IDEA - IRL

INTEGRATED DESIGN OF FLOATING WIND ARRAYS IRELAND

Floating Offshore Wind Innovations Analytical Hierarchy Process Report (Part 2)

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Executive Summary

Work package four (WP4) of the Integrated design of floating wind arrays – Ireland (IDEA-IRL) project is focused on analysing the needs of the industry and the views and requirements of floating offshore wind stakeholders. The work is split into two primary parts – marine spatial planning (MSP) and policy interviews, and innovation management.

This report is a deliverable prepared for the IDEA-IRL project as part of the innovation management research carried out by WP4. It is a continuation of a previous deliverable, the *Floating Offshore Wind Innovations Analytical Hierarchy Process Report* [1], the first deliverable of WP4. The first deliverable described the methodology for creating a ranking of floating wind innovations using the analytical hierarchy process (AHP). This deliverable presents the results and the ranking.

The innovation management section of WP4 aims to survey industry stakeholders about what innovations they think would be most beneficial for the industry in terms of their environmental, economic, and social benefits. To find this out, a list of innovations was adapted from the Offshore Wind Innovation Hub's floating wind technology roadmap and an online survey was created. In this survey, respondents were asked to compare pairs of innovations to determine which one they think would enable more positive economic, social, and environmental impacts of floating wind.

The survey was live between the 30th of November 2023 and the 6th of February 2024. It was answered anonymously by ten respondents, eight of which work as research and development (R&D) engineers in the offshore renewables industry.

Upon analysing the results, three innovative areas emerged as the highest priority ones:

- Optimised O&M and major component service strategies and condition monitoring for floating conditions.
- Port infrastructure improvement to enable substructure manufacturing.
- Manufacturing of current and disruptive floating concepts.

These results suggest the overall opinion of the respondents is that R&D efforts should be focus on improving the way the machines are built and operated, with improving the design of current wind turbine and floater technology not seen to be of as high of a priority for the industry at this time. This could be seen as a signal that the floating wind industry is close to making the leap to commercial scale projects.

Similar results were obtained during a workshop carried out at the IDEA/IEA Task 49 meeting in Trondheim in January 2024. At this workshop, participants were asked to rank the same innovation areas as were used for the survey based on how much they think the industry would benefit from them. The same top three innovative areas were identified by the survey and by the workshop.

During the MSP interviews for WP4, participants were asked which research areas were the most important for the advancement of floating wind in their country. They quoted cost-reduction, an improved approach to environmental impact assessments (EIA), improvements in O&M methodology, installation, manufacturing and decommissioning processes, moorings and cables and

value creation within the supply chain as the main research focus areas. The answers differed based on the domestic country of each interviewee and the requirements of that market, but the general tone was in agreement with the findings of both the survey and the Trondheim workshop.

Based on these findings, the following feedback is made to the other IDEA-IRL work packages:

- There is a need for improved O&M strategies. A lot of failure in the floating wind environment is driven by operational fatigue. Maintenance strategies and operations for current floating offshore wind farms should be investigated in more detail, including the recently announced maintenance on the Hywind Scotland project.

- Port infrastructure must be improved. IDEA-IRL should focus on providing concrete requirements for what this infrastructure should look like – cranage requirements, berth size and depth requirements, marshalling space requirements and so on. This should be developed for installation, manufacturing, O&M, and decommissioning scenarios. Research on this topic has already been completed as part of WP1, which can be expanded on. Government intervention may be considered for required port infrastructure upgrades, as well as other sources of funding, such as Connecting Europe Facility (CEF) funding. Progress on this is already being made for example in the Port of Amsterdam. While current National Ports Policy in Ireland is that ports should be self-funding, this may change in the future, with responses to the recent consultation on the National Ports policy currently under review by Government.

- Advancing the mooring and cabling technology is important. The reference designs for moorings produced by WP2 should include modern mooring considerations like quick connectors and load reduction devices. As part of this, recommendations on the mooring spread and array layout should be made by WP2.

To continue the efforts described here, key enabling technologies and innovations in line with those priority areas described above will be identified for consideration by the other IDEA-IRL WPs and in future reference wind farm designs from WP2.

Further work in WP4 should consider supply chain integration in further detail and investigate what is being done in other countries to promote the growth of the domestic supply chain. This is particularly timely with the recent release of Ireland's offshore wind industrialisation strategy – Powering Prosperity [2].

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Acronyms

Acronym	Meaning
AHP	Analytical hierarchy process
ANOVA	Analysis of variance
CAPEX	Capital Expenditure
CEF	Connecting Europe Facility
CI	Consistency index
CR	Consistency ratio
EEZ	Exclusive economic zone
EIA	Environmental impact assessment
FLOW	Floating offshore wind
GDG	Gavin and Doherty Geosolutions
HAWT	Horizontal axis wind turbine
HSD	Honestly significant difference
HVDC	High-Voltage Direct Current
IDEA-IRL	Integrated design of floating wind arrays - Ireland
IEA	International Energy Agency
LCoE	Levelized cost of energy
MCR	Major Component Repairs, Replacement or Exchange
MSP	Marine spatial planning
O&M	Operations and maintenance
OEM	Original equipment manufacturer
OPEX	Operational Expenditure
ORE	Offshore renewable energy
OREC	Offshore renewable energy catapult
OW	Offshore wind
OWIH	Offshore wind innovation hub
R&D	Research and development
RI	Random index
SCBA	Social cost benefit analysis
SEAI	Sustainable Energy Authority of Ireland
TCP	Technology Collaboration Programme
TRL	Technology readiness level
UCC	University College Cork
WEI	Wind Energy Ireland
WP	Work package, followed by number
WTG	Wind turbine generator

1 Introduction

This report has been prepared by the Integrated design of floating wind arrays - Ireland project as the second part of the second deliverable for WP4 of the project (WP4 D2B). The IDEA-IRL project is being carried out in collaboration by project partners University College Cork (UCC), Wind Energy Ireland (WEI), and Gavin and Doherty Geosolutions (GDG).

The project's goal is to accelerate the sustainable development of Floating Offshore Wind (FLOW) both domestically and internationally. This will be achieved by building upon key background knowledge and by coordinating and leveraging the international FLOW research effort under the framework of the supported IEA Technology Collaboration Programme (TCP) Wind Task 49.

WP4 of the IDEA-IRL project is dedicated to Stakeholder Integration and Research Requirement Classification. It will be used to ensure the project has the required information from stakeholders, providing key input to the other more technically focused WPs (1-3) within the IDEA-IRL project.

This report follows the first deliverable of WP4 of the project, and presents results of the innovation ranking process outlined in the first deliverable – *Floating Offshore Wind Innovations Analytical Hierarchy Process Report*, which introduced the methodology and motivation of the work [1].

The report presents the findings of a survey in which IEA Wind Task 49 members were asked to rank FLOW innovation areas based on their perceived potential positive impact on the FLOW industry in terms of social, environmental, and economic benefits. In other words – if this innovation is put onto the market successfully, how much will it positively impact the industry and the social, environmental, and economic benefits which are attached to it, compared to if that innovation was not introduced. These potential impacts are varied. A list of example impacts is presented in Table 1.1

Table 1.1 – Examples of potential positive social, environmental, and economic impacts unlocked by new FLOW innovations.

Social impacts	Environmental impacts	Economic impacts
Increased local employment and job creation	Access to low-carbon energy	Lower running costs compared to thermal energy plants
Higher industrialization of the area	Enabling low-carbon fossil fuel alternatives (green hydrogen)	Lower installation costs compared existing methods
Improved local infrastructure	Lower air and water pollution risks compared to thermal plants	Possibility to generate in deeper water - new opportunities
Community investment	Lower risk of spill of fossil fuels to the environment	Potential to unlock new O&M methodology
Direct, indirect, and induced business opportunities for locals	Potential to remove generation equipment during decommissioning	Potential to improve and reduce cost of manufacturing

The report illustrates how a list of FLOW innovations was compiled with the help of the work [3] published by the Offshore Renewable Energy Catapult's (OREC) Offshore Wind Innovation Hub (OWIH), and how this list was ranked using the analytical hierarchy process (AHP). The analysis of the results is described along with comments on their statistical significance. Using information from this report, other WPs of the IDEA-IRL project can better align their work with the requirements of the industry, recognising the benefits that technological innovations can also bring.

This work contributes to fulfilling one of the objectives of the International Energy Agency (IEA) Wind Task 49:

> *"Engage with the international groups developing innovations for the floating wind energy industry, categorise in terms of multidisciplinary impact and ensure that functionality for their development is included in the reference sites and/or reference farm definitions."*

The survey was sent out to IEA Wind Task 49 participants on the 30th of November 2023 and the last responses were accepted on the 6th of February 2024.The results of the survey ranking are also compared to the results of an innovation ranking workshop which took place during the 2024 DeepWind conference in Trondheim, where attendees were asked to rank the same list of innovations in terms of which they think would be most useful to the FLOW industry.

Section 2 of this report gives an outline of the methodology used including background on the ranking method, the survey used, the selection process and descriptions of the innovative areas, and the processing of the results.

Section 3 shows the ranking of the innovation areas along with a statistical analysis of the results and a discussion of the results of various statistical tests, which have been carried on the data collected.

In Section 4, results are discussed and put into a broader context by considering the group of survey respondents and comparing the results to the findings of the MSP interviews carried out as part of WP4 and the findings of the January 2024 IEA Wind Task 49 workshop in Trondheim.

In Sections 5and 6, a feedback loop to technical WPs of the IDEA project is provided along with suggestions for future work.

2 Methodology

When deciding the resource allocation and focus of the direction of research during innovation management activities, it is critical that the decisions are based on fact as much as possible and are as free of bias as possible. One method to make preferential decisions is the AHP, which uses decomposition; splitting the goal into achievement criteria and looking at how different alternatives of solutions would compare based on the success criteria. In this case, the alternatives are the various innovations, the criteria are the environmental, social, and economic impact and the goal is to improve the overall positive impact of FLOW. The AHP compares pairs of alternatives based on their performance with respect to a criterion.

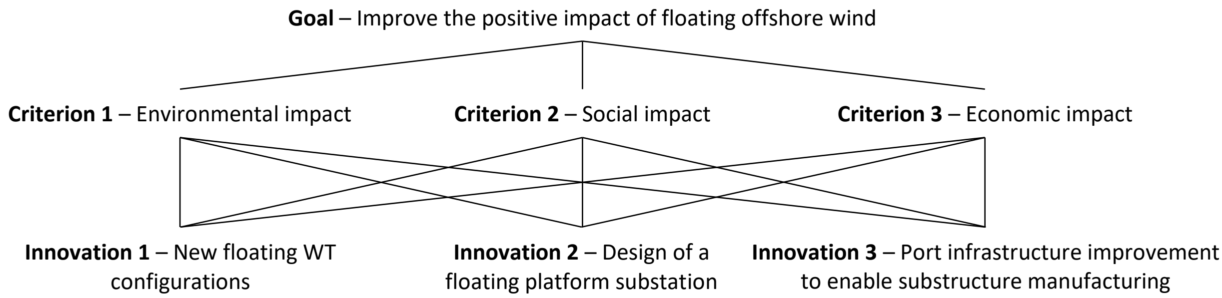


Figure 2.1 – Scheme of the analytical hierarchy process ranking system.

2.1 Survey method

In practice, carrying out the AHP method for ranking FLOW innovations involved using an online survey where participants were asked to compare pairs of innovations. Referring back to Figure 2.1 where the scheme of the AHP method is shown, the person completing the survey is asked this: with the goal to *Improve the positive impact of floating offshore wind* in mind, where the success is being judged by three criteria: *social impact, environmental impact, economic impact*, which of these two innovations, if brought to the market, could have a better environmental impact – *New floating WTG configurations* or the *Design of a floating platform substation*? The person then decides which of the two is preferred and by how much. Such a question is asked for all pairs of innovations with respect to all criteria, with the underlined words updated as needed. The survey was constructed in Microsoft Forms and the individual questions take the form as shown below in Figure 2.2.

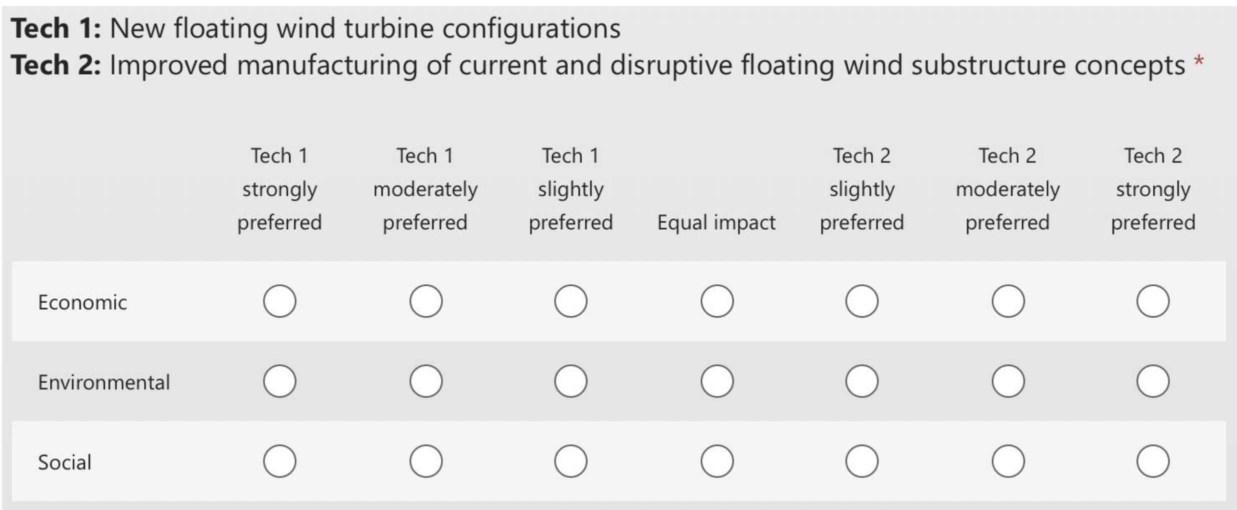


Figure 2.2 – Example question from the survey used to create the innovation ranking.

2.2 Compilation of the list of innovations

Initially, the list of innovations was taken from the OREC OWIH Floating Wind Innovations roadmap [3], as outlined in the first part of this report [1]. This is an extensive list including over 20 innovative areas and projects. This full long list is included in Appendix A: Long list of innovations. Since the AHP method requires pair-wise comparisons, comparing 20 innovations would require a questionnaire with 570 questions which is impractical. To attempt to encourage survey responses, a shortlisting exercise was undertaken with IEA Wind Task 49 members, and the number of innovations was reduced to eight priority innovation areas, giving 84 questions. For the shortlisting, the initial list from OWIH was circulated with task members to ask which could potentially be the most impactful ones using a simple ranking of 1-10. Based on the outcomes of this exercise, some topics were combined, and others were removed. The final list of innovations which was included in the survey along with a description of each, is below:

1. **New floating WTG configurations:** Current commercially produced offshore wind turbines are three-bladed, horizontal axis, pitch-regulated and upwind, mounted on a tubular tower and with yaw system designed to keep the turbine facing the wind during operation. Most current aero-elastic codes such as Bladed by DNV-GL and HAWC2 by DTU are restricted to horizontal axis wind turbines. Limited commercial or open source aero-elastic code exists for vertical axis WTGs (see QBlade), and as obtaining loads using aero-elastic tools is the first step in the design chain this is a stumbling block for vertical axis. Longer-term, there are possibilities to implement 2-bladed, down-wind, multi-rotor turbine, braced tower or vertical-axis solutions. Such innovations generally aim to improve energy production without significantly increasing CAPEX or OPEX.

2. **Manufacturing of current and disruptive floating concepts:** Floating offshore wind support structures are currently manufactured in facilities designed for fixed-bottom offshore wind, shipbuilding, or oil and gas production. The manufacturing process is bespoke, with long lead times and high costs. Continuous serial production methodologies should be established. Manufacturing equipment will be required that can handle such large structures at a low cost. Many current substructure concepts will generally use steel and are not tailored for serial manufacturing which might become a limitation at some point in the future. There are exceptions to this such as the Stiesdal Tetra foundation [4] or Marine Power Systems' PelaFlex floating platform [5] which are designed with industrial production in mind.

3. **Design for whole lifecycle cost reduction:** Design improvements in the support structure will enable cost savings through more efficient use of materials. This will result in lower-mass structures being produced. Design changes that enable more efficient manufacturing processes will also be important. Designs can include cost-saving measures not only in terms of CAPEX, but also in terms of OPEX, installation and decommissioning costs incurred during the lifetime of the project.

4. **Consolidation in the number of designs:** Currently there are conservatively around 100+ floating wind concepts in development. Such abundance of concepts is a sign of a nascent industry, which does not instil confidence in the investors and makes it harder to bring floating wind to full commercialisation. Through time and natural selection, the number of concepts will decrease, however an independent review of technologies needs to be performed to ensure that the most technically promising designs are allowed to develop, rather than just those with the most financial backing.

5. **Optimised O&M and major component service strategies and condition monitoring for floating conditions:** Major Component Repairs, Replacement or Exchange (MCR) can be defined as any corrective actions which require the change of an entire main component of the turbine, such as a gearbox, generator, blade, nacelle, etc. If occurring on a bottom-fixed offshore windfarm, MCRs would require the use of a jack-up or heavy lift vessel (HLV). The use of jack-up vessels for floating wind MCRs is not feasible due to water depth constraints. One option for floating wind major repairs is to tow the wind turbine(s) back to shore to conduct the works at a port or sheltered area. This will allow major repairs to be carried out onshore or at the quayside which would decrease the amount of work done offshore and avoid the need for expensive heavy-lift vessels. However, there are several uncertainties relating to this O&M strategy: The availability and cost of suitable onshore or quayside areas and crane capacity; the types of electrical cable connectors and mooring connectors required to allow efficient uncoupling and re-coupling of the turbine and; the need for additional electrical cabling to maintain the flow of power through the array when one turbine is removed. Floating to floating repairs using a HLV may also be an option. The best method for floating wind MCRs needs to be established.

6. **Design of a floating platform substation:** In some cases, water depth and/or seabed conditions are prohibitive to bottom-fixed substations, with floating platforms being required instead. The substation equipment needs to resist the motions of the hull, both in terms of extreme motions and fatigue over the lifetime of the wind farm. Designs of floating platform substations will need to include load resistance for low frequency, high acceleration events alongside a larger number of fatigue cycles over their lifetime. Even though there are no major barriers to feasibility and existing technology is largely considered to be suitable, such technology will require modifications. Some designs are already on the market but require further optimisation and commercialisation, particularly if High-Voltage Direct Current (HVDC) is to be used.

7. **Port infrastructure improvement to enable substructure manufacturing:** Currently, floating offshore wind substructure manufacturing capacity is limited in most European jurisdictions. Not having manufacturing facilities within a reasonable proximity of a project requires long and expensive transport solutions. Improving ports ad harbours to enable domestic manufacture could enable supplying substructures for the European market for cheaper than importing them from other jurisdictions.

8. **Floating electrical and mooring system connections:** Connection and disconnection of floating structures takes place in two stages, the mooring, and the array cable. Disconnection is performed when turbine requires repairs or decommissioning and is towed back to port. With improvements in the design of the mooring and connection system, the connection and disconnection of the array cable will get faster, meaning that installation and major unplanned operations can be done more quickly. This will reduce cost and in the case of operations should also reduce downtime. Where standard tug vessels are used, only minor vessel change will occur. Where larger vessels are used, these will become more specialised to their floating offshore wind application. Connection technologies will significantly differ between mechanical and electrical elements.

It should be noted that many of the innovations included in the list above could be described as innovation areas, rather than specific innovations. It was decided in consultation with other WPs that at this stage of the work, the focus should be on identifying the key areas of floating offshore wind that could benefit from innovation. Once this has been established through the AHP, specific innovations that target these areas and can be incorporated into reference wind farm designs, can be identified, and implemented into design iterations.

2.3 Answer analysis

The output of the AHP method is a list of priority ratings where priority is a measure of preference of one alternative compared to the other ones. This is explained in more detail in the first part of this report [1]. Once the survey was closed, the answers were analysed using an algorithm, which completes the maths required in the AHP method as described in [1] and [6]. The priority ratings were calculated for each answer separately, therefore for each answer from each respondent a separate priority rating matrix was created as shown in Table 2.1. The final rating was calculated as the average of all individual ratings. Note that the individual ratings are normalized so that the sum of the total priority for all innovations is unity.

In Table 2.1, the total priority column determines the final ranking. This means that the respondent whose survey answers created this ranking believes that innovation 2 – *Manufacturing of current and disruptive floating concepts* has the highest priority, therefore the highest potential beneficial impact on the FLOW industry, if improved. On the other hand, the respondent thinks that innovation 3 – *Design for whole lifecycle cost reduction* is the least important. The respondent also thought that innovation 2 will have the highest potential social and environmental benefits.

Table 2.1 – Example of the priority ratings calculated from one survey answer.

Innovation	Social priority	Economic priority	Environmental priority	Total priority
1	0.01102	0.00180	0.06785	0.08067
2	0.07139	0.01389	0.20357	0.28885
3	0.00957	0.02111	0.03689	0.06757
4	0.00842	0.00367	0.06537	0.07746
5	0.04581	0.01307	0.08847	0.14735
6	0.02510	0.00573	0.06809	0.09892
7	0.04066	0.01178	0.09959	0.15204
8	0.01880	0.00587	0.06248	0.08715

3 Results

From the responses to the survey, the priority ratings for each criterion were calculated as the average rating across the respondents for the given innovation and criterion. A standard deviation was also calculated for each of the ratings. The numbers are normalised so that the sum of the total priorities of all technologies is unity. The results are presented in Table 3.1. In some cases, the standard deviation is of a similar magnitude to the mean of the priority rating, which indicates that the answers to the survey were dissimilar across respondents.

Table 3.1 – Results of the AHP priority ranking, in descending order of the total priority value.

Innovation	Social Priority	Social STDEV	Economic Priority	Economic STDEV	Env. Priority	Env. STDEV	Total Priority	Total STDEV
5	0.03910	0.04156	0.06419	0.03835	0.05690	0.03326	0.16019	0.04137
7	0.04079	0.03325	0.05855	0.05387	0.05492	0.03219	0.15427	0.02731
2	0.03232	0.02299	0.03572	0.02298	0.07537	0.06098	0.14341	0.06743
8	0.02384	0.01024	0.05357	0.05918	0.05243	0.02956	0.12984	0.05344
3	0.01844	0.01498	0.04754	0.02202	0.05877	0.04860	0.12475	0.04308
6	0.03228	0.03871	0.03811	0.03510	0.05039	0.03017	0.12079	0.02807
4	0.02536	0.02603	0.04709	0.03821	0.03396	0.01890	0.10641	0.04994
1	0.00944	0.00799	0.01406	0.01214	0.03685	0.03215	0.06034	0.03366

3.1 AHP Matrix consistency calculation

When creating the comparison matrix, it may or may not be set as a requirement for the ratings to be consistent. Consistency in AHP means that if a person ranks A to be twice as important as B and B to be three times as important as C, then it should follow that A is six times as important as C. This is not a requirement in this analysis.

Table 3.2 – Example pairwise comparison matrix, its principal eigenvector and principal eigenvalue.

	1	2	3	4	5	6	7	8	Principal eigenvector	Principal eigenvalue
1	1.00	0.16	0.18	0.37	0.19	0.48	0.19	0.37	-0.07704	9.48288
2	6.30	1.00	0.48	1.11	0.48	2.10	0.60	3.33	-0.36587	
3	5.70	2.10	1.00	1.80	0.67	3.30	1.67	1.50	-0.47341	
4	2.70	0.90	0.56	1.00	0.42	1.11	1.00	3.33	-0.32002	
5	5.40	2.10	1.50	2.40	1.00	3.60	1.20	0.30	-0.48202	
6	2.10	0.48	0.30	0.90	0.28	1.00	0.33	3.30	-0.24561	
7	5.40	1.67	0.60	1.00	0.83	3.00	1.00	1.20	-0.37171	
8	2.70	0.30	0.67	0.30	3.33	0.30	0.83	1.00	-0.32068	

This approach will create ranking inconsistencies, which can be tolerated if at a reasonable level. Saaty, the developer of the AHP method suggests 10% of inconsistency as the limit [6]. Saaty also suggest a way to check the level of inconsistency of the ranking matrix. This is done by first calculating a consistency index (CI), which is done using Equation 3.1, where $\lambda_{principal}$ is the principal eigenvalue of the pairwise comparison matrix (shown in Table 3.2) and n is the size of the matrix, which is 8 in the case of the matrices for the innovations with respect to the three criteria and 3 for the matrix for comparing the individual criteria among each other [6].

$$CI = \frac{\lambda_{principal} - n}{n - 1}$$

Equation 3.1

The measure of consistency of the ranking matrix is called the Consistency Ratio (CR) and is calculated by dividing the CI of the pairwise comparison matrix by a Random Index (RI), where the RI represents a CI of a pairwise comparison matrix, where the comparisons were done randomly and without any consideration by the person doing the ranking. The values of RI are pre-determined by Saaty based on the matrix size n as shown below:

Table 3.3 – Random indices (RI) for matrix of size n [6].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio is then calculated simply by $CR = CI/RI$. For the results to have an acceptably low inconsistency, they should have a CR of less than 0.1 [6]. The results of the consistency calculations are shown in Table 3.4. The only ranking which is consistent enough according to Saaty's work is the criteria ranking matrix, the other ones have a CR > 0.1. This means that the results produced from the ratings done by the respondents are not completely dissimilar to those that would be produced if the ranking had been done randomly.

This is most likely down to the relatively large length of the survey. Respondents may have lost track of how they answered in each question, which would be simple to do in a survey of over 85 questions which all appear similar at first glance. Nevertheless, results have been analysed and the general observed trends were compared to other sources of ranking, as shown in sections 3.4 and 4.2.

Table 3.4 – Consistency indices, random indices, and consistency ratios for the average AHP comparison matrices.

Rating	Consistency Index	Random Index	Consistency Ratio
Criteria	0.03143	0.58	0.05419
Social	0.42115	1.41	0.29869
Environmental	0.50418	1.41	0.35757
Economic	0.42588	1.41	0.30205

3.2 Data statistics

The survey was answered by ten respondents after it had been issued to IDEA partners. This is a lower number than hoped for and creates some challenges with analysing the data. The data was analysed using Analysis of Variance (ANOVA) method to find whether there are any statistically significant differences between the priority ratings as calculated and using a Tukey Honestly Significant Difference (HSD) test to find where these differences lie, if any are found. The confidence level used is 95% (p-value of 0.05).

The ANOVA test has several assumptions which should be met:

1. The data points should be independent observations.
2. The distribution of residuals is normal.
3. The variance of data in groups should be the same (homoscedastic).

The first condition is met by the method in which the data was obtained, however the other two assumptions need to be checked. In this case, the method for checking the normal distribution was the Shapiro-Wilk test (confidence level 95%) and homoscedasticity was checked using the Bartlett test (confidence level 95%).

Some of the assumptions can be checked using a visualisation of data. Figure 3.1 shows a boxplot of the total priority ratings for each innovation. The means of all data groups appear to be different, however the data spread is large, especially for groups two and eight. Whether the data groups have similar variance is difficult to tell, groups one and three to seven seem similar, however whether two and eight are also similar is unclear. The boxplot does not offer enough information to make the decision whether to proceed with an ANOVA and Tukey HSD test, so the Shapiro-Wilk and Bartlett tests need to be carried out.

Table 3.5 shows the results of the Shapiro-Wilk test to check the normal distribution of the data. The null hypothesis of the Shapiro-Wilk test is that the sample has been generated from a normal distribution, therefore a p-value of less than 0.05 in this case signifies that with a confidence level of 95%, the sample does not come from a normal distribution. This is the case for quite a few of the data sets, as seen in the table. Fortunately, a one-way ANOVA such as conducted in this analysis is reported to be resilient to type I and type II errors even when data does not come from a normal distribution [7], [8].

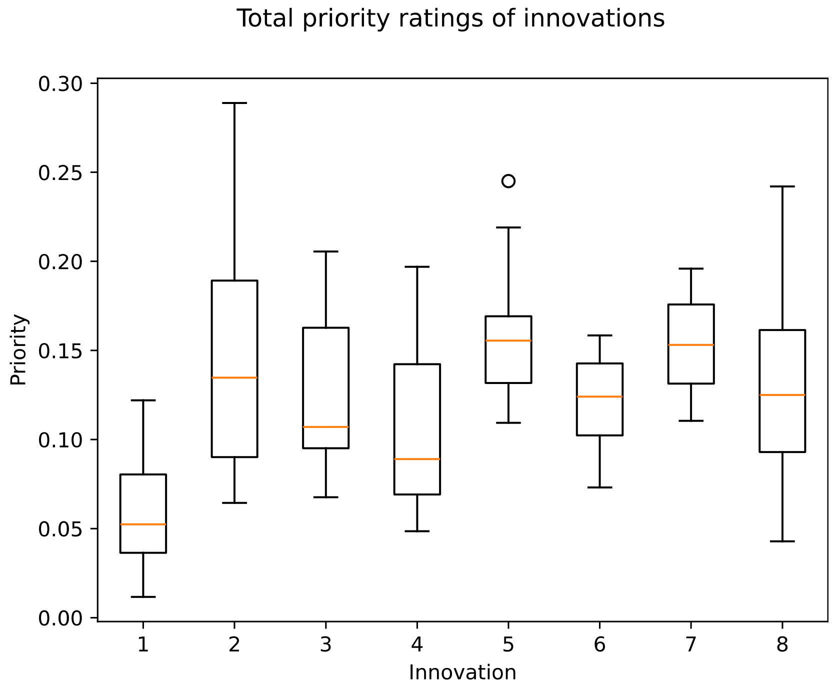


Figure 3.1 – Boxplot of priority ratings in the "total" category for all innovations showing the variation of how much priority they got from different survey respondents.

Table 3.5 – Results of the Shapiro-Wilk test for normal distribution of the data.

	Shapiro-Wilk test (p-values)			
Innovation areas	**Social**	**Environmental**	**Economic**	**Total**
New floating WTG configurations	0.05203	0.09548	0.08844	0.79635
Manufacturing of current and disruptive floating wind concepts	0.03320	0.12161	0.11405	0.36953
Design for whole lifecycle cost reduction	0.00350	0.03486	0.98999	0.18294
Consolidation in the number of designs	0.00315	0.70234	0.17203	0.27354
Optimised O&M and major component service strategies and condition monitoring for floating conditions	0.00076	0.35043	0.32619	0.31863
Design of floating platform substation	0.00012	0.91295	0.06431	0.63018
Port infrastructure improvement to enable substructure manufacturing	0.08989	0.41697	0.02884	0.76111
Floating electrical and mooring systems connection	0.67038	0.98945	0.00847	0.94590

Table 3.6 shows the results of the Bartlett test to check whether the data has the same variance across the priority categories.

Table 3.6 – Results of the Bartlett test for homoscedascity of data.

Criterion	Bartlett Statistic	Bartlett p-value
Social	35.27349	0.00001
Environmental	15.10442	0.03468
Economic	26.31345	0.00044
Total	11.95448	0.10207

The null hypothesis is that the variances of the populations from which samples are drawn are equal, and a p-value of less than 0.05 signifies, that with a 95% confidence level, there is a difference between the variances. From the results it appears that the total priority is the only one where the variances can be considered the same.

Based on the Shapiro-Wilk and Bartlett test results, it was decided to only analyse the differences between the total priority ratings, because the data for the total priority fulfils two out of three of the requirements of the ANOVA test and ANOVA is being considered as robust against violations of the normal distribution requirement. Nevertheless, the ANOVA calculation was done for all criteria. The results are shown in Table 3.7.

The null hypothesis of ANOVA is that all means of the analysed data sets are the same, therefore a p-value of less than 0.05 gives a 95% confidence level that there is a difference between at least two means. This is not the case for any of the individual priority ratings (social, environmental, or economic) and for these the null hypothesis is accepted; however, the results of the ANOVA indicate that there is a statistically significant difference between at least two means in the total priority rating. That is to say that at least one innovation is preferred to at least one other innovation.

Table 3.7 – Results of the ANOVA test for determining a statistically significant difference between means.

Criterion	ANOVA Statistic	ANOVA p-value
Social	1.35842	0.23621
Environmental	1.06527	0.39462
Economic	1.51497	0.17596
Total	4.46510	0.00036

However, ANOVA does not give any more information than that. Finding where this difference lies requires the Tukey HSD test. This test was applied to the total priority ranking only. The null hypothesis of the Tukey HSD test is that for each pairing of the data groups the means are the same. This means that when a p-value is lower than 0.05, it can be said that with a 95% confidence level, there is a difference between the means of two data groups (in this case between the total priority ranking of two innovations).

The results of the Tukey HSD test are presented in Table 3.8 for pairs of innovations where the p-value is less than 0.05, which can be talked about as statistically different. The test shows, that with 95% confidence, technologies two, five, seven and eight are preferred to technology one. In Table 3.8 the Tukey HSD statistic then gives information on the difference between the total priority.

Table 3.8 – Results of the Tukey HSD test for determining statistically significant differences between pairs of means. Results for pairs of technologies where p-value < 0.05

Innovation 1	Innovation 2	Tukey HSD statistic	Tukey HSD p-value
5	1	0.09985	0.00029
7	1	0.09393	0.00081
2	1	0.08307	0.00463
8	1	0.06950	0.03225

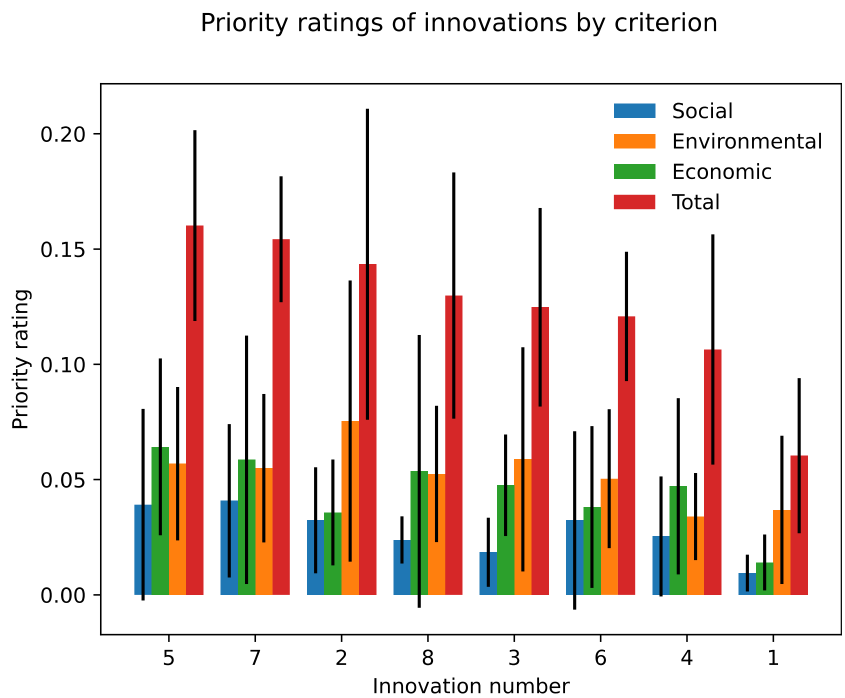
Anyone using the ranking must keep in mind that not all information contained in the ranking can be backed up by statistical calculation. Potentially, the issues with the data could have been caused by a low number of answers. The survey, even with the list of innovations cut down, took a long time to fill in and this may have dissuaded potential respondents. AHP, though a good tool for making objective decisions, is quite bulky and the requirement for pair-wise comparisons means this method may not be well-suited for comparing many alternatives.

In future surveys, a different method may be better suited. However, a ranking still can be constructed, and this is still useful for identifying the most important areas that the industry and academia need to focus on. A later study can then determine what are the critical technologies which would enable progress in the innovative areas highlighted in this report as priority.

3.3 Priority ranking of innovative areas

The whole results, and ranking is presented in Figure 3.2 and comments are made on the ranking as a whole, while keeping in mind the results of the statistics shown in section 3.1. The results roughly split the innovative areas into three categories – higher priority (optimised O&M, improvements of port infrastructure, manufacturing), medium priority (FLOW connectors, LCoE reductions, floating substation) and lower priority (consolidation in the number of designs, new WTG configurations).

The most important criterion, according to respondents, was the potential environmental benefit, with economic benefits in second place and social in third. The innovation ranked as having the highest potential environmental benefit was the improved manufacturing methods, while the dedicated FLOW O&M strategies were perceived as most important in terms of their potential economic impacts. Improved port infrastructure received the highest potential social impact rating.



5. Optimised O&M and major component service strategies and condition monitoring for floating conditions.
7. Port infrastructure improvement to enable substructure manufacturing.
2. Manufacturing of current and disruptive floating concepts.
8. Floating electrical and mooring system connections.
3. Design for whole lifecycle cost reduction.
6. Design of a floating platform substation.
4. Consolidation in the number of designs.
1. New floating WTG configurations.

Figure 3.2 – Priority ratings of innovations sorted in descending order by the "total" category. Error bars show ± 1 standard deviation of the priority ratings from individual survey respondents. Innovation numbers are as shown in section 2.2.

3.4 Comparison to of the survey results to the results of the Trondheim workshop

On the 16th of January 2024 IEA Wind Task 49 partners met in Trondheim, Norway, for the annual in-person Task 49 meeting. During this meeting, there was a short WP4 workshop to rank the same list of innovations based on their overall potential impact and discuss the future of these.

The rankings from the workshop and the survey are similar – the maximum difference between them being two ranks. Both rankings identify the same innovations as the top three, although in different order. Both rankings also identify innovation 8 as the one having the lowest priority.

Table 3.9 – Comparison of the priority ranking results from the Trondheim workshop and the AHP survey.

Innovation	Workshop ranking	Survey ranking
Optimised O&M and major component service strategies and condition monitoring for floating conditions	2	1
Port infrastructure improvement to enable substructure manufacturing	3	2
Manufacturing of current and disruptive floating wind concepts	1	3
Floating electrical and mooring systems connection	6	4
Design for whole lifecycle cost reduction	4	5
Design of floating platform substation	7	6
Consolidation in the number of designs	5	7
New floating WTG configurations	8	8

From analysing the results of the survey, in combination with the workshop rankings, the priority innovation areas can be identified as:

- Optimised O&M and major component service strategies and condition monitoring for floating conditions.
- Port infrastructure improvement to enable substructure manufacturing.
- Manufacturing of current and disruptive floating wind concepts.

4 Discussion

The results show a preference for improving existing technologies and carrying out incremental innovation, rather than aiming for radical conceptual innovations. The highest ranked areas focus on O&M, installation, and manufacturing: this highlights a couple of points.

1. The installation, O&M, decommissioning, and manufacturing procedures for FLOW will not be the same as those used for fixed bottom. The survey respondents identified O&M, manufacturing, and port infrastructure, as the areas which could provide the most significant benefits, if innovated. This suggests respondents believe the best way forward is to focus on more efficient manufacturing and operation of current FLOW concepts and to channel R&D efforts towards making them work better rather than creating new ones.

2. The technology behind the WTG machinery itself is mature and appears to be working well in FLOW projects to date. The recent announcement that after six years of operation, the five WTGs of the Hywind Scotland project (rated 6MW) will require some major maintenance work [9], and the reasons for this, is something that should be monitored as it could suggest the contrary. Regardless, survey respondents have not highlighted a need to develop new concepts specifically for floating wind as a priority at this time. Based on the current project pipeline assessed as part of this work [10], the capacity of deployed turbines in FLOW projects is expected to rise towards 20-25 MW towards the end of this decade, as shown in Figure 4.1. This expected increase in turbine capacity, if realised, is expected to be as a result of incremental increases and improvements to existing concepts, rather than new innovations or concepts as described in this survey, however.

   Conventional horizontal axis wind turbines (HAWT) with higher than currently normal power ratings will likely require a corresponding increase in platform righting moment and therefore potentially increased mass and cost. It is expected, however, that the increased power production provided by the larger turbine would more than compensate for the additional CAPEX cost for the larger hull sizing required to provide the increased restoring force. One way to reduce the required mass of the platform is to use multiple smaller rotors on the same platform [11], as trialled by the W2Power project by Pelagic Power and others. This would be a new WTG configuration for floating wind, but perhaps the industry will find ways to stabilise conventional HAWTs, even with power ratings of 25 MW or above. Whether WTGs of this power rating will come on the market in the next decade also remains to be seen.

3. By looking at the previous two points, it appears that the FLOW industry is very close to making the leap to fully commercial scale projects. The respondents believe the technology of the machines is now good enough and think the industry should focus on how best to use them, which can be seen as foreshadowing of an imminent transition from technology readiness level (TRL) 8 to 9 for the floating offshore wind turbines. This is also reflected in the market predictions for the upcoming five to ten years [10].

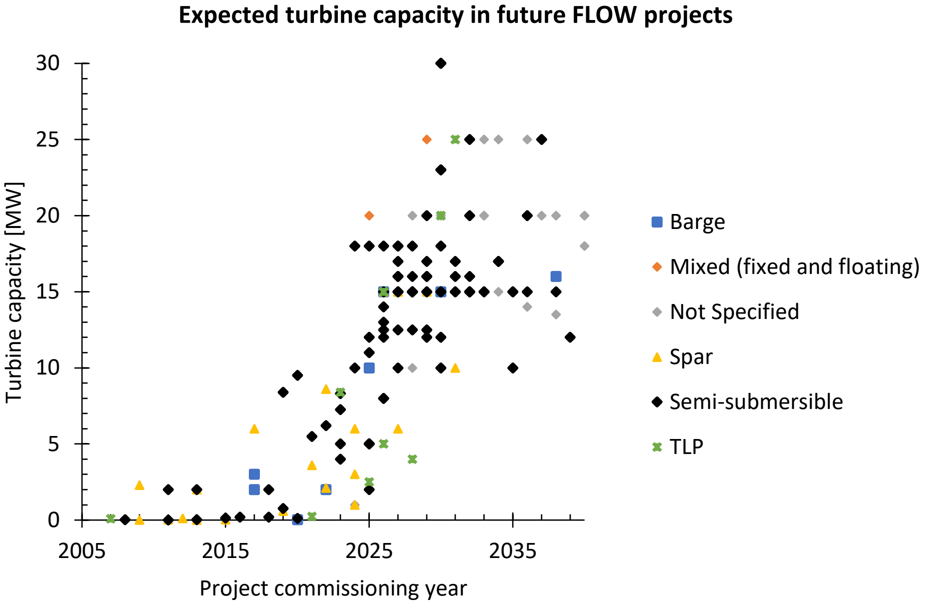


Figure 4.1 – Turbine capacity of FLOW projects in the pipeline [10], shown by type of floating foundation they are expected to employ. Data from a database licenced to Gavin & Doherty Geosolutions by TGS 4C Offshore in November 2023. Any low values are for test-scale projects.

4.1 The survey respondents

A part of the survey asked the respondents which sea use stakeholder group they represent and what their role is in their company. 90% of the respondents work in offshore renewable energy and all of them are involved in R&D or engineering/design work. Therefore, the survey does not provide a cross-sectoral view on the innovative areas in FLOW and provides a view of R&D workers and engineers in ORE. The nature of the survey itself perhaps led to this as the potential impact of innovations might be difficult to imagine if one is not working in a field directly dealing with these innovations. Nevertheless, the results of this report, as Figure 4.2 shows, may not be seen as a view of many stakeholder groups, but rather as a view of ORE engineers and researchers. This may be a potential source of sampling bias and non-response bias in the results presented in this report. Other groups will be engaged in future as part of WP4, to ensure a cross-sectoral view.

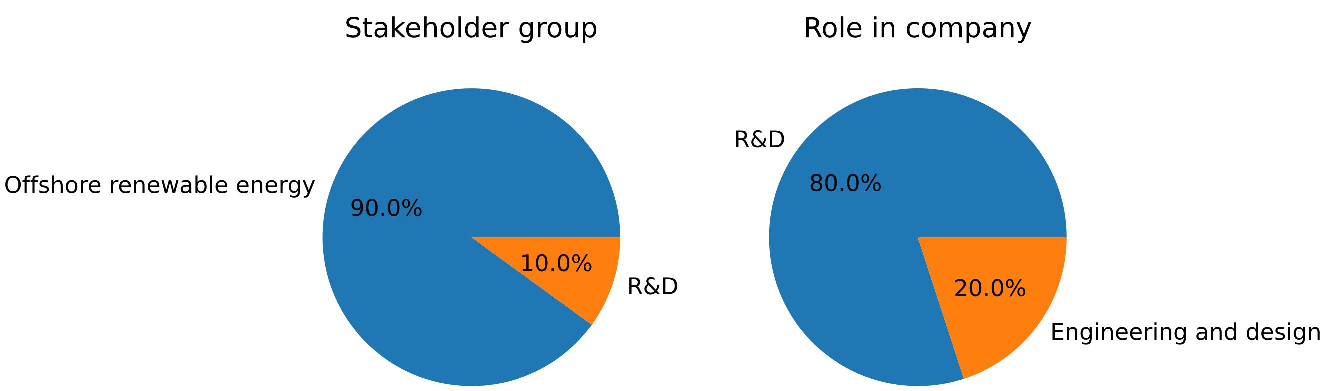


Figure 4.2 – The survey respondents by sea user stakeholder group and their role in their company.

4.2 Survey responses compared to MSP Interview Discussions

The other work stream of WP4 is focused on carrying out marine spatial planning (MSP) interviews with representatives from partner countries to find out how various stakeholders are involved with FLOW projects and what the legislative framework concerning ORE and FLOW developments is in the country. During the interviews conducted as part of WP4, the interviewees were asked what they think are the most important research topics in FLOW for their market.

Interviewees identified various country-specific requirements, however there was considerable overlap between some of the answers. The research areas mentioned the most were:

1. Lowering the costs of FLOW.
2. Creating better-informed environmental impact assessments and lifecycle carbon assessments with FLOW-specific considerations.
3. Developing O&M methodology, manufacturing, and decommissioning methods specifically designed for FLOW including major component service strategies and material recycling.
4. Creating a better understanding of the FLOW supply chain efficiency and industrial value creation and finding how best to integrate domestic industry in it.
5. Technical advancement in moorings and cables– mooring spread, array layout, Environmental Impact Assessment (EIA) of mooring lines and anchors on benthic environments, dynamic cables, potentially alternative power transport mechanisms like hydrogen.

The general sentiment of these areas is very similar to the results of both the survey and the Trondheim workshop: priority should be given to incremental innovation of the processes, equipment and infrastructure involved with installing, maintaining and decommissioning existing WTG and floater technology in FLOW conditions. In addition to mentioning this, the interviewees generally agree that technological advancement is required in mooring and cable technology, which was also pointed out in the survey results.

Aside from the topics mentioned above, the interviewees noted co-existence as an important research focus. Wind arrays are expected to occupy considerable portions of many countries' maritime EEZs and currently they are often displacing other users, especially fishers. Focusing more on creating an understanding of which industries could co-exist together within the boundaries of a wind farm should become one of the focus points of future WP4 MSP interviews, along with supply chain integration.

More detail on the findings of the first round of the MSP interviews is available on the MaREI website in the IDEA-IRL project site, deliverables section [12].

5 Feedback loop to technical work packages

Most of the innovations considered in this report are innovative areas rather than specific technologies, however some specific suggestions to other WPs can be made.

1. The results show a need for improved O&M strategies, improved condition monitoring, and major component change-out strategies. A significant proportion of maintenance work is linked to component lifetime, which is often dictated by fatigue. The need for better O&M strategies should be investigated. A review should be undertaken of the planned maintenance work on the Hywind Scotland project, where the WTGs are being towed across the North Sea to Norway for quay-side maintenance and the process is expected to take around four months [9].

2. A need for improved port infrastructure is also identified. As part of WP1, specifications are made for what the expected requirements are for a port which would be able to provide installation, O&M, manufacturing or integration services to floating offshore wind project. This includes marshalling space requirements, cranage requirements, minimum berth size and depth, and other relevant factors. A technical note produced by WP1 deals with this topic, which may be expanded on in more detail.

   There is a case to be made for governments to push for port infrastructure improvements, which would enable FLOW manufacturing and have positive externalities for other sectors as well. This is already seen in major ports, for example in the Port of Amsterdam, where a dedicated area for offshore wind is being designed in 2024 [13] as a cooperation between government authorities, port authorities and manufacturers. The estimated Social Cost Benefit Analysis (SCBA) ratio for the project is 1.9, indicating a large potential for positive impact.

   Effort has already been made to assess the condition and suitability for offshore wind operations of the ports in Ireland [14]. A National Port Study was completed by GDG for Wind Energy Ireland in 2022, outlining the state of Irish port infrastructure and focusing on how much of it can be used to support ORE projects. The study found only one port in Ireland – Belfast Harbour D1 can carry out marshalling activities for fixed-bottom projects of the GW scale and no ports are able to support manufacture and staging of FLOW projects. A further report completed by GDG for WEI in 2023, the *Irish Port Funding Study* then looked at ways to fund the needed improvements in Irish port infrastructure [15]. While current National Ports Policy in Ireland is that ports should be self-funding, this may change in the future, with responses to the recent consultation on the National Ports policy currently under review by Government.

3. WP2 also considers the design of mooring systems. One of the medium-priority innovative areas identified was mooring and electrical system connectors. Including connectors and perhaps load-reduction devices in the mooring design within WP2 may be investigated as part of WP2.

6 Further work

Future working linking to the results of this study should break down the innovative areas into more concrete innovations and technologies the industry should focus on to maximise positive impact. This will be done in collaboration with the other WPs, and these innovations can then be considered for inclusion in design iterations prepared by WP2.

A second area of future work would be involving more sea user groups in the study to identify technologies and innovations which could promote better co-existence of industries and enable multi-use sea areas, where multiple industries can share the space effectively.

Finally, future work for WP4 should investigate domestic integration of the FLOW supply chain and what countries are doing to capture value locally and support local FLOW suppliers, as well as co-existence.

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Appendix A: Long list of innovations

Description	Start TRL	Potential to Reduce LCoE	Case for intervention
Rotors			
Pitch control for floating wind	TRL 6	M	M
New floating WTG configurations	TRL 5	H	M
Powertrain			
Drivetrain design for floating conditions	TRL 2	H	L
Advanced floating WTG controller design	TRL 2	H	M
Testing methodologies for floating wind components (drivetrain)	TRL 2	M	H
Magnetic gearing	TRL 5	M	H
Project Development			
Optimisation of design during FEED	TRL 3	H	L
Environmental impact of floating substructures	TRL 3	L	M
Installation			
Mooring systems connection	TRL 4	M	M
Floating electrical systems connection	TRL 4	M	M
Introduction of turbine assembly strategies for generic harbours	TRL 3	H	L
Offshore floating assembly activities	TRL 4	M	L
Operations and Maintenance			
O&M strategy for dynamic floating conditions	TRL 4	M	M
Balance of plant condition monitoring for floating wind	TRL 4	M	M
Floating substructures lifetime assessment - established methodology and technology	TRL 2	H	H
Optimised O&M major component change strategies	TRL 3	H	H
Access & egress for floating offshore wind	TRL 7	M	L
Electrical Infrastructure			
Improvements in HVAC dynamic cables	TRL 6	H	H
Improvements in HVDC dynamic cables	TRL 3	M	M
Design of electrical components to withstand floating wind conditions	TRL 5	L	M
Design of floating platform substation	TRL 4	L	L
Testing methodologies for electrical floating wind components	TRL 3	M	H
Lead-free dynamic cables	TRL 3	M	M
Substructures			
Manufacturing of current floating wind concepts	TRL 4	H	M
Manufacturing of disruptive floating wind concepts	TRL 2	H	H
Design for whole lifecycle cost reduction	TRL 5	H	M
Floating hybrid energy platforms	TRL 5	H	L
Consolidation in the number of designs	TRL 7	M	M