Marine multi-use in practice

Comparing offshore wind and hydrogen production applications

SEI brief
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Key messages

- **Marine multi-use projects are generally in early stages of development, with a strong focus on demonstration to prove scalability of technology combinations, clarify potential business cases and secure adequate funding.**
- **A systematic review of online information on marine, multifunctional, mobile, and modular (M4) projects and insights from semi-structured interviews showed that combinations of offshore wind energy and hydrogen production are highly promising.**
- **Centralized offshore hydrogen production from wind energy with pipeline transmission to the shore is estimated to have a levelized cost of hydrogen (LCOH) of 5.8 EUR/kg for a 2 GW wind farm, slightly lower than previous estimates.**
- **Including multi-use in non-price criteria for offshore wind project bids, filling regulatory gaps, and simplifying permitting procedures will be key to commercialization.**

1. The future of marine multi-use: M4 (marine, multifunctional, mobile, and modular)

Driven by resource and space availability, a variety of economic sectors have begun activities offshore. This continuing trend creates new conditions for environmental impacts, logistics, operations, regulations, and financing. Furthermore, conflicts between different actors may emerge as the competition for ocean space increases (European MSP Platform, 2019).

In response to the need for more sustainable and efficient use of marine space, concepts such as ocean multi-use and multi-purpose platforms have emerged as promising solutions. Both solutions have the aim of sustainably delivering critical services while achieving resource efficiency and economic advantages through the integration of different marine uses by sharing space, infrastructure or, in some cases, both (Schupp et al., 2019). For example, offshore wind farms could share the space with other renewables such as floating solar or wave energy, as well as other activities such as aquaculture, hydrogen or electrofuel[1] production, and nature conservation initiatives. Depending on the technologies combined, different infrastructure configurations and components might be needed; for example, equipment may be needed for transmitting electricity from multi-use platforms to the shore, for converting one form of energy to another, or for growing algae.

IMAGE (ABOVE): Wind turbines
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[1] An electrofuel is a synthetic, carbon-based fuel obtained from carbon dioxide and water in a process that uses renewable electricity as the main source of energy (Ridjan et al., 2016).

Marine multifunctional solutions have usually been fixed in terms of position and capacity, making it difficult to adapt to shifting conditions that could result from changes in demand, demographics or regulatory environments. This could be counteracted by incorporating modularity and mobility into the design, improving the outlook for widespread adoption. For this reason, the M4 framework – which classifies these solutions into marine, multifunctional, modular and mobile – has been proposed to include these two additional dimensions. A previous systematic literature review indicated a wide variety of technology and setup combinations where offshore wind combined with hydrogen production dominates, but mobility and modularity have not been explored as much compared to classic static multifunctionality (Xylia et al., 2023).

In this brief we focus on industry-led M4 projects in order to understand the outlook for up-to-date and currently planned projects, including emerging opportunities and barriers for upscaling. With a systematic review and project classification, it is possible to get a picture of which solutions and multi-use combinations are the most promising. We present the results of a systematic review of available online information on M4 projects, combined with insights from semi-structured interviews with stakeholders active in the M4 field. We complement this with specific results from a case study assessing the combination of offshore wind energy and hydrogen production, one of the M4 alternatives with most potential for future expansion.

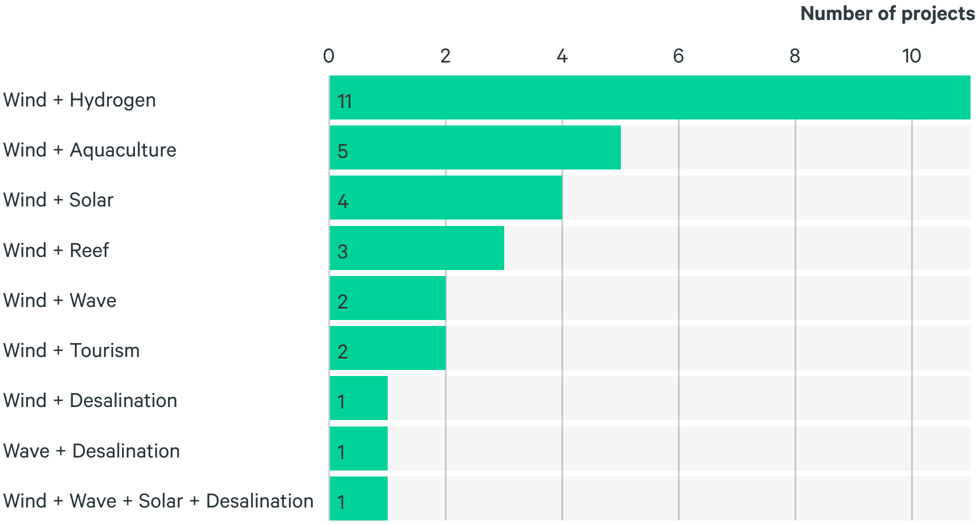
In total, 30 projects around the world were identified and classified, showing a continuous increase in the number of projects since 2019, with the majority of projects (75% of those analyzed) located in Europe. This may be due to several EU-funded projects exploring such solutions. Offshore wind projects are also rapidly expanding in Europe, and these might be combined with other technologies in multi-use applications. Projects are largely focused on the combination of offshore wind energy with other solutions such as wave energy, offshore floating solar energy, aquaculture and hydrogen production. The combination of wind and hydrogen production is by far the most common, with a total of 11 projects (Figure 1). M4 projects are at an early stage of development, with 28 projects at the concept or pilot testing phase, and widespread commercial deployment is not to be expected in the short term. A description of some of the reviewed projects can be found in Table 1. As previously seen in Xylia et al. (2023), there is little information about projects in other parts of the world beyond Europe.

Table 1: Selected M4 projects by location, technologies, and implementation stage.

Name	Location	Combination of technologies	Description	Stage
EU Scores Project	Belgium/Portugal	Wind, Solar/Wind, Wave	EU project aimed at testing prototypes and further commercial deployment	Concept
AquaWind	Spain	Wind Energy, Aquaculture	Floating wind platform with plans to attach aquaculture cage to the base of the platform	Pilot
Dalian Wind Farm	China	Wind Energy, Aquaculture	Aquaculture cage co-located with bottom-fixed offshore wind farm	Pilot
Middelgrunden Tours	Denmark	Wind Energy, Tourism	Offshore wind farm tours, part of UNITED project	Operational
PosHydon	Netherlands	Wind Energy, Gas, Hydrogen	Repurposing of oil and gas extraction platform to produce hydrogen from offshore wind	Pilot
Orsted ReCoral	Taiwan	Wind Energy, Nature conservation	Artificial reef in Greater Changhua offshore wind farm	Pilot
North Sea Farm 1	Netherlands	Wind Energy, Aquaculture	First commercial-scale seaweed farm in offshore wind farm	Concept
Orsted Power-to-X	Denmark	Wind Energy, Hydrogen	Plans for large-scale Power-to-X facility in Denmark	Concept
ERM Dolphyn	Scotland	Wind Energy, Hydrogen	Floating wind platform with in situ electrolysis plant	Concept

Implementation stages were classified according to the following definition: **Concept**: Planning and design phase with no physical infrastructure deployed. **Pilot**: Testing functional prototypes or exploring mature technology combinations at sea. **Operation**: Projects in full commercial operation.

Figure 1: Multi-use combinations found in the reviewed projects.



2. The economics of offshore hydrogen production from wind

Aside from being the most frequently occurring among the reviewed projects, the combination of offshore wind energy and hydrogen production was also deemed promising in interviews with industry representatives and a researcher working with renewable energy solutions and marine multi-use combinations. This is due to hydrogen's role as an energy carrier, which could improve revenues through excess energy storage or selling to hard-to-abate sectors.

We thus did a technoeconomic analysis to evaluate different offshore hydrogen production strategies based on their levelized cost of hydrogen (LCOH), across a range of different wind farm sizes. LCOH is an indicator that shows the cost of producing 1 kg of hydrogen, including the cost of the investment and the operation of the production assets throughout the lifetime of the project.

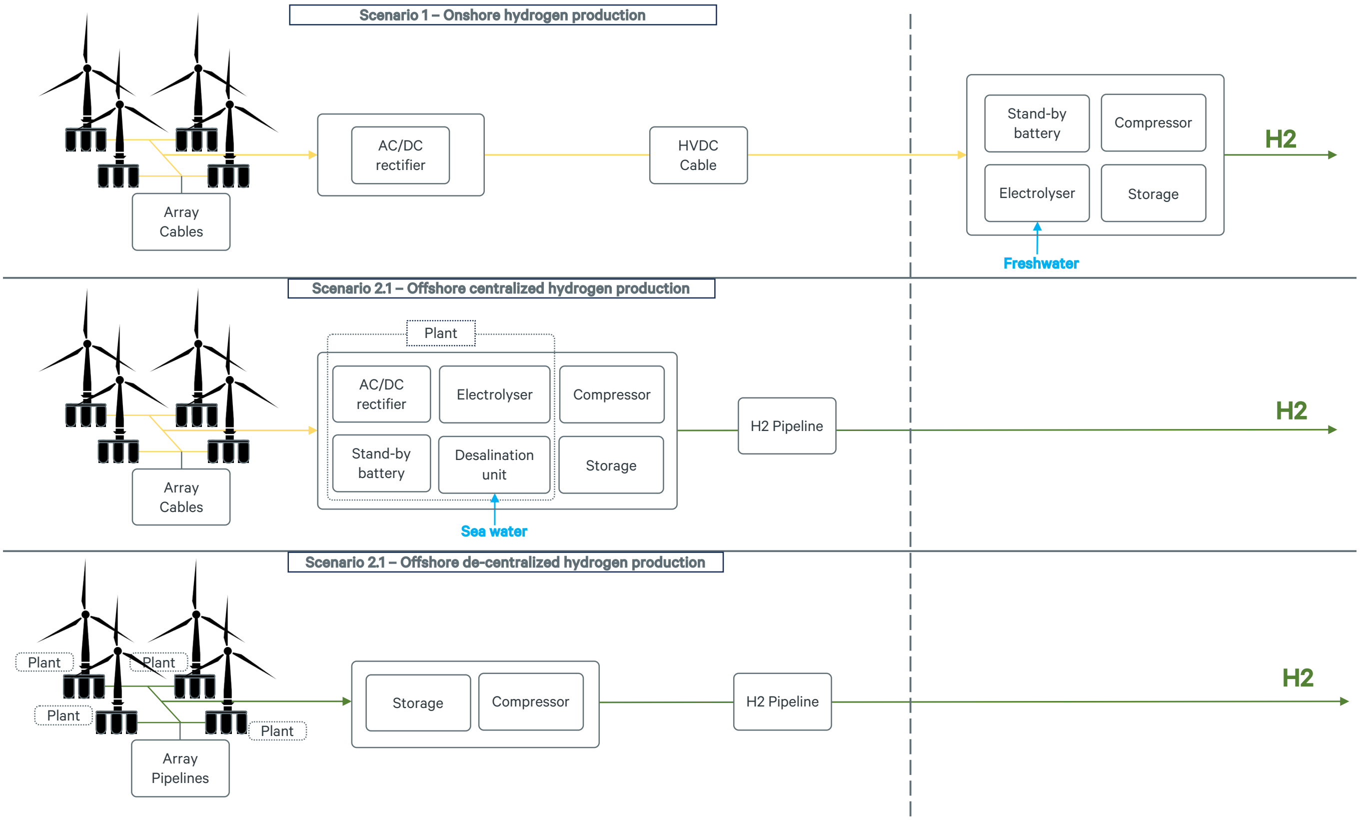
The LCOH is calculated as follows:

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

where T is the project lifetime, r is the discount rate, CAPEX is the capital expenditure, OPEX is the operational expenditure and M_{H2} is the annual amount of hydrogen produced, in kg.

The location of a future floating offshore wind farm off the coast of Scotland was chosen for the analysis, and three scenarios were developed to compare centralized and decentralized as well as offshore and onshore production. In centralized production, the energy from the wind farm would be used to produce hydrogen in a single location, whereas in the decentralized case, hydrogen would be produced in every individual wind turbine platform with a smaller electrolyser and an array of pipelines leading to the central one. A fully assembled decentralized solution such as this one has not been tested today, but there are several ongoing tests for offshore electrolysis. The three scenarios are illustrated in Figure 2.

Figure 2: Hydrogen production scenarios: onshore vs offshore hydrogen production from centralized and decentralized facilities.

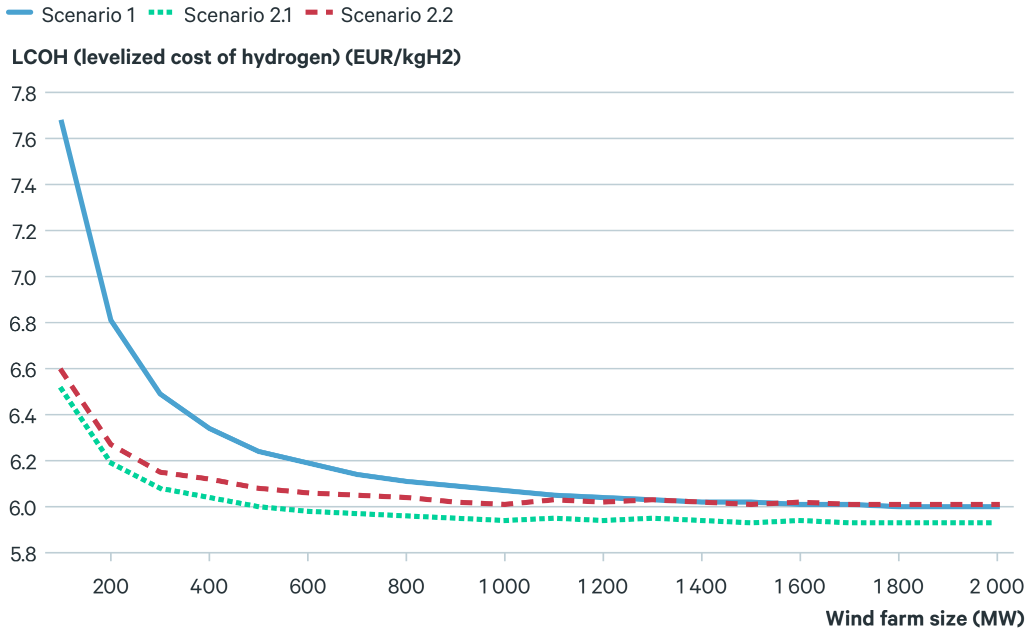


Centralized hydrogen production offshore, with subsequent transmission to land via pipeline, was deemed as the most beneficial alternative since it led to the lowest LCOH across the entire range of wind farm sizes, reaching a lowest value of 5.9 EUR/kg for a wind farm size of 2 GW (see Figure 3). This closely matches previous estimations with similar methodology at 6.3 EUR/kg by 2025 (BloombergNEF, 2021). The data used for the analysis can be found in the Appendix.

The LCOH value starts to visibly converge after around 600 to 800 MW for the wind farm size, meaning that smaller installed capacities will show much larger differences to LCOH in the three scenarios. The scale of the project therefore decreases both the LCOH as well as the differences between scenarios.

The LCOH can be sensitive to different factors, such as the levelized cost of electricity (LCOE), distance from the wind farm to shore, and the cost of adapting individual offshore wind turbine platforms to accommodate an electrolysis plant in the case of decentralized offshore production. Our analysis shows that LCOH showed the highest sensitivity to the assumed LCOE, primarily because electricity represents by far the largest share of costs throughout the 30-year lifetime of the project.

Figure 3: Levelized cost of hydrogen for all scenarios and wind farm sizes.



3. Stakeholder insights

Interviews with five representatives from companies working in this field showed that there are no major perceived technical or economic barriers, and that there is a strong focus on conducting demonstrations. These would prove how different technologies can successfully work together and yield valuable data in terms of operations and project economics. This would in turn enable developers to refine the business cases and eventually secure financing for commercial scale projects. It is important to note, however, that markets, supply chains and in some cases technologies themselves are still immature, so the results of such demonstrations will be critical for the adoption of these solutions.

On the other hand, the lack of an enabling regulatory environment and regulatory gaps were cited as a major barrier. Existing regulations do not consider the combined use of marine space for different commercial uses and lack specific incentives to developers. For example, according to one interviewee, most countries do not include multi-use in their Marine Spatial Plans (MSPs), and some of them do not even have an MSP in place. To address this, overarching guidelines and incentives are needed to create a stable environment for project implementation. There are interesting developments in this direction where the spaces between turbines in offshore wind farms are assigned to different uses, such as in the case of the “area passports” recently implemented in the Borssele offshore wind farm in The Netherlands (Nordzeeloket, 2023). However, if interactions between uses are not evaluated beforehand, there is a risk of arbitrary allocation and technology choices, compromising stakeholder benefits.

4. Conclusions and policy recommendations

M4 (marine, multifunctional, mobile, and modular) solutions are being increasingly explored by industry actors due to their potential to yield economic benefits from more efficient operations and use of marine space leading to increased revenues and improved ecosystem services, comparing with single use practices. Such practices have so far been hindered by regulatory gaps for multi-use and lack of information. For this reason, there is a strong focus among stakeholders to conduct demonstrations before starting commercial scale deployment.

Combining intermittent energy production with storage and transmission opportunities such as the ones from hydrogen or batteries can increase flexibility, resilience, and even revenue streams for implemented projects. Our case study shows that, among the studied hydrogen production strategies, centralized offshore production presents the lowest levelized cost and is therefore the preferred strategy at larger deployment scales. Local considerations, especially on the demand side, will still be crucial in determining the production strategy on a case-by-case basis. For example, lack of hydrogen transport infrastructure once hydrogen has reached the shore can be a major barrier, and high upfront costs for such investments can also be a major challenge for project developers.

Implementing all aspects of the M4 concept, including modularity, was not considered in detail in the scenarios due to the fact that LCOH does not include project revenues, but it is a straightforward indicator of project costs that easily allows for comparisons between different scenarios. However, it can be assumed that including modularity and calculating project feasibility from a net-present value and cash flow perspective would give the modular options substantial advantages, as gradually building up the platforms will secure more stable revenue flows over the lifetime of a project and assist overcoming the barrier of high upfront costs.

The development of clear frameworks that ensure simple permitting procedures and effectively manage how the space will be shared between uses will be critical. However, such frameworks will also need to ensure that local realities and priorities are considered when developing M4 projects. Additionally, many of these projects will be built at large scales and will need large capital investments. For this reason, economic incentives may be needed to accelerate their development and to ensure that key technologies reach higher technology readiness levels.

Wind energy production may be the dominating economic factor driving the implementation of these projects, but additional perspectives from a sustainability and ecosystem preservation point of view should be considered for a well-balanced project that does not disturb marine environments. For this reason, we recommend including marine multi-use within the non-price criteria that can be applied when ranking bids for offshore wind projects. As for permitting procedures, their simplification should first lie with the state, as there are usually several agencies involved in granting permits which further complicates the field for organizations interested in venturing into multi-use projects.

Marine spatial planning frameworks should incorporate tailored regulatory instruments addressing the permitting and management issues identified above, incorporating an approach centered around multi-use in the design of such frameworks.

The question remaining is how authorities together with stakeholders can implement such projects so that smaller, more vulnerable marine communities can also benefit from the advantages of multi-use. One strategy would be the development of methodologies that do account for non-economic benefits, such as impact on job creation or biodiversity preservation, when evaluating the feasibility of such projects. Public-private partnership models particularly aiming at vulnerable communities would help overcome upfront investment costs. Knowledge exchange, especially cross-regionally and internationally, would help in filling regulatory gaps with the appropriate regulations and incentives.

Further studies are nevertheless needed for identifying which types of smaller scale M4 projects could be most feasible to deliver services to remote coastal or island communities, since evidence of such projects was missing from online resources. Working language and scale of these projects might need more local approaches to be adopted.

References

André, J., Auray, S., De Wolf, D., Memmah, M.-M., & Simonnet, A. (2014). Time development of new hydrogen transmission pipeline networks for France. *International Journal of Hydrogen Energy*, *39*(20), 10323–10337. https://doi.org/10.1016/j.ijhydene.2014.04.190

BloombergNEF. (2021, June 30). *Offshore Wind-to-Hydrogen Sounds A Starting Gun*. BloombergNEF. https://about.bnef.com/blog/offshore-wind-to-hydrogen-sounds-a-starting-gun/

BloombergNEF. (2022, December 27). 2H 2022 Levelized Cost of Electricity Update. *BloombergNEF*. https://about.bnef.com/blog/2h-2022-levelized-cost-of-electricity-update/

European MSP Platform. (2019). *Addressing conflicting spatial demands in MSP: Considerations for MSP planners : final technical study.* Publications Office. https://data.europa.eu/doi/10.2826/151447

Fan, Z., Sheerazi, H., Bhardwaj, A., Corbeau, A.-S., Castañeda, A., Merz, A.-K., Woodall, D. C. M., Orozco-Sanchez, S., & Friedmann, D. J. (2022). *Hydrogen leakage: a potential risk for the hydrogen economy.*

Giampieri, A., Ling-Chin, J., & Roskilly, A. P. (2023). Techno-economic assessment of offshore wind-to-hydrogen scenarios: A UK case study. *International Journal of Hydrogen Energy*, S0360319923006316. https://doi.org/10.1016/j.ijhydene.2023.01.346

International Energy Agency. (2019). *The future of hydrogen*. https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

Nordzeeloket. (2023). *Borssele wind farm zone*. Borssele Wind Farm Zone. https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/free-passage-shared-use/borssele-wind-farm-zone/

Ridjan, I., Mathiesen, B. V., & Connolly, D. (2016). Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: A review. *Journal of Cleaner Production*, *112*, 3709–3720. https://doi.org/10.1016/j.jclepro.2015.05.117

Schupp, M. F., Bocci, M., Depellegrin, D., Kafas, A., Kyriazi, Z., Lukic, I., Schultz-Zehden, A., Krause, G., Onyango, V., & Buck, B. H. (2019). Toward a common understanding of ocean multi-use. *Frontiers in Marine Science*, *6*, 165. https://doi.org/10.3389/fmars.2019.00165

Xylia, M., Passos, M. V., Piseddu, T., & Barquet, K. (2023). Exploring multi-use platforms: A literature review of marine, multifunctional, modular, and mobile applications (M4s). *Heliyon*, e16372. https://doi.org/10.1016/j.heliyon.2023.e16372

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Appendix

Technoeconomic analysis data table

Electrolyser		(Giampieri et al., 2023)
Efficiency (%, LHV)	65	
Stack Lifetime (h)	75000	
CAPEX (EUR/kW)	467.3	
O&M (% CAPEX/y)	1.5	
Replacement (% CAPEX)	12	
Stand-by battery		(Giampieri et al., 2023)
CAPEX (EUR/kW)	40.8	
AC/DC Converter		(Giampieri et al., 2023)
Losses (%)	1.5	
Desalination Unit		(Giampieri et al., 2023)
Electricity consumption (kWh/m3)	3.5	
Lifetime (y)	30	
CAPEX (EUR/m3/d)	1244.2	
OPEX (% CAPEX/y)	2	
Freshwater (EUR/m3)	1.58	
Hydrogen Compressor		(André et al., 2014)
Lifetime (y)	10	
Efficiency (%)	88	
CAPEX (EUR/kW)	2378.5	
OPEX (% CAPEX/y)	3	
Replacement (%CAPEX)	100	
Hydrogen Storage		(Giampieri et al., 2023)
CAPEX (EUR/kg H2)	429.8	
O&M (% CAPEX)	2	
High-voltage DC Cable		(Giampieri et al., 2023)
Losses (%/100 km)	0.3	
Hydrogen Pipeline		(Fan et al., 2022)
Losses (%/100km)	0.4	
O&M (% CAPEX)	2	
Array Pipelines		(International Energy Agency, 2019)
Losses (%/100km)	0.4	
CAPEX (M€/km)	0.5	
O&M (% CAPEX)	2	
Electricity		(BloombergNEF, 2022)
LCOE (EUR/MWh)	67.29	