: Total installed wind and solar power generation capacity from 2020 to 2050 in supply chains as optimized by the model for scenario 1

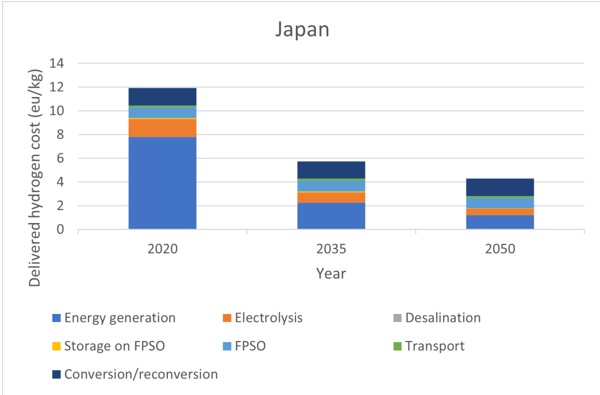

Figure 13: Cost distributions scenario 1 in 2020, 2035 and 2050

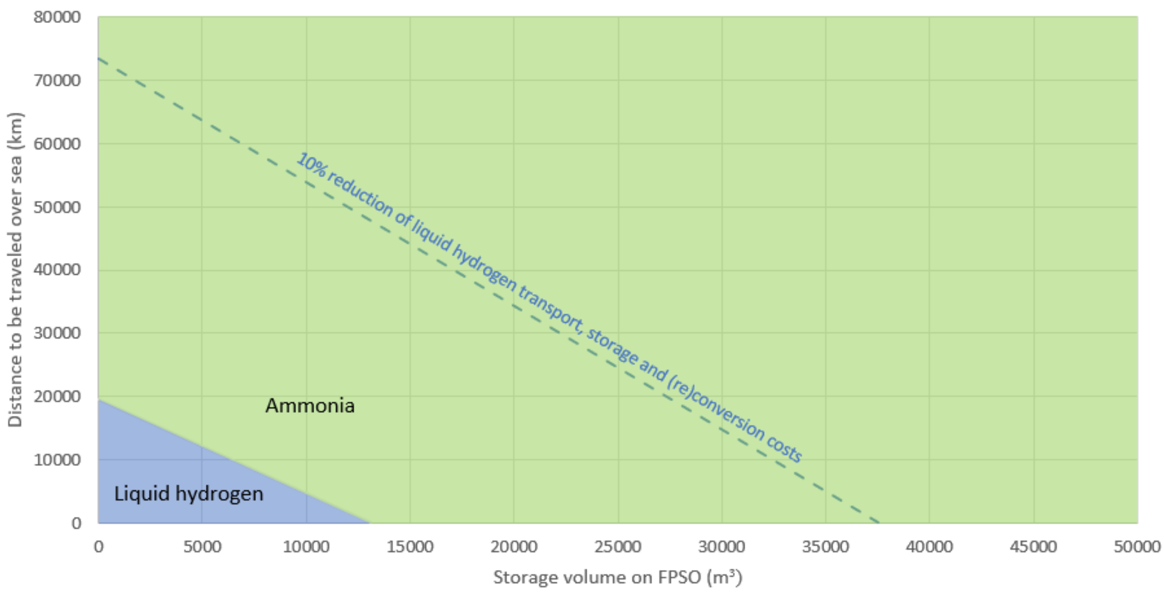

Figure 14: Visualization of preference for liquid hydrogen or ammonia based on distance to be traveled over sea and storage volume on the FPSO for scenario 1 in 2050

DISCUSSION

In the previous section, the results have been presented. Some side notes should however be placed with these results. First of all, as the field of far offshore green hydrogen is relatively new, data availability is limited. Therefore, the input data as used in this research should continuously be developed in follow-up research once more data becomes available.

Furthermore, follow-up research could look into further extending the model to make sure it becomes even more complete and accurate. The model could be extended by including size limitations of offshore locations, the effects of economy of scale, the costs of longer electricity cables for bigger wind parks (increasing the attractiveness of adding solar platforms), differences in OPEX worldwide, and a more accurate estimation of the distance to be traveled over sea. These points are discussed in more detail in the report this paper was based on. Next to the model developed in this research, the model used to determine the green hydrogen local production and import costs also has several limitations, as discussed by Brändle et al. (2021).

Lastly, it should be mentioned that this research mostly looks at the techno-economic potential of far offshore green hydrogen, while geopolitical and social factors may also greatly influence its feasibility. Despite the comments mentioned in this section, valuable insights were created into what the global potential is of far offshore green hydrogen towards 2050 and what influences this potential. The conclusions drawn will be discussed further in the next section.

CONCLUSION

The techno-economic analysis of the selected scenarios in the present study shows a levelized cost of delivered green hydrogen from far offshore production locations of 3.5 to 5 euro/kg in 2050, coming from a cost of 7.5 to 12 euro/kg in 2020. A clear decreasing trend of the levelized cost of hydrogen (LCoH) can be observed for the coming decades up to 2050 across all scenarios. For two out of the six scenarios analyzed in our study (combination of far offshore production location and final delivery destination onshore), an LCoH below 5 euro/kg seems feasible from 2030 onwards, and from 2035 this is expected to be the case for another two scenarios. This cost may be considered as marginally competitive with alternatives such as local production of green hydrogen onshore or import of green hydrogen from other places in the world. Although the far offshore production costs are (slightly) higher in most scenarios, the considerable advantages of far offshore production, such as avoidance of scarce land usage in crowded areas and certain geopolitical considerations, should be taken into account when considering the competitiveness of the far offshore green hydrogen option and increase its feasibility. It should also be noted that techno-economic analysis of far offshore green hydrogen is still a relatively new research topic and that many aspects have not yet been thoroughly explored. Estimated cost may therefore still be lower or higher in certain specific scenarios, making or breaking the far offshore green hydrogen option. The most important uncertainty seems to be the development of the cost (CAPEX and OPEX) of critical components such as floating offshore wind, floating offshore solar and large size electrolysers for installation on a central floating production unit.

When going into a bit more detail, it was concluded that PEM electrolyzers would be most suitable for far offshore green hydrogen production. Furthermore, it was confirmed that combining wind and solar energy generation in far offshore hydrogen production can be beneficial, but it was also found that this not the case in every scenario. In addition, it was concluded that the optimal combination of wind turbines, solar platforms and electrolyzers strongly depends on the production location and the year considered. Furthermore, it was found that until at least 2050, ammonia appears to be the most suitable transport medium for green hydrogen produced far offshore under the current assumptions. In addition, it was found that the cost distribution of far offshore green hydrogen will develop strongly over the years. In 2050, the simulations predict the ammonia (re)conversion costs to account for the biggest part of the total costs, closely followed by the energy generation. Finally, it was found that the interest rate, floating wind costs, floating solar costs, ammonia (re)conversion costs, FPSO costs and large changes in water depth can have significant influence on the costs per kilogram of hydrogen.

Having come to these conclusions, a tangible outlook on the worldwide potential of far offshore green hydrogen towards 2050 has been created. This outlook, together with the developed model and gathered input data, will form a base from which future research will be able to explore this new and exciting research field in various directions. This research may be one of the first bricks in the wall for the development of a future where far offshore green hydrogen is a part of our energy mix. However, much research is still to be done, including further analysis with the existing model, expanding the model in different directions, and related research such as in depth technical studies of floating wind turbines and social studies to create insight into less tangible factors influencing the potential of far offshore green hydrogen production.

CONTRIBUTION STATEMENT

T. Melles: conceptualization; methodology; software; validation; formal analysis; investigation; data curation; writing - original draft; visualization; project administration. **J.F.J. Pruyn:** conceptualization; supervision; writing – review and editing. **J.L. Gelling:** conceptualization; supervision; writing – review and editing. **J.J. de Wilde:** conceptualization; supervision; writing – review and editing.

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