Multi-purpose marine infrastructure

The outlook of M4 solutions and a case study of offshore hydrogen production

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Multi-purpose offshore infrastructure has emerged as a way of sustainably providing demands for critical services in marine and coastal environments due to the possibility of integrating different marine activities in the same space. This study focuses on marine, multifunctional, modular, and mobile (M4) solutions, with the aim of understanding the outlook, opportunities, and barriers that industry led M4 projects face. Additionally, it has the goal to determine which use combinations are the most promising and evaluating them from a technical and economic perspective. A mixed methods approach, including a systematic review of online information and semi-structured interviews with stakeholders, was employed. Additionally, a case study on the combination of offshore wind energy and hydrogen production was conducted by means of a technoeconomic analysis. 30 projects were identified worldwide, primarily combining offshore wind energy with sectors such as wave energy, offshore floating solar energy, aquaculture, and hydrogen production. Hydrogen production emerged as the most prevalent combination. Most projects are in the concept or pilot testing phase and stakeholders have a strong focus on demonstration to showcase successful technology integration. The lack of an enabling regulatory environment is cited as the main barrier as existing regulations do not account for multiple use of marine space. Offshore hydrogen production from offshore wind shows significant promise due to hydrogen's role as an energy carrier, and the case study shows that the LCOH decreases with wind farm size and that centralized offshore hydrogen production, with transmission to shore via pipeline yields the lowest LCOH among the studied configurations. Overall, overcoming regulatory barriers and developing clear frameworks are essential for successful implementation of M4s. Incentives are crucial to supporting large-scale projects and advancing technology readiness. Future research should focus on small-scale M4 projects for remote communities, addressing regulatory gaps, and comparing hydrogen-based 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.

Resumo

As infra-estruturas offshore polivalentes surgiram como uma forma de satisfazer de forma sustentável a procura de serviços críticos em ambientes marinhos e costeiros devido à possibilidade de integrar diferentes actividades marinhas no mesmo espaço. Este estudo centra-se nas soluções marinhas, multifuncionais, modulares e móveis (M4), com o objetivo de compreender as perspectivas, oportunidades e barreiras que os projectos M4 liderados pela indústria enfrentam. Além disso, tem como objetivo determinar quais as combinações de utilização mais promissoras e avaliá-las numa perspetiva técnica e económica. Uma abordagem de métodos mistos, incluindo uma revisão sistemática de informações em páginas virtuais e entrevistas semi-estruturadas com as partes interessadas. Além disso, foi realizado um caso de estudo sobre a combinação de energia eólica offshore e produção de hidrogénio através de uma análise tecno-económica. Foram identificados 30 projectos a nível mundial, principalmente combinando a energia eólica offshore com sectores como a energia das ondas, a energia solar flutuante offshore, a aquicultura e a produção de hidrogénio. A produção de hidrogénio surgiu como a combinação mais predominante. A maior parte dos projectos encontra-se na fase de conceção ou de ensaio-piloto e as partes interessadas concentram-se na demonstração para mostrar o sucesso da integração tecnológica.A falta de um ambiente regulamentar favorável é citada como o principal obstáculo, uma vez que a regulamentação existente não tem em conta a utilização múltipla do espaço marinho. A produção de hidrogénio offshore a partir da energia eólica offshore é muito promissora devido ao papel do hidrogénio como observado no caso de estudo, que o LCOH diminui com o tamanho do parque eólico e que a a produção centralizada de hidrogénio offshore, com transmissão para onshore através de um gasoduto, produz o LCOH mais baixo entre as configurações estudadas. Em geral, a superação das barreiras regulamentares e o desenvolvimento de enquadramentos legais são essenciais para o êxito da implementação das M4. Os incentivos são cruciais para apoiar projectos de grande escala e promover a tecnologia. A investigação futura deve centrar-se em projectos de M4 em pequena escala para comunidades remotas, colmatando as lacunas regulamentares e comparando os sistemas à base de hidrogénio e sistemas baseados no hidrogénio e na eletricidade em análises de custos em todo o ciclo.

Palavras-chave

Ambiente marinho, multiusos, offshore, energia, energia eólica, hidrogénio, barreiras, análise tecno-económica, custo nivelado do hidrogénio.

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List of abbreviations:

CAPEX	Capital Expenditures
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
MPP	Multi-Purpose Platform
MSP	Marine Spatial Planning
MU	Multi-use
MUP	Multi-use Platform
O&G	Oil and Gas
O&M	Operation and Maintenance
OPEX	Operational Expenses
OWE	Offshore Wind Energy
OWF	Offshore Wind Farm
PEM	Proton Exchange Membrane
VSC	Voltage Source Converter
WEC	Wave Energy Converter
WF	Wind Farm
WT	Wind Turbine

1. Introduction

1.1 Motivation

The marine environment has seen the rise of a multitude of sea-based industries, driven by the availability of a wide variety of resources and the increasing demands of a growing and developing human population. The provision of services such as energy, food production, shipping, and recreation serve as examples of industries that have all converged in marine settings, creating a complex economic environment commonly referred to as the blue economy. In recent years, the use of ocean space has intensified as new industries have moved offshore to provide the aforementioned services.

This move has been motivated by various factors, such as the need for emission free generation sources which has driven the energy industry to search for areas with abundant renewable resources. With competition for land increasing, the ocean space offers both an abundance of resources such as wind and solar radiation, as well as vast amounts of space to exploit them [1], [2]. The development of technologies that can harness tidal and wave energy creates yet another industry sector that is set to populate the offshore space in the near future.

Similarly, in the case of food production, considerations regarding resources and space have driven the aquaculture industry to move offshore to benefit from the more stable marine conditions and available space when compared to inland or near-shore operations [3]. Moreover, industries that provide services such as seawater desalination and sanitation services have begun looking into expansion offshore as a way of alleviating the pressures and conflicts that may result from the continuous decrease of useful inland space.

However, even though the marine environment offers a significant amount of space, the rapid intensification of its use raises concerns about the impacts these activities have on the environment and coastal communities, and the overall sustainability of the blue economy. One of such impacts is biodiversity loss as a product of exploitation, pollution, and habitat destruction, which if kept unchecked could seriously harm the ocean's ability to provide vital ecosystem services. The urgency of protecting marine biodiversity has been recently highlighted by international efforts which have culminated in the United Nations High Seas Treaty, which lays out the groundwork for the establishment of vast marine protected areas (MPA) beyond national jurisdictions, an important milestone in achieving the COP 15 goal of protecting 30% of the ocean by 2030 [4]. Efforts such as this reinforce the notion that sea-based human activity should be conducted in a way that guarantees that its impacts on marine ecosystems do not outweigh the societal benefits that are a product of economic activity, and therefore efficiency in the use of marine resources should be maximized while minimizing its footprint.

In addition to environmental concerns, the rapid intensification of the use of ocean space can result in crowded areas just as it happens inland, creating a set of new conflicts between the users of the marine areas. Furthermore, additional issues regarding logistics, regulations, operations, and financing may emerge when moving these new industries offshore.

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.

Although centered around the same issues and general idea, these concepts differ in terms of specifics. While 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 [5]; MPPs and MUPs specifically refer to offshore structures that combine two or more distinct uses into a single physical unit [6].

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 that could arise from variations in demand, demographics, or regulatory environment. 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.

For example, an MUP designed to provide energy and freshwater to a settlement, that has been conceived as modular from the design stage could be deployed at a small scale and then progressively be scaled-up according to the increase in demand by simply adding additional modules. This would result in financially attainable and widely accessible solutions as it would eliminate the need for large up-front investments that are otherwise needed when building large infrastructure. Furthermore, making a solution mobile would allow the operator to move the platform to respond to changes in demand and even respond to disaster situations in places where regular service has been interrupted. Additionally, a mobile platform could be transported to a location with more favorable conditions in the case of an uncertain regulatory environment or increasing competition, thereby eliminating the risk of having stranded assets.

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. M4 solutions have so far been studied at length, with research mostly concentrating on conceptual definitions of the field, conceptual designs, and evaluations of the viability of different use combinations.

However, as these solutions move out from the academic environment and start being deployed as part of real industry applications, there is a need to assess the current state of commercially focused M4 projects. As previously mentioned, research has so far concentrated on academic efforts and, furthermore, analyses tend to be concentrated in specific regions. As a result, there is a lack of understanding about the current state of industry led M4 projects from a global perspective, as well as the opportunities and barriers they face. Furthermore, as a wide variety of solutions start being deployed, there has been no comprehensive analysis regarding which of these presents the most beneficial opportunities. Therefore, attempts should be made to identify the most promising solution within the M4 framework, as well as to quantify the benefits they offer both technically and economically.

Therefore, the motivation for this thesis is to contribute to the efforts being made around the world to achieve a more sustainable use of marine resources by providing a deeper understanding of how M4 solutions can effectively be deployed and provide essential services while reducing conflicts over the availability of space and minimizing the impact on the surrounding environment.

1.2 Objective

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:

> RQ 1: What is the outlook of currently planned M4 projects?
> RQ 2: What are the main barriers for the adoption of M4 solutions? How can they be addressed?
> RQ 3: 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.

This report consists of the following structure: in Chapter 2, background information is presented, relevant concepts are defined and the previous research on the topic of M4s is presented. Chapter 3 provides a detailed description of the methodology followed during the first two stages of the project, namely the systematic review and the stakeholder interviews, the results of which are presented in Chapter 4. In Chapter 5, the context, methodology and results of the case study are presented in detail. In Chapter 6, an overall discussion of the results obtained in all three stages of the project is presented and finally, Chapter 7 provides conclusions and recommendations for future work.

2. Background

In this chapter, the background for this project is provided in the form of an explanation of the underlying concepts and the current state of research on the topic of M4s. The conceptual definitions and relevant research performed to date on the concepts of ocean multi-use and multipurpose platforms are provided, which after the inclusion of the modularity and mobility dimensions lead up to the definition of the M4 framework. Finally, this chapter provides a detailed summary of the work performed so far within that framework, which constitutes the starting point for this project.

2.1 Ocean multi-use (MU)

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 tool to manage these conflicts, marine spatial planning (MSP) was created and adopted as a means to achieve effective ocean governance. However, despite the adoption of MSP practices across different regions, the approach to planning has remained siloed by limiting the practice of MSP to the designation of different areas to different uses, overlooking possible synergies between uses that could be exploited.

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. The following is a definition of multi-use proposed by [5]:

"Ocean multi-use is the joint use of resources in close geographic proximity by either a single user or multiple users. It is an umbrella term that covers a multitude of use combinations in the marine realm and represents a radical change from the concept of exclusive resource rights to the inclusive sharing of resources and space by one or more users".

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. A significant number of research articles have been conducted in Europe as part of EU funded projects, each with a different focus and building upon the results of its predecessors. A summary of such projects and their objectives is summarized in Table 1.

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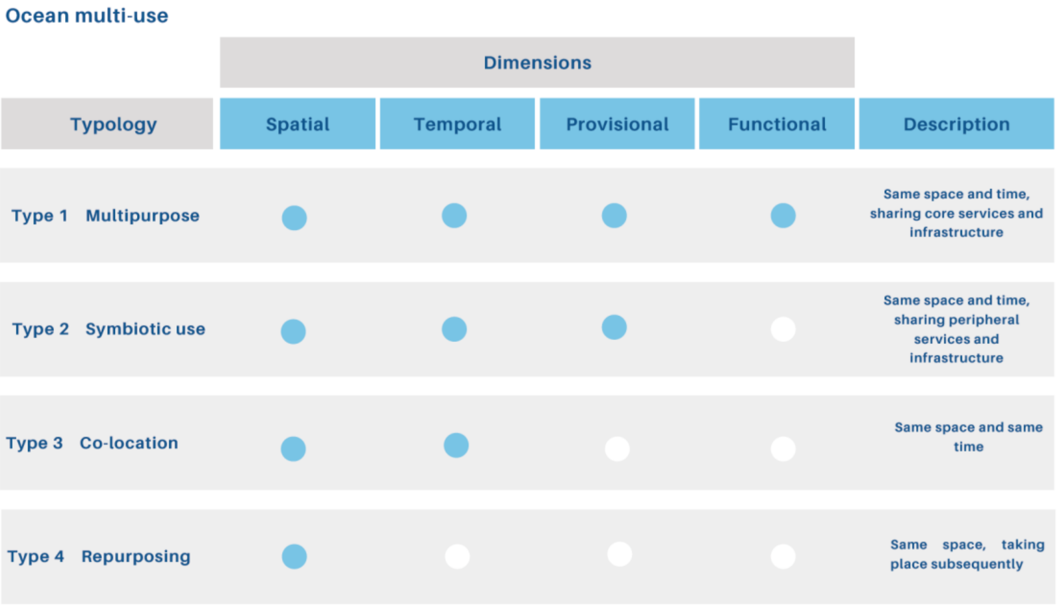
Table 1 EU funded multi-use projects [7]–[9]

Project	Programme	Focus
MERMAID [7]	Seventh Framework Programme (FP7)	Technological design of offshore platforms for MU.
MARIBE [8]	Horizon 2020	Business case analysis for promising multi-use combinations
MUSES [9]	Horizon 2020	Analyzing the state of multi-use in Europe. Identifying key drivers and obstacles

As part of the MUSES project, [5] 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, which are summarized in Figure 1. In addition to developing the typology, the paper recommends joint development and licensing processes, clear regulatory frameworks, legislated relationships, and the development of regulatory frameworks to evaluate the environmental impact of repurposing infrastructure for each type of multi-use. Additionally, such frameworks should account for each user's rights and responsibilities, guaranteeing the free and equitable flow of information between all users, and establishing which structures are fit for which use.



Ocean multi-use

	Dimensions				
Typology	Spatial	Temporal	Provisional	Functional	Description
Type 1 Multipurpose	●	●	●	●	Same space and time, sharing core services and infrastructure
Type 2 Symbiotic use	●	●	●	○	Same space and time, sharing peripheral services and infrastructure
Type 3 Co-location	●	●	○	○	Same space and same time
Type 4 Repurposing	●	○	○	○	Same space, taking place subsequently

Figure 1 Multi-use typology. Adapted from [10]

A representative example of the purpose of the MUSES project can be found in the work of [11], where they propose an analytical framework for assessing the potential of multi-use (MU) as a concept for sustainable resource exploitation and smart space allocation in eight EU countries of the Euro-Mediterranean sea basin, focusing on three maritime sectors: tourism, renewable energy, and the oil & gas industry. They identify ten existing and potential MU combinations and analyze the opportunities and challenges associated with MU development in terms of drivers, added values, barriers, and impacts (DABI). The authors highlight tourism-driven MU as having the highest potential due to facing fewer barriers than other sectors, while also identifying combinations with emerging potential, such as floating offshore wind energy and aquaculture and the repurposing of decommissioned oil and gas platforms. The authors provide a series of recommendations, such as developing EU-wide financial support programs, creating regulation that addresses MU safety, insurance and permitting process standards, and establishing pilot sites to test MU designs. The identified combinations, as well as the DABI factors are illustrated in Figure 2.

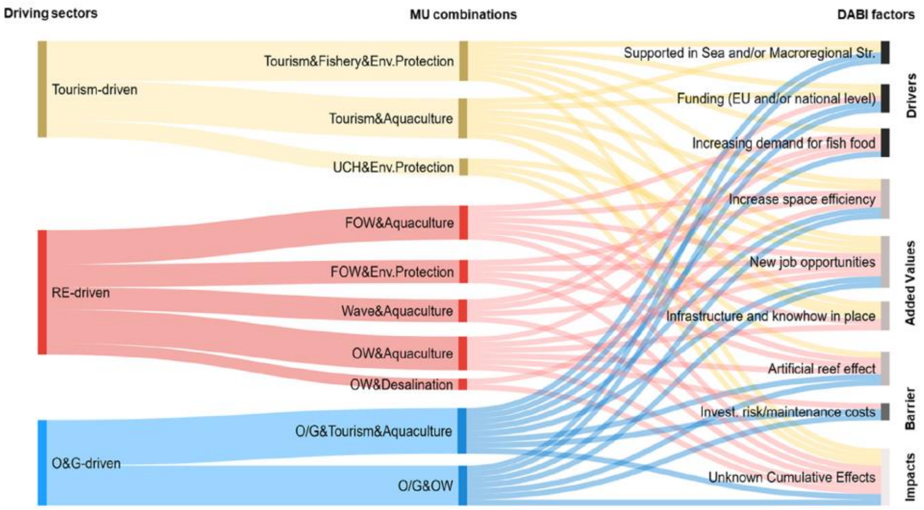


Figure 2 Multi-use DABI factors [11]

A series of studies were conducted as part of the MARIBE project to develop business cases for promising multi-use combinations. One of such combinations is the co-location of OWFs and aquaculture, which is frequently identified as having large potential for development as there are apparent synergies between the two uses, such as potential reductions in O&M costs that could be achieved by, for example, having shared multipurpose vessels.

One of such studies performed a business case analysis to quantify the benefits of multi-use aquaculture of blue mussels in offshore wind farms, specifically in the Borssele wind farm in the North Sea [3]. The analysis used a specific design for the aquaculture farm, with input parameters taken from previous literature, and a risk assessment was conducted based on defined hazards. The analysis showed that the business case is profitable, achieving positive IRR and NPV, and a sensitivity analysis confirmed the business case's robustness. The authors suggest that the OWE sector is unlikely to pursue this type of multi-use due to perceived lack of benefits and safety concerns, and the initiative falls with the aquaculture sector, which lacks resources and organization compared to the wind energy sector. They recommend building a full-scale pilot to showcase the benefits of this combination and create momentum for development at scale.

Upon conclusion of the MUSES and MARIBE projects, researchers conducted joint work in order to gather the findings of both projects and identify the main research gaps and actions required to foster the development of multi-use platforms [12] .

The study proposes a new typology to classify the different types of multi-use based on the combinations explored in two previous projects as well as merging the typologies established by [5] and [13]. After establishing the typology, the authors identify and classify the barriers that were identified in the reviewed literature. Most barriers fall under the economic category, specifically related to the high cost of multi-use platforms and the lack of supporting business cases. Technical and social barriers also pose obstacles to the development of multi-use platforms as drivers of blue growth, with the former associated with the lack of technology and infrastructure for grid connection and the latter related to the lack of acceptance from local communities and trust building between involved sectors.

In conclusion, the authors highlight the need to further study the social dimension of multi-use platforms, as it can be a significant obstacle to their development. They also suggest that research should identify concepts that deliver benefits not only from a technical and economic perspective but also from an environmental and societal standpoint. Finally, they emphasize the need for in situ trials to address both technical and non-technical barriers, such as increasing investor confidence and social acceptance.

Building on the future work needs and research gaps that were clearly identified in the previous projects, the H2020 UNITED project was started in 2020 as a way of addressing the identified barriers for multi-use through the deployment of a series of in situ demonstrators. As a way to clearly assess how all types of barriers are evaluated and addressed, the project is built on five pillars, namely technological, economic, environmental, societal and governance, thereby ensuring that there is robust evidence to support the development of multi-use activities as a viable option economically, environmentally and socially.

The project will consist of five demonstrator projects located in 3 different regional seas in the European Union (North, Baltic, and Mediterranean seas), which will first be tested near-shore in milder conditions, before being implemented offshore in critical conditions. Furthermore, the tests performed within the project aim to take the technologies across three different technology readiness levels (TRL), from TRL5 to TRL7, demonstrating the prototypes in their operational environment.

The five demonstrator projects will cover five sectors of the blue economy through different multi-use combinations, such as renewable energy, aquaculture, bio-resources, tourism, and maritime transport. The pilots involve multiple countries, each focusing on specific combinations. Among the combinations that will be explored are the combination of OWE and floating solar energy with aquaculture of seaweed and blue mussels, aquaculture with nature restoration and the relationship between OWE and tourism. All the pilots will be conducted in three operational phases, mirroring the phases that projects of this kind will have to undergo once they are deployed at commercial scale, such as a pre-operational, operational and a decommissioning phase.

2.2 Multi-purpose platforms (MPPs)

Within the field of ocean multi-use, a technological concept enabling the combination of different ocean-based activities into a single physical unit has emerged in the form of multipurpose 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 [6].

Such platforms could be supported by floating or bottom-fixed structures and be located near shore or at large distances offshore depending on their purpose. For instance, a device that combines a wind turbine (WT) with a wave energy converter (WEC) could consist of a floating platform located far offshore and be connected to an electrical grid through undersea cables. Conversely, in the case of remote islands and communities without access to utility grids, an MPP could be located near shore to provide electricity, drinking water or food, depending on the demand for these services.

MPPs have been researched at length, with work so far being concentrated in the technical design and technoeconomic evaluation of different offshore renewable energy (ORE) technology combinations, with a comparatively lower number of studies incorporating aquaculture and seawater desalination.

One early example of such research is the work of [14], which studies the combination of OWE with wave energy, as a response to the need of both industries to reduce costs and optimize the exploitation of resources. Their study consists of a comprehensive review of this combination, addressing the general aspects of it, such as synergies, the different options for combining the two technologies, as well as the technical aspects involved.

The review starts with an evaluation of the combined wave and wind resource in Europe, focusing on three European regional seas and identifies synergies between the two technologies. Following this, it identifies the synergies between the two technologies, cataloguing them as legislative or project/technology synergies. Legislative synergies include the development of a common regulatory framework and the simplification of licensing procedures, while project and technology synergies include increased energy yield and operational benefits, such as smoother power output, reduction in system balancing costs and the possibility to share logistics, substructures, and O&M costs.

After identifying synergies, the study proposes a classification of combined wind-wave systems in three categories, namely co-located systems, hybrid systems and floating islands. Such systems could be independent or combined, and they could consist of bottom-fixed or floating structures. Both hybrid systems and floating islands are MPPs, while in co-located systems the core infrastructure is not shared.

Following the trend of technoeconomic analysis of different MPP configurations, [15] developed a model for the reconversion of end-of-life Oil & Gas (O&G) platforms into MPPs. In their work, they evaluate different configurations for the production of renewable energy (from wind or solar), green hydrogen, synthetic natural gas (SNG) and freshwater from desalination, based on two types of common O&G platforms present in the North Sea and in the Adriatic Sea. In the study, nine different technical scenarios are studied, and for each scenario the economic and environmental feasibility is evaluated based, respectively, on a discounted cash flow analysis (DACF) and a comparative life-cycle analysis (LCA) with respect to a standard decommissioning scenario.

The study concludes that for the case of the Adriatic Sea, the most beneficial scenario is the production of hydrogen and electricity from an offshore solar power plant, given largely to the fact that among all the products, the green hydrogen is the most profitable, followed by the electricity provided to the grid. The same is true for the case of the North Sea, where all the scenarios present a shorter payback period and positive return on investment, mainly due to the higher quality wind resource. Scenarios including water desalination present a negative return on investment and are deemed adequate only for regions that have a critical demand for freshwater.

Perhaps the most comprehensive study performed to date on MPPs is that of [6]. 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 [14] and moving on to a variety of large projects with different outcomes, such as the MARINA platform project, and the ORECCA project and TROPOS projects. Large research projects such as H2OCEAN and MERMAID are also included in the review. 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.

In terms of the aspects considered in the review, the authors perform a comparison of functionality to establish the differences between the designs for both ORE and ORE-aquaculture combinations. Furthermore, they identify environmental and social impacts as well as the main risks associated with MPPs.

Acoustic disturbance is identified as the main environmental impact of ORE, while increased parasite and pathogen densities represent the main impact of aquaculture. Noise and visual pollution are identified as the main socioeconomic impacts derived from ORE installations, together with possible restrictions on the use of marine space, while the negative socioeconomic effects of aquaculture are difficult to quantify. Finally, the corrosion of equipment and high forces due to operation in an offshore environment, the complicated bureaucracy, conflicts with traditional marine space users and low social acceptance are identified as the main risks associated with MPPs.

Similarly to what occurred in the UNITED project, efforts were also made to produce a demonstrator for an MPP within the Horizon 2020 program, in a project known as The Blue Growth Farm. The project had the purpose of designing and MPP hosting aquaculture operations and wind and wave energy harvesting at large scale, as well as building and testing a prototype in 1:10 scale to achieve TRL5. Furthermore, the project had the goal of developing a suitable business plan to facilitate future investment.

The project started in June of 2018 and concluded in March 2022, when the demonstrator platform, that was in operation off the coast of Reggio Calabria, Italy was decommissioned. The main outcomes of the project were a series of technical advancements on the design and operation of a wind-wave-aquaculture MPP, such as the generation of new scaling strategies for the physical models of MPPs [16] a detailed engineering approach for the design of the MPP to optimize all three activities [17] and, among others, a study on the perception local communities have on MPPs in Europe [18].

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

As previously mentioned, MUPs have traditionally been understood as fixed, ad hoc solutions for a specific set of uses and conditions. However, the inclusion of mobility and modularity into the design of such platforms adds a degree of flexibility that can unlock the full potential of MUPs to accelerate the transition to more sustainable service provision while increasing resilience in island and coastal geographies.

As a result, 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[19].

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. A combination of methods was used to conduct the review. First, systematic literature review methods were applied to screen, classify, and analyze recent research in the field. Then, keyword text mining and data visualization techniques were used to identify trends, synergies and aspects not covered in the literature.

After following the systematic literature review steps, the included articles were classified according to a set of parameters regarding, i.a, the geographical focus, type of structure and combination of technologies. Furthermore, they are scored in terms of their M-degree, with each M referring to one dimension in the M4 framework. For example, a solution that is marine and multifunctional has an M-degree of M2 whereas a solution that is marine, multifunctional, and mobile has an M-degree of M3, and so on. The results of this classification are then visually summarized in terms of their M-degree, geographic focus, and interlinkages between types of technologies, which can be seen in Figure 3.

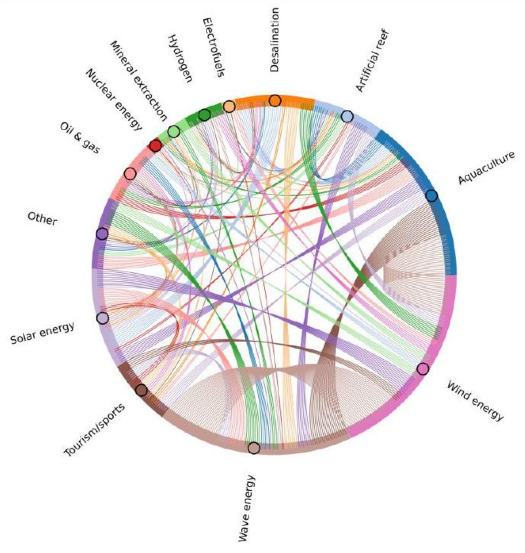


Figure 3 M4 technology combinations [19]

Then, in order to identify the main discussed themes within each M4-degree, a keyword text mining technique was applied based on the Term-frequency – inverse document frequency (TF-IDF) computational methodology [20]. This is a method that scores keywords based on two factors: their frequency of appearance in a document and their frequency of appearance across the whole set of reviewed documents.

The results of the analysis show that the dimension of multifunctionality is prioritized in the literature, while modularity is the least explored concept. M2 solutions appear as the most frequently addressed, being either marine-multifunctional or marine-mobile, followed by M3 solutions, while only 15% of the solutions explored in literature qualified as M4. Figure 4 shows the number of papers where each dimension is addressed, as well as the M-degrees present in each dimension. Regarding geographical focus, the studies were found to be concentrated in Europe, with the North Sea region featuring prominently as the most discussed location, while on the other hand, only one study focused on the African continent and no studies featured South America.

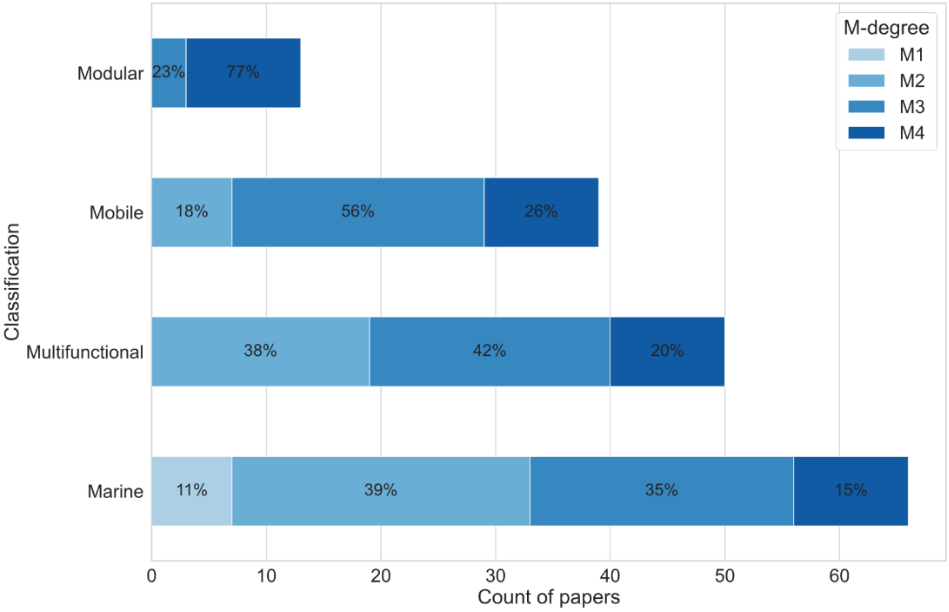


Figure 4 M-degree classification of reviewed literature [19]

The results of the keyword analysis within the M-degree categories showcases how different themes emerge as one moves from M1 to M4, with the decommissioning and repurposing of O&G platforms dominating the M1 category, while combinations of different renewable energy technologies are most frequently discussed within M2 and cost considerations start to emerge in the M3 category, showcasing how economic concerns come into play as the complexity of the solutions increases. Throughout the categories, it is evident that there is a lack of focus on modularity and mobility as central themes.

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. For this reason, they suggest that a valid alternative is to include non-scientific literature as a source of information which should be systematically reviewed and analyzed incorporating the methods described in the paper. It is on this final recommendation that the scope of the present study is built.

3. Methods

To answer the research questions specified in Chapter 1, a mix of quantitative and qualitative methods was used, allowing for a comprehensive analysis of the state, outlook, opportunities, and barriers faced by M4 solutions.

The first quantitative method used was that of conducting a systematic online search to identify the amount of M4 projects that are currently planned, as well as quantitatively establishing a comparison in terms of stage, location, use combinations, M-degree, and other criteria. This step provides a clear understanding of the characteristics of the different projects, as well as identifying the combinations that are being predominantly explored, therefore hinting at the most promising use cases.

Secondly, a variety of stakeholders involved in the studied projects are selected for semi-structured interviews, with the purpose of gathering qualitative insights about specific projects as well as about M4s as a whole, in terms of opportunities, barriers, business cases and business models from a technical, economical, strategic, and regulatory point of view.

Finally, based on the previous mix of methods, an M4 use case is selected for a quantitative technoeconomic analysis. The combination of OWE and green hydrogen production is selected based on the share that this type of project represents in the total number of studied projects, as well as the opportunities and benefits it is expected to offer based on the conversations with stakeholders. The methodology followed for the case study is presented in detail in Chapter 5.

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 [21] for the systematic review of grey literature through the use of online search engines.

As a first step, a pre-screening was performed by typing the original search string from [19] into the Google search engine

Search string: _((((ALL=energ*) AND ALL=(off$shore OR marine OR aquaculture) AND ALL=(multi$purpose OR multi$use OR multi$mod* OR platform OR mobil*))))_

However, given that this is an approach that is typically fit for academic databases, the relevance of results for pre-screening was limited. Therefore, a second pre-screening search was performed by incorporating different combinations of search terms, taken from the main combinations of technologies identified in the literature review. In this stage, at least one relevant result was identified for each of the main combinations, which provided information as to the nature of the content to be found online regarding M4 projects, which mainly consisted of news articles and press releases.

After all useful information was extracted from the pre-screening, a strategy for the main search was designed. A new consolidated search string was established, given that creating different search strategies for each possible combination may cause some combinations to be overlooked, as well as affecting the consistency of the search and creating an overwhelming volume of results for screening. This new search string differs from the one used in the literature review in two ways: 1) the word *energy* and its variations are removed from the search, because its inclusion leads to a great number of non-relevant results; 2) the keyword *project* is introduced given that it produces results directly related to ongoing projects in the field.

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 listed in Table 2.

Table 2 Project coding categories

Category	Variable
Project Name	Name of project or involved organization
Region	Continent where project is located
Specific Location	Country where project is located
Type Of Structure	Floating, static or both
Combination	Combination of uses or technologies
M-Degree	M1 to M4
Energy Source	Energy production technologies
Stage	Concept, pilot or operation
Publication Year	Year of publication of web result

Within the stage category, projects are sorted into one of three stages. The ***concept*** stage refers to projects undergoing the planning and design phases and that have no physical infrastructure deployed at the moment of writing. The ***pilot*** stage consists of projects where physical infrastructure has been deployed at sea in the form of functional prototype tests or projects exploring combinations of mature technologies. Finally, ***operation*** refers to projects that are effectively in commercial operation.

In total, 29 projects were identified as relevant to the scope of the study. The search results span the last five years (2019-2023) while 2022 presents the largest number of results. Only 3 results belong to the year 2023 given that the search was concluded in March of that year. Relevant results consisted mainly of press releases and news articles, and in a handful of cases they belong to online publications by the responsible organizations in the form of web articles. Figure 5 shows the number of relevant review results obtained for each year.

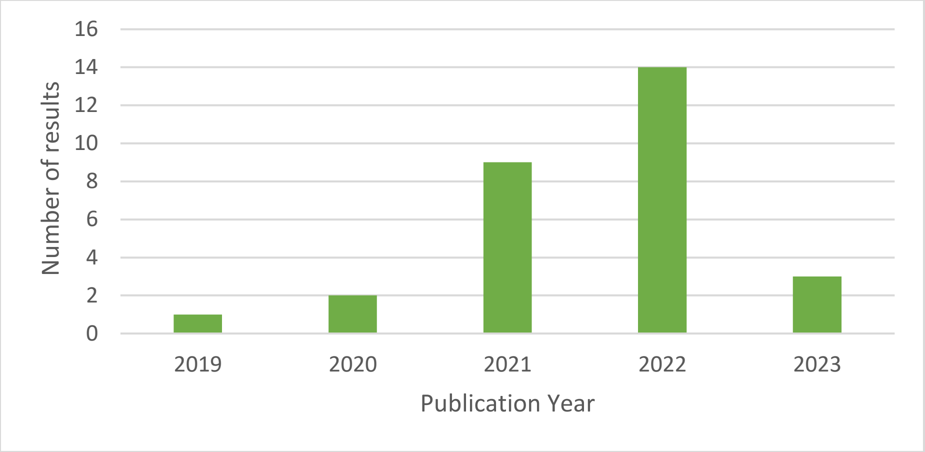


Figure 5 Publication year of online review results

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:

- Researchers: Researchers involved in M4 or multi-use projects identified in the online search or that participated in projects described in the background research for this project, as well as researchers involved in adjacent fields such as MSP.
- NGOs: Non-profit organizations or industry organizations currently involved in demonstration projects.
- Marine renewable energy OEMs: Technology providers who are currently participating in projects at the concept, pilot or operational stage. Mainly wave energy and floating solar PV technology providers.
- Renewable energy project developers: Representatives from offshore renewable energy development and operation companies.
- Authorities: Representatives from government agencies tasked with developing and enforcing water and marine space use regulations.
- EU project representatives: Individuals involved in international M4 projects funded by the European Union. Stakeholders in this category were also part of one of the previous categories in most cases.

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.

The interviews were performed with the main goal of answering the research questions posed in Chapter 1. In order to gather the largest amount of information possible, eliminate the risk of interviewer bias and allow for additional comments from interviewees, an interview protocol was designed to conduct semi-structured interviews, lasting between 30 and 45 minutes depending on each case. The interview questions were divided into 6 main areas: introductory questions, technical aspects, project planning and strategy, economic considerations, and policy/regulatory aspects. The interview protocol can be found in Appendix C.

4. Results

In this section, the results of the first two stages of the project, namely the systematic online review and the stakeholder interviews, are presented in detail and are briefly discussed.

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.

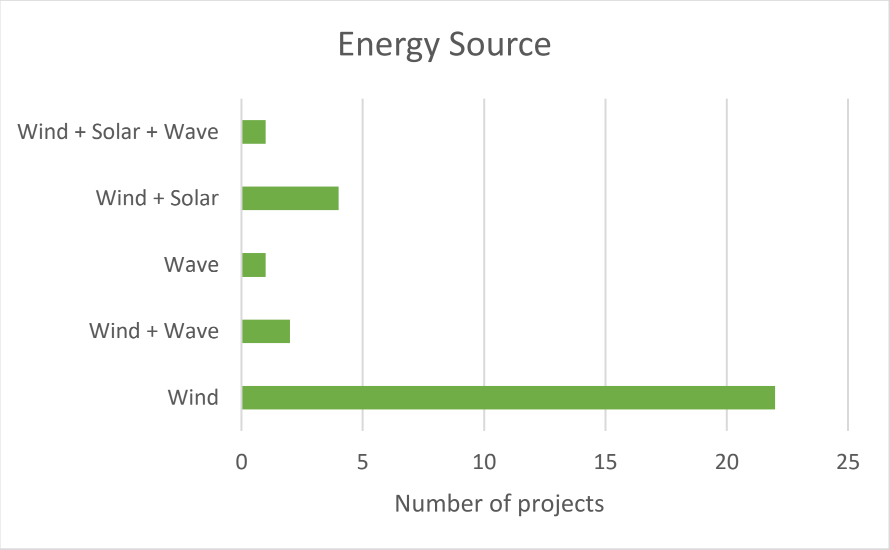


Figure 6 Energy source of reviewed projects

In total, 9 different use combinations were identified and are presented in Figure 7. The combination of electricity production from OWE and the production of hydrogen stands out as the combination with the most ongoing projects, which could be explained by the growth that the OWE industry is experiencing and the emergence of green hydrogen as a viable carbon-free energy carrier. Following this combination is that of OWE and aquaculture, where a series of projects are underway with the aim of producing seafood in the vicinity or at the base of the turbines. The combination of OWE and offshore floating solar power appears as the third combination with the most ongoing projects, including pilot projects that feature the collaboration between floating solar technology providers and wind farm developers in pilot projects and wind farm bids.

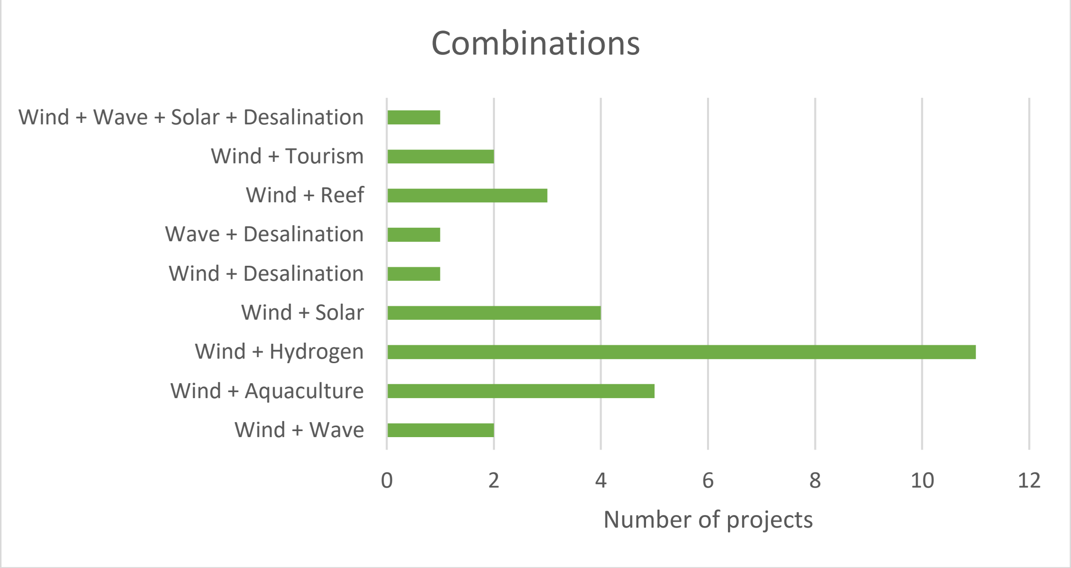


Figure 7 Use combinations of reviewed projects

With regards to the type of structure on which solutions are built, 62% of the selected projects are based on static or bottom-fixed structures, while the rest are made up, in similar proportions, of floating structures and the combination of both types. The predominance of static structures can be explained by the fact that most combinations are dependent on OWE and, to date, virtually all of the installed capacity belongs to bottom-fixed structures [22], [23]. However, in the case of solar energy, all the reviewed projects consist of a floating structure for the solar PV plant and fixed structures for the wind turbines. Similarly, most projects combining aquaculture and OWE consist of bottom-fixed turbines, while the aquaculture facilities mainly consist of moored floating longlines for the cultivation of seaweed or mussels, or cages used to grow and harvest finfish.

The projects were also classified according to their M-degree, as explained in Section 3.1. In the case of this study, the classification was made manually according to the characteristics of each solution, given that multifunctionality, mobility and modularity were not explicitly mentioned in the reviewed publications. The results depicted in Figure 8 show that only one of the reviewed projects qualifies as M4. This is the MUSICA H2020 project, that has the aim of designing and testing a modular, floating MPP for the provision of renewable energy and freshwater for islands.

Of the 29 reviewed projects, 8 qualify as M3 due to their mobility characteristics. However, the possibility for these solutions to be moved is mainly associated with the fact that they are based on floating platforms and are not necessarily designed to be moved between different sites during their operational lifetime. The remaining 20 projects do not incorporate the mobility nor the modularity dimension, and therefore qualify as M2, being marine and multifunctional.

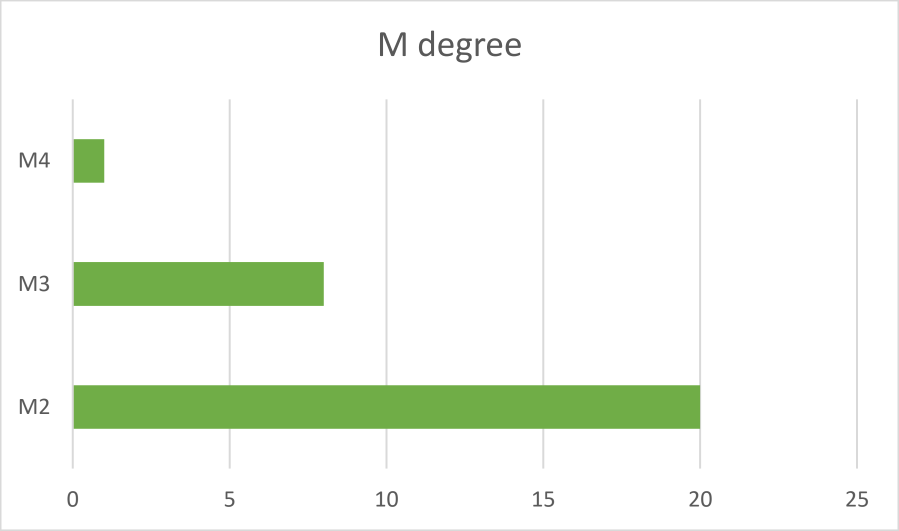


Figure 8 M-degree of reviewed projects

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 [19]. 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. The projects being conducted in Taiwan and the United States consist of nature conservation efforts through the creation of artificial reefs at the base of bottom fixed OWTs, conducted respectively by Orsted and The Nature Conservancy. The last one of the identified projects taking place outside of Europe is a plan by ANCAP, a state-owned refinery, which has released several offshore sites for the production of green hydrogen with electricity produced by OWFs.

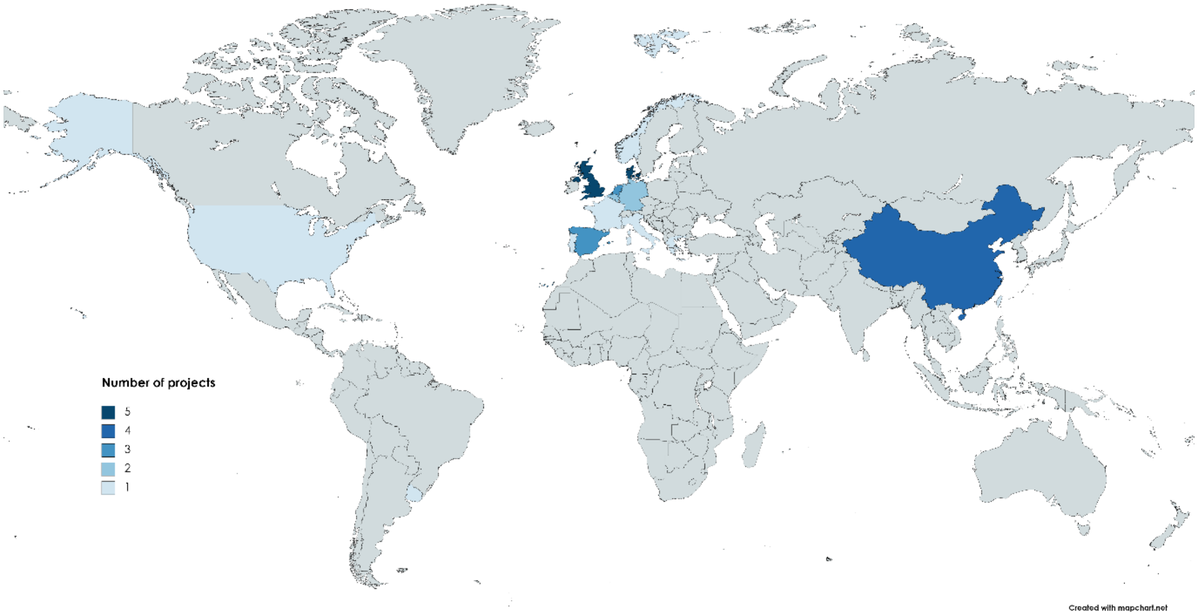


Figure 9 Geographical distribution of reviewed projects

4.2 Stakeholder interviews

As outlined in Chapter 3, the designed interview protocol divided the questions into six main categories, namely: introductory questions, technical aspects, project planning and strategy, economic considerations, and policy/regulatory aspects. In this section, the main insights gathered from the interviews are presented following this structure.

4.2.1 General knowledge

As shown in Appendix C, the introductory questions were meant to assess the knowledge the interviewee had on M4s or ocean multi-use before the interview and, if applicable, to get an introduction by the interviewee to the specific project they were participating in.

There was a varying level of knowledge about the field multi-use among the participants, with only two of them being familiar with the term and having actively worked within the field, either in academic research or in a private organization. The rest of the participants were not familiar with the term and were mostly focused on the combination of different renewable energy sources (which they called multi-source) and technologies such as hydrogen and Power-to-X (the use of renewable electricity to produce a different energy carrier). In spite of the different levels of familiarity with the term, the recurring theme among participants was that the combination of different uses of the marine space had the goal and potential of introducing technical and cost efficiencies in operations, and that the most intuitive combination would be the one between different sources of energy, while the integration of completely different commercial offerings would entail increasing complexity, as it would require the integration of technologies and providers which tend to specialize in their own fields.

In terms of the projects themselves, most of them were aimed at demonstrating individual technologies and how different technologies would perform when combined. One example of this is the EU Scores project, where tests are currently taking place to demonstrate the combined functioning of offshore wind farms with floating solar power plants, as well as the combination of floating offshore wind energy and wave energy. Other projects are instead in a design and planning stage, where technological designs have been produced and testing sites have been secured but no demonstrations are yet ongoing, such as is the case for hydrogen and Power-to-X projects.

4.2.2 Technical aspects

In terms of technical aspects, the interview questions centered around understanding if there were any necessary technological developments that were needed to enable the development of the interviewee's projects. These questions also had the purpose of determining if there were any innovations that were expected to emerge once these projects were deployed at commercial scale.

A common theme that emerged among participants was that there are no major technological barriers as most, if not all, of the necessary equipment to carry out these projects already exist. There are however technologies that are still immature and therefore there is a pressing need for in-situ demonstration in order to move forward with commercialization. In the case of the combination of different renewable energy sources, conducting demonstrations while connected to the grid is expected to be an enabling development as it will produce reliable data on the combined functioning and integration of different technologies. A similar thing occurs when combining OWE and hydrogen production, with some equipment still needing third-party certification and the main technical challenges are expected to come from the development of the supply chain and hydrogen offtake.

When discussing possible innovations that could emerge from the different projects and multi-use cases, a common thought among interviewees was that developments would mostly come from the areas of control and optimization. These developments could enable the operation of a multi-source farm with the simultaneous control of the different energy sources and optimizing annual energy production. Similar developments are expected in the area of offshore hydrogen production, where the integration of the different components will be crucial. Finally, in the case of combined wind energy and aquaculture, advances towards energy independent and automated aquaculture are expected.

One consideration that stood out when conducting the interviews was that contrary to what is found in literature [3], the sharing of moorings and foundations might not be appealing for some stakeholders such as renewable energy developers and operators. Even if technically possible, the possible savings and efficiencies that could be derived from it do not seem to outweigh the possible structural and operational risks.

Finally, in two interviews the aspect of modularity was addressed. In the case of wave energy, it was mentioned that there is a benefit in building modular farms made up of smaller WEC units, given that they are easier to build, transport and install, as well as making it easier to swap faulty units while the rest of the farm remains in operation. Additionally, it allows for reduced complexity and the use of smaller vessels in offshore maintenance operation, as well as having a smaller onshore infrastructure for onshore maintenance activities. In general, the inclusion of modularity into the design makes the projects more attractive in terms of O&M, since both costs and downtime are decreased, resulting in larger annual energy production. Finally, modular configurations allow for projects to be built in phases and to subsequently be scaled up in capacity, which was a benefit also mentioned for projects that combine floating OWE and hydrogen production.

4.2.3 Project planning and strategy

The project planning and strategy questions were aimed at understanding the relationships between stakeholders and determining if any type of stakeholder played a more important role in enabling the widespread adoption of ocean multi-use and M4 solutions. Additionally, this section had the goal of understanding where the potential for this type of project can be found, according to stakeholders involved in the field.

The perception of which stakeholder plays a more important role in enabling their project or multi-use case varies significantly between interviewees and largely depends on the type of activity they perform. In the case of EU funded projects, no stakeholder is identified as playing a more important role than another, as they are all compelled to work together and are exposed to the challenges of other participants. When it comes to commercial deployment, however, one relationship that stands out is that between technology providers and project developers. Technology providers largely depend on project developers to test and deploy their equipment, as developers are the ones who participate in bids and have the financial capability to support these projects. On the other hand, developers rely on technology providers to develop and test their equipment, as a multi-use case simply would not exist if these technologies were not available. Unsurprisingly, partnerships between these stakeholders were found to be the most common.

One category of stakeholder that was identified as important by all the interviewees are policymakers and regulators. They are perceived to play a central role in enabling multi-use projects because existing regulations are targeted to exclusive use of marine space and multi-use is not considered. For this reason, it is considered impossible to deploy commercial multi-use projects at the moment.

There are also differences between interviewees regarding which combination offers the most potential given that, as expected, they largely perceived their own case as the most beneficial. In spite of this, the combination of different renewable energy sources stood out, followed by the integration of hydrogen production in OWF, and finally the combination of offshore renewables and aquaculture. When discussing which regions offered the most potential, the role of regulators was again highlighted, as it was frequently said that regions with local policy support will offer a clear advantage.

4.2.4 Economic aspects

The interview questions on economic aspects had the goal of identifying the perceived advantages and disadvantages of the different cases, as well determining the level of uncertainty that is faced when developing a business case for multi-use projects and identifying which business models or business interactions offer the most benefits.

Similarly to what was found in literature, the main economic advantages that would result from these projects would come from savings in operation and maintenance (O&M). In the case of the combination between OWE and aquaculture, the expected developments in automation would reduce the need for periodic maintenance and human operation. Additionally, the access to cleaner waters and better nutrients offshore is expected to increase the yield of aquaculture products, resulting in higher income and better project economics when combined with the expected O&M reductions. Savings in O&M are also expected when combining different RES, given that onshore infrastructure for maintenance facilities could be shared between different technologies. Savings could also come from the use of common maintenance fleets which would allow maintenance crews to perform different functions simultaneously.

Alternatively, in the case of incorporating hydrogen production into OWF, the benefits differ depending on the case. When hydrogen production is incorporated as an offtake of excess electricity produced by the wind farm, the main economic benefits would come from the possibility to convert electricity that would otherwise be curtailed and sell it as hydrogen for different uses or convert it back to electricity which could be sold in periods of high electricity prices, or to provide services to the grid. Conversely, when OWE and hydrogen production are combined with the sole purpose of producing and selling hydrogen, the main benefits would come as a result of the increased utilization rate of the electrolysers, which would result in a lower levelized cost of hydrogen (LCOH). In both cases, there was a difference of opinion among interviewees on whether it would be more beneficial to produce hydrogen offshore or onshore, given that it is still uncertain if the benefits that could be obtained by producing offshore would outweigh the additional costs and added complexity when compared to onshore production.

When it comes to economic disadvantages, a common opinion was that most of these projects would require large CAPEX, which could deter investors in early stages as the projects will be perceived to have a higher risk than traditional investment. However, they suggest that this could be counteracted by building the projects in phases, and adding new capacity once the performance is proven, thereby de-risking investment in these new projects.

One common theme identified between all the cases is the high level of uncertainty that is involved when developing a business case for any of these projects. In the case of offshore wind and aquaculture, this uncertainty is mainly related to the fact that no large-scale demonstrations have been conducted and, in the case of small-scale applications, one interviewee attributes the uncertainty to the fact that there are no small-scale offshore wind farms in operation and few, if any, small-scale aquaculture farms. In the case of combinations of RES and the combination of OWE and hydrogen, it is possible to develop comparative business cases, but it is difficult to establish absolute values given that most technologies are still immature, and the lack of large-scale demonstrators means that there is still skepticism regarding the performance and survivability of certain technologies offshore. Finally, the convergence of maintenance schedules as well as other possible synergies have not yet been explored to a significant level of detail.

4.2.5 Policy and regulation

In the case of policy and regulatory considerations, interviewees pointed out a series of key aspects that affect the development of their projects. In general, there is a common concern that there are a series of gaps in existing regulations, and in the cases where there are regulations in place, these are largely ineffective.

One example is the case of OWE and hydrogen, which falls into a regulatory gap as current policies address either OW or O&G, and hydrogen falls in the middle, causing significant uncertainty. Conversely, in the case of projects combining different RES, regulations are clear and similar for each technology, but projects face significant delays due to cumbersome permitting processes, making the regulations inconsistent with national strategies and ineffective at achieving national goals.

In that sense, the development of policies targeting multiple use of ocean space is considered as a crucial step in enabling its widespread adoption. At the moment, the Netherlands is the only country that has rolled out MU policies, but interviewees mentioned their involvement with authorities in different countries, with promising developments in Portugal, Ireland, and the Canary Islands in Spain.

Regulators should develop policies targeting multi-use or leave maneuvering room when developing MSP policies, as mentioned by some interviewees. The case of the Netherlands serves as a good example, where the policy of "area passports" has been put in place in the Borssele OWF, dividing the farm into different areas and assigning it to different uses [24]. There was however a degree of skepticism among interviewees for this type of policy, as it carries the risk of arbitrary designations of space or technology choices. It was mentioned that in recent bids for OWF, authorities are including requirements for offshore solar and hydrogen production, without providing much justification, which could lead to forced coexistence without adequate evaluation.

4.2.6 Barriers

The final set of questions of the interviews had the purpose of identifying, from the point of view of the involved stakeholders, the main barriers faced by M4 projects, as well as the actions that could be taken to counteract them.

A recurrent theme was the lack of an enabling regulatory environment, as there are no policies which specifically incentivize the development of areas with multiple use of ocean space, with the previously mentioned exception of the case of the Netherlands. It was mentioned by one interviewee that the MSP policies currently in use around Europe took longer than a decade to develop, which would put the development of multi-use policies beyond the short-term plans of some countries. This lack of regulation could put countries with limited marine space at a disadvantage since the available space would fill up faster and cause them to miss out on valuable opportunities both for business and achieving environmental and economic goals.

The other main barrier identified by stakeholders was the immaturity of the technologies involved in most M4 projects. The immaturity of supply chain and markets was also cited for the case of hydrogen production. Given that there are currently a limited number of test sites, the demonstration of these technologies is one of the most pressing concerns, as the bankability of these projects remains uncertain.

To address these concerns, the consensus among interviewees was that marine multi-use should be incorporated into regulations, and that there should be engagement with policymakers by all types of project stakeholders in order to share experiences and develop common technical and regulatory standards. In that sense, the case of the Netherlands could serve as an example, but it will be interesting to see the developments in other countries.

In the case of hydrogen production offshore, it was pointed out that policy support is needed to ensure that the technology competes on a level playing field with electricity. This is because at the moment, bids for OWF areas are mostly awarded based on electricity price, without taking into account the end-to-end costs associated with both technologies, such as the need to increase the capacity of onshore transmission grids to accommodate the new electricity that will be produced. If these end-to-end costs were taken into consideration, together with a clear understanding of which sectors could be decarbonized by either electricity or hydrogen in each case, the competition between the technologies would be more objective.

In the meantime, an increase in the number and size of demonstrators is understood as the most effective short-term measure, as it would create a wealth of reliable data about the performance, costs and overall benefits of these projects. This would in turn reduce the uncertainty of the business case, de-risk new technologies, bring further investments and make a clear case for the development of an enabling regulatory environment.

5. Case study: Hydrogen production from offshore wind energy

As mentioned in Chapter 1, upon conclusion of the online review and stakeholder interview stages, a case study was performed to quantitatively assess a technology combination identified as promising according to the results of the previous stages. This chapter presents the context and relevance of said case study within this project followed by a description of the methodology that was used. Finally, the obtained results are presented and discussed.

5.1 Context

In Section 4.1, the results of the online review clearly show that 11 out of 30 reviewed projects belong to the combination of OWE and hydrogen production, with projects at different stages of development showing that there is indeed a clear intention to develop this combination further and deploy it at commercial scale.

Moreover, the stakeholder interviews conducted during the second phase of the project further validate these findings. The production of hydrogen from electrolysis with electricity fed directly from an OWF was mentioned by interviewees as either a complement for electricity production where excess electricity could be used to produce hydrogen, or as an alternative to electricity as a final product, where the electricity produced by the farm is entirely dedicated to the production of hydrogen. In both cases, there exists the option to produce hydrogen either onshore or offshore, with different options to transmit either the electricity or the hydrogen.

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, as mentioned in Section 4.2.1, 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. Finally, one of the identified projects consisted of not only producing hydrogen offshore, but in doing so directly on the platforms of floating offshore wind turbines, in a decentralized manner, and transporting the hydrogen to shore via pipeline. This additional configuration brings with it an added dimension of modularity, making it especially relevant in the context of the M4 solutions being studied in this project.

As previously mentioned, the main differences between the production alternatives lie in the location (onshore or offshore) and the transmission infrastructure. In the case of offshore production, the most commonly explored configuration is to transmit the electric power to shore by means of a high voltage direct current cable (HVDC), whereas in the case of offshore production, the most commonly explored alternative is that of transporting the hydrogen to shore in compressed gas form by means of a dedicated pipeline, while options to transport it in the form of liquid hydrogen, ammonia or liquid organic hydrogen carriers (LOHC) also exist. Each strategy has its own associated challenges and costs. For example, HVDC systems are expensive due to the cost of the cables and the necessary converter stations. Conversely, according to some authors, hydrogen pipelines have a higher cost per unit length, but possess larger energy transmission capacity, resulting in lower normalized costs when transmitting the same energy [25].

Studies such as those by [26] and [27] 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 [28] and [29]. One shared characteristic between these studies, especially those centered around production strategy comparisons, 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. For example, the increase in electricity generation and in corresponding hydrogen production could justify the additional costs that would stem from the installation of a complex transmission infrastructure.

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. The analysis is based on the different factors that define each hydrogen production strategy and has the aim of evaluating the effect that the sizing of the wind farm can have on determining which strategy is more beneficial. The following sections of this chapter describe the methodology used to carry out this analysis, as well as the obtained results and corresponding discussion.

5.2 Methodology

To carry out this analysis, three scenarios were developed to compare the different production strategies. In the first scenario (Scenario 1 – Onshore hydrogen production) electricity produced by the OWF is converted to DC by a Voltage Source Converter (VSC) in an offshore substation, is transmitted to shore via an HVDC cable and is then fed to an electrolyser to produce hydrogen. The second scenario consists of offshore hydrogen production and is divided in two: in Scenario 2.1 (Centralized hydrogen production), the electricity from the OWF is also converted to DC but is fed to a centralized electrolysis plant located in an offshore platform in the vicinity of the wind farm. This platform contains the power converter, a desalination unit, an electrolyser, a stand-by battery to serve as backup when the electrolyser is in stand-by mode, a storage unit and a compressor. The compressed hydrogen is then transmitted to shore via a dedicated pipeline. Finally, in Scenario 2.2 (Decentralized hydrogen production), hydrogen production takes place at each of the wind turbine platforms. In this scenario, all the components of the electrolysis plant are present in each platform except for the storage unit and the compressor, which remain in a separate centralized platform from which the hydrogen is sent to shore via pipeline just as in Scenario 2.1.

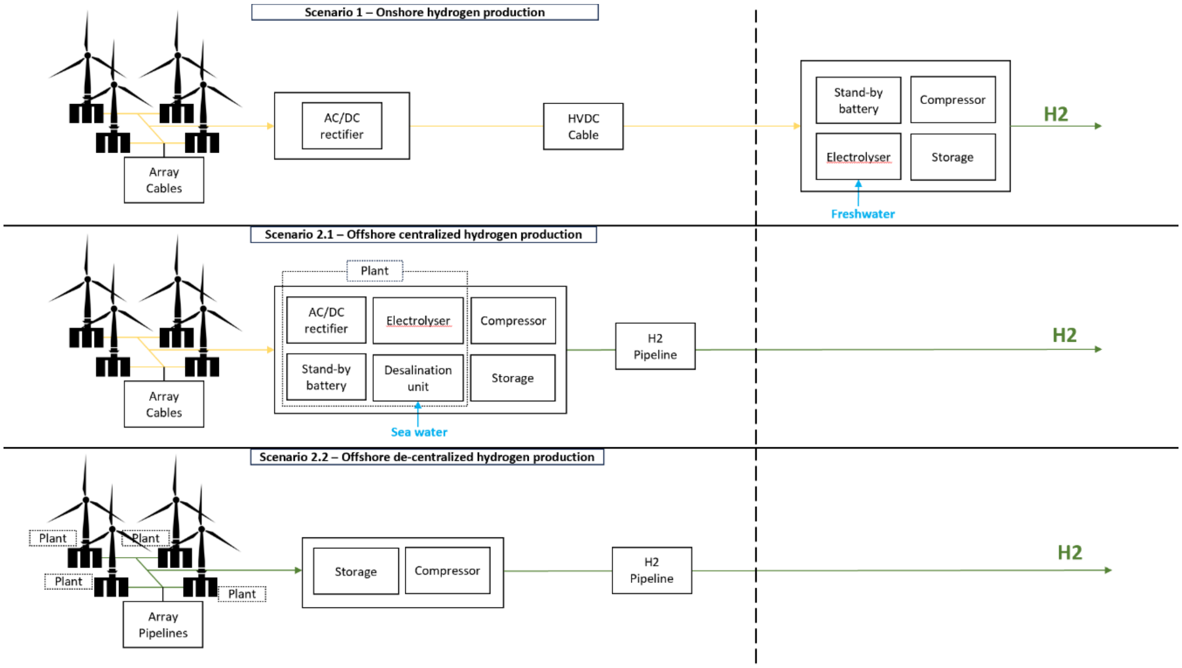


Figure 10 Case study scenarios

For the purpose of the calculations performed in this study, the centralized platforms or substation were located 2 km from the wind farm. Figure 10 provides a graphic description of the three studied scenarios, which can also be found in Appendix D in a larger format.

All scenarios were evaluated based on the levelized cost of hydrogen (LCOH) for 20 different wind farm sizes ranging from 100MW to 2GW. The levelized cost of hydrogen is a measure that indicates the cost of producing 1 kg of hydrogen by considering the total amount of hydrogen produced over the lifetime of a project or plant, and the total costs incurred in the same period. The LCOH is calculated according to the following Equation:

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

Where T is the project lifetime in years, r is the discount rate and M_{H2} is the annual amount of hydrogen produced, in kg.

5.2.1 Offshore wind farm

The next necessary step to conduct this analysis was to identify a feasible production site, for which the previous stages of the project were especially helpful. During the online review stage, the North Sea was identified as an area of concentration of this type of projects, and the stakeholder interviews further highlighted this as an area of particular interest. Moreover, one of the projects studied during both stages, which aims to build floating OWFs dedicated to the production of hydrogen directly on each floating platform, is planned to start off the coast of Scotland, having not yet secured a location for commercial operation.

To have a more concrete case to base the calculations on, 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 which is co-owned by Shell and Scottish Power and will be located 100km off the coast of Peterhead, Scotland, with an installed capacity of 2 GW. Since the average water depth in the site is around 77 m, the wind turbines will have to be installed on floating platforms. Figure 11 shows the location of the projects in the ScotWind leasing round, where Campion Wind is identified with the number 4 [30].

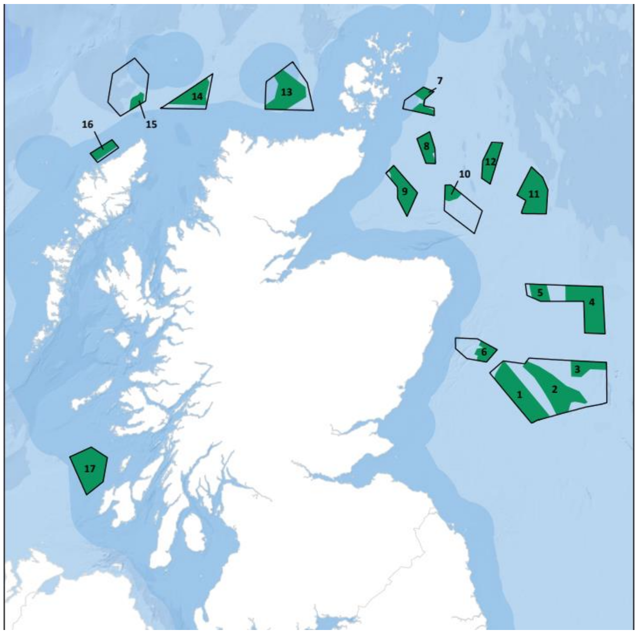


Figure 11 Map of ScotWind lease areas [30]

Once the location was chosen, hourly wind speed data of the site was collected from [31] for the year 2022. Then, to calculate the hourly power output of each of the wind farm sizes, it was necessary to select a specific wind turbine model. 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. Figure 12 shows the power curve of the chosen wind turbine model [32].

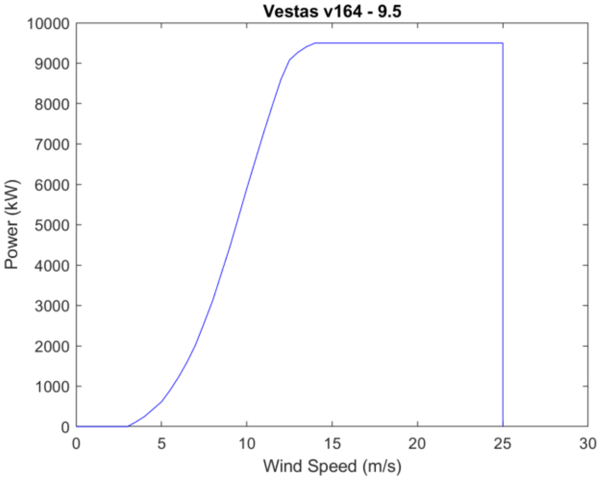


Figure 12 Power curve of Vestas V164 - 9.5 wind turbine

The wind speed data of the site, which was obtained for a reference height of 50m, is adjusted for a hub height of 105 m chosen for the turbine, according to Equation 2. Then, the power output of the farm can be obtained by adding the power output of each turbine, as per Equation 3. The power output of each wind farm size can then be obtained by simply increasing the number of turbines.

$$U_{wind} = U_{href}\left(\frac{Z_H}{Z_{href}}\right)^a$$

(2)

$$P_{farm}(t) = \sum_{i=1}^{NT} P(U_{wind})_i$$

(3)

In Equation 2, U_{wind} represents the wind speed at the turbine hub height, U_{href} is the wind speed at the reference height, Z_H is the hub height, Z_{href} is the reference height and a is the Hellman coefficient, taken as 0.15 in this case [33]. In Equation 3, $P_{farm}(t)$ represents the hourly power output of the farm, NT is the number of turbines and $P(U_{wind})$ is the power output of each turbine, which will vary in each hour depending on the wind speed. Figure 13 shows the hourly power output of one turbine for an entire year.

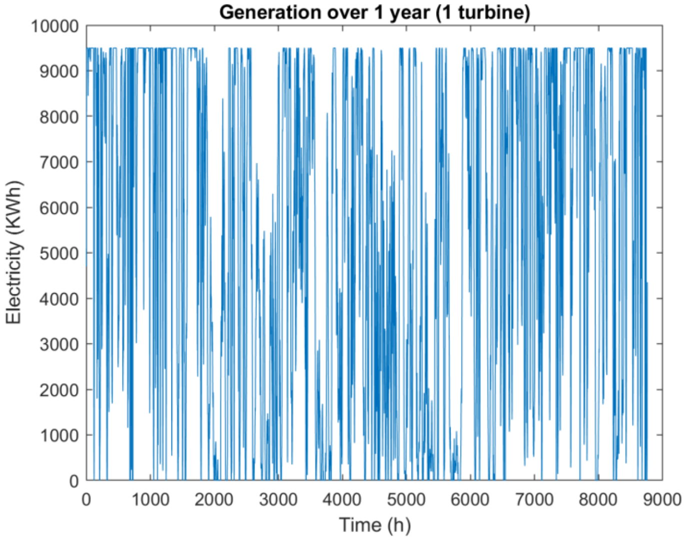


Figure 13 Hourly electricity generation over 1 year in the selected site

5.2.2 Component sizing and costs

Once the power output of the farm is calculated, the next step is to size the components of the electrolysis plant, as well as the transmission infrastructure used in the different scenarios, and to calculate the investment and operational costs of said components.

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 [26]. The investment cost of the converter is taken from [34], and is calculated according to Equation 4, where C_{VSC} is the investment cost in M€ and P_{farm} is the rated power of the wind farm, in MW.

$$C_{VSC} = 0.1437 \cdot P_{farm}$$

(4)

HVDC Cable

Given that in Scenario 1, hydrogen is produced from electricity transmitted through an HVDC cable, this component needs to be sized, and its losses need to be accounted for when calculating the amount of produced hydrogen. 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 [34] using Equation 5, where P_{cab} is the rated power of the cable and C_{HVDC} is the investment cost, expressed in M€/km.

$$C_{HVDC} = 1.452 \cdot \left(1.31 \cdot 10^{-7} \cdot P_{cab}^{2} + 1.47 \cdot 10^{-4} \cdot P_{cab} + 0.29 + 0.85\right) \tag{5}$$

Electrolyzer

For this analysis, a PEM electrolyser was chosen due to its high operational flexibility and quick ramp-up and ramp-down times. PEM electrolysers operate at high current densities and in a wide range of temperatures, which allows them to adjust to variable power levels within seconds and makes them especially suitable for hydrogen production from variable renewable electricity sources [35].

To size the electrolyser, the theoretical hydrogen production that could be obtained in every hour is calculated from Equation 6, 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.

$$W_{H2_{theoretical}}(t) = \frac{P_{farm}(t)}{\frac{E_{elec}}{\eta_{conv}} + E_{aux}} \tag{6}$$

Then, the size of the electrolyzer can be obtained by multiplying the electricity consumption by the maximum theoretical hourly hydrogen production (Equation 7).

$$P_{H2,plant} \leq max W_{H2theoretical}(t) \cdot E_{elec} \tag{7}$$

In order to maintain efficient operation and to preserve the lifetime of the PEM stack, 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. PEM electrolysers typically have a minimal load between 0% and 10% of the rated power, and this is mainly due to gas purity and safety concerns associated with gas crossovers that occur inside the electrolyser [36].

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 8 summarizes the operation of the electrolyser based on the power output of the wind farm [37].

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

(8)

To calculate the CAPEX of the electrolyser, a specific cost was obtained from [26], expressed in €/kW of electrolyser capacity. Since a PEM electrolyser was chosen for this analysis, the specific cost was kept equal across all values of rated capacity, since it is assumed that PEM electrolysers can be modularly stacked to achieve higher capacities without sacrificing efficiency [38].

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 [26].

Desalination unit

The energy requirements and the cost of the desalination plant can be calculated based on the water requirements. Equation 9 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 [39]. The density of sea water is represented by ρ_{H2O}.

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

(9)

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.

$$E_{des} = V_{H_2O} \cdot e_{des}$$

(10)

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 a 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 [26].

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

(11)

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 12 [40].

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

(12)

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 [41]), 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 13 [26] and the annual OPEX was assumed to represent 2% of the CAPEX.

$$CAPEX_{storage} = C_{storage} \cdot M_{H2_{day}} \cdot t_{storage}$$

(13)

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 14 [40]. 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 [42].

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

(14)

Platform adaptations

Given that Scenario 2.2 contemplates the location of an electrolysis plant in each of the floating turbine platforms, modifications need to be made to create a base on which the plant can stand, and to accommodate the additional weight associated with it. The cost of these adaptations was estimated at 5% of the cost of one platform, based on discussions during one of the stakeholder interviews. Even though an exact value was not provided, it was mentioned that the modifications did not represent a significant increase in cost. The cost of one floating platform was estimated at 13 million €, and was obtained from [43]. The resulting cost of the platform adaptation was therefore taken as 650000€ per turbine.

Array pipelines

Since electricity from the wind turbines is converted into hydrogen at each wind turbine in Scenario 2.2, the wind farm would have a series of inter-array pipelines, which would replace the traditional AC inter-array cables that would be present in the other scenarios and would bring the produced hydrogen to the collection platform that houses the compressor and storage unit. Given that the mass flow of hydrogen in these pipelines would be significantly lower when compared to what occurs in the transmission pipeline, the cost of the inter-array pipelines was assumed to be the same as that of a hydrogen distribution pipeline, in line with [44]. The cost of these pipelines is therefore estimated at 500000€/km.

LCOH Calculation

Once the components have been sized for each scenario and for each wind farm size, the next step is to calculate the LCOH for each case according to Equation 1. The project lifetime was set at 30 years, with a discount rate of 7%. This calculation allows a comparison to be made between the different production strategies described in each scenario, and to evaluate the impact the size of the wind farm would have on choosing the most appropriate strategy. A summary of the values used for the sizing and cost calculations of each of the components is presented in Table 3.

Table 3 Summary of technoeconomic analysis data

Electrolyser		[26]
Efficiency (%, LHV)	65	
Stack Lifetime (h)	75000	
CAPEX (€/kW)	467.3	
O&M (% CAPEX/y)	1.5	
Replacement (% CAPEX)	12	
Stand-by battery		[26]
CAPEX (€/kW)	40.8	
AC/DC Converter		[26]
Losses (%)	1.5	
Desalination Unit		[26]
Electricity consumption (kWh/m^3)	3.5	
Lifetime (y)	30	
CAPEX (€/m^3/d)	1244.2	
OPEX (% CAPEX/y)	2	
Freshwater (€/m^3)	1.58	
H_2 Compressor		[40]
Lifetime (y)	10	
Efficiency (%)	88	
CAPEX (€/kW)	2378.5	
OPEX (% CAPEX/y)	3	
Replacement (%CAPEX)	100	
H_2 Storage		[26]
CAPEX (€/kg H_2)	429.8	
O&M (% CAPEX)	2	
HVDC Cable		[26]
Losses (%/100 km)	0.3	
H_2 Pipeline		[45]
Losses (%/100km)	0.4	
O&M (% CAPEX)	2	
Array Pipelines		[38]
Losses (%/100km)	0.4	
CAPEX (M€/km)	0.5	
O&M (% CAPEX)	2	
Electricity		[46]
LCOE (€/MWh)	67.29	

5.3 Case study results

The goal of this case study is to provide a technoeconomic assessment of different strategies to produce hydrogen from floating offshore wind energy. This assessment was performed on the basis of calculating the LCOH of the proposed scenarios for ten different wind farm sizes, ranging from 100 MW to 2 GW, in intervals of 100 MW. The LCOH is the indicator of choice as it allows for a normalized comparison between alternatives, in a similar way to what is done with the levelized cost of electricity (LCOE) when comparing electricity production technologies. The goal of this calculation was to determine how the LCOH would change with the wind farm size and if the size of the wind farm would have an impact on the choice of preferred hydrogen production strategy, e.g., centralized vs decentralized or onshore vs offshore.

In this section, the results of the technoeconomic assessment are presented and discussed. Firstly, the calculated values of LCOH are presented, showing the relationship between the different scenarios and the behavior of the indicator along the chosen range of wind farm sizes. Then, the subcategories that make up the LCOH calculation are examined in more detail for a representative wind farm size, before evaluating and comparing the total costs of the system in each scenario. Finally, a sensitivity analysis is performed to determine how changes in different variables affect the results of the assessment.

In line with the methodology described in the previous section, the values for the LCOH were obtained for each case. In Scenario 1 (Onshore hydrogen production), the LCOH decreased from 7.67 €/kg for a farm size of 100 MW to 5.99 €/kg for a farm size of 2 GW, a reduction of 21.9%. Similarly, in Scenario 2.1 (Centralized offshore hydrogen production), a reduction of 8.9% is observed, with the highest LCOH found at 100 MW farm size at a value of 6.51 €/kg and the lowest value being 5.93 €/kg in the 2 GW case. Finally, Scenario 2.2 (Decentralized offshore hydrogen production) shows a similar behavior as the other two scenarios, with the highest LCOH recorded at 6.58 €/kg and the lowest at 6 €/kg, for 100 MW and 2 GW farm sizes respectively, representing a reduction of 8.8% along the studied farm size range.

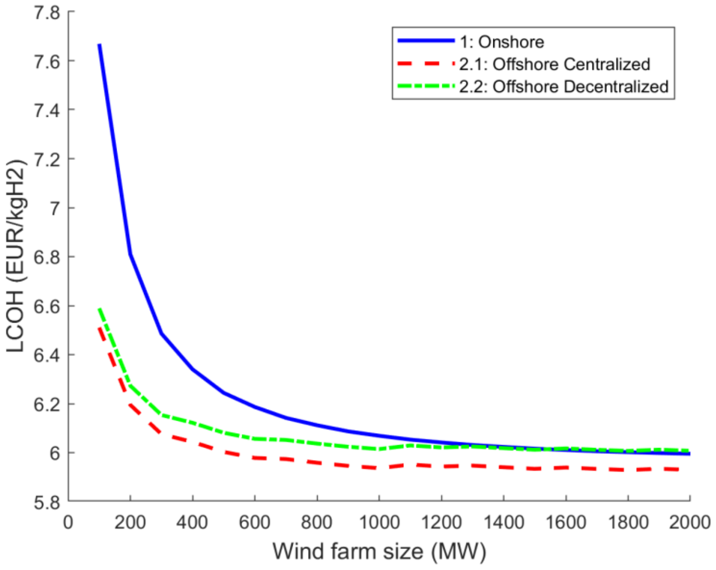


Figure 14 Levelized Cost of Hydrogen for all scenarios and WF sizes

Figure 14 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.

It is also worth noting how for all scenarios, the LCOH drastically decreases in the 100MW-600MW range, then presents a gradual decrease up to 1.2GW, after which the LCOH stabilizes, showing a reduction from 5.94 €/kg to 5.93 €/kg at 1.2GW and 2GW respectively for Scenario 2.1, which is barely visible in the chart.

The relative differences between the different scenarios also experience a change in these ranges. This can be seen by comparing the LCOH of Scenario 1 against that of Scenarios 2.1 and 2.2. For a size of 100 MW, the LCOH of Scenario 1 is 17.8% higher than for Scenario 2.1 and 16.6% higher than for Scenario 2.2. When moving to 600 MW this difference is reduced and the LCOH of Scenario 1 is 3.48% and 2.22% higher than for Scenarios 2.1 and 2.2 respectively. When reaching a 2 GW wind farm size, the LCOH of all scenarios presents similar values, with Scenario 1 having a value of LCOH merely 1.1% larger than Scenario 2.1 and even falling below Scenario 2.2 by 0.2%.

Given that Scenario 2.1 presents the lowest LCOH over the entire range of WF sizes, centralized offshore hydrogen production stands out as the preferred strategy for hydrogen production from dedicated wind energy infrastructure.

5.3.1 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 to examine the amount of hydrogen produced, the cost subcategories and the total costs that would be present in each scenario. This wind farm size is chosen because it is the case in which the values of LCOH are the closest among the three evaluated scenarios, and it is therefore useful to pinpoint where these differences are encountered, in order to see which factors could alter them. In this case, 211 wind turbines are used, resulting in a rated capacity of 2004.5 MW.

Annual hydrogen production

As per Equation 1, the amount of hydrogen produced by the electrolysis plant will largely influence the achieved LCOH. Figure 15 shows the annual quantity of hydrogen, in kg, that would be produced in the Campion Wind OWF in each of the studied Scenarios.

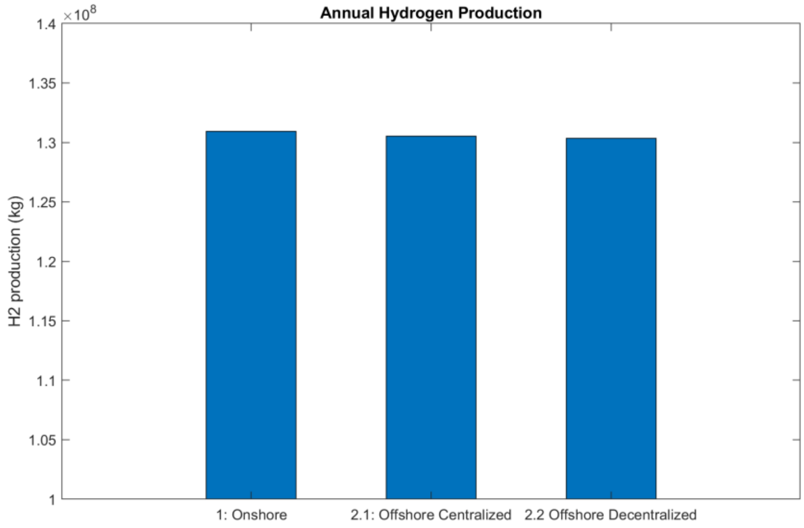


Figure 15 Annual hydrogen production for all scenarios - 2 GW WF size

The annual hydrogen production for all scenarios stands around 130 thousand tons of compressed hydrogen per year. With Scenario 1 standing at 130930 t/y, Scenario 2.1 at 130510 t/y and Scenario 2.2 at 130060 t/y. The differences between scenarios are not particularly significant, given that between the highest yielding scenario and the lowest there is a mere difference of around 0.7%.

These differences are mainly due to the fact that there are larger losses assumed for the hydrogen pipelines than for the HVDC cable, as shown in Table 3. Studies such as [26] assume losses of around 0.01% in the hydrogen pipeline, considerably less than what considered in this study, which is based on assumptions from [45]. One additional factor that results in the differences in annual hydrogen production is the fact that in Scenario 1 there is no desalination unit, and therefore more electricity from the wind farm is available for use in the electrolyser.

The chosen lifetime for the project was 30 years, which means that over the entire period, Scenario 1 would produce 12600 tons of H_2 more than Scenario 2.1 and 17100 tons of H_2 more than Scenario 2.2. Even if these values appear considerably large, the relative differences are almost insignificant in percentual terms, with Scenario 1 producing 0.32% more than Scenario 2.1 and 0.44% more than Scenario 2.2.

One factor that could affect the annual hydrogen production was not considered in this study, and that is the difference in maintenance downtime that could exist between the different configurations. For example, a hydrogen pipeline might need more maintenance than an HVDC cable, which would result in lower lifetime production for Scenarios 2.1 and 2.2. Additionally, when comparing Scenarios 2.1 and 2.2, the fact that there would be an electrolysis plant in each turbine means that there would be a considerably larger number of components to maintain which would also reduce the lifetime hydrogen production. This could however be counteracted by the fact that a modular configuration would mean that if one electrolysis plant fails, the rest could continue with normal operation. Estimating these downtimes was considered out of the scope of this study, as there are currently no hydrogen pipelines built from an offshore wind farm to shore, as well as modular hydrogen producing wind farms such as those studied in Scenario 2.2, and any estimation of these downtimes would at best consist of a guess.

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 €.

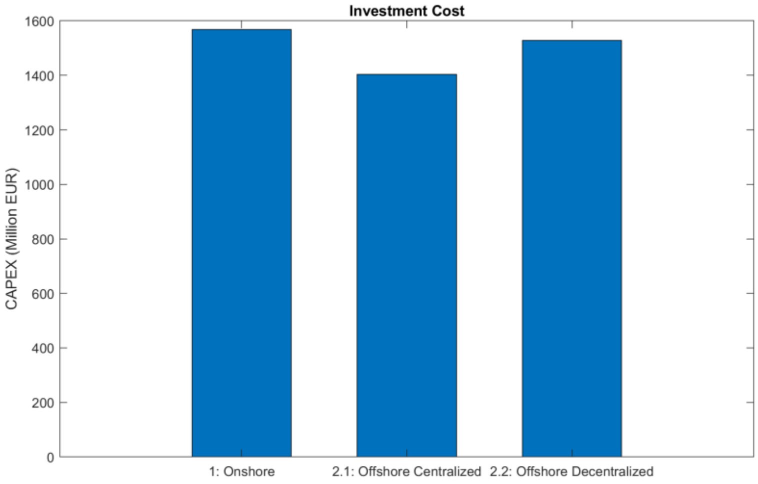


Figure 16 Investment cost for all scenarios - 2 GW WF size

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.

Figure 17 shows the investment cost expressed in terms of the components present in each Scenario. The electrolyser is the most expensive component, with a cost of around 608.34 million € in all scenarios, as it is sized according to the maximum theoretical production. The cost of the electrolyser represents 38.8%, 43.3% and 39.8% of the investment cost of Scenarios 1, 2.1 and 2.2 respectively.

Another component common in all scenarios is the power converter, necessary to convert the alternating current coming from the wind farm into direct current used for the electrolysis plant. The cost of the VSC (voltage source converter) stands at around 288 million €, representing 18.4%, 20.5% and 18.8% of the total investment cost of the respective scenarios. Similarly, the storage unit is present in all three scenarios, with a value of around 154 million €, and representing roughly 9.8%, 11% and 10% respectively. This shows that the storage unit is a relatively expensive component, especially considering that it was sized to contain 1 day of maximum hydrogen production.

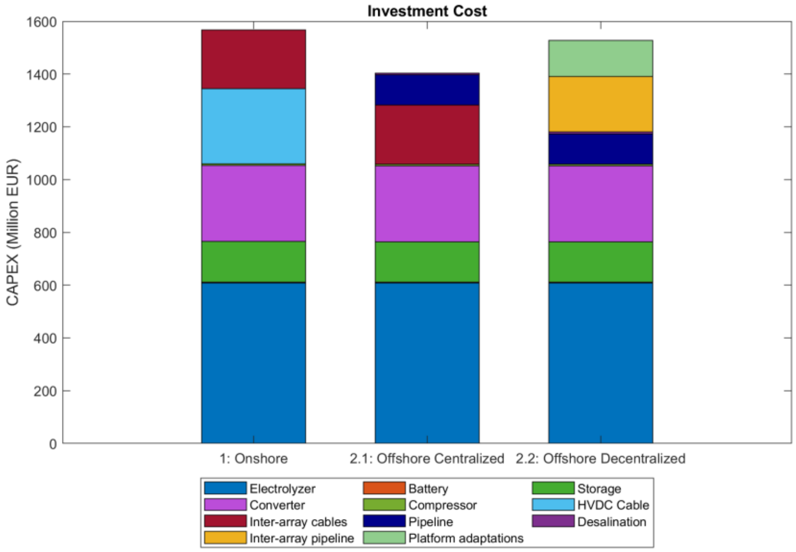


Figure 17 Investment cost per component - 2 GW WF size

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. Another difference in energy transmission components is the fact that in Scenarios 1 and 2.1, electricity from the wind farm is transmitted to the VSC converter through inter-array AC cables. Conversely, in Scenario 2.2 inter-array pipelines are present to bring the hydrogen produced in each floating turbine platform to the centralized storage and compression platform. The cost of these components however is similar, at around 0.5 million €/km, and therefore does not represent a major difference in the investment costs.

As previously mentioned, Scenario 2.2 requires adaptations for each floating platform to accommodate the electrolysis plant. For a 2 GW wind farm, these adaptations add a considerable investment cost of 137 million €, which represents 8.9% of the total investment cost of Scenario 2.3. The increase in costs due to the platform adaptations and the losses in the hydrogen pipeline are what ultimately contribute to Scenario 2.3 having the highest LCOH.

Finally, components such as the stand-by battery, desalination unit and compressor do not represent a significant cost when compared to the components previously described, and therefore have virtually no effect on the total investment cost and LCOH of the system.

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 [26], 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.

There are some parameters affecting these results. The electricity cost represents the largest share of the total cost of the system, given that for this case study, all the electricity coming from the wind farm is being used to produce hydrogen, and there is no grid connection which would allow to sell the electricity that is not being used when the output of the farm falls under the lower operational threshold of the electrolyser. The electricity costs add up to 21.1 billion €, representing roughly 90.1% of the total costs of Scenarios 1 and 2.2 and 91.8% in the case of Scenario 2.1. This percentage is considerably higher than what is typically expected, as the electricity cost is expected to constitute around 75% of the LCOH when hydrogen is produced from PEM electrolysis [47]. As shown in Table 3, an LCOE of 67.29 €/MWh was used for this study, which is the global average for offshore wind projects globally [46]. This LCOE average is mainly made up of bottom-fixed turbine projects, however it was assumed that by the commissioning date of this wind farm (2028) the cost of floating offshore wind electricity could reach the same value as that of bottom-fixed.

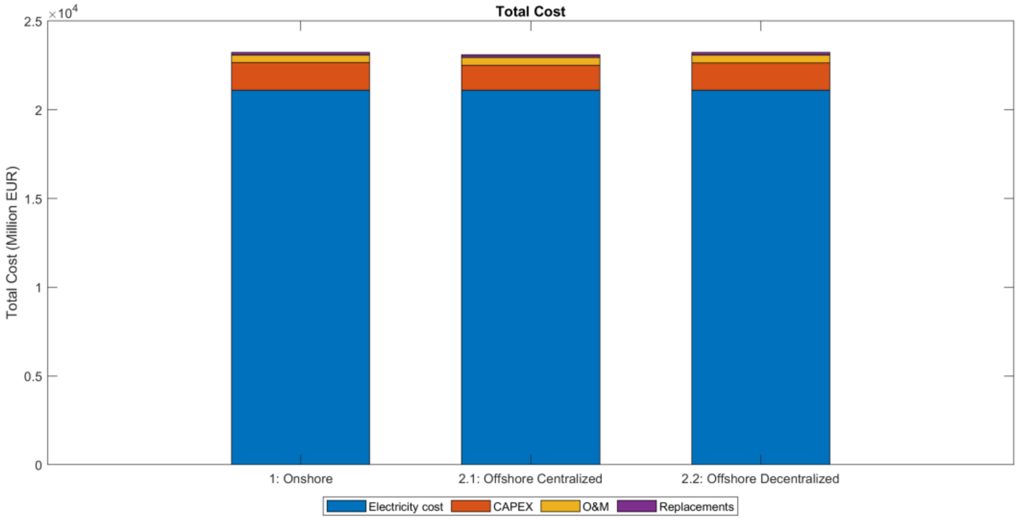


Figure 18 Total lifetime costs – 2 GW WF Size

The share that the rest of the cost items represent of the remaining share of the total costs can barely be observed in Figure 18, for this reason the total costs are represented in Figure19 without the electricity costs, allowing to distinguish between the different cost components and to visualize the difference between scenarios.

In Scenario 2.1, CAPEX represents 73.5% of the total costs when electricity costs are not considered, while O&M costs represent 19.1% and the replacement costs represent 7.4%. As previously seen, the CAPEX is lower in Scenario 2.1, which is why it represents a lower share, standing at 70% of the total costs excluding electricity. Meanwhile, O&M costs represent 22% and replacement costs represent 7.9%. Finally, in Scenario 2.2, CAPEX represents 71.8%, O&M represents 20.7% and replacements represent 7.5% of the total costs when electricity costs are excluded.

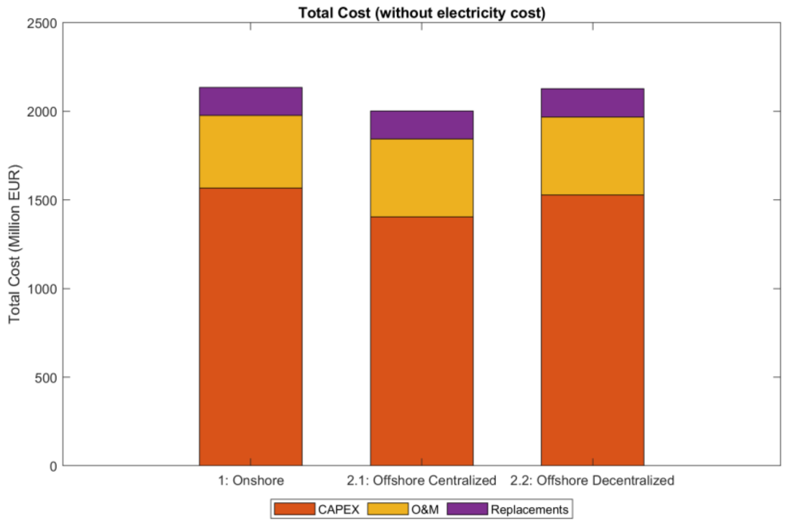


Figure 19 Total lifetime costs excluding electricity costs - 2 GW WF Size

Given that the desalination unit is assumed to last for the entire lifetime of the project, the replacement costs remain the same throughout all scenarios. If that wasn't the case, Scenarios 2.1 and 2.2 would naturally have an increase in replacement costs, which would however not be significant given that, as seen previously, the CAPEX of the desalination unit is barely noticeable when compared to the other CAPEX elements. Finally, there is a slight difference in O&M costs, due to the fact that in Scenarios 2.1 and 2.2 the O&M of the desalination unit is considered, whereas in Scenario 1 this is replaced by the cost of freshwater. Table 4 provides a summary of the results obtained in the studied scenarios.

Table 4 Summary of technoeconomic analysis results

	Scenario 1 Onshore production	**Scenario 2.1 Centralized offshore production**	**Scenario 2.2 Decentralized offshore production**
LCOH (€/kg)			
Highest	7.67	6.51	6.58
Lowest	5.99	5.93	6
2 GW wind farm			
Rated power (MW)		2004.5	
Hydrogen production (t/y)	130930	130510	130060
Lifetime costs			
CAPEX (billion €)	1.57	1.4	1.57
O&M (billion €)	0.41	0.44	0.44
Electricity (billion €)		21.1	
Replacement CAPEX (billion €)		0.16	
Total costs (billion €)	23.2	23.1	23.2

Sensitivity analysis

In order to evaluate the effect that different cost elements would have on the final value of LCOH, a sensitivity analysis was conducted. Given that Scenario 2.1 (Centralized Offshore Production) presents the lowest LCOH and is the preferred scenario, the sensitivity analysis presented here is for this scenario alone.

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. It is also useful to evaluate the effect of the distance from shore, given that this is a variable parameter for every wind farm. The map of the ScotWind lease areas shown in Figure 11 shows the location of all the projects that were part of the leasing round, and it can be seen how the distance from shore will vary from project to project.

In a similar manner to the LCOE analysis, the distance from shore was changed while keeping all other variables unchanged. Since the effect of the change in distance from shore would affect the CAPEX, and this represents around 7% of the total costs, the range of values used for the distance from shore was larger than the one used for the LCOE analysis. The selected range was between 40% and 500% of the original distance from shore. Figure 20 shows the results of the sensitivity analysis for Scenario 2.1.

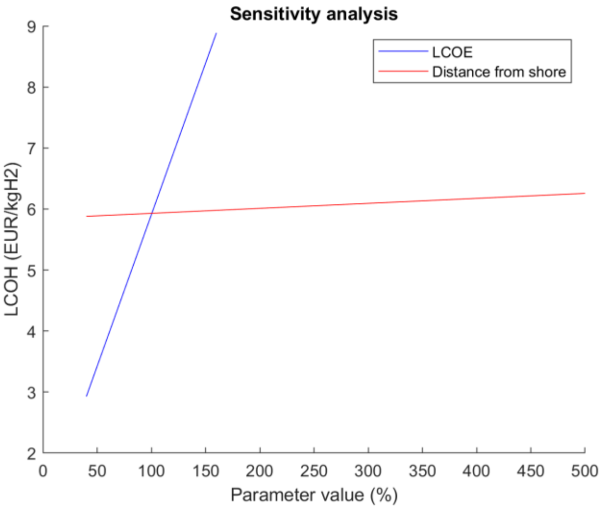


Figure 20 Sensitivity to LCOE and distance from shore - Scenario 2.1 (2 GW WF size)

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 cost was taken as a fraction of the cost of a WindFloat floating platform since this platform is expected to be used for this type of hydrogen production system. In order to evaluate the sensitivity of LCOH to changes in this parameter, a range of 50% to 150% of the original value was used, while keeping other variables unchanged. The results are shown in Figure 21.

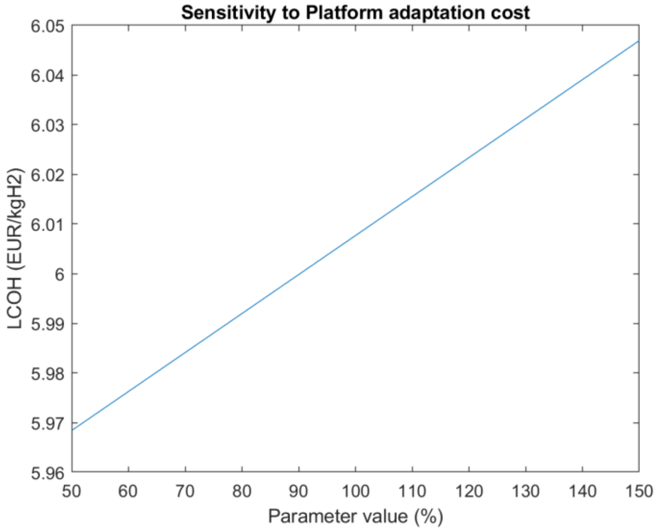


Figure 21 Sensitivity to platform adaptation cost - Scenario 2.2 (2 GW WF size)

The results show that for the selected range, the LCOH is not particularly sensitive to the change in platform adaptation costs. A reduction of 50% of the cost would result in a 0.65% reduction in LCOH, while a 50% cost increase would result in a 0.66% increase in LCOH.

Effect of distance from shore on choice of production strategy

As seen in the sensitivity analysis, the distance from shore does not have a significant impact on the value of LCOH for the selected case. However, since the main goal of this case study was to compare the LCOH of the different hydrogen production strategies across a range of wind farm sizes, it is interesting to determine if a change in the distance from shore would affect the choice of preferred strategy in any of the studied wind farm sizes.

For this purpose, two additional distances from shore were introduced: 50 km and 200 km, representing 50% and 200% of the original value, respectively. Then the calculations of LCOH were performed for the entire range of wind farm sizes for each of these distances and the results were compared to those obtained in the original case. The results of these calculations can be seen in Figure 22.

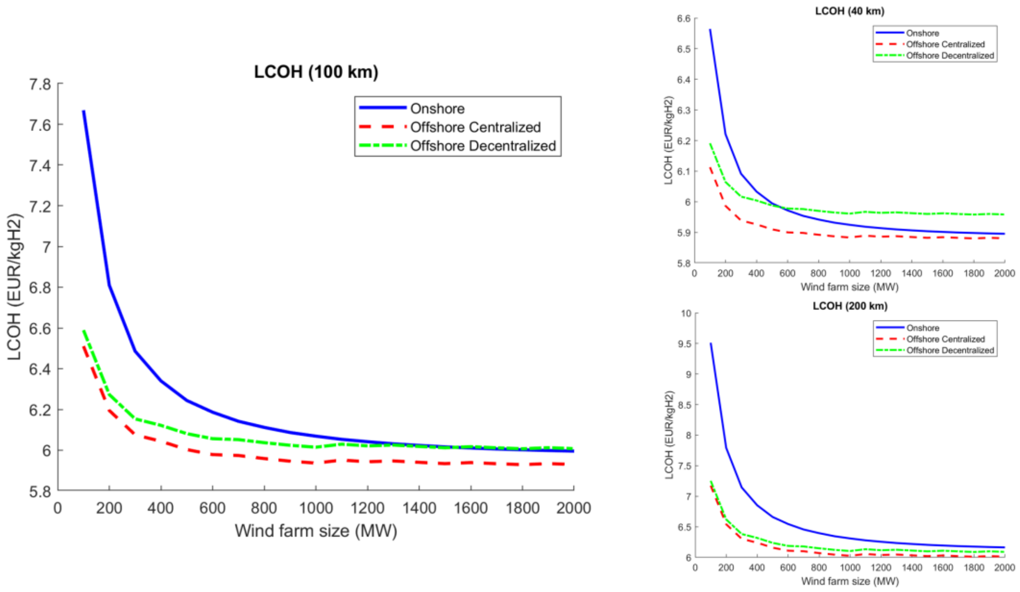


Figure 22 LCOH vs WF Size for different distances from shore

The results show that for a distance of 40 km, Scenario 1 would have a lower LCOH than Scenario 2.2 for farm sizes larger than 500 MW, which changes the relationships between strategies, as in the original case, Scenario 1 has lower LCOH only when reaching 2 GW. In the case of a 200 km distance, the relationship between the scenarios remains unchanged when compared to the original case, with the exception that Scenario 1 has a higher LCOH even for a 2 GW farm size.

Given that for a distance of 40 km from shore, wind farms would typically be of the bottom-fixed type, this result cannot be directly applied to this case study, as it was conducted for a floating OWF. Finally, it is worth noting the distance from shore does have an impact on the LCOH in the lower ranges of wind farm size, and this could be due to the fact that the large investments made in transmission infrastructure for both electricity and hydrogen would not be compensated by the amount of hydrogen that is produced over the lifetime of the project.

6. Discussion

This chapter presents a discussion of the results that were obtained during the three phases of the project, namely, the systematic online review of marine, multifunctional, modular and mobile (M4) projects, the interviews with relevant stakeholders and the technoeconomic analysis performed in the case study.

6.1 Systematic online review

The systematic review of online information on M4 projects provided a measure of the quantity, status and individual characteristics of currently ongoing projects. The classification of these projects into the different subcategories provides an indication of the general status and direction that multi-use marine platforms are taking. Characteristics such as energy sources and use combinations, deployment stage, and geographical distribution were found to be amongst the most useful to describe the outlook for M4 projects.

The online nature of the review meant that the information that was retrieved belonged for the most part to news articles or press releases from which further information was extracted through the review process. Given that utility-scale projects in which large organizations are involved predominantly gather media attention, a large portion of the results were obtained from announcements made for these types of large-scale projects. However, rather than showing that the benefits of M4s are exclusive to large-scale applications, these results simply indicate that the efforts being made to deploy M4s at this scale are generating the most announcements and therefore gathering most attention.

As mentioned in the introduction and background sections, the benefits of M4s could be particularly useful for island and remote coastal communities, where large, utility-scale projects are unlikely to be located as these locations do not represent points of significant demand for services such as energy. However, only two of the 30 reviewed projects were focused on local applications. These were the MUSICA and the AquaWind project, both of which are EU-funded projects. The low occurrence of small-scale projects among the results of the online review could indicate that these solutions are currently not being deployed or explored at length in these settings or could simply show a limitation in the used review method in detecting the occurrence of this category of projects. A modification of the used method or the definition of a new method, focused exclusively on this category, could be useful in identifying the status of M4s in these settings.

One additional consideration that should be made is that the concepts of marine multi-use, multi-purpose platforms and M4s are not frequently used outside of the academic environment, and therefore in order to identify relevant projects, a search string was designed to find projects related to the technologies that make up these solutions. Once the search string was defined, detailed examination of the search results was needed to determine if the projects could be included within the M4 framework.

Finally, the concentration of projects in the northern hemisphere, and particularly around the area of the North Sea, is intrinsically tied to the fact that a large fraction of the reviewed projects are linked to the offshore wind energy industry, where this area plays a central role due to the high availability of renewable energy resources and its proximity to large energy demand centers in Europe. This result is in line with the findings of the literature review conducted by [19], where a similar geographic concentration was found in academic studies. Therefore, the online review did not significantly modify the perspective when it comes to the geographical distribution of M4 solutions.

6.2 Stakeholder interviews

The results of the interview phase provide insight into the field of M4s from the point of view of stakeholders involved in currently ongoing projects. The methodology followed during the semi-structured interviews made identification of common themes and perspectives possible.

One of such themes is the fact that technological developments are not perceived as major challenge or barrier when it comes to the discussed projects. Even though the involved technologies are at different stages of commercialization, most of them have been demonstrated to work in their own specific application, as for example shown by the demonstrators performed by Oceans of Energy [48] and Corpower [49], for floating offshore solar and wave energy, respectively. However, challenges remain when it comes to combining different technologies to work together at sea, and there is therefore an overarching focus on demonstration. This focus on demonstration was expressed in all interviews, as it is the final step before commercial deployment of M4 projects can take place.

There was also a common understanding when it came to the possible economic benefits that M4 projects could bring. These were in large part related to savings in O&M costs that came with combining different technologies or commercial offerings, improvements in energy yields due to the complementarity of different renewable energy sources, and increased revenues due to reductions in electricity curtailment. Even though the nature of economic benefits is clear, there is still a high degree of uncertainty regarding the absolute values that such benefits could amount to, which at the moment results in uncertain business cases. This reiterates the need for commercial scale demonstration projects, which would enable project developers to accurately quantify expenses and reduce financial uncertainty and risk.

Such projects could consist of collaborations between large project developers and technology providers, where the developers can offer their project sites for testing as well as providing much needed funding. The benefit for developers would lie in accelerating the development of technologies that will in the future be incorporated into their projects and improve their commercial offerings and revenues. Demonstrator projects could also take place as part of research and innovation government funded programs. The EU Scores project, found in the results of the project mapping, stands out as an example of privately led projects, whereas the UNITED project, mentioned in Section 2, constitutes a good example of a government funded initiative.

Finally, another common theme identified across interviews is the existence of regulatory gaps and the fact that existing policies fail to provide a clear regulatory framework for M4 projects. Current MSP regulations tend to separate marine areas for different uses and do not contemplate the coexistence of different marine based industries in a single space, which creates significant uncertainty for M4 project developers. Consequently, the lack of an enabling regulatory environment is cited as the main barrier M4 projects face nowadays. The reason for the existence of such regulatory gaps could lie in the fact that M4 solutions are a new development in the field of marine-based activities, as evidenced by the early-stage state of most projects. For this reason, the formulation of specific policies and regulations could face some uncertainties of its own, as there is still no definitive idea of how the sector will develop.

6.3 Case study

The technoeconomic assessment of hydrogen production from dedicated offshore wind energy established a comparison of different hydrogen production strategies based on the levelized cost of hydrogen (LCOH) The location chosen for this analysis was that of the Campion Wind project off the coast of Scotland, where a 2 GW wind farm is expected to be commissioned in 2028.

The results show that for a range of wind farm sizes between 100 MW and 2 GW, producing hydrogen offshore in a centralized platform and transmitting it to shore via a hydrogen pipeline was the strategy that yielded the lowest LCOH over a 30-year period.

The main components that constitute the LCOH were evaluated in more detail for a wind farm size of 2 GW, since that is the expected rated capacity of the project and most importantly, because it is the wind farm size where the lowest values of LCOH are obtained for all the studied scenarios.

In terms of CAPEX, the main differences were encountered when comparing the cost of the hydrogen pipeline to the cost of the HVDC transmission cable, with the latter being 34.5% more expensive. This difference in CAPEX is also the only significant source of differences when comparing the total costs over the project lifetime, given that the differences in O&M costs and replacement of components are insignificant and all scenarios share the same electricity costs, which were evaluated as a separate cost component. The electricity costs, in turn, represent by far the largest share of the cost and therefore exert the most influence on the LCOH, as evidenced by the sensitivity analysis, where a 50% increase in LCOE would result in a 50% increase in LCOH. This perfectly proportional relationship can be explained by the fact that this is a simplified model, where the assumption was made that the hydrogen production facilities would bear the cost of all the electricity produced by the wind farm, which might not be the case under different circumstances.

This sensitivity to LCOE suggests that in order to establish a business case for this type of project, it will be critical to accurately estimate this factor. In the analysis performed here, the value of LCOE was assumed as 67.29 €/MWh, as it is the global average for offshore wind energy projects in 2022. This average value is constituted by bottom-fixed offshore wind energy projects since, in 2023, floating offshore wind is just entering its commercialization phase. Therefore, an assumption was made that between the present day and the project's commissioning date of 2028, the LCOE of floating offshore wind electricity will reach a similar value to what bottom-fixed projects have today.

However, if one were to use a current value for the LCOE of a floating project, the strike price awarded to the TwinHub floating offshore wind project in the 4th round of the contracts for difference scheme in the UK would provide an approximate measure [50]. At around 100 €/MWh, this would represent a 48% increase in the cost of electricity, which would bring the LCOH close to 9 €/kg of hydrogen. This means that the values obtained here can provide a reasonable range for the final values of LCOH, but should not be taken as an absolute benchmark, as the LCOE can vary significantly from project to project, and it is uncertain what the LCOE will be in the future, especially for new technologies such as floating offshore wind.

There are additional uncertainties which can affect the calculated values of LCOH, and these are related to the assumed cost of the system's components. The first one of these is the fact that the investment cost of some components was calculated based on set values of specific cost per capacity, resulting in a linear increase when increasing the wind farm size. This does not take into account the possible effects on economies of scale on the cost of components, where the cost per capacity may be lower as component size increases. This effect was not incorporated into the model because no information could be found regarding the effect of scale on the cost of components such as electrolysers, hydrogen pipelines and hydrogen compressors. As more large-scale hydrogen production projects are commissioned in the future, more precise data could be obtained, and the effect of scale could be considered in analyses such as the one performed in this study.

Another uncertainty that is worth mentioning is related to the costs and losses of hydrogen pipelines. These values were taken from different peer-reviewed studies; however, they are largely based on natural gas pipelines, with assumptions made regarding the increased losses due to the size of the hydrogen molecules and the increase in material costs that would be incurred when building dedicated hydrogen pipelines. It will be possible to estimate these costs more accurately once dedicated hydrogen pipelines are more widespread, as so far, they are limited to refineries and chemical plants [51].

A final factor that was not quantified in this study and that could positively impact project viability, is that of the gradual capacity buildup that could be possible in the scenario where hydrogen is produced offshore in a decentralized manner, in each of the floating wind turbine platforms. Since each turbine would be equipped with its own electrolysis plant, the project could be built in stages and benefit from lower initial investment and start obtaining revenues before reaching full capacity. This would represent an advantage over centralized production scenarios since the latter could only start production when the full capacity is built.

7. Conclusions and future work

7.1 Conclusions

This thesis project was motivated by the quest for a more sustainable use of marine space in the provision of services for human activities. In this context, marine, multifunctional, modular and mobile solutions (M4) can contribute to this goal by integrating different uses of marine space through the combined use of a common area or infrastructure, while achieving higher resource efficiency when compared to traditional single use scenarios. In addition, economic advantages could be derived from the exploitation of synergies existent between different uses.

Consequently, in this report the current state of commercial deployment of M4 solutions is explored to acquire a deeper understanding of what the outlook for these solutions looks like in the short to medium term. The research questions answered in this project are:

> RQ 1: What is the outlook of currently planned M4 projects?
> RQ 2: What are the main barriers for the adoption of M4 solutions? How can they be addressed?
> RQ 3: What are the most promising use combinations? How can they be assessed from a technoeconomic point of view?

As seen in the results of the online review, focusing on RQ1, the number of industry-led M4 projects has consistently increased, from 1 project in 2019 to 14 in 2022 and 3 in the first three months of 2023 alone, with projects present in 4 different continents. This signals increasing attention to these solutions due to synergies that exist between different industries and the economic and operational benefits that these could bring. This conclusion was further reinforced by the answers given by stakeholders during the interview stage, which showed that momentum is indeed building in the field.

Results also show that even though there is increasing interest, commercial deployment is still at a very early stage and a considerable shift into a fully operational stage is not expected in the short term, as 28 out of 30 projects are still in the concept or pilot testing phases. For this reason, there is a strong focus across involved stakeholders on conducting large-scale demonstrations to accelerate the shift into commercial operation. The general perception among the interviewed stakeholders is that once these demonstrations are carried out, developing clear business cases and securing financing for large scale projects should not represent a major difficulty, as the economics and technological developments behind the projects are not perceived as major barriers. This perception, however, comes with a caveat, and it is the fact these expectations would only be fulfilled if the main barriers facing the development of these solutions are addressed.

The stakeholder interviews were particularly useful for addressing RQ2, as they provided the opportunity to hear from those directly involved in various projects. During this process, two main barriers were identified. The first one is found in the immaturity of the markets for some of the technologies involved in these projects. Even though most individual technologies are approaching maturity, markets and supply chains are still not mature enough to sustain widespread commercial deployment and a consistent reduction in costs. This is especially true for technologies such as wave energy, offshore floating solar and hydrogen production. This barrier can be successfully addressed by the deployment of demonstrators and the subsequent deployment of commercial projects, where capacity can be added in stages. However, such progress is not expected to be achieved immediately, with some initial demonstrators projected to conclude in 2025.

The second and most important barrier that was identified was the regulatory gaps and the overall lack of an enabling regulatory environment. It was pointed out that the combined use of marine space to provide different commercial offerings is not currently contemplated in existing regulations, and even though certain policies mention that the benefits of this should be considered when developing MSP frameworks, there are no measures that specifically incentivize it.

To address this barrier, overarching guidelines and incentives should be put in place in order to provide a stable environment for these projects to develop. Initial progress has been made in this direction and the case of the "area passports" in the Netherlands, where the areas between turbines in an offshore wind farm are assigned to different uses, seem to be a step in the right direction. However, if the interactions between the different uses are not evaluated before designating these spaces, there is the risk that both the allocation and the choice of technologies could be done arbitrarily, which would compromise the benefits that stakeholders can obtain. For this reason, developments such as this one should be closely studied in order to gather lessons for the future development of common regulatory and technical guidelines.

Regarding RQ3, the online review showed that the combination of offshore wind energy and hydrogen production represents a considerable majority of currently ongoing projects, followed by the combination of different RES and by the combination of offshore wind energy and aquaculture. Then, the stakeholder interviews provided insight into why these combinations were the most promising. In the case of the combination of different RES, the complementarity in production profiles as well as savings in O&M costs were the major factors. The access to better nutrients and improvement of environmental conditions neat the wind farm were the main advantages in the case the combination of offshore wind energy and aquaculture. Finally, hydrogen production was highly present due to hydrogen's role as an energy carrier, which could improve revenues through its use to store excess energy from RES, or to be sold for use in hard to abate sectors.

To further assess the benefits of producing hydrogen offshore with renewable electricity from OWFs, a technoeconomic analysis was performed in which the LCOH of different hydrogen production strategies were compared for a range of wind farm sizes. It was concluded that, at the moment, producing hydrogen in a centralized offshore platform and transmitting it to land via a hydrogen pipeline should be the preferred strategy, reaching an LCOH of 5.9 €/kg. The results of this analysis also show that the cost of producing hydrogen through electrolysis is highly dependent on the LCOE, indicating that achieving reductions of this total cost component will be the most impactful measure to achieve competitive hydrogen costs.

7.2 Future work

Future studies should aim to provide further detail into the areas explored in this project by extending the boundaries of the three executed work streams. In the case of the online review, efforts should be directed towards finding projects that focus on small scale applications, in order to determine if the potential of M4s to deliver effective solutions in isolated regions is currently being exploited. For this purpose, a deviation from the methodology that was followed in this study should be designed to bypass the overwhelming quantity of search results that relate to large and utility scale projects. If proven ineffective, it could be worth considering a deviation from the systematic online review process altogether and consider approaching local actors in different regions in an effort to determine if such projects are indeed taking place.

Future work should also be directed into pinpointing the exact regulatory gaps that exist for each of the explored M4 configurations, and exploring what kind of public policy instruments should be developed to incentivize the successful development of multiple use of marine space and its integration into marine spatial planning (MSP) frameworks. Different starting points could be suggested for these type of studies, such as an analysis of the EU MSP directive [52], an evaluation of the processes that led to the formulation of the "area passports" practice in The Netherlands, and a close monitoring of regulatory developments elsewhere, such as the ones in Portugal, Ireland and Spain cited in the interviews.

Finally, future work could focus on extending the case study that was performed in this project. An immediate extension could consist of the development of a cashflow analysis of the three explored scenarios, which would allow an evaluation of the benefits that could be obtained by the modular build-up of infrastructure, such as what is proposed in the decentralized offshore hydrogen production scenario. In this way, the different revenues obtained over time could be considered, and indicators such as NPV (net present value) and ROI (return on investment) could be used to determine the financial performance of each scenario.

Furthermore, as pointed out in the stakeholder interviews, it is necessary to gain an understanding of how the end-to-end costs of a hydrogen-based energy infrastructure would compare to those of an electricity based one. For this reason, studies that evaluate these costs from the initial stages of project development to the final use cases of the delivered energy should be developed. In addition, location-specific studies that perform these evaluations should be conducted to not only determine which alternative would have the lower cost, but to also take into account the already existing infrastructure, decarbonization needs and future energy demand of a region. Such studies would allow to determine which system configuration is the most adequate on a case-by-case basis and ensure that much needed investments are targeted effectively.

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Appendix A – List of projects resulting from the online review

Name	Region	Specific location	M4 type	Type of structure	Combination of technologies	Energy source	M-degree	Stage	Publication year
EU Scores Project	Europe	Multiple	Co-located	Static/Floating	Wind, Solar / Wind, Wave	Multiple	2	Concept	2022
Floating Power Plant	Europe	Denmark/Canary Islands	Hybrid/Combined	Floating	Wind Energy, Wave Energy	Wind,Wave	3	Pilot	2021
WavePiston	Europe	Denmark/Canary Islands	Hybrid/Combined	Floating	Wave Energy, Desalination	Wave	3	Pilot	2022
AquaWind	Europe	Spain	Hybrid/Combined	Static	Wind Energy, Aquaculture	Wind	3	Pilot	2022
Dalian OWF	Asia	China	Co-located	Static	Wind Energy, Aquaculture	Wind	2	Pilot	2021
CGN New Energy	Asia	China	Co-located	Static	Wind Energy, Aquaculture	Wind	2	Concept	2021
CTG	Asia	China	Co-located	Static	Wind Energy, Aquaculture	Wind	2	Concept	2019
FWD Synlift	Europe	Germany	Hybrid/Combined	Static	Wind Energy, Desalination	Wind	2	Concept	2021
Rampion Wind Farm	Europe	UK	Co-located	Static	Wind Energy, Tourism	Wind	2	Operational	2023
Middelgrunden Tours	Europe	Denmark	Co-located	Static	Wind Energy, Tourism	Wind	2	Operational	2020
Vattenfall	Europe	UK	Co-located	Static	Wind Energy, Hydrogen	Wind	2	Concept	2022
PosHydon	Europe	Netherlands	Hybrid/Combined	Static	Wind Energy, Gas, Hydrogen	Wind	2	Pilot	2021
Lhyfe	Europe	France	Co-located	Static/Floating	Wind Energy, Hydrogen	Wind	2	Pilot	2022
RWE Aquaventus	Europe	Germany	Co-located	Static/Floating	Wind Energy, Hydrogen	Wind	2	Concept	2020
RWE Floating Solar 1	Europe	Belgium	Co-located	Floating	Wind Energy, Floating Solar	Wind, Solar	3	Pilot	2022
RWE Floating Solar 2	Europe	Netherlands	Co-located	Floating	Wind Energy, Floating Solar	Wind, Solar	3	Concept	2022
Orsted Taiwan	Asia	Taiwan	Hybrid/Combined	Static	Wind Energy, Nature conservation	Wind	2	Pilot	2022
Orsted Denmark	Europe	Denmark	Hybrid/Combined	Static	Wind Energy, Nature conservation	Wind	2	Pilot	2022
TNC	North America	United States	Hybrid/Combined	Static	Wind Energy, Nature conservation	Wind	2	Concept	2021
Amazon Seaweed	Europe	UK	Co-located	Static	Wind Energy, Aquaculture	Wind	2	Concept	2023
SPIC Floating Solar	Asia	China	Co-located	Static/Floating	Wind Energy, Floating Solar	Wind, Solar	3	Pilot	2022
Musica	Europe	Greece	Hybrid/Combined	Floating	Wind Energy, Solar, Wave, Desalination, Grid services	Wind, Solar, Wave	4	Concept	2021
Orsted Power to X Denmark	Europe	Denmark	Co-located	Static	Wind Energy, Hydrogen	Wind	2	Concept	2022
Oyster consortium FCHJU	Europe	UK	Hybrid/Combined	Static/Floating	Wind Energy, Hydrogen	Wind	2	Concept	2021
Uruguay offshore green H2	South America	Uruguay	Co-located	Static	Wind Energy, Hydrogen	Wind	2	Concept	2021
Deep purple pilot	Europe	Norway	Co-located	Static	Wind Energy, Hydrogen	Wind	2	Pilot	2023
HyMed Floating H2	Europe	Italy	Co-located	Static	Wind Energy, Hydrogen	Wind	3	Concept	2022
Salamander ERM Dolphyn	Europe	Scotland	Hybrid/Combined	Floating	Wind Energy, Hydrogen	Wind	3	Concept	2022
AmpHytrite	Europe	Netherlands	Co-located	Static	Wind Energy, Hydrogen	Wind	2	Pilot	2022

Appendix B – Description of projects

- **EU Scores Project:** EU Project aimed at testing prototypes and further commercial deployment with participation of large developers such as RWE.
- **Floating Power Plant:** Floating wind platform with WEC at the bottom (Secured PLOCAN test site, no construction yet).
- **WavePiston:** WEC coupled with desalination technology (testing in PLOCAN)
- **AquaWind:** Floating wind platform with plans to attach aquaculture structure at the bottom of the platform. Currently testing in PLOCAN.
- **Dalian OWF:** Aquaculture cage co-located with bottom-fixed OW. Pilot ongoing with fish farm deployed.
- **CGN New Energy:** Aquaculture co-located with bottom-fixed OW. No further information about deployment.
- **CTG:** Aquaculture co-located with bottom-fixed OW. No further information about deployment.
- **FWD Synlift:** Bottom-fixed OW with large desalination plant at the bottom. No documented tests.
- **Rampion Wind Farm:** Offshore wind farm tours, adapted by local diver.
- **Middelgrunden Tours:** Offshore wind farm tours, part of UNITED project.
- **Vattenfall:** Offshore wind farm and electrolyzer pilot project.
- **PosHydon:** Repurposing of O&G platform to produce hydrogen from offshore wind.
- **Lhyfe:** Offshore electrolysis, currently testing quayside.
- **RWE Aquaventus:** Offshore electrolysis, concept.
- **RWE Floating Solar 1:** Pilot project between RWE & SolarDuck for co-locating offshore wind and floating solar in Merganser.
- **RWE Floating Solar 2:** Succesful bid for HKW Wind farm including floating solar.
- **Orsted Taiwan:** Artificial reef in Greater Changhua OWF, ReCoral project coral seeding.
- **Orsted Denmark:** Artificial reef in Anholt OWF for Atlantic Cod.
- **TNC:** Project to incorporate artificial reefs in OWF, has list of artificial reef manufacturers (Turbine Reefs).
- **Amazon Seaweed:** First commercial scale seaweed farm funded by Amazon to be built soon, in collaboration with North Sea Farmers.
- **SPIC Floating Solar:** Project testing 0.5MW Floating Solar from OceanSun.
- **Musica:** Development of multi-use platform for Greek island of Oinousses.
- **Orsted Power to X Denmark:** Plans for large scale Power-to-X facility in Denmark.
- **Oyster consortium FCHJU:** Consortium between Orsted, Siemens Gamesa, ITM Power to build combined turbine and electrolyzer.
- **Uruguay offshore green H2:** Government plan to build offshore hydrogen production facility from OW.
- **Deep purple pilot:**
- **HyMed Floating H2:** Plan to build large OW+H2 facility in Italian waters between Aquaterra Energy and SeaWind Ocean technology.
- **Salamander ERM Dolphyn:** Testing of ERM Dolphyn technlogoy on Salamander floating project, Principle Power awarded FEED.

- **AmpHytrite:** Project to test feasibility and build offshore H2 production unit.

Appendix C – Interview protocol

Interview script

Date and Location:

Interviewee:

Color code:

Text in red is not meant to be seen by or mentioned to interviewee and are there only as guidance for the interviewer as examples or to identify themes in the answer.

Text in light blue is to be read out as is and it is meant for the main questions that need to be asked during the interview.

Text in dark blue is used for optional or follow-up questions that can be asked depending on the specific case.

Introductory statement

As mentioned in our email, we are conducting a project with the aim of mapping ocean multi-use projects around the world and understanding their current state, main advantages and challenges. In that sense, this interview will be about multi-use of marine space, in the context of your project (name project here, if interviewing regulatory body or agency just refer to MU). The interview is made up of 5 parts and should take between 30-45 minutes.

Multi-use refers to the joint use of marine space by two or more users, which takes place in the same area and at the same time and, depending on the case, could share core or peripheral services and infrastructure. With that in mind, let's get started with the questions about your project (their specific case).

1. Introductory questions

1.1. Are you familiar with the concept of MU? Is it a present consideration in your organization?

1.1.1. Could you tell us more about the project in your own words?

2. Technical aspects of multi-use case

2.1. Do you think technological/technical developments could enable your specific multi-use case?

2.2. Do you think the combination of different technologies/uses could lead to shared technological developments?

3. Project Planning & Strategy

3.1. Have you identified any particular stakeholder that plays a fundamental role in enabling your specific multi-use case?

3.2. Have you established any strategic partnerships for present and future multi-use projects?

3.3. Where do you see the most potential for MU applications in terms of combinations of uses and application in different regions of the world?

3.4. Are you aware of any other multi-use projects that we should know about?

4. Economic/Funding considerations

4.1. Are there any economic advantages from combining X and X? What do you think are main ones from the point of view of both participants? (New sources of revenue, cost reduction, cost sharing, access to funding)

4.2. What level of uncertainty is involved when quantifying these benefits and developing an MU business case?

4.3. What do you think would be the main economic disadvantages and how could they be addressed?

4.4. What kind of business model/interaction do you see as offering the most potential in a multi-use scenario?

5. Policy & Regulation

5.1. What aspects do you think should be targeted by authorities to make the environment more favourable for multi-use projects?

(Support, policies, incentives, conflict prevention)

5.2. What are the necessary licenses or permits for your type of MU? What is the procedure to obtain them?

5.3. Is there any overlap or conflict between regulations?

6. Barriers

6.1. What do you think are the main barriers MU projects are facing?
(Interconnection issues, administrative, O&M, legal & liability, regulation, etc)

6.2. (AGENCY) What are the main barriers for the application of multi-use areas?

6.3. What are some actions that could be taken to address these barriers by your organization and other involved stakeholders?

Appendix D – Case Study scenarios