Multi-purpose marine infrastructure: outlook of M4 solutions and a case study of offshore hydrogen production

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Abstract

This study explores multi-purpose offshore infrastructure, focusing on marine, multifunctional, modular, and mobile (M4) solutions. The goal is to understand the outlook, opportunities, and barriers faced by industry-led M4 projects. The research uses a mixed methods approach, including a systematic online review and stakeholder interviews. A case study on offshore wind energy and hydrogen production is analysed through a technoeconomic analysis. 30 projects worldwide were identified, with hydrogen production as the dominant combination. Most projects are in the concept or pilot testing phase, emphasizing the importance of demonstrations for successful technology integration. The main barrier is the lack of an enabling regulatory environment that doesn't account for multiple marine space use. Offshore hydrogen production from wind shows promise as an energy carrier. The case study indicates that LCOH decreases with wind farm size, with centralized offshore hydrogen production and transmission via pipeline yielding the lowest LCOH. To ensure successful M4 implementation, addressing regulatory barriers and developing clear frameworks are crucial. Future research should focus on small-scale M4 projects, regulatory gap analysis, and comparing hydrogen and electricity-based systems in end-to-end cost analyses.

Keywords: Marine, multi-purpose, multi-use, offshore, energy, wind energy, hydrogen, barriers, technoeconomic analysis, levelized cost of hydrogen.

1. Introduction

In recent years, the use of ocean space has intensified as new industries have moved offshore to provide a variety of services. As an answer to the need for more sustainable and efficient use of marine space, concepts such as ocean multi-use (MU), multi-use platforms (MUP) and multipurpose platforms (MPP) have emerged as viable and effective solutions. These concepts are all centered around the idea that integrating different uses to share an area or infrastructure can satisfy the demand for various services with increased resource efficiency and offer an economic advantage, while avoiding potential space disputes by adequately articulating the use of the marine space. MU refers generally to the joint use of marine space by two or more users which coincides in space and time and may share services and infrastructure [1]; MPPs and MUPs specifically refer to offshore structures that combine two or more distinct uses into a single physical unit [2]. These platforms have traditionally been understood as fixed units, designed to satisfy the demand of a specific service in a determined set of conditions. Such constraints make it difficult for this type of infrastructure to respond to changing conditions. Innovations that address this lack of flexibility by incorporating modularity and mobility in the design of these platforms could significantly increase their possibility of deployment.

The M4 framework, which classifies these solutions into marine-multifunctional-modular-mobile (M4) solutions, is useful to study multipurpose solutions in the marine environment and expanding the research scope to include the mobility and modularity dimensions. This project aims to provide a comprehensive review on the state of ongoing M4 projects, as well as providing insight into the main opportunities, business models and barriers that these projects face. More specifically, the objective is to answer the following research questions:

RQ1: What is the outlook of currently planned M4 projects?
RQ2: What are the main barriers for the adoption of M4 solutions? How can they be addressed?
RQ3: What are the most promising use combinations? How can they be assessed from a technoeconomic point of view?

The research questions are answered by performing a systematic review of available online information regarding M4, a series of semi-structured interviews with relevant stakeholders and a case study assessing the technoeconomic viability of the combination of offshore wind energy and hydrogen production.

2. Background

Conflicts can arise between users due to the intensification of activity in marine space, be it by the incursion of new industries, the growth of existing ones or, in most cases, the combination of both. As a result, a new approach has emerged in the form of multi-use of ocean space, built on the idea that a single space can be allocated to more than one use in cases where the different uses could coexist, and the inclusion of this approach into MSP would thereby increase spatial efficiency, reduce competition for the same space and minimize potential conflicts.

Extensive research has so far been conducted in the field of multi-use, including the technical design of specific use combinations, comparisons between them, techno-economic feasibility studies, business case evaluations, and analyses regarding the potential of different regions to host multi-use solutions. As part of the MUSES project, [1] aim to provide a universal definition of multi-use of space through reviewing the state of the art in Europe, resulting in a typology built on the interactions between uses in four dimensions: spatial, temporal, provisional and functional, yielding four distinct types of multi-use.

2.1 Multi-purpose platforms (MPPs)

MPPs are offshore platforms that serve the need of different offshore industries, which aim at exploiting the synergies and addressing the conflicts that arise when closely locating systems from these industries [2]. MPPs have been researched at length, with work so far being concentrated in the technical design and technoeconomic evaluation of different offshore renewable energy technology combinations, with a comparatively lower number of studies incorporating aquaculture and seawater desalination. Perhaps the most comprehensive study performed to date on MPPs is that of [2]. where a multidisciplinary review of the state of the art of MPPs is performed, complemented by single purpose or single discipline studies where relevant. The review is built on the outcome of previous MPP projects and provides a recollection of insights regarding the technical, economic, environmental, and social aspects of MPPs studied to date. The overview offered by this study covers a significantly wide range of studies and projects, starting with the work of [3] and moving on to a variety of large projects. These projects explore the combinations of different OREs as well as their combination with aquaculture in different ways, all with the aim of proposing designs for an MPP. Additionally, commercial MPPs which combine OWE and WE are evaluated.

2.2 Marine-multifunctional-mobile-modular (M4s): Framework and previous work

the framework of M4 solutions was developed within SEI's Gridless Initiative as a way to incorporate these two dimensions into the analysis of MUPs, MPPs or in general, solutions in the field of multi-use of marine space, and to classify them in a systematic way. M4 stands for Marine, Multifunctional, Mobile, and Modular solutions[4]. As a first step within this new framework, a systematic review was conducted to explore how M4 solutions have been addressed so far in peer-reviewed literature and to identify the synergies and most common themes discussed in the field.

Overall, the results of the study show that the most explored combination of M4 technologies is that of wind and wave energy, followed by their combination with aquaculture. Interestingly, a focus on marine solar technologies and hydrogen also emerges, showing how recent developments in these technologies have been gathering more attention from the scientific community. Furthermore, there is an evident concentration of studies in Europe, which could be explained by the large EU funded projects previously discussed in this chapter. In their conclusion, the authors of the study point to the need for future research to increasingly focus on the aspects of mobility and modularity to explore the full potential of M4 applications. Moreover, it is recommended that the state of the art beyond euro-centric studies and conceptual designs should be studied in order to understand what solutions are the most feasible and beneficial, as well as the scale and potential location of most promising alternatives.

3. Methods:

3.1 Systematic online review

In order to identify ongoing M4 projects that fall outside of scientific literature, a systemic online search was conducted, adapting the systematic review methods utilized in the previously described literature review, and incorporating the principles described in [5] for the systematic review of grey literature through the use of online search engines. Furthermore, all identified technologies are included using Boolean operators, resulting in the following search string:

Search string: *offshore AND (multi-use OR wind OR aquaculture OR solar OR wave OR desalination OR tourism OR artificial reef OR hydrogen) AND project*

Once the search string is established, criteria for the inclusion of results into the review are defined. Firstly, only results related to ongoing projects were included. News articles referring to general targets, plans and intentions either by industry or government are excluded from the analysis. Secondly, projects regarding single use, i.e., the use of ocean space by only one of the researched industries are excluded. So too are projects which fulfil multiple uses within the same industry, such as multipurpose ships which fulfil different functions in the O&G sector.

With the defined search string and inclusion and exclusion criteria, results from the Google search engine are screened in order of appearance, as this search engine produces results in order of relevance according to the input search terms. Each Google page produces ten results, and pages were screened until most results in one page were found to be no longer relevant and there was a high occurrence of results referring to projects identified in previous pages. Relevant results are then selected for coding and classification. Aside from the projects that are a direct result of the search, additional projects mentioned in the search results are included if deemed relevant.

Following the screening stage, the selected projects were coded and classified based on the categories

3.2 Stakeholder interviews

Upon conclusion of the systematic online review, the next step of the project was that of identifying, contacting, and interviewing a variety of relevant stakeholders. Stakeholders that are actively participating in the field of M4s were identified through their involvement in one or more of the projects resulting from the previous stage. When selecting stakeholders to contact, the underlying goal was to gather a diversity of viewpoints by interviewing participants belonging to organizations that play different roles in the field, as described in the following paragraph:

A total of 18 individuals were contacted for an interview, of which 9 agreed to participate, and finally 7 interviews were held, leading to a participation rate of 38.88%. The participants were asked to participate in the interview to address specific projects in which they were involved or, in a few cases, to discuss their general involvement and considerations regarding the topic of M4s. The interviews took place in the months of April and May of 2023.

4. Results

4.1 Systematic online review

After the screening phase, the selected projects were classified according to the categorization described in the previous Section. As mentioned previously, a total of 29 projects were identified, however one of them, specifically the EU Scores project, consists of testing two different technology combinations in two different geographies, and therefore in some of the results presented hereafter, the total number of projects will amount to 30. Appendix A shows the coded list of projects in detail.

The results show that currently ongoing M4 projects are predominantly centered around the OWE industry. In fact, all but one of the identified projects featured wind energy as one of the uses in the M4 case. A significant majority (73%) of the projects were found to be based around OWE as the sole energy generation technology, followed by the combination with floating solar photovoltaic. 23% of the projects feature the combination of wind with another energy source, while only one project was found to combine wind, wave, and solar PV into one single platform. Figure 6 shows the distribution of energy generation technologies identified in the selected projects.

The development stage of the projects was also explored, showing that even though M4 solutions have been studied at length in scientific literature and have gained increasing attention from industry and policymakers in recent years, the concept is still in early stages when it comes to commercial deployment. Of the 29 reviewed projects, only 2 are fully operational and both consist of a combination of OWE and tourism. Of the remaining projects, 15 are in the concept stage while 12 have physically deployed pilots.

Finally, the geographical distribution of the reviewed projects was also examined. Figure 9 shows the geographical distribution of the identified projects, as well as the concentration per country. It is worth nothing that 3 projects are listed twice, given that they take place in two countries, such as the EU Scores project which takes place in Belgium and in Portugal, and the WavePiston (combined wave energy and desalination) and Floating Power Plant (combined wind and wave energy) projects, which are being tested in Spain by Danish companies.

There is a clear concentration of projects in Europe, more specifically in the North Sea, which replicates the pattern identified in the systematic literature review on M4 solutions [4]. The few exceptions are represented by seven projects located in China, Taiwan, the United States and Uruguay. In China, three of the four ongoing projects consist of a combination of wind energy and aquaculture while the remaining project is a pilot conducted between SPIC and Ocean Sun to test the coupling of an offshore floating solar power plant with an OWF.

4.2 Stakeholder interviews

The interview protocol, covered six main categories: introductory questions, technical aspects, project planning and strategy, economic considerations, and policy/regulatory aspects. Here, we present the key insights gathered from the interviews, organized according to these categories.

4.2.1 General knowledge

The introductory questions aimed to assess the interviewee's knowledge of M4s or ocean multi-use and, if applicable, gather an introduction to their specific project. Some participants were familiar with multi-use, having worked in academic research or private organizations, while others focused on combining renewable energy sources like hydrogen and Power-to-X. The recurring theme was the potential technical and cost efficiencies achieved through different uses of marine space. Projects primarily aimed to demonstrate individual technologies or were in planning stages, with testing sites secured.

4.2.2 Technical aspects

The questions explored necessary technological developments and expected innovations when deploying projects at a commercial scale. Participants agreed that existing equipment can support these projects, but immature technologies require in-situ demonstration. Control and optimization innovations were anticipated for multi-source farms, offshore hydrogen production, and combined wind energy and aquaculture. The sharing of moorings and foundations might not be appealing to some stakeholders due to perceived structural and operational risks.

Modularity benefits were highlighted, such as ease of building, transport, and installation of smaller units, reducing complexity and maintenance downtime. Modular configurations allowed phased construction and capacity scaling, offering advantages for floating OWE and hydrogen production projects.

4.2.3 4.2.3 Project planning and strategy

Questions aimed to understand stakeholder relationships and identify those crucial in enabling ocean multi-use and M4 solutions. Policymakers and regulators were considered key stakeholders, but gaps and inefficiencies in existing regulations posed challenges. Partnerships between technology providers and project developers were common in commercial deployment, with developers relying on technology providers to test and deploy equipment. National policies supporting multi-use projects were seen as crucial, and the Netherlands was cited as a good example.

4.2.4 4.2.4 Economic aspects

Interviewees highlighted savings in O&M as the main economic advantage of these projects. Automation in OWE and aquaculture reduced maintenance needs, while combining different renewable energy sources allowed shared infrastructure and maintenance fleets. Economic benefits of combining offshore hydrogen production and OWE varied based on production and offtake purposes. Projects faced uncertainty due to immature technologies and a lack of large-scale demonstrators. Economic disadvantages included high initial CAPEX, potentially deterring early-stage investors.

4.2.5 4.2.5 Policy and regulation

Stakeholders noted gaps in existing regulations, particularly in incentivizing multi-use of ocean space. Policymaker engagement and incorporation of marine multi-use into regulations were seen as essential to enable widespread adoption. The Netherlands served as a positive example. Policymaker support was considered vital to ensure fair competition between hydrogen production and electricity generation.

4.2.6 4.2.6 Barriers

Key barriers included a lack of enabling regulatory environments, immature technologies, and uncertain business cases. Interviewees recommended incorporating marine multi-use into regulations, engaging with policymakers, increasing the number of demonstrators, and addressing end-to-end costs in policy assessments.

5. Case study: Hydrogen production from offshore wind

Given the scope of this project and given the fact that all the identified projects belonging to the combination of OWE and hydrogen production consist of offshore production, it is relevant to assess this configuration. Furthermore, there was a difference of opinion among interviewees on whether offshore production was truly more beneficial than the onshore alternative, indicating that it would be useful to compare the two options. Studies such as those by [6] and [7] assess the different production strategies while accounting for these differences, while other studies simply evaluate one strategy for a specific region or project, such as [8] and [9]. One shared characteristic between these studies is that they do not take into consideration the effect that the size of the wind farm could have on the viability of the different strategies and on which strategy could be more beneficial. Therefore, a technoeconomic analysis was designed to comprehensively evaluate and compare the different configurations of hydrogen production from offshore wind energy encountered during the previous stages of this project.

5.1 Methodology

To carry out this analysis, three scenarios were developed to compare the different production strategies. Scenario 1 consists of onshore centralized hydrogen production while Scenario 2 consists on offshore production, subdivided into centralized (2.1) and decentralized (2.2), with pipeline transmission to shore. All scenarios were evaluated based on the levelized cost of hydrogen (LCOH) for 20 different wind farm sizes ranging from 100MW to 2GW.

The LCOH is calculated according to the following Equation:

$$LCOH = \frac{\sum_{i=0}^{T} \frac{CAPEX+OPEX}{(1+r)^{i}}}{\sum_{i=0}^{T} \frac{M_{H2,i}}{(1+r)^{i}}} \quad (1)$$

5.1.1 Offshore wind farm

A wind farm was chosen from the list of ScotWind projects, the latest offshore wind leasing round by Crown Estate Scotland. The chosen project is the Campion Wind OWF . Once the location was chosen, hourly wind speed data of the site was collected from [10] for the year 2022. Given that the largest wind turbine currently in operation in a floating platform is the Vestas V164 – 9.5 in the Kincardine OFW, this model was chosen for the analysis.

5.1.2 Component sizing and costs

AC/DC Converter

The first considered component is the power converter, taken in this case as a VSC converter. The rated power of the converter is the same as the rated power of the wind farm, and the losses are assumed as 1.5% according to [6]. The investment cost of the converter is taken from [11], and is calculated according to Equation 2, where C_{VSC} is the investment cost in M€ and P_{farm} is the rated power of the wind farm, in MW.

$$C_{VSC} = 0.1437 \cdot P_{farm} \quad (2)$$

HVDC Cable

Similarly to the power converter, the rated power of the HVDC cable is that of the wind farm, and the losses are taken as 0.3% per 100km of cable. The investment cost of the power converter is calculated according to [11] using Equation 3, where P_{cab} is the rated power of the cable and C_{HVDC} is the investment cost, expressed in M€/km.

$$C_{HVDC} = 1.452 \cdot (1.31 \cdot 10^{-7} \cdot P_{cab}^2 + 1.47 \cdot 10^{-4} \cdot P_{cab} + 0.29 + 0.85) \quad (3)$$

Electrolyzer

For this analysis, a PEM electrolyser was chosen due to its high operational flexibility and quick ramp-up and ramp-down times, which makes them especially suitable for hydrogen production from variable renewable electricity sources [12].

To size the electrolyser, the theoretical hydrogen production that could be obtained in every hour is calculated from Equation 4, where E_{elec} is the theoretical electricity consumption of the electrolyser in kWh/kg, η_{conv} is the conversion efficiency and E_{aux} is the consumption of the additional components in the electrolysis plant, which are the desalination unit and the compressor.

$$W_{H2_{theoretical}}(t) = \frac{P_{farm}(t)}{\frac{E_{elec}}{\eta_{conv}} + E_{aux}} \quad (4)$$

Then, the size of the electrolyzer can be obtained by multiplying the electricity consumption by the maximum theoretical hourly hydrogen production (Equation 5).

$$P_{H2,plant} \leq max W_{H2theoretical}(t) \cdot E_{elec} \quad (5)$$

A value of 5% of the rated power of the electrolysis plant, P_{low}, was chosen as a lower threshold for the operation of the electrolyser. [13]. When the power output of the wind farm is larger than the energy demand of the electrolyser and additional components of the plant, the hydrogen production would depend exclusively on the electrolyser's electricity consumption and conversion efficiency. Equation 6 summarizes the operation of the electrolyser based on the power output of the wind farm [14].

$$W_{H2,prod} = \begin{cases} 0 \; when \; P_{farm}(t) < P_{low} \\ \frac{P_{farm}(t)}{\frac{E_{elec}}{\eta_{conv}} + E_{aux}} \; when \; P_{low} < P_{farm}(t) < P_{H2,plant}\left(1 + \frac{E_{aux}}{E_{elec}} \cdot \eta_{conv}\right) \\ \frac{P_{farm}(t)}{E_{elec}} \eta_{conv} \; when \; P_{farm}(t) > P_{H2,plant}\left(1 + \frac{E_{aux}}{E_{elec}} \cdot \eta_{conv}\right) \end{cases} \quad (6)$$

To calculate the CAPEX of the electrolyser, a specific cost was obtained from [6], expressed in €/kW of electrolyser capacity. The specific cost was kept equal across all values of rated capacity, since it is assumed that PEM electrolysers can be modularly stacked [15]. The additional costs associated with the electrolyser plant are the annual operation and maintenance costs, assumed here to represent 1.5% of the CAPEX, and the costs incurred when replacing the electrolyser stack at the end of its lifetime, which was assumed to represent a 12% of the CAPEX.

Stand-by battery

A stand-by battery is included in the electrolysis plant to serve as a back-up power source in the moments when the electrolyser is in stand-by mode. The batter is sized to 5% of the electrolyser capacity and has a specific CAPEX of 40.8 €/kW [6].

Desalination unit

The energy requirements and the cost of the desalination plant can be calculated based on the water requirements. Equation 7 calculates the daily requirements of the electrolyser based on hydrogen production. The necessary amount of water to produce 1kg of hydrogen from electrolysis, Q_{H2O}, is theoretically 9kg, however 15kg of water were assumed to account for possible water losses [16]. The density of sea water is represented by ρ_{H2O}.

$$V_{H_2O} = \sum_{i=1}^{24} W_{H2,prod,i}(t) \cdot Q_{H_2O} \cdot \rho_{H_2O} \quad (7)$$

The daily energy consumption of the desalination unit is then calculated by taking the product of the daily water requirement and the specific energy consumption of a reverse osmosis desalination unit, taken as 3.5 kWh/m^3.

$$E_{des} = V_{H_2O} \cdot e_{des} \quad (8)$$

The investment cost of the desalination unit is calculated based on the daily water requirement and is taken as 1244.2 €/m^3/day, while the annual operation and maintenance costs are assumed to represent 2% of the total investment cost. Given that there is no desalination unit present in Scenario 1, the water requirements of the electrolyser are satisfied by freshwater that is procured on land, representing an annual operational cost, which is calculated according to Equation 11, where a 60% percent discount is applied due to the large consumption volume, and the specific cost of freshwater is taken as 1.58 €/m^3, in line with [6].

$$OPEX_{freshwater} = C_{freshwater} \cdot (1 - 0.6) \cdot \sum_{i=1}^{365} V_{H_2O,i} \quad (9)$$

Hydrogen compressor

In all the studied scenarios, the produced hydrogen is compressed when leaving the electrolyser, in order to deliver it to the storage unit or to the final consumption point. In Scenarios 2.1 and 2.2, the compressor serves the purpose of achieving the desired pressure at the pipeline inlet and hydrogen flow rate. The CAPEX of the compressor is estimated at 2378.5 €/kW of compressor power, which is calculated from Equation 10 [17].

$$P_{comp} = Q \cdot \frac{ZTR}{M_\eta} \cdot \frac{N\gamma}{\gamma - 1} \cdot \left(\frac{P_{outlet}^{\gamma - \frac{1}{N\gamma}}}{P_{inlet}} - 1 \right) \quad (10)$$

Where Z is the compressibility factor (assumed as 1) , T is the inlet temperature, R is the universal ideal gas constant M is the molecular mass of hydrogen, η is the compressor efficiency (assumed as 88% in this case), N is the number of compressor stages (6, in line with [18]), γ is the ratio of specific heat (1.4) and P_{outlet} and P_{inlet} are the pressures at the outlet and inlet of the compressor, respectively assumed as 10 and 7 MPa.

Hydrogen storage

The cost of the hydrogen storage tank was calculated based on the daily hydrogen production and the storage period, which for this analysis was assumed as 1 day. The specific cost of the hydrogen tank was estimated at 429.8 €/kg of hydrogen, according to Equation 11 [6] and the annual OPEX was assumed to represent 2% of the CAPEX.

$$CAPEX_{storage} = C_{storage} \cdot M_{H2_{day}} \cdot t_{storage} \quad (11)$$

Hydrogen pipeline

A hydrogen pipeline is necessary in order to transport the produced hydrogen to shore in Scenarios 2.1 and 2.2. The investment cost of the pipeline, expressed in €/km, is calculated from Equation 12 [17]. The original equation is expressed in US Dollars and therefore a conversion factor of 1.07 USD/€ (as of June 1st, 2023) is used. The specific pipeline cost calculated in Equation 14 depends on the pipeline diameter, which in turn depends on the mass flow of hydrogen for each wind farm size. The pipeline diameters were estimated in line with [19].

$$C_{pipeline} = \frac{1}{1.07} \cdot (418869 + 762.8 \cdot D + 2.306 \cdot D^2) \quad (12)$$

5.2 Case study results

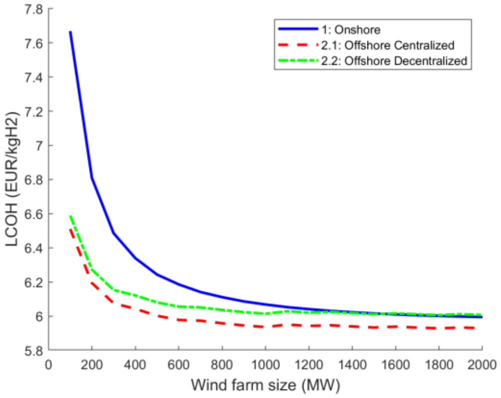


Figure 1 shows the results obtained for the three scenarios and 10 wind farm sizes. It shows how Scenario 1 (named “Onshore” in the figure legend) has a considerably higher LCOH in the range of 100-600MW. It can also be observed how Scenario 2.1 (named “Offshore Centralized” in the figure legend) presents the lowest values of LCOH for all wind farm sizes. Additionally, it is worth noting that after reaching a farm size of 1.3GW, Scenario 2.2 (“Offshore Decentralized” as per the figure legend) and Scenario 1, present virtually no difference in LCOH, with both reaching 6.02 €/kg at a farm size of 1.4GW. Therefore, it can be concluded that LCOH stabilizes for both scenarios at around 1.3 GW assumed wind farm size.

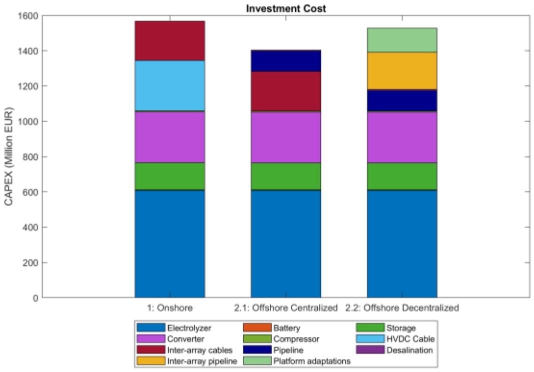
5.2.1 2 GW Wind Farm

In order to evaluate in more detail the components that make up the LCOH for the different scenarios, a wind farm size of 2 GW is chosen as a representative case

Investment costs

Another major component of the LCOH calculation are the investment costs, or CAPEX (capital expenditures) of the project. The total CAPEX of the three Scenarios was calculated by adding the CAPEX of each of the components. The total investment cost for the three studied scenarios is presented in Figure 16. Scenario 1 is the largest with a total of 1567.9 million €, which 2.6% higher than Scenario 2.2 with a total investment of 1528.3 million €. When comparing with Scenario 2.1, the difference is more pronounced, with the CAPEX of Scenario 1 being 11.7% higher than for Scenario 2.1 which stands at 1404 million €.

The investment cost of each scenario can be expressed in terms of each component in order to determine which of these has the most influence in terms of the total CAPEX. The major differences in components are that Scenario 1 requires no desalination unit and transmits electricity to shore via an HVDC cable, while Scenarios 2.1 and 2.2 transmit hydrogen to shore via a hydrogen pipeline, require desalination units (1 in Scenario 2.1 and 211 in Scenario 2.2), and platform adaptations in the case of Scenario 2.2.



The differences in investment costs become more evident when the different energy transmission components are evaluated. The HVDC cable present in Scenario 1 has a CAPEX of 175 million €, whereas the hydrogen pipeline present in the remaining scenarios has a CAPEX of 115 million €, meaning that it costs 34.5% less. This results in the HVDC cable representing 11.2% of the total investment cost in Scenario 1, while the hydrogen pipeline represents 8.17% and 7.52% of the total CAPEX of Scenarios 2.1 and 2.2 respectively.

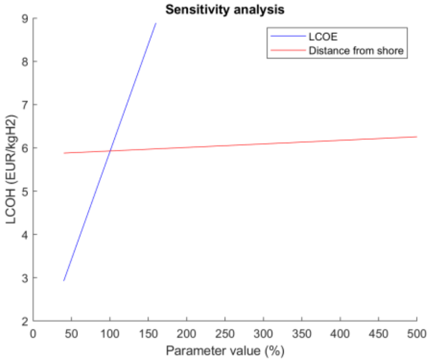
Total costs

In order to fully understand the costs affecting the LCOH, the total costs of the system over the entire lifetime of the project are evaluated. Aside from the CAPEX, the other cost components of this project would be the O&M costs, the replacement cost of the electrolyser stack and the compressor, and the electricity costs incurred when running the equipment. The lifetime costs in the 30 years of operation of the project are presented in Figure 18 for each of the studied scenarios. The total costs of the three scenarios are similar and are all within the range of 23 billion €. Scenario 1 presents the largest total cost at 23.24 billion €, while Scenarios 2.1 and 2.2 respectively stand at 23.1 and 23.23 billion €. The total costs found in this study are in a similar range to what is found in [6], where the total costs for a hydrogen production system in a 1.3 GW OWF range from 22.2 billion € for centralized offshore hydrogen production and transmission via pipeline, and 25 billion € for HVDC electricity transmission and onshore hydrogen production.

5.3 Sensitivity analysis

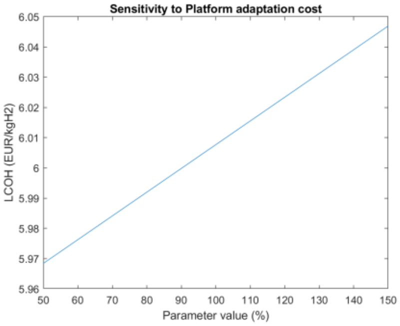
As seen in the previous subsection, the cost of electricity represents most of the total costs of the project and therefore exerts a high influence in the value of LCOH, regardless of the scenario that is chosen. In order to evaluate this in more detail, a sensitivity analysis is conducted by varying the value of the LCOE and calculating the corresponding LCOH while maintaining all other variables unchanged. The values of LCOE were changed from 50% to 150% of the original value (equivalent to 100% in Figure 20).

The sensitivity to the wind farm's distance from shore was also analyzed, given that it has a direct impact on the energy transmission components which, as seen previously, represent the largest share of CAPEX after the electrolyser.



As expected, the LCOH is highly sensitive to the LCOE. When a change of 50% of the value of LCOE is made, a resulting change of 50% is observed in LCOH, constituting a 1:1 relationship. The LCOH goes from 2.93 €/kg for an LCOE of 33.65 €/MWh, to 8.8 €/kg for an LCOE of 100.94 €/MWh. The effect of the distance from shore is minimal when compared to that of the LCOE, as the LCOH changes from 5.88 €/kg to 6.26 €/kg in the range of 40km to 500km, representing a change of LCOH of 6.5%, for a change in distance from 40% to 500% of the original value.

Another parameter chosen for a sensitivity analysis was the cost of the platform adaptations needed in Scenario 2.2. This is because the assumed cost is highly uncertain, as there are currently no built prototypes for this configuration.



The results show that for the selected range, the LCOH is not particularly sensitive to the change in platform adaptation costs.

6. Conclusions

This thesis aims to promote a more sustainable use of marine space by exploring marine, multifunctional, modular, and mobile solutions (M4) that integrate various uses of the marine environment, leading to higher resource efficiency and economic advantages. Results indicate a growing interest in industry-led M4 projects, with 14 projects in 2022 and 3 in the first three months of 2023, present on 4 continents. However, commercial deployment is still in early stages, and large-scale demonstrations are needed to accelerate progress.

Stakeholder interviews highlighted two key barriers: the immaturity of markets for some technologies involved and the lack of an enabling regulatory environment. To address these challenges, deploying demonstrators and developing overarching guidelines and incentives are essential.

The most promising M4 combinations include offshore wind energy and hydrogen production, different renewable energy sources, and offshore wind energy and aquaculture. A technoeconomic analysis revealed that producing hydrogen offshore via a centralized platform and hydrogen pipeline is a preferred strategy.

Future work should focus on small-scale applications, pinpointing specific regulatory gaps for each M4 configuration, and evaluating end-to-end costs of hydrogen-based energy infrastructure compared to electricity-based systems.

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