PivotBuoy

An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind

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D7.5 – PivotBuoy Project final report, results, lessons learnt and best practices for the wind sector

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RE	Restricted to a group specified by the consortium (including Commission Services)	
CO	Confidential, only for members of the consortium (including Commission Services)	

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LIST OF ACRONYMS

AEP	Annual Energy Production
CAPEX	Capital Expenditure
CDR	Critical Design Review
DDR	Detail Design Review
FAT	Factory Acceptance Testing
FMECA	Failure Mode Effect and Criticality Analysis
FOW	Floating Offshore Wind
GHG	Greenhouse Gas
GVA	Gross Added Value
IEA	International Energy Agency
IO	Input-Output
ISO	International Standardization Organization
LCA	Life Cycle Assessment
LCoE	Levelized Cost of Energy
O&M	Operations and Maintenance
OPEX	Operational expenditure
PDR	Preliminary Design Review
PAT	Portside Acceptance Testing
SAT	Site Acceptance Testing
SPM	Single Point Mooring
TEM	Techno-economic Model
TLP	Tension-Leg Platform
TRL	Technology Readiness Level

1 INTRODUCTION

This document presents a summary of the main tasks executed during the PivotBuoy project and the corresponding results. The PivotBuoy Project refers to an innovative offshore wind system that aims to reduce the costs of mooring systems and floating platforms, enable faster and cheaper installation and more reliable and sustainable operation. The concept integrates advantages of the single point mooring (SPM) systems - pre-installation of the mooring and connection system using small vessels -, and those of the tension-leg platforms (TLP) - weight reduction, reduced mooring length and enhanced stability -, potentially leading to a weight reduction of more than 50% compared to the state of the art of floating wind systems installed at the project start in 2019. Furthermore, it allows an important simplification in the installation of conventional TLP systems. It was proposed to demonstrate and validate the concept at the test site of Plataforma Oceánica de Canarias, integrating a prototype of the PivotBuoy SPM system in a 225kW downwind floating platform developed by X1 Wind. It was expected that over the course of the project relevant innovative procedures regarding the assembly, installation and O&M would be validated.

The project consortium includes X1 Wind (Project Coordinator), ESM Energie- und Schwingungstechnik Mitsch GmbH (ESM), WavEC – Offshore Renewables (WavEC), Plataforma Oceánica de Canarias (PLOCAN), Intecsea B.V. (INTECSEA), EDP – Center for New Energy Tecnologies (EDP-CNET), Danmarks Tekniske Universitet (DTU), DNV GL UK Limited (DNV) and Desarrollo y Gestion Industrial y del Medio Ambiente (DEGIMA). The consortium was funded by the European Commission's H2020 program.

This deliverable compiles the extensive work developed over the four years of the PivotBuoy project. The summary is divided by work packages, each covering a given stage or aspect of the project, from the design, a variety of numerical modelling, risks assessment, manufacturing, assembly and installation, environmental impacts, carbon emissions, LCoE, and results communication and dissemination. Each work package presents the specific tasks and objectives, the challenges, results and lessons learned.

Overall, the consortium managed to accomplish the main objectives of this ambitious project. The X30 prototype was designed, built, installed and demonstrated in a real operational environment reaching TRL6, obtaining valuable data from multiple sensors showing an excellent hydrodynamic and self-aligning performance and exporting electricity into PLOCAN's Smart Grid via a dynamic cable, as well as surviving several significant storm conditions given its part-scale, presenting a very promising response.

All components of the product lifecycle (functionality, manufacturing, assembly, installation, O&M, decommissioning and disposable) were carefully considered since an early stage of design, contributing to a decrease of the LCoE relatively to the state-of-the art at the beginning of the project ranging from 46% to 67% (estimations for three sites). The PivotBuoy's project design procedure lead to less use of material, which represents lower carbon emissions comparing with the state-of-the-art. Furthermore, an industrialization plan towards the serial full-scale PivotBuoy units production for commercial farms was developed, with the main focus of reducing the time of each phase of the PivotBuoy system life span. The highly modular design of the PivotBuoy components provides relevant benefits to the fabrication in large scale. The consortium also gathered an important understanding regarding the numerical modelling of floating offshore wind systems, particularly the PivotBuoy concept.

The project suffered some delays due to Covid-19 pandemic and how it affected the manufacturing phase as well as constraints in the availability of local vessels for the installation phase, which resulted in a one year extension which led to the obtention of the excellent data and results beforementioned.

Overall the partners consider it is a very successful project which will now be followed up with the scaling up of the technology into a commercial-scale pilot (NextFloat Project).

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2 SUMMARY OF THE WORK PACKAGES

Each of the following subsections describes the works conducted within a specific work package (WP), from WP2 to WP7, comprising the technical work, and WP8, related with the communication and dissemination of results.

2.1 WP2 – PivotBuoy Subsystems Design

Overview

Work Package 2 (WP2) "PivotBuoy Subsystems Design" proposed a systematic concurrent design approach to the project, integrating early in the design process elements of the product life cycle such as manufacturing, assembly, installation, O&M and environmental, health and safety (EHS) considerations, shortening the total time compared to a traditional sequential design.

The specific objectives of WP2were:

- Define system and subsystem level requirements for a 1:3 prototype at PLOCAN & key metric definition.
- Facilitate Preliminary Design Review (PDR) and define criteria for advancement to detail design.
- Create engineering drawings and technical documentation for systems and key components.
- Facilitate Detail Design Review (DDR) and define criteria for advancement to procurement.
- Provide a methodology for input from other WPs to be feed back into iterative design loops.
- Develop a condition monitoring system to monitor potential failures and working conditions.
- To assess a preliminary PivotBuoy design for large 10-20MW floating systems.

WP2 was led by X1 Wind with support and contribution from ESM, WAVEC, PLOCAN, INTECSEA, EDP CNET, DTU, DNV GL UK, and DEGIMA. The tasks and deliverables defined under WP2 are depicted in Figure 1.

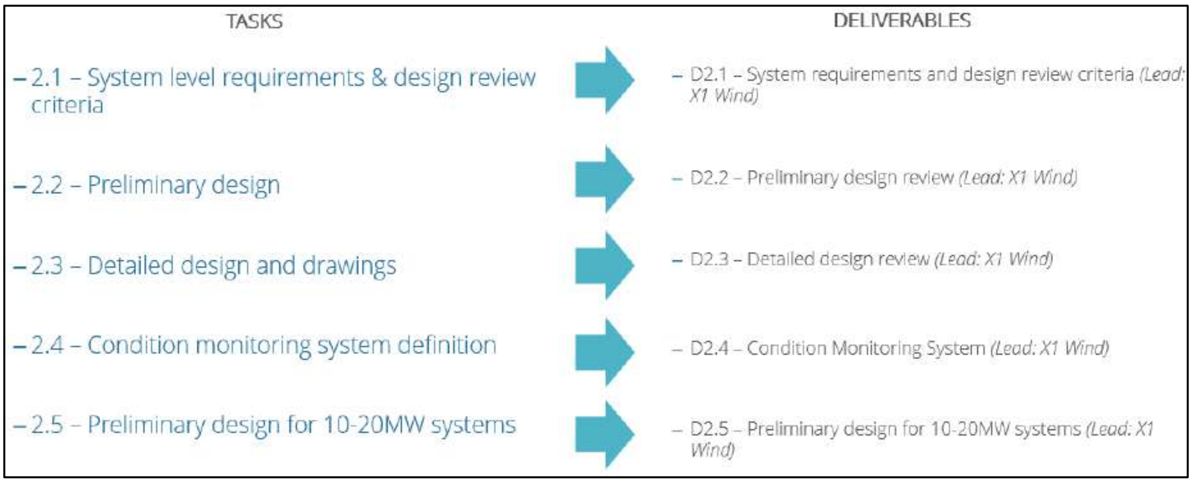

Figure 1. WP2 tasks and deliverables overview

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System requirements & design review criteria

The system level requirements for each subsystem (structural, coupling system, mooring system and dynamic cable) were derived from the conceptual design and the metocean conditions of the test site. These set an initial high-level design criteria for the structural design in direct relation to the relevant international standards and design guidelines, to ensure that the design methodology fitted for certification. Also, the design review criteria process was implemented during this early stage.

Design evolution: from concept design to detailed design

The project workplan was design based on concurrent engineering principles, with the premise that all elements of the product lifecycle (from functionality, production, assembly, testing, maintenance, environmental impact, disposal and recycling) should be taken into careful consideration in the early design phases. So, the design evolved through iterative design loops where the design team (WP2, led by X1 Wind) was in continuous communication with the manufacturing team (WP3, led by DEGIMA) and the installation team (WP4, led by PLOCAN), to ensure their requirements were included and introduced early in the design process. At the beginning and after each iterative loop the results were assessed against KPIs including performance (WP5, led by DTU), risks (WP6, led by INTECSEA) and the LCOE, socio-economic impact and other aspects related to the business exploitation (WP7, led by EDP CNET). Thus, WP2, which involved specifications and subsystems design, interacted with WP3-7 in and optimization loop, where the results for the different WPs feed into WP2 in order to optimize the system in an iterative process.

The PivotBuoy® connection is a novel system that integrates the mooring, anchoring system and the electric cable in a single point (single point mooring – SPM), allowing faster connection of floating platforms.

- Single Point Mooring to allow weathervanning (no active yaw)
- Mini-TLP mooring system to reduce platform weight and ballast
- Low-cost & efficient connection
- Single anchor point, reducing footprint & facilitating installation

This PivotBuoy® system is integrated in the X30 platform, an experimental downscaled (1:3) version of the X90 platform concept. This is a novel system that integrates the mooring, anchoring system and the electric cable in a single point mooring, allowing faster connection of floating platforms. In this way, it was kept in mind that the full-scale system aims to enable installation of existing 6MW wind turbines as well as large-scale 10-20MW in the long-term. To this end, and whenever possible, subsystem design tried to avoid design choices that limited scalability and went instead for the solution that seemed best for the full-scale system, even if it was not the cheapest or optimal solution for the scaled down version.

The design evolved from the concept design (April 2018), defined for the proposal stage; to the preliminary design (July 2019) and finally to the detailed design (March 2020). This iterative evolution, from the initial to the final result, is depicted in Figure 2.

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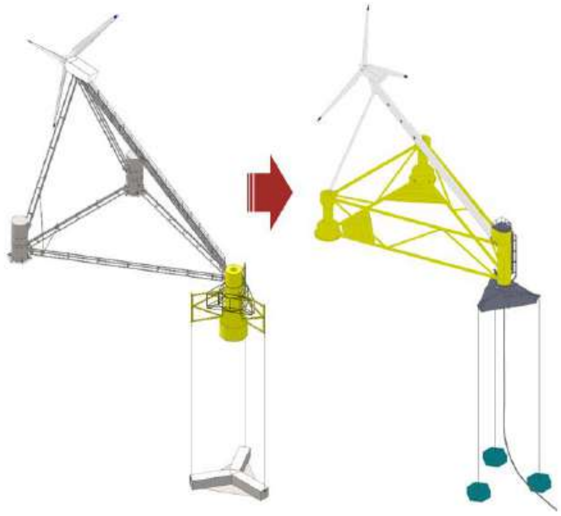

Figure 2. Concept design of PivotBuoy® and X30 floating platform (left) and its evolution to the detailed design (right)

During the design review process, several review meetings were arranged with all consortium partners:

- Preliminary Design Review (PDR) – July 17-18th, 2019.
- Detailed Design Review 1 (DDR-1) – December 5th, 2019.
- Detailed Design Review 2 (DDR-2) – March 4-5th, 2020.

The DDR meeting was split in two separated stages (DDR-1 and DDR-2), so that DEGIMA (manufacturing partner and WP3 leader), could start purchasing materials and manufacturing some of parts earlier.

As above shown, the design has been evolving during the preliminary and detailed design phases, since the cost reduction targets of the project are based on a thorough "design for manufacturing" philosophy.

Preliminary design for 10-20MW systems

PivotBuoy® project developed the design, manufacturing, assembly, installation and operation of the X30 model, which is the 1:3 part-scale model floating offshore wind platform prototype. In this platform it has been installed a 225kW downwind turbine. After completing the part-scale design, the learning was incorporated to scale up into a X140 full-scale floating platform design using the developed PivotBuoy® technology. This platform is designed to accommodate turbines in the range of 10-20MW and it provides a preliminary design of the X90 platform (for a 6MW turbine) to show the positive scalability of this innovative solution.

Figure 3. Scalability from the current part-scale prototype (X30), to 6MW (X90) and 14MW design (X140)

One of the main advantages of the proposed structural design is precisely its scalability for larger turbines. Since the developed solution avoids the usage of traditional vertical tower, it reduces the large bending moments that increase with the cube of the rotor radius. With the tripod configuration loads are transmitted in tension (and compression) and the dimensions, weight and costs of the proposed platform scales sub linearly when compared to the turbine rating, bringing economies of scale with usage of larger turbines. There are other relevant cost centers, such as installation, subsea cable interconnection, etc. which also benefit, in cost per MW installed, when scaling up the turbine and floater size. Additionally, due to its downwind configuration, the system allows for the blades to be lighter, longer and cheaper as they can bend away from the structure. This will be another key advantage in the long-term cost reduction required to make floating offshore wind competitive.

The following table summarizes the main parameters for both models comparing its main characteristics.

Parameter	**X30**	**X140**
Turbine capacity [-]	225 kW	14 MW
Hub height (from water level) [m]	25	138
Length (between axes of columns & Pivot Column) [m]	34	<100
Platform width (between column's axes) [m]	25	<100

Figure 4. Main dimensions of the platform models (dimensions for X140 are approximate but not the actual dimensions with design optimization loops being carried out and due to confidentiality)

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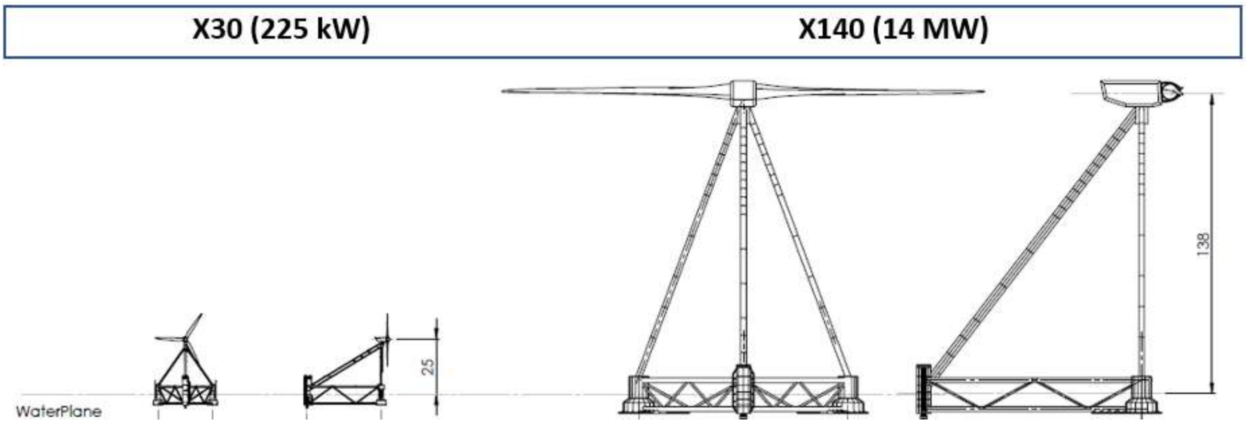

Figure 5. General assembly drawings of X30 (left) and X140 (right) concept designs

WP2 Conclusions

The deliverables produced as part of WP2 have contributed to the success of the PivotBuoy® project by providing the design of the X30 platform unit before its manufacturing, assembly and installation. Furthermore, WP2 deliverables provide valuable input for the development of full-scale platform designs for 10-20MW turbines.

It is recommended that the WP2 deliverables are used as guidance for future development of floating platforms and their subsequent subsystems during the designing phases.

2.2 WP3 – Subsystems Manufacturing, Assembly and Acceptance Testing

Overview

Work Package 3 (WP3) "Subsystems manufacturing, assembly and acceptance testing" involved the manufacturing of the PivotBuoy® system and X30 floater at DEGIMA and the factory acceptance testing (FAT) of the key components. It also the included the transportation to a local shipyard at the Canary Islands so that the assembly and site acceptance testing (SAT) could be performed before the deployment at PLOCAN testing area.

The specific objectives of WP3 were:

- Design the manufacturing and assembly plan of the system.
- Ensure environmental, health and safety aspects are considered.
- Procure and manufacture the parts of the PivotBuoy system.
- Perform factory acceptance testing (FAT) for key components.
- Assemble and test the system before deployment in site (PAT: Portside acceptance testing).
- To prepare an industrialization plan for serial production of large farms.

WP3 has been led by DEGIMA with support and contribution from X1 Wind, ESM, PLOCAN, INTECSEA, EDP CNET and DNV GL. The tasks and deliverables defined under WP3 are depicted in Figure 6.

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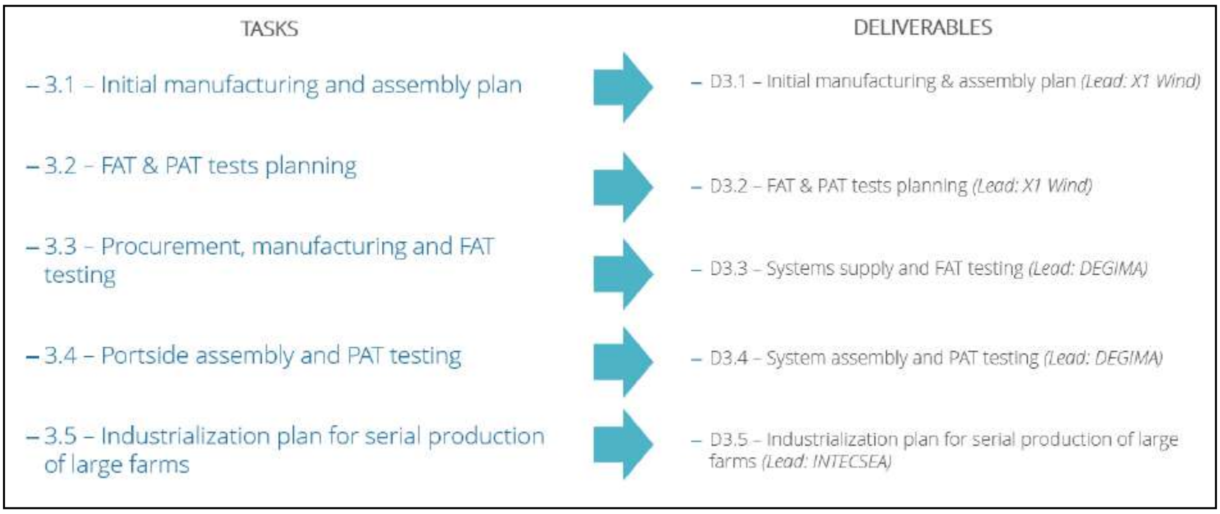

Figure 6. WP3 tasks and deliverables overview

<u>Initial plan: manufacturing, assembly and tests</u>

A first manufacturing and assembly plans, as well as FAT and PAT tests plans, were proposed with detailed a step-by-step planning of how components would be manufactured and assembled, based on the inputs from the preliminary design of the system, so that a feasible manufacturing and assembly process were in place at an early stage. Then it continued in parallel during the rest of the design phase, since the cost reduction targets of the project were based on a through "design for manufacturing" philosophy, seamlessly integrating manufacturing and assembly considerations into the design process.

<u>Systems supply and FAT testing</u>

Several partners and suppliers were involved in this stage. Furthermore, the manufacturing and the tests have been realized in different locations depending on the element. Thus, the main involved consortium partners are the following:

- DEGIMA, that manufactured all the main structural steel components of the PivotBuoy and X30 floating unit in their workshop at Santander (Spain).

- ESM, that manufactured the elastomeric components for the coupling system and tested then the system once assembled in their facilities at Heppenheim (Germany).

- X1 WIND, that was responsible for purchasing the rest of the components and contracting other suppliers that have either manufactured other parts or performed the necessary tests to ensure the appropriated quality of the system.

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Figure 7. Parts being manufactured at DEGIMA

FAT of key components were carried out at the manufacturing facilities to ensure quality control. Prior to shipping the parts to Gran Canaria, a pre-assembly test was performed at DEGIMA to ensure that manufacturing tolerances were met and that no misalignment issues would arise during the assembly phase.

After each component was manufactured and tested, they were all sent to Gran Canaria and gathered at HIDRAMAR SHIPYARDS, where the prototype was going to be finally assembled prior to its installation. The most challenging shipment was sending all steel components from Santander to Gran Canaria. Thus, PivotBuoy and X30 floater parts were loaded dismantled in blocks on a cargo vessel.

Figure 8. Calypso cargo vessel

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Figure 9. Different blocks being loaded / unloaded at the port

The V29 VESTAS downwind turbine was directly purchased by X1 WIND. The main gearbox, as well as other components, were adapted to run in downwind configuration.

Figure 10. V29 turbine at the yard's warehouse

<u>System assembly and PAT testing</u>

After each component was manufactured, they were all sent in blocks to Gran Canaria and gathered at HIDRAMAR SHIPYARDS, where the prototype was finally assembled prior to its installation. Thus, the main stakeholders involved in this stage were X1 WIND and HIDRAMAR, although there were some other involved suppliers.

Figure 11. Parts being unloaded and positioned

The assembly was done in an area in the dock with enough space for the platform assembly and the cranes movements. Next to the assembly zone, HIDRAMAR had a covered workshop that was also used as a warehouse to gather and store the different subcomponents and supplies that were sent from mainland Europe to the Canary Islands. Initially, the three main columns were positioned, and then the pontoons were cut, positioned and welded; forming a full structural triangle. Afterwards, the three masts were installed, as well as the turbine's nacelle on the top of them.

Figure 12. Assembly steps and load-out

The launching was the most important operation conducted at the yard, so many port assembly tests were performed on some parts before it, ensuring that the platform would perform as expected once it would be in the water. Furthermore, an extensive preparation was carried out in the yard and on the platform before the operation. The load-out was performed with two cranes lifting the platform in parallel. The first step was to approach the platform to the quay, then the PivotTop was positioned in cantilever before the full platform was floated off.

Figure 13. Platform moored at quay after load-out

Once the platform was in the water and properly moored, the last step was the rotor assembly. First, the rotor was assembled on the floor, and afterwards it was lifted and assembled to the nacelle.

Figure 14. Rotor assembly

Once assembled, both mechanical, electrical, control systems and instrumentation were tested at port (PAT), in ideal controlled port conditions prior to commissioning the system at PLOCAN.

Regarding the gravity anchors, the three concrete blocks were directly manufactured at the yard. The tethers and shackles for connecting them to the floating platform were also left pre-installed.

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Figure 15. Concrete block of the gravity anchor

Industrialization plan for serial production of large farms

Once the manufacturing and the assembly of the scale prototype were finished, a generic industrialization plan for the serial production of full-scale PivotBuoy systems for commercial scale offshore wind farms was developed based on the lessons learned during the project implementation. The focus of this industrialization plan was the reduction of the time required to obtain materials and components, to fabricate the main structure, to assemble and launch the structure and to prepare the fully assembled floating offshore wind unit for installation offshore. The time required for these activities ('lead times') and the associated supply-chains currently present a barrier for full-scale floating systems compared to fixed foundation systems.

To reduce the lead times, the production line shifts from a 'one-off' production to a production line including expanded group of suppliers, secondary fabrication sites and one or more primary assembly yards. The growing number of involved parties and associated material movements increase the logistical complexity of the overall production process. To identify critical points in the process, the criticalities of the following aspects are assessed: system components, fabrication & assembly sequence, and full-scale launch & installation.

Figure 16. Render of a primary assembly yard

In the system component assessment, the different components are rated on fabrication, transportation, and storage criteria to identify critical components. It was concluded that due to PivotBuoy's highly modular design, most components are not expected to be critical to the industrialization when qualified fabricators are available. However, the handling and transportation of the pontoons becomes complex for full-scale systems due to their slenderness and long dimensions. Three methods for fabrication and transportation were discussed, where ultimately the final choice is

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a trade-off between complexity of transportation, required operations and available space at the primary assembly yard.

As a result of PivotBuoy's 'design for manufacturing' philosophy, few criticalities are observed at the supplier and secondary fabrication site level. Due to the high modularity and compact dimensions of the individual system components, each separate component can be fabricated by a broad range of secondary fabrication sites and transported to the primary assembly yard. This flexibility allows the utilization of long-term regional suppliers together with qualified local project-specific suppliers.

The increased dimensions of the full-scale PivotBuoy (vs. the X30 prototype) and number of units typically required for a commercial scale floating wind development will require large assembly and storage areas at the primary assembly yard. In the final industrialization plan, the selection of sites will be a trade-off of many factors such as budget, available local infrastructure, and local governmental rules. It was noted that the high modularity of the PivotBuoy concept conveys a significant advantage in terms of industrialization with respect to most competitors. The supply chain can be easily spread out and tailored to different project sites, which is more difficult for other concepts that require specialized fabricators and fabrication sites due to their larger dimensions and associated handling requirements.

Regardless of the final primary assembly selection, several final steps are required to prepare the PivotBuoy for installation. When the floater is fully assembled, it will be launched and towed to the assembly anchorage. Two launch methods will be assessed: by semi-submersible barge and by slipway. The final method selection will be a trade-off between CAPEX, OPEX and available infrastructure. To increase the flexibility of the production sequence, the assembled floaters will be stored at the assembly anchorage prior to outfitting. After outfitting, the finalized systems will be towed to the marshalling anchorage. Here a buffer of PivotBuoys ready for installation will be gathered, to be installed when anchoring systems are ready offshore and conditions at site are appropriate.

It is desirable that all the final preparatory steps (assembly anchorage, outfitting and marshalling anchorage) can be located near each other and as close as possible to the project site. However, if the project conditions don't allow for this setup, these steps can also be spread over a wider geographical area. This will increase the required transportation distances but improves applicability for a wider range of project sites. Ultimately, the location selection will depend on whether there is availability of sheltered waters for anchorage nearby the primary assembly yard.

Concluding, the industrialization plan for a full-scale commercial windfarm development using PivotBuoy will not be governed by capacity of a single fabrication site, but rather will be an optimization of logistics. By taking measures to optimize the industrialized supply chain by clever use of the modularity of the PivotBuoy system, it is expected that the lead times can be reduced significantly, thus overcoming the barriers perceived for full-scale commercial implementation of floating offshore wind.

<u>WP3 Conclusions</u>

The deliverables produced as part of WP3 contributed to the success of the PivotBuoy® project by providing the explanation and steps of the manufacturing and assembly stages of the X30 platform unit, after its design and before its installation. Furthermore, WP3 deliverables provide valuable input for the development of full-scale platform industrialization plan for serial production of large farms for 10-20MW turbines.

It is recommended that the WP3 deliverables are used as guidance for future development of floating platforms and their subsequent subsystems during the manufacturing and assembly phases.

2.3 WP4 – Installation, Testing and Monitoring in Relevant Environment

Overview

Work Package 4 (WP4) "Installation, testing & monitoring in relevant environment" involved the installation of the PivotBuoy® system and X30 floater at PLOCAN test site. The O&M stage after the deployment was also considered, as well as the monitoring of the system and the environment.

The specific objectives of WP4were:

- Define the environmental conditions at the site.
- Define and execute the installation process.
- Define test and validate the 1:3 scale PivotBuoy system in a relevant environment.
- Test different preventive and corrective operation and maintenance strategies.
- Monitor and gather data for the environmental, performance and reliability assessment.
- To build recommendations for the installation, operation and monitoring for future projects.

WP4 was led by PLOCAN with support and contribution from X1 Wind, WAVEC, INTECSEA, EDP CNET, DNV GL UK and DEGIMA. The tasks and deliverables defined under WP4 are depicted in Figure 6.

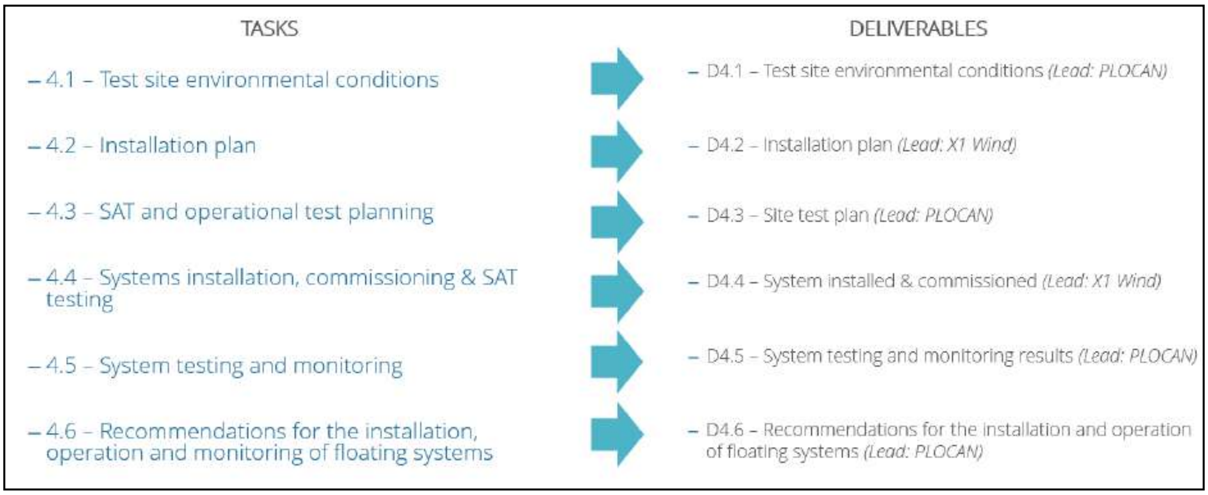

Figure 17. WP4 tasks and deliverables overview

Test site environmental conditions

Initially, the environmental conditions of the location where the system would be deployed and tested were fed into the design process in WP2 and thus guaranteeing that the prototype and its mooring system were properly dimensioned and arranged. This included bathymetric data, seabed conditions,

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wave, currents and wind regimes, and other relevant data for the environmental characterization such as water quality or submarine noise.

Within the project, two environmental monitoring campaigns were completed, one before the X30 prototype installation at PLOCAN's test site, and a second one during the prototype operation phase.

Initial plan: installation, SAT and operational test planning

A first detailed step-by-step plan for installation, site acceptance tests (SAT), operational and testing was developed after the deployment based on the inputs from the preliminary design of the system, so that a feasible installation was in place at an early stage. Then it continued in parallel during the rest of the design phase, integrating installation considerations into the design process in line with the concurrent design philosophy of the project. This plan also fed the testing plan for the commissioning and operation of the platform on site, including the SAT as well as the environmental monitoring campaign and O&M tasks after the commissioning. The availability of weather windows for each operation was also assessed.

Systems installation, commissioning & SAT testing

Once the floater was assembled and tested at the port, the installation at PLOCAN test site was performed in several steps. First, the anchor system, formed by three concrete blocks, was installed. Before being towed to PLOCAN test site, each block was laid and stored on the seabed in a selected available area at Las Palmas port. Then, VB BEVER tugboat, a 70-ton BP vessel that was available at that time at Las Palmas port, picked and towed one block per day till to PLOCAN site.

Figure 18. Gravity anchor installation

Also, TRAMES UNO was used as an auxiliary vessel for the placement of the blocks, since the tugboat without DP could not lay them with the needed accuracy. TRAMES UNO is a local workboat that can provide support during the operations to install the X30 platform, perform the cable lay or assist other vessels; its base port is Taliarte, the closest to PLOCAN. In parallel with the previous operation, PLOCAN platform was being setup for the cable installation. Thus, after the anchor system installation, the umbilical cable was laid on the seabed also by TRAMES UNO. This cable connects the floater with PLOCAN offshore platform.

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Figure 19. Cable installation

Afterwards, the X30 floating platform was towed and hooked-up on the previously installed subsystems. The main stakeholders in this stage were X1 WIND, PLOCAN and TRAMES which were involved in each operation. Also, some other suppliers were specifically involved in each step. The X30 platform installation was performed in two stages, each one being a 1-day operation. On the initial day, two maneuvering vessels unmoored the platform from the quay and guided the platform through Las Palmas port until the structure was hooked to the two vessels that performed the towing operation. The main towing vessel was the VB BALEAR and the auxiliary vessel the VB ALEGRANZA. The latter was connected to the platform through an auxiliary line tied from the stern of the platform to the vessel's bow. This vessel also served to transport the team from Las Palmas to PLOCAN while supervising the towing. The tow to site took near 3 hours. In parallel to the above operations, that same morning TRAMES DIEZ vessel (similar to TRAMES UNO previously used as an auxiliary vessel during the anchors installation), was pre-moored at the expected X30 floater position at PLOCAN, waiting for the floater's arrival. Once the floater was at the installation point, TRAMES DIEZ took the command of the operation; so the floater was connected to it, and the vessel set the X30 platform swung to its expected position while it was still connected to the main tug (VB BALEAR). Once in position, the two towing vessels (main & auxiliary) went back to Las Palmas port; so the X30 floater was only hooked by TRAMES DIEZ, which performed the rest of the operation, connecting the floater to the 3 tendons and gravity blocks previously installed.

Figure 20. X30 platform being towed to PLOCAN

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Figure 21. Hook-up

The second day the cable pull-up was performed. The end of the cable, which was laid during its installation, was hooked and approached to the lower part of the Pivot Bottom, where there was a hole to enter it throughout the yaw axis and up to the Pivot Top. The cable was pulled up with a winch until the mechanical room and once there, the electrical wires of the cable were inserted in the slipring. Thus, X30 floater was ready for electrical connection and the second journey of the towing and hook-up operation finished.

Figure 22. Cable pull-up

Finally, once the platform was installed, commissioning and site acceptance tests (SAT) were performed to ensure that the systems (mechanical, electrical, control and instrumentation) were working as intended and to validate the platform in operational offshore conditions. The most relevant results are those were proving the weather vanning of the system and the stability conditions of the platform.

Figure 23. X30 floater installed

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System testing and monitoring

Once each subsystem was installed and commissioned, the testing campaign at PLOCAN to validate the project key performance indicators (KPIs) started. Thus, performance, reliability and environmental data were obtained with both X30 platform instrumentation, instruments deployed by PLOCAN for onsite monitoring and periodic visits. This data is crucial for the validation of the simulation models for WP5, and it can be split into the following three groups: performance data, reliability and maintainability O&M data and environmental data. Also, different tests covering a diverse range of O&M activities were carried out to validate assumptions regarding weather windows and expected periodic O&M activities.

The first testing phase included the validation of the X30 platform PivotBuoy® system without power production. Below it is depicted the alignment of the platform with the wind through from Nov-March. As it can be seen, alignment is usually within +/- 10° and there no points outside the range over 5 m/s. Most of the time the platform has less than +/- 5° of misalignment, specially at higher wind speeds.

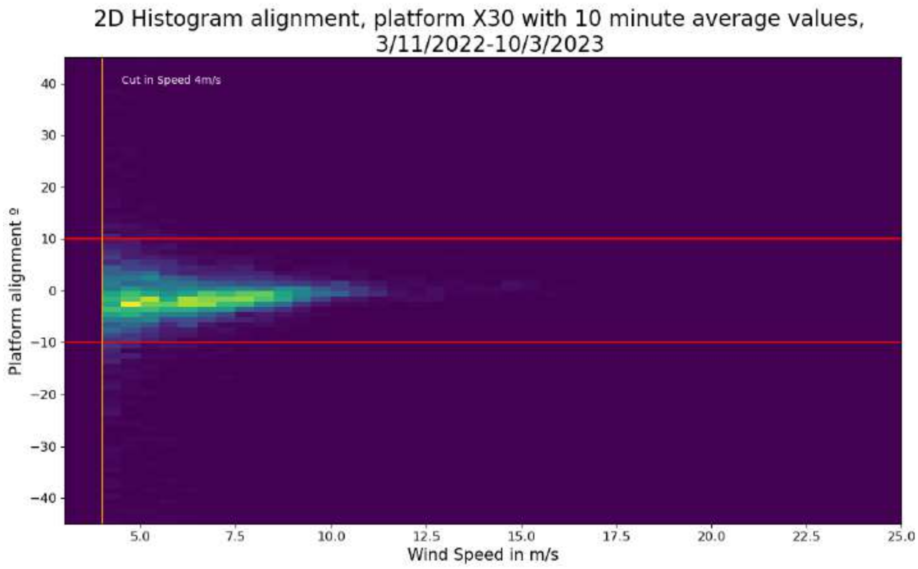

Figure 24. Histogram alignment, X30 platform 10-minute average values from 03/11/2022 to 10/03/2023

Furthermore, a comparison of the alignment of the X30 with the LiDAR-based Senvion 3.2MW turbine is shown in Figure 25. It can be seen that the X30 platform with weather-vaning aligns at least as good as or even better than the other one with active yaw.

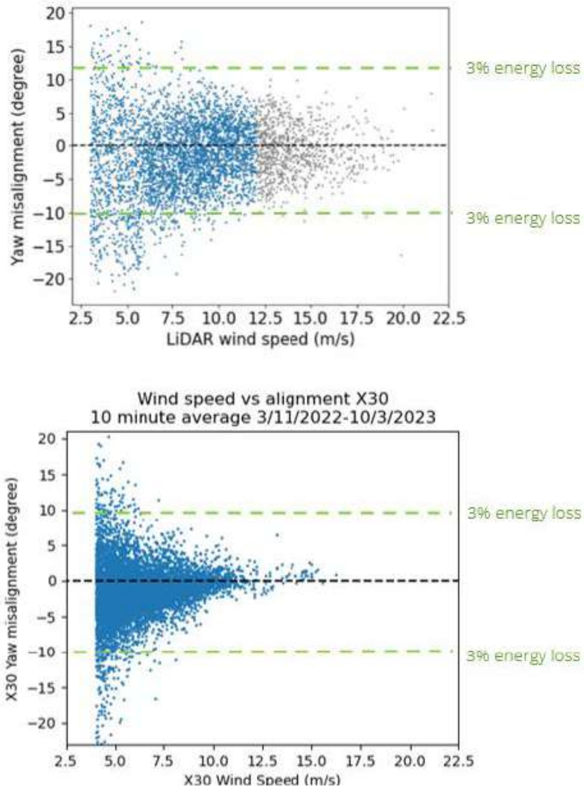

Figure 25. Yaw misalignment comparison

Regarding the extreme weather conditions, the biggest faced storm (December 27th, 2022) had the following characteristics:

- Hs = 3,78 m
- Hmax = 6,72 m (equivalent to Hmax = 20,16 m for an equivalent 1:1 scale platform)
- Wind speed max. = 18 m/s

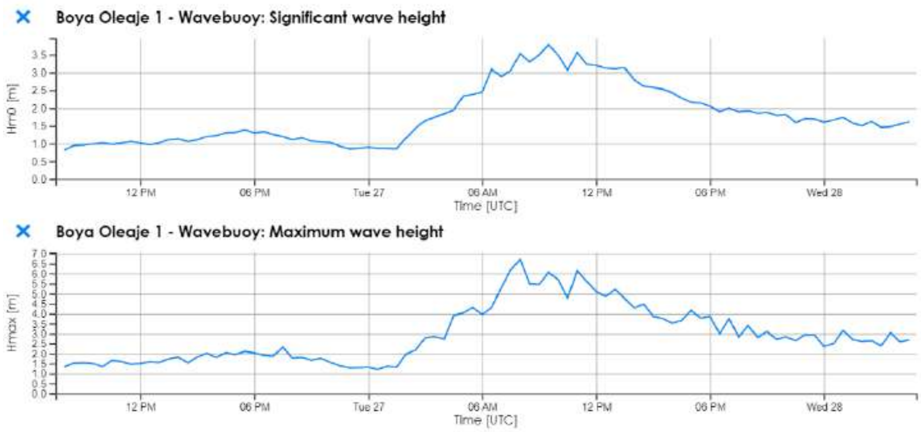

Figure 26. Weather conditions on December 27th, 2022

During that day, X30 floating platform behaved well, as the pitch and roll degree values presented in Figure 27 show. More information on the data for model and platform behavior validation can be found in WP5.

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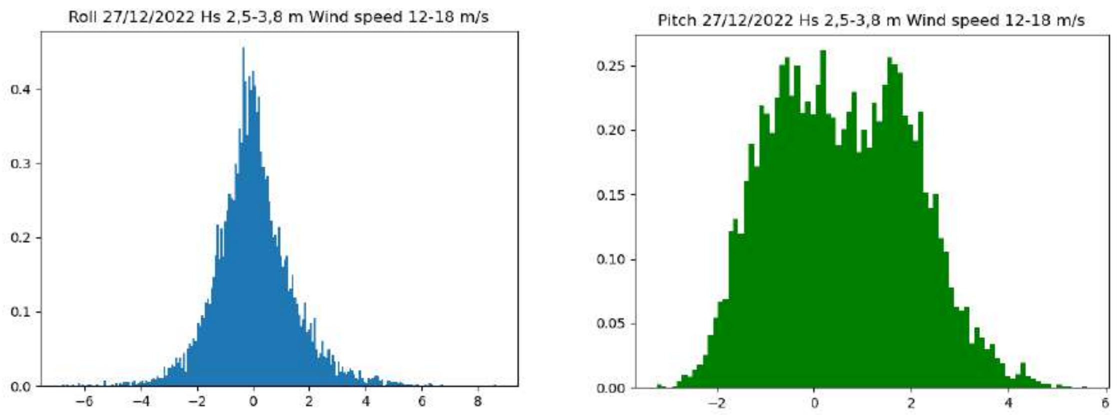

Figure 27. Pitch and roll during December 27th, 2022.

Figure 28. X30 floating platform during December 27th, 2022 (see video [here](#)).

Finally, once the Smart Grid at PLOCAN test site was ready, on March 3rd started the last phase of the testing plan which is the system validation with power production which will last until May (see video of the turbine commissioning). Initial results show very good power performance with excellent alignment with the wind (as in the previous tests without production), low accelerations and pitch angle during operation, and power output above the V29 power curve at equivalent wind speeds for existing onshore wind turbines. The data is being used to validate simulation models and will be integrated into the final report to EC due in May 2023.

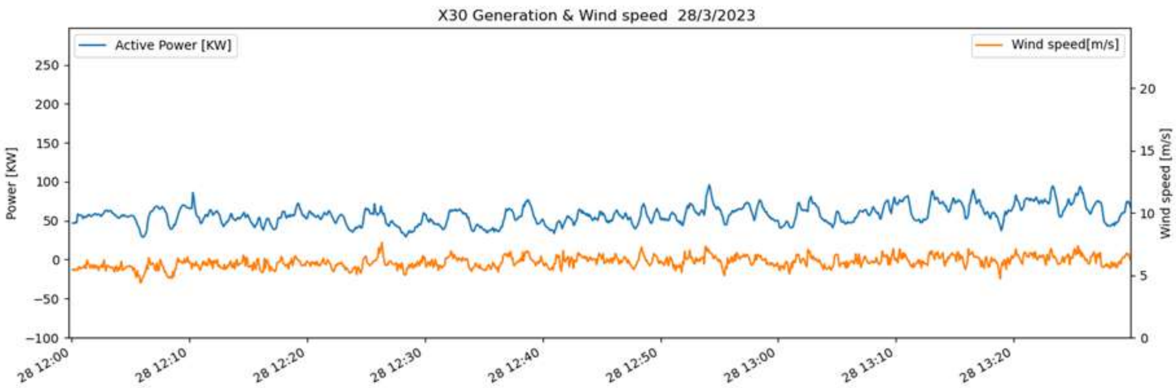

Figure 29. Power output reading X30 platform SCADA on March 28th for 6 m/s mean wind speed.

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Recommendations for the installation, operation and monitoring of floating systems

At the end of the testing period, the results and learning of all WP4 was summarised into a final report providing best practices for the development of future floating wind farms, this also included the lessons learned during both the installation and commissioning, as well as during the environmental monitoring and O&M of the system.

WP4 Conclusions

The deliverables produced as part of WP4 contributed to the success of the PivotBuoy® project by providing the explanation and steps of the installation, commissioning, and testing stages of the X30 platform unit, during its installation and all the operational stage. Furthermore, WP4 deliverables provide best practices and valuable input for the development of installation and operational tests plans for future full-scale floating wind farms.

It is recommended that the WP4 deliverables are used as guidance for future development of floating platforms and their subsequent subsystems during the installation, commissioning, environmental monitoring, operation and maintenance stages.

2.4 WP5 – Numerical Modelling and Performance Assessment

Overview

The aim of WP5 was to create, benchmark, and validate numerical models of the PivotBuoy 1:3 prototype (the X30) and a large-scale PivotBuoy integration (the X140). The specific WP objectives were as follows:

- Set-up and calibrate numerical models with tank testing results.
- Optimize the design of the PivotBuoy 1:3 prototype for PLOCAN conditions.
- Optimize the design and of the PivotBuoy full-scale design for sea conditions in different regions.
- To simulate the integration of PivotBuoy in large scale 10-20MW floating platforms.
- To Benchmark of PivotBuoy versus other floating systems.
- To improve the state-of-the-art in numerical models with the cross-validation of three different numerical models and with results from real sea tests.
- Advance in best practices and standards for the assessment of floating wind systems.

All objectives achieved in this work package. The relevant results for each objective are presented below.

Set-up and calibrate numerical models with tank testing results

A tank test of the 1:50 scale model of the NREL 5 MW PivotBuoy concept was conducted at the ECN Hydrodynamic and Ocean Engineering Tank as part of the MaRINET2 programme. Tests were performed in 4 main categories: transient free-decays, regular and irregular waves without wind, and regular and irregular waves with wind. An image of the tank test is given in Figure 30. The hydrodynamic parameters of the OrcaFlex model were calibrated using the tank-testing data, and the

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response-amplitude operators (RAOs) in the heave direction were shown to have very good correlation after tuning (Figure 30, right plot).

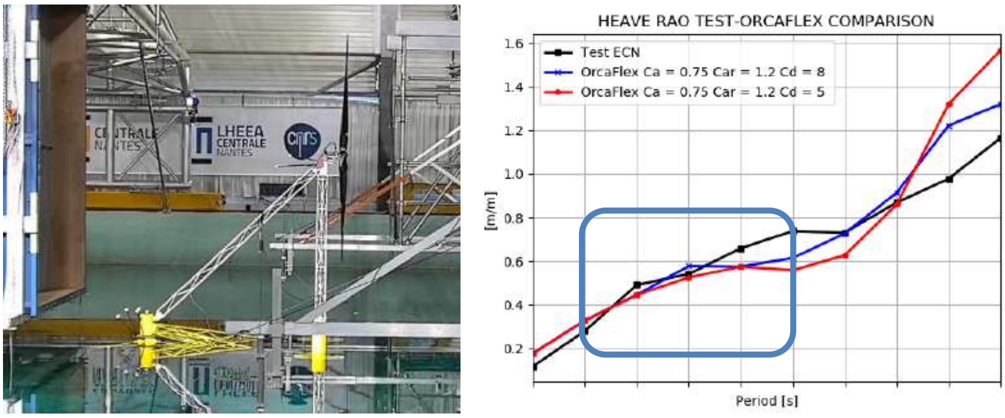

Figure 30. Tank test conducted at ECN in 2019 (left) and heave RAOs after hydrodynamic tuning. Blue box in right plot indicates wave periods of interest.

<u>Optimize the design of the PivotBuoy 1:3 prototype for PLOCAN conditions</u>

The X30 was modelled in both OrcaFlex and HAWC2 for detailed loads simulations for the PLOCAN site. The two codes were used and cross-verified, as HAWC2 has advanced turbine dynamics whereas OrcaFlex has advanced hydrodynamic modelling. OpenFAST was also considered but it was ultimately removed from the project as it assumes a tubular tower in the substructure, which the PivotBuoy concept does not have.

The X30 was modelled in multiple stages: first in an initial concept design and then iteratively updated through the preliminary and critical design reviews (PDR and CDR) to the final pre-manufacturing specifications (Figure 31).

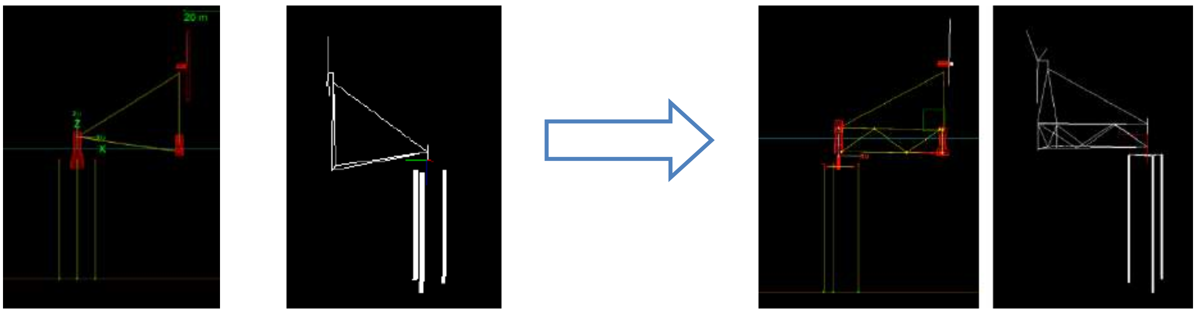

Figure 31. Concept design (left) and pre-manufacturing design (right) of model in OrcaFlex (red/yellow) and HAWC2 (white).

To provide input to the PDR and CDR, the site-specific extreme and fatigue loads at the connection point between the platform and the nacelle were calculated. The V29 rotor was modelled in HAWC2 using publicly available data, and site-specific design load cases (DLCs) for the PLOCAN test site were defined and simulated. An example of the fatigue and extreme loads for the PLOCAN site is shown in Figure 32.

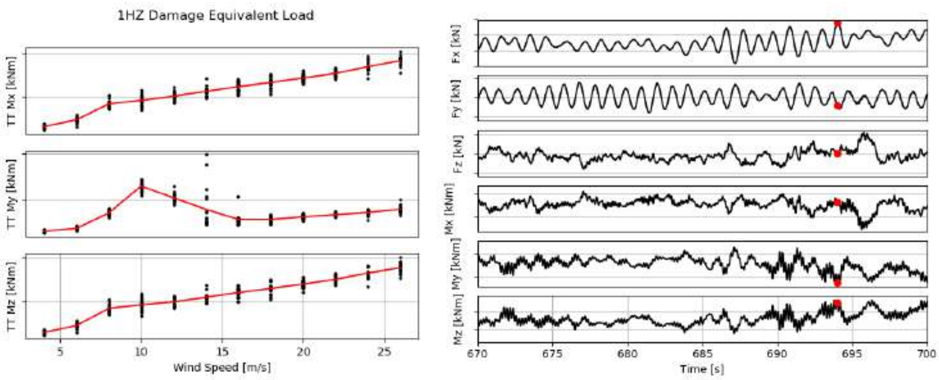

Figure 32. Fatigue (left) and extreme (right) design loads for the PLOCAN test site.

After the two design reviews, the model was updated based on the changes of the platform, and the models in the two codes were cross-verified to ensure adequate accuracy.

The potential impact of a 50-year extreme wave was simulated by WAVEC using the CFD software ReFRESCO. The simulation modelled the PivotTop as a simple cylinder and extracted loads at different vertical stations along the PivotTop. Snapshots of the breaking wave and the resulting shear force are shown in Figure 33. These shear forces were used in the final design process for the PivotTop.

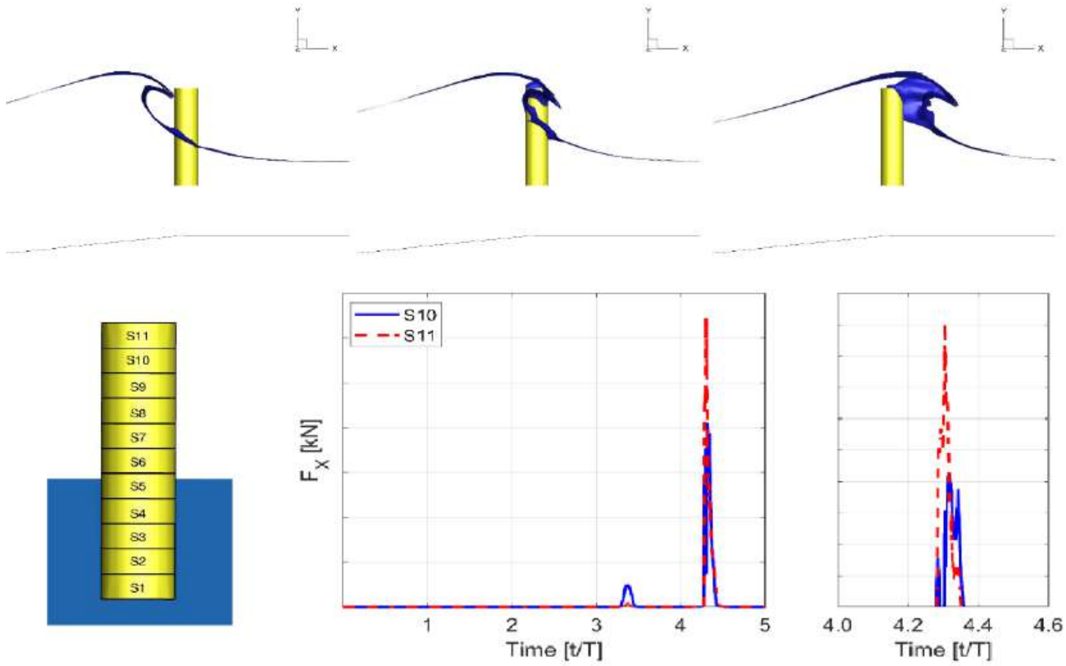

Figure 33. CFD simulations of a 50-year extreme wave using ReFRESCO. Bottom left: PivotTop modelled as a simple cylinder, and loads extracted from different vertical locations. Top: Snapshots of the breaking wave impacting the PivotTop at different times. Bottom right: time series of the shear force at two sections of the PivotTop.

<u>Optimize the design and of the PivotBuoy full-scale design for sea conditions in different regions</u>

The X140 platform was implemented in both HAWC2 and OrcaFlex and simulated at three sites: Begur (Mediterranean), Silleiro (North Atlantic) and Canary Islands. Silleiro was generally found to have the largest extreme loads due to the more severe wind and wave storm conditions. The performance of the platform was generally satisfactory on all relevant metrics, but the comparisons between sites

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highlights the importance of tailoring the design of the platform to each site. An individual pitch controller (IPC) was implemented and found to reduce yaw misalignment significantly.

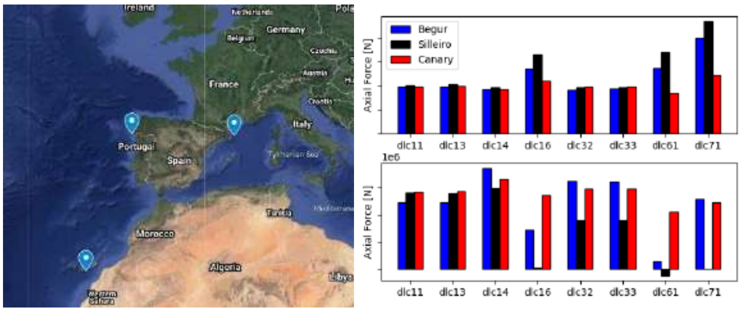

Figure 34. Left: map of site locations. Begur, in the Mediterranean, Silleiro, in the North Atlantic, and Canary Islands. Right: maximum (top) and minimum (bottom) extreme axial force in the TLP.

<u>Simulate the integration of PivotBuoy in large scale 10-20MW floating platforms</u>

The integration of the PivotBuoy concepts in other floating energy sectors was evaluated in terms of several different metrics, including current TRL of the sector, market size, etc. The resulting evaluation is shown in Figure 35. As expected, the floating offshore wind sector is most suitable for the PivotBuoy concept, as it ranks superior to both tidal and wave energy in all metrics except for current TRL. Tidal energy is a close second, however, performing almost as well as wind energy in many metrics.

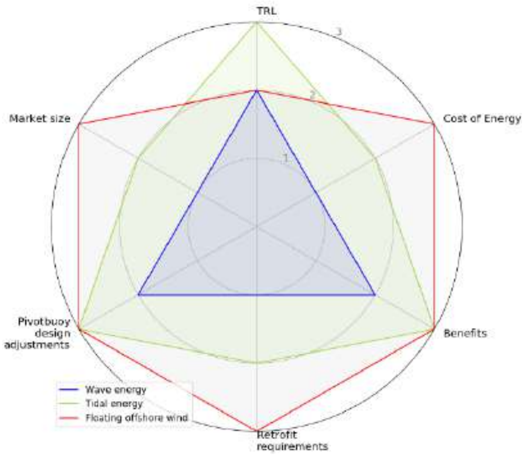

Figure 35. Integration of PivotBuoy in floating energy sectors.

<u>Benchmark of PivotBuoy versus other floating systems</u>

The X140 was benchmarked versus three other floating platforms whose designs were based off the same rotor: the UMaine (Volturn) semisubmersible, the ActiveFloat design, and the WindCrete spar buoy. The platforms were generally found to have similar performance, but the X140 was significantly lighter: approximately 3.5 to 7.5 times lighter than the UMaine and WindCrete models.

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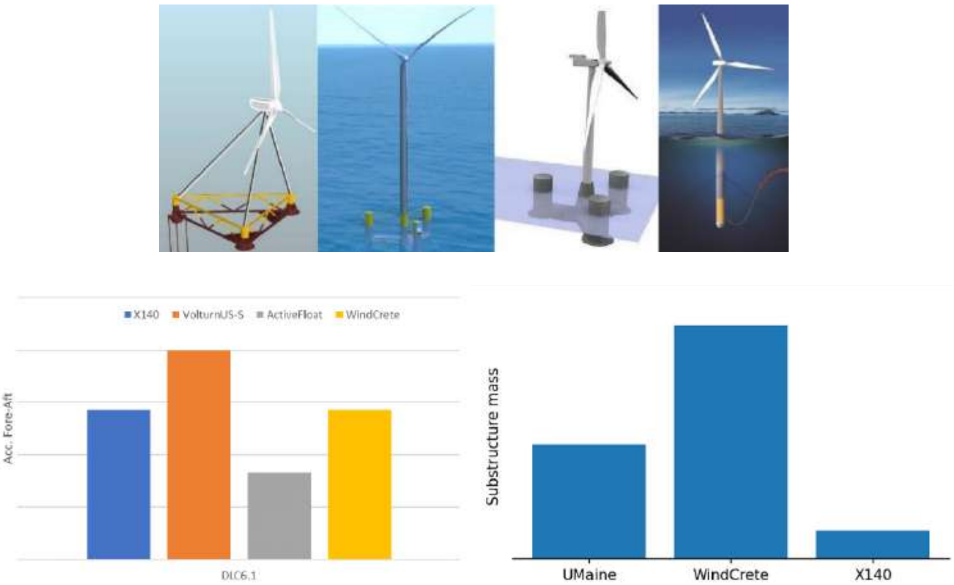

Figure 36. Top: diagrams of the four compared concepts. From left to right, UMaine (Volturn) semisubmersible, the ActiveFloat design, and the WindCrete spar buoy. Bottom left: comparisons of maximum fore-aft acceleration for the different concepts. Bottom right: normalized mass of the substructure.

<u>Improve the state-of-the-art in numerical models with the cross-validation of three different numerical models and with results from real sea tests</u>

Unfortunately, due to delays in the installation and commission of the turbine, production data, which was only available from March 2023, is not included in this document. However, extensive validation of the floater frequencies and on the wave parameters were completed. Limitations of the modelling aspects of OrcaFlex and HAWC2 have been identified. The platform is determined to behave extremely well, with low pitch and roll angles, and there is little deviations from the data to the models.

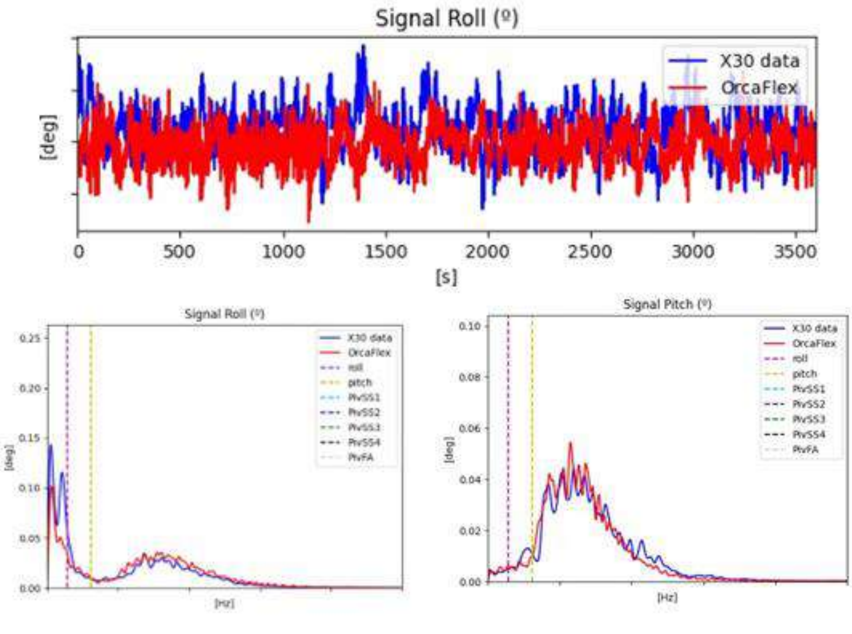

Figure 37. Comparison of data and OrcaFlex.

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Advance in best practices and standards for the assessment of floating wind systems

The work package has resulted in significant advances in the consortium's understanding of modelling floating platforms in general, and the PivotBuoy platforms in particular. A turbine module in OrcaFlex was released at the very beginning of the project and has been updated over the course of the work, and the comparisons with HAWC2 have provided insight into the subsequent changes in both aerodynamic loading and platform performance. The hydrodynamics in the HAWC2 code have also been improved in the course of the project, resulting in better cross-code comparisons and better sparring with the OrcaFlex results.

Lessons learned

The research activities and deliverables in work package 5 have led to the following key lessons:

- It is important to model the turbine and controller early in OrcaFlex and to cross-validate with other aeroelastic softwares.
- The PivotBuoy mooring system enables the use of standard fixed-foundation controllers, facilitating modeling and eliminating the need for complex controller adaptations that are an issue in other floaters due to the appearance of negative damping phenomena when using the standard fixed-bottom controller on a floating foundation.
- It is important to proceed with a dedicated tank testing campaign for each floater design to get an early model validation. The PivotBuoy project used data from a previous test campaign assuming that many of the results and most hydrodynamic parameters would be valid and skipped having a dedicated tank testing campaign also due to lack of time. However, a lack of direct data regarding floater RAOs is a shortcoming of this strategy.

2.5 WP6 – Risk Assessment including Reliability, Environment, Health and Safety

Overview

WP6 aimed to de-risk the PivotBuoy X30 system by identifying critical failure modes and analysing system reliability. Due to the very limited application of floating wind systems worldwide, there is only limited data available in the public domain on risks and failure modes specifically relevant for these systems. However, there is a wealth of experience and data available from cross-cutting fields in other relevant sectors. Regarding the PivotBuoy subsystem and its components, experience from the oil & gas sector, and particularly from the design, installation, and operation of Single Point Mooring (SPM) systems, Tension-Leg Platforms (TLP) and dynamic riser and cable systems, can be applied to identify potential risks. This experience data includes relevant information on failure modes and events.

The specific objectives of WP6 were:

- Identify critical failure modes and de-risk the development of the PivotBuoy system.
- Develop predictive maintenance strategies and analyse system reliability.
- Ensure that Environmental, Health & Safety regulations were followed.
- Ensure adequate environmental monitoring was in place.
- Establish maintenance methodologies relevant for single-point mooring systems.

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WP6 was led by Intecsea (a company in the Worley Group) with support and contributions from X1Wind, WAVEC, PLOCAN, EDP CNET, DNV UK, and Degima. The tasks and deliverables defined under WP6 are depicted in Figure 38.

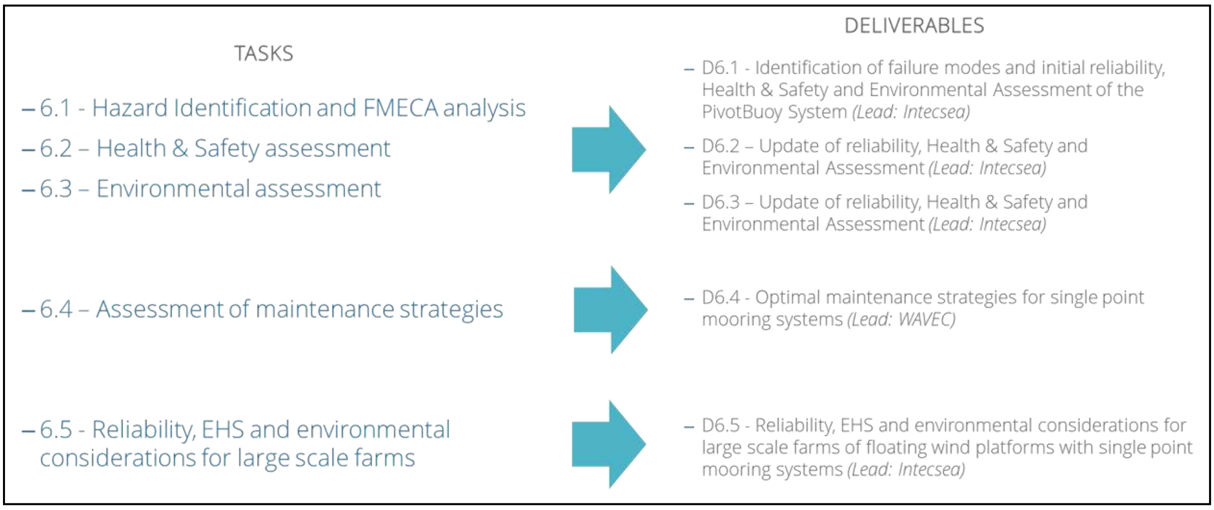

Figure 38. WP6 Tasks and Deliverables Overview

Risk Assessment Methodology

The general timeline for WP6 is shown in Figure 39. Work on Task 6.1 started during the preliminary design phase by performing a technology assessment for the concept system design applying the technology qualification methodology described in offshore industry recommended practice DNVGL-RP-A203. This resulted in a technology categorization rating for each major component of the PivotBuoy system. Subsequently, an initial Failure Mode Effect and Criticality Analysis (FMECA) was performed to chart the probability of system and component failure modes against the severity of their consequences. Both the technology qualification assessment and the FMECA are tools to support the systematic identification and management of technical risks during a project. As stand-alone documents (registers), they have limited value. However, they are highly valuable when integrated into the overall design process where they can be utilized to assess a developing design in terms of technical risks on a continuous basis. The continuous feedback allows risks to be 'designed out' at an early stage, which is the most effective means of risk reduction as well as the most cost-effective.

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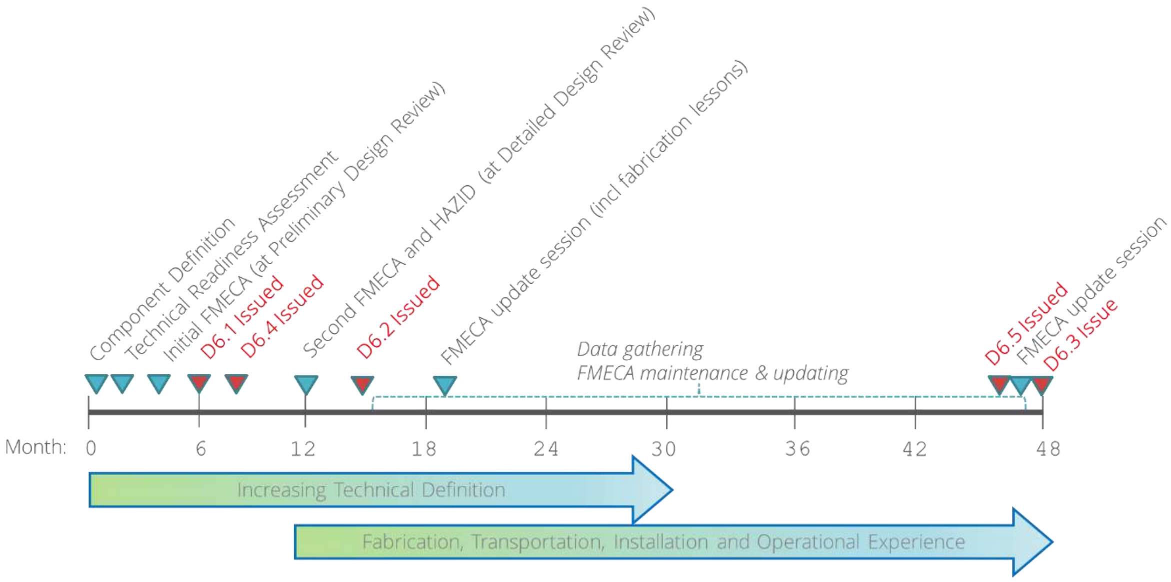

Figure 39. WP6 Timeline

The initial FMECA findings for PivotBuoy were fed into the detailed design phase so that the identified risks could be addressed and mitigated to a practicable extent. This initial work is presented in deliverable D6.1 "Identification of failure modes and initial reliability, health & safety, and environmental assessment of the PivotBuoy system", which was issued in September 2019 (M6).

The second deliverable under WP6 is D6.2 "Update of Reliability, Health & Safety, and Environmental Assessment of the PivotBuoy system", which was issued in June 2020 (M15). It documents the work performed to update, maintain and implement the results of reliability, health and safety, and environmental risk assessment up to the point of near complete design (Second Detailed Design Review, DDR2) and initiation of fabrication. The main vehicle for this effort continued to be the FMECA register, which was maintained as a 'live' document throughout the design process; i.e. the risk assessment was developed in parallel with the design itself. This was an interactive and iterative process whereby initial designs were assessed and associated risks were identified. The identified risks were then addressed in the design, and further rounds of FMECA sessions were held to review the status. Where justified, risk ratings were adjusted to reflect the mitigating actions taken, and new actions were assigned where appropriate.

After the issue of deliverable D6.2, various minor design optimizations were made while the procurement of materials and components started to allow initiation of the construction process (mainly at DEGIMA). A subsequent FMECA session was held in November 2022 (M20), to discuss minor design changes and fabrication aspects, but the main focus remained on risk-reducing measures for the installation and operational phases.

A final FMECA session was held in February 2023 (M47) to evaluate the feedback and lessons learned from the various development phases up to installation and commissioning (up to activation of the turbine). This final session resulted in the finalization of the FMECA register as reported in deliverable D6.3 "Final Reliability, Health & Safety and Environmental Assessment of the PivotBuoy system".

Separately from the FMECA, a Hazard Identification (HAZID) review was performed with a focus on the installation methodology. This was done on March 5, 2020, in conjunction with the detailed design reviews, and was attended by the consortium partners. The purpose of the HAZID was to identify the risks associated with the transportation and installation of the PivotBuoy X30 unit offshore Gran Canaria. A set of HAZID guidewords was used to stimulate the discussions and ensure the identification of typical risks. The HAZID register has served as input to the detailed installation procedures and was revisited during the review of these procedures.

FMECA

To prioritize the design development efforts for a technologically innovative offshore project, a method is required that not only categorizes the technology complexity but also considers the consequences of component malfunction on system performance and on the project in general. The selected failure mode identification technique for PivotBuoy is the Failure Mode, Effects and Criticality Analysis (FMECA) as described in DNVGL-RP-A203.

The FMECA method is most effective when applied early in the design process of an innovative project so that it focuses risk-reducing efforts where they have the most effect. Such early implementation was achieved for PivotBuoy, and the development and update of the FMECA during the project design phase were documented in D6.1, D6.2 and D6.3.

For the purpose of FMECA assessment, the PivotBuoy system was broken down into 9 main systems and 46 sub-systems. A total of 336 unique entries were defined, probability and consequence ratings were applied based on defined classes, risk ratings (low / medium / high) were assigned, and mitigating measures were defined for all risks deemed medium or high. During the course of the project, various entries were set to inactive, primarily due to changes in the design that made them irrelevant for the PivotBuoy X30 system. This left 295 'active' entries remaining in the final FMECA register. Note that the inactive entries are maintained visible in the FMECA register since they may be relevant for future designs (i.e. X90 – X140).

The FMECA process has been a collaborative effort with input from the consortium members. Sessions have been held both as part of planned project meetings and as stand-alone meetings. The results of these sessions have been documented directly in the FMECA register.

Figure 40 provides an example of the FMECA findings. On the left-hand side of the figure is a tabulation of the unmitigated risk ratings as presented in D6.1, i.e. early in the design process. On the right-hand side is a tabulation of mitigated risks from D6.2, i.e. late in the design process. In each figure the risk categories are color-coded : low=green, medium=yellow, and high=red.

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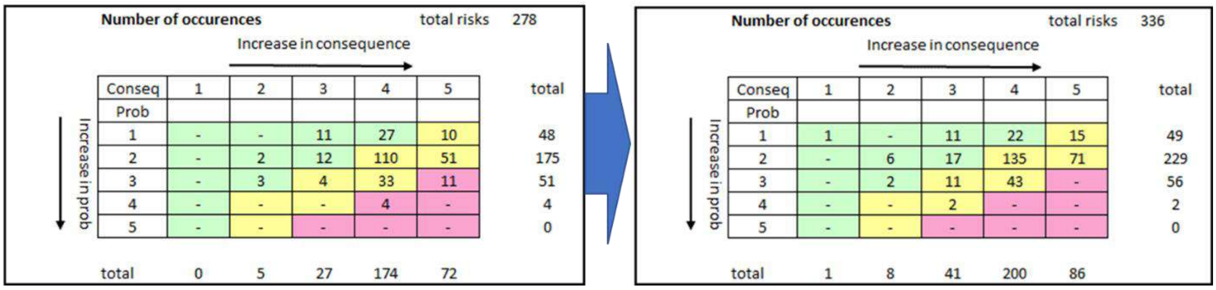

Number of occurences — total risks 278

Increase in consequence → ; Increase in prob ↓

Conseq / Prob	1	2	3	4	5	total
1	-	-	11	27	10	48
2	-	2	12	110	51	175
3	-	3	4	33	11	51
4	-	-	-	4	-	4
5	-	-	-	-	-	0
total	0	5	27	174	72	

Number of occurences — total risks 336

Increase in consequence → ; Increase in prob ↓

Conseq / Prob	1	2	3	4	5	total
1	1	-	11	22	15	49
2	-	6	17	135	71	229
3	-	2	11	43	-	56
4	-	-	2	-	-	2
5	-	-	-	-	-	0
total	1	8	41	200	86	

Figure 40. Tabulation of FMECA entries risk ranking; left from D6.1, right from D6.2

Figure 40 shows that the FMECA process has successfully reduced the number of higher-risk entries. By looking in detail at the mitigation actions taken for each entry in the FMECA register, it is also evident that the FMECA process has contributed to achieving a more robust, lower-risk design overall.

Risk to Environment

Risks to the environment were considered during the initial risk assessment activities; however, the technology assessment and FMECA processes (being based on reviews at the component level) do not always identify all relevant environmental risks. A separate desk-top exercise was therefore conducted with the specific objective of identifying environmental risks during the three main phases of the offshore project: the installation phase, the operating phase, and the removal phase. These risks have been considered during the design process and are being carried forward into the operational phase. A summary is provided in the table below.

Phase	**Risks**
Installation	• Potential for spills • Above-water noise emissions • Below-water noise emissions • CO_2 and NOx emissions • Disturbance of the seabed sediments and benthic species
Operations	*As for installation, plus:* • Vibrations • Harm to aquatic fauna (fish, cetaceans, etc.) • Harm to bird life • Interaction with other users of the marine space (fishing, shipping, recreation etc.)
Removal / Decommissioning	*As for installation*

Operations & Maintenance Strategies

As part of WP6, WAVEC assessed optimal maintenance strategies in relation to the PivotBuoy system. This assessment is documented in deliverable D6.4, which was issued in Month 8.

The operation and maintenance (O&M) of a wind farm has a significant impact on its overall costs and, ultimately, on the cost of the energy produced. The wind industry has recognized the importance of

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O&M and has been investigating how to optimize O&M operations, reducing their costs, and increasing overall farm availability.

For offshore wind farms, both fixed and floating, some of the main O&M cost drivers are the high vessel rates, site accessibility, and equipment failure rates (typically expressed in terms of the mean time between failure (MTBF) and the mean time to repair (MTTR)). An ideal O&M strategy is the result of an optimization of these parameters within certain constraints to achieve the lowest expected life-cycle O&M cost. However, this is not a trivial task. The vessel rates are not fixed throughout the lifetime of an offshore wind farm are dependent on the vessel fleet size and on specific vessel availability at the time of operation. Offshore site accessibility can be evaluated statistically using hindcast data, but in practice it will be dependent on the short-term weather forecast at the moment in-situ work is required. The equipment failure rates are predicted based on limited publicly available data and must be extrapolated to different site conditions and specific equipment selections. Clearly, the main input parameters of offshore wind O&M modelling have a non-negligible degree of uncertainty that will be reflected in the outcome of an optimization analysis. This inherent uncertainty is exacerbated by the industry trend towards larger turbines and harsher environments located further offshore.

One main motivation for implementing the PivotBuoy system in a floating offshore wind turbine development is to simplify heavy maintenance operations, which traditionally must be performed on site, using costly (and scarcely available) heavy lift crane vessels. With the PivotBuoy quick disconnection system, the wind turbine may be disconnected and towed back to port for maintenance, using relatively inexpensive and more readily available tug vessels (see Figure 41).

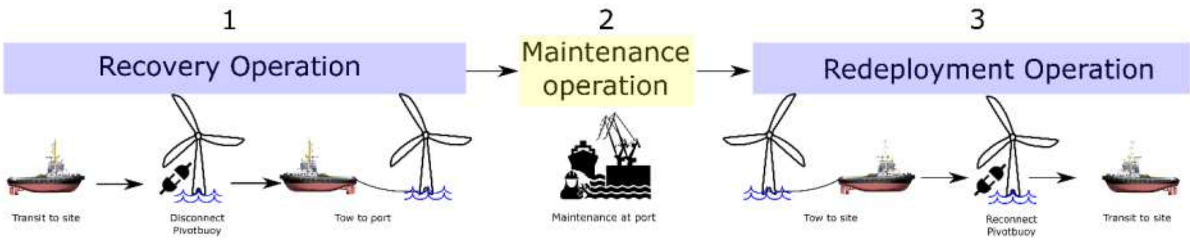

Figure 41. Schematic representation of tow-to-port maintenance strategy

For the purpose of evaluating what the potential benefits of implementing a PivotBuoy system on the O&M stage are, an operational analysis based on hindcast data was carried out comparing a PivotBuoy solution to a standard (non-PivotBuoy) reference solution. The study was based on a reference farm situated southeast of Gran Canaria. In this study, connection and disconnection durations were defined as 4 hours and 2 hours, respectively, and the Port of Las Palmas was selected as the base O&M port. Typical failure rates and repair durations were defined, and the breakdown of marine operations for retrieving and redeploying the floating wind turbine was described in detail.

It was found that for the considered site, when compared to the reference weather limits (Hs =1,5m and Ws=15m/s), selecting a slightly more restrictive operations limits & conditions (OLC) (Hs =1,0m and Ws=10m/s), greatly increases the waiting time due to weather and, consequently, the total downtime of the wind farm. On the other hand, increasing the OLC to (Hs =2.0m and Ws=15m/s) leads to relatively small reductions on total downtime (below 5%), suggesting that for the site under analysis, the minimum OLC should not be under Hs=1.5m and Ws=15m/s. This is valid for both the connection/disconnection and wet tow activities.

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Results also indicate that the downtime is less sensitive to the disconnection/connection duration than it is to the Operation Limits and Conditions. It can be expected that a quick connection system (4-hour duration) such as the one enabled by the PivotBuoy can reduce the downtime by 20% to 30% when compared to a scenario without a quick connection system, which is here assumed to take 24 hours.

WP6 Conclusions

The deliverables produced as part of WP6 have contributed to the success of the PivotBuoy X30 project by de-risking the design and improving the installability, reliability and operability of the X30 unit. Furthermore, WP6 deliverables provide valuable input for the development of O&M strategies for future designs (i.e. X90 – X140).

It is recommended that the WP6 deliverables be used as a starting point for further development so that the improvements realized in the PivotBuoy design, and the lessons learned during the fabrication, installation and operations of the X30 unit remain firmly embedded in the system design basis.

2.6 WP7 – LCOE Assessment, Socio-Economic Impact and Exploitation Plan

Overview

Work Package 7 (WP7) "LCOE Assessment, Socio-Economic Impact and Exploitation Plan" assessed the costs of the technology and integrated both performance and reliability metrics to ensure that the overall LCOE was minimized. The WP also analysed socio-economic impacts and possible business strategies to exploit the results of the project.

The specific objectives of WP7 were:

- Assess the PivotBuoy impact on the levelized cost of energy (LcoE).
- Identify critical cost drivers and opportunities for cost reduction.
- De-risk the technology to make it bankable for future projects.
- Analyse the socio-economic impact from a life-cycle perspective.
- To perform a life-cycle assessment (LCA) to estimate the carbon and energy intensity of PivotBuoy versus other systems.
- Develop an exploitation plan for the PivotBuoy and other products and services deriving from the project.
- Develop recommendations for the whole floating wind sector and, in particular, body-yawing systems with single-point mooring systems regarding the path forward.

WP7 was led by EDP-CNET, with the contributions of WavEC, X1WIND and PLOCAN. The summary here presented does not cover the exploitation plan since it has been considered a report available only for the consortium partners and the European Commission services.

Techno-economic assessment

A techno-economic model (TEM) was designed with the aim of accurately costing a number of potential projects and applying future economy of scale's effects to predict how cost savings would benefit large-scale build out after the successful deployment of the prototype demonstrator in the Canary Islands. From the 225kW demonstrator, the TEM applied a range of scenarios at three potential

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future locations and using various sizes of wind turbines. The locations were chosen for having realistic potential to accommodate floating offshore wind (FOW) projects, all with strong, consistent wind resources ranging from 6-9m/s:

- Viana do Castelo – Atlantic site off the northern coast of Portugal, current location of the WindFloat Atlantic project. Water depth up to 100m, 7km from shore and 10km from port.
- Golf du Lyon – Mediterranean site in Southeast France. 75m water depth, 17.5 km from shore and 22km from port.
- Gran Canaria – Atlantic site in the Canary Islands that currently is home to the 1:3 scale demonstrator project. This site has the strongest wind resource, 100m water depth with a shore's distance of 8km and a port distance of 10km.

A wide variety of sites across Europe were chosen to show how LCoE changes across different wind resources, water depths, and at various distances to shore, driving both port distances and increasing cable costs, whilst also shortening weather windows to increase installation and O&M costs. These were key factors in driving different LCoE values, along with the scale effects of larger wind turbines and larger quantities. For each site, four scenarios were run using the TEM designed specifically for this project, from a baseline scenario up to a commercial farm:

- 30MW Baseline (3 x 10MW) – Arguably a pre-commercial set up, with 66kV array cables supplying one 66kV export cable. IEA 10MW wind turbine used.
- 48MW Pre-commercial (4 x 12MW) – Larger 12MW GE Haliade wind turbines are deployed in this scenario, with one 132kV export cable and 66kV array cables.
- 45MW Pre-commercial (3 x 15MW) – largest size wind turbine used in this study, the IEA reference 15MW wind turbine, with 66kV array cables and one 132kV export cable.
- 420MW Commercial scenario (28 x 15MW) – Expected wind turbine size from 2026-2030. Due to the size and transferred power, two 220kV export cables are used and a layout is designed to maintain 66kV array cables using shorter strings.

The results of these sites are defined as key performance indicators (KPIs) which are compared against a well-defined site that has already had a pre-commercial FOW array. This project already demonstrated threefold cost reductions through scale effects and learning rates from initial demonstrator to pre-commercial status. The location off the Northwest coast of Scotland, situated 29km from shore and in 95-120m water depth and with a strong wind resource. The main KPIs used to measure the three sites in this study against the Scotland site were as follows:

- CAPEX – Overall 54% reduction through platform weight reduction; mooring and anchoring costs decrease; low-cost connection, assembly using local infrastructure; and upscaled downwind rotors.
- OPEX – 19% reduction through increased reliability and maintainability and upscaled wind turbines
- AEP – 4% increase through increased reliability, maintainability, and reduced platform weight.
- LCoE – 49% decrease to LcoE through all the above effects.

The model itself is spreadsheet-based, was designed specifically for this project and follows a proven modular approach. Site, turbine, and balance of plant options are all selected on a main input screen, with results automatically calculated and displayed on the same page. There are CAPEX, OPEX and Decommissioning Expenditures modules with a final financial screen which calculates all main indicators over a variety of project lengths, ranging from 5 to 25 years.

Advances in the model designed for the project are achieved through a high granularity in time steps, with hourly wind data applied to different wind turbine power curves. This allows for real-life project complexities such as low or extreme wind speeds to affect wind farm availability. Modules such as installation and commissioning (I&C), O&M and decommissioning and disposal (D&D) use locational metocean data stretching back over 30 years of hindcast data to create weather window complexities that influence costs and wind turbine availability and annual energy production, in turn affecting LCoE results. Also, a logistical model was included to estimate the costs of transportation of the main wind farm components from the OEM base to the site location.

For component costs and distance-based vessel calculations, a range of cost functions were derived for this project, either based on developer functions or in the creation of this model. These allowed for costs to change with varying site conditions, such as soil profiles affecting cable laying rates and vessel speeds. These were also applied for balance of plant, with larger turbines requiring thicker cables that sized themselves according to the farm's specifications.

Wind speed had a large impact on LCoE, as wind speeds are the main driver for higher annual energy production (AEP) results. As none of the three sites in this study had access to direct measurements from a LIDAR or met mast, satellite data was used which has the benefit of hourly values dating back up to 30 years, but accuracy can vary especially closer to shore. As such, a new method was used that combined mesoscale satellite wind speeds with microscale average values. This adjustment allowed for higher accuracy in annual wind speed forecasting, whilst maintaining the hourly granularity of the timesteps and the size of the dataset. The new method which combines the positives of both of the above, results in an 14% LCoE improvement to the Golf du Lion site, an 8% improvement to the Viana do Castelo site and interestingly a 2% drop in LCoE for the Gran Canaria site. This could be due to the complex wind flow around the islands recording lower wind speeds not picked up by the broader range of the mesoscale modelling approach.

Overall results for the baseline scenario show an LCoE range of between 80-130€/MWh, a 46-67% decrease compared to the state of the art. This highlights the importance of site selection, through port distances, cable lengths and, most importantly, the local wind resource.

When comparing larger wind farms with economy of scale benefits, LCoE drops on average 7% from the 3 x 10MW farm to the 4 x 12MW. As the wind farm increases to larger 3 x 15MW units, LCoE drops by a further 12% due to the more powerful generators with less marine operations required for installation, O&M and decommissioning phases. Finally, LCoE drops by another 27% on average to the full commercial wind farm, thanks to increased learning rates and better and more efficient use of balance of plant equipment such as substations, array cables and export cables.

This LCoE analysis showed that the expected scale up from pre-commercial size to commercial deployment has the potential to deliver large LCoE savings of up to 67%, if scale effects and learning rates can be fully realised. Also, site selection is crucial, with a wide band of LCoE values across the four sites. The largest effect is from the local wind resource, followed by the distances to ports and cable lengths.

<u>Life cycle assessment</u>

To assess the socio-economic and environmental (carbon and energy intensities) impacts of the project from a life cycle perspective, it was considered a future commercial scenario consisting of 28 turbines of 15MW each, to be installed in the Canary Islands (Spain), operating for 20 years.

The Life Cycle Assessment (LCA) method was implemented to quantify the potential cumulative impacts of the PivotBuoy system from the extraction of raw materials until its disposal by applying a methodology that specifies the main stages of the assessment and complies with international standards ISO 14040. The Functional Unit used was 1 kWh of electricity delivered to the Spanish electricity network from an offshore floating wind turbine. The SimaPro 8 was the software used to model the system, with Life Cycle Inventory data sourced from the Ecoinvent (3.5) database.

This analysis focused on the components, materials, and stages of the life cycle with the most significant environmental burdens. Manufacturing, Assembly & Installation, Operation & Maintenance (O&M), and Decommissioning & Disposal stages were analysed in detail, and data on the energy, materials, emissions, and waste products associated were gathered. Data collection has been conducted in close cooperation with the project partners involved in the design of PivotBuoy.

The resulting carbon intensity of 11,24 gCO2 eq/kWh and cumulative energy demand of 149 kJ/kWh proved to be lower compared to other forms of energy production, such as coal, natural gas, nuclear, and solar photovoltaic. The Global Warming Potential (GWP) results presented consistency in comparison to the range of some wind energy devices analysed in the literature reviewed (10,9 - 23,0 gCO2 eq). Relative to other marine renewable energies, studies suggest that wave energy converters may hold a carbon intensity of around 13 – 126 gCO2 eq/kWh, presenting a wide range depending on the technologies and materials adopted, whilst for tidal energy converters the carbon emission can be around 8.6 – 23.8 gCO2 eq/kWh. Due to the lower level of technological maturity of the wave and tidal technologies, some uncertainties should be considered, showing that the PivotBuoy as a device for wind energy production is likely to present positive benefits in terms of carbon footprint. Globally, both carbon and energy payback times were found to be slightly below 1 year, 8.6 and 9.9 months respectively, emphasizing once again the capability of renewable energy sources to pay back the energy and greenhouse gases (GHG) emissions embedded in their life cycle. Figure 42 summarises the results from the life-cycle assessment.

MAIN RESULTS			
Global Warming Potential (GWP)	Cumulative Energy Demand (CED)	Carbon Payback Time (CPT)	Energy Payback Time (EPT)
11,24 g CO2 eq/kWh	149 kJ/kWh	8,6 months	9,9 months

Figure 42. PivotBuoy's results for the global warming potential, energy intensity, carbon and energy payback times

Due to the adopted PivotBuoy's tow-to-port strategy, a reduction in the time required for O&M, and consequently the emissions along the project's lifespan can be expected. Most of the carbon intensity is derived from the Manufacturing phase, driven by the high amount of material, mainly steel from the

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structures and concrete from the gravity anchor. It is attributable to the choices made at the conceptual phase, which may vary depending on the site location and potential design improvements. The material choices are crucial for the results of design, performance, and environmental impacts. In contrast to components made of steel, the composite materials, despite having potential impact reduction during the manufacture, still lack efficient recycling processes. Therefore, currently, their disposal phase comprises landfill or incineration processes, which can cause large GHG impacts, and pose risks to human health, reinforcing the important role played by end-of-life and recycling.

Socio-economic impact analysis

The socioeconomic impact analysis assessed the regional and national potential economic impacts and job creation, through Input-Output (IO) models, integrating the same life cycle stages assumed both in the techno-economic analysis and the LCA model to maximize realism and ensure consistency of the results.

The creation of an associated techno-economic-LCA-IO model required all CAPEX and OPEX inputs to be associated with their embodied energy and carbon, also requiring detailed categorisation for IO assessment of macroeconomic effects. As this analysis occurred immediately after the prototype's deployment, it was possible to obtain more realistic data and from the knowledge acquired during this task, it was possible to estimate CAPEX at a commercial level. Due to the ongoing stage of the project, it has not yet been possible to obtain more accurate data associated with OPEX, therefore, the costs associated with O&M have been estimated based on the economic model developed for this project (D7.1 - Techno-economic model).

The tertiary sector is the main driver of the current economic characteristics of the Canary Islands, specifically tourism. However, despite the small share in the secondary sector, the potential for developing opportunities in the Canary Islands value chain is notable when considering the untapped capacity at the local level. Considering the prospect of Canarian participation in industrial activities, the analysis indicated the opportunity for job generation, with peaks of over 20,000 in the Canary Islands during the O&M over the 20-year total life of the project, and between approximately 7,000 and 9,000 jobs nationally for the combined Manufacturing and Installation phases in Spain, stimulating directly many sectors, coupled with those associated with the insurance and financial sectors, project management and specialised services. Other sectors indirectly linked to the project, such as accommodation and communications, may also experience benefits through the development of the economy.

Given the correlation between jobs and the value generated by the production of goods and services, the global value added (GVA), an analogous trend within project stages was observed. In the Canary Islands, the O&M proved to be the most representative impact, with GVA varying between 569 and 861 M€, depending on the assumed local content capacity. Due to the local profile of the Canarian Islands, the Manufacturing stage showed to be more representative outside the island, indicating a range of 527 to 557 in Spain. The estimation of job demand and GVA over the life span of the commercial scenario is presented in Figure 43.

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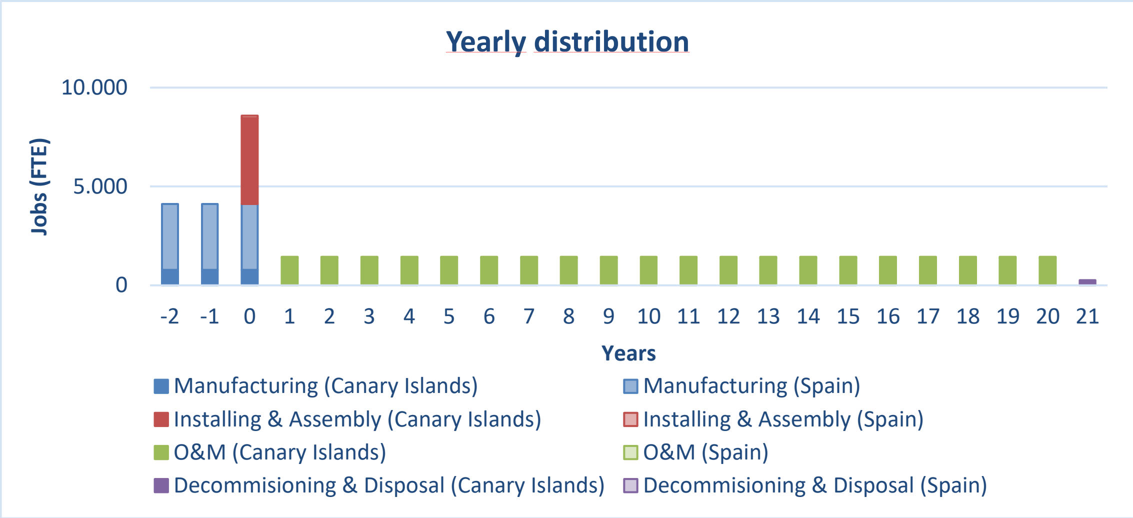

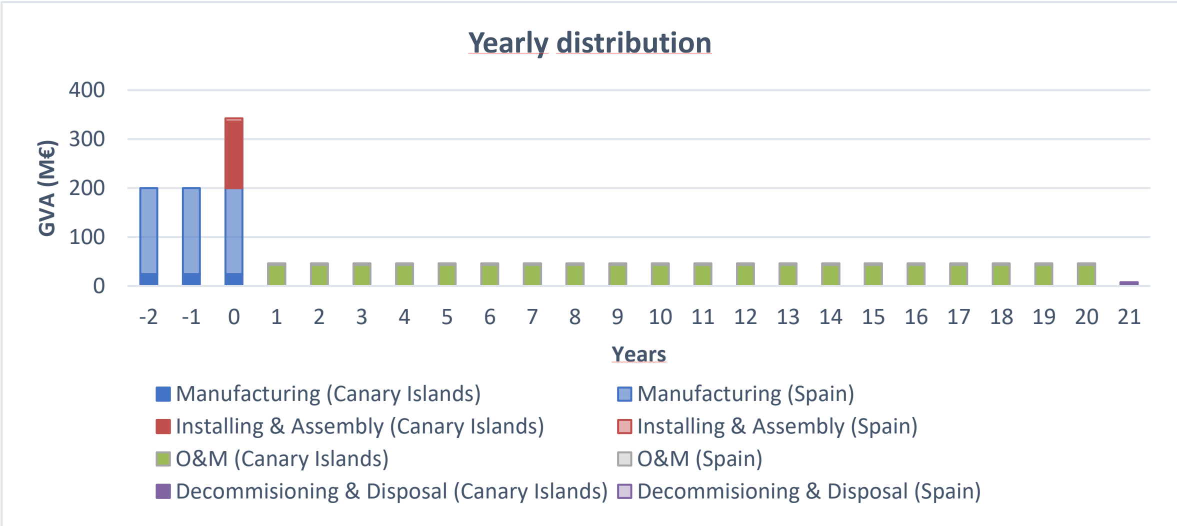

Figure 43. Yearly distribution of job demand (top) and GVA (bottom) for the whole span of the PivotBuoy commercial scenario

Despite some community concerns, a reasonable level of social acceptance is generally expected for renewable energy, when a higher level of perceived benefits is achieved, especially in the economic and environmental aspects.

Conclusions

The outcomes from this assessment highlighted the wide-reaching macro-economic value of this type of project, providing additional information to decision-makers when combining socioeconomic, environmental, and techno-economic terms.

The quality of the data in this preliminary study was constrained by the lack of input data, mostly not yet available during the conceptual and prototype testing phases. Some justifiable assumptions were made from previously published studies and these secondary data estimates can lead to errors that

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propagate through the literature undetected. In addition, some data from the statistical bodies may be a little outdated, which may lead to some deviation from the current economic scenario.

The conclusions were based on the conceptual strategies for the prototype, adapted to a commercial scale envisioning. It was reported preliminary results that may vary when scaled up to a real commercial project, which may present different types of materials and execution strategies.

Deliverables D7.1 – Techno-economic model, D7.2 – LcoE of the PivotBuoy concept and D7.3 – Socio-economic impact and life-cycle assessment are public and available on the project website.

2.7 WP8 – Communication and Dissemination of Results

Work Package 8 (WP8) “Communication & dissemination of results” was to disseminate the learning gained from the project and demonstrate the industry-wide benefits of the project outcomes. WavEC led the WP, to which all partners contributed. This general goal was accomplished by carrying out different tasks, each with a defined objective.

The specific objectives of WP8 were:

- Definition of a communication plan: this was done at the start of the project in order to provide some guidelines to the partners on what messages would be delivered, what tools and channels would be available, and to what audiences.
- Project public reporting: several communication materials were produced, namely: a logo, Word and PowerPoint templates, a website, social media, leaflets and roll-ups, and press releases.
- Publications: a data management plan has been set early in the project, several abstracts have been submitted and X1 Wind attended some technical conferences.
- Stakeholders’ engagement: 2 workshops, November 2021, and the final event in March 2023.
- Audio-visual materials: one video was released in September 2020 to introduce the technology, goals and challenges, and another one in March 2023 to present the final results. Other shorter videos were available on social media.

The metrics initially defined were widely achieved, such as the press releases, website visits, and the workshops received very positive feedback from the stakeholders.

The Performance Indicator Log, Figure 44, lists the communication actions of the project, the objective and date of its accomplishment. The following results are highlighted:

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	Objective Midterm	Final Result	Comments
Website	2000 visits by M36	13 523	
SOCIAL MEDIA			
Twitter	150 followers	116 followers	Low impact on the project social media accounts but very high project impact on the companies' media accounts.
LinkedIN	150 followers	78 followers	
EVENTS			
Leaflets distributed at events	1000 leaflets M36	200	Covid disrupted the possibility of leaflets distribution
Poster displayed	1 poster by M36	2	WindEurope Bilbao 2019 and WindEurope Copenhaguen 2019
Presentations at congresses/events	6 presentations by M36	12	
Attendance external events/fairs/workshops	12 attendances by M36	13	9 Conferences, 1 webinar, 1 event and 2 workshops
MEDIA			
Press releases	6 by M36	11	
Nr. of articles in newspapers	6 by M36	120	Regular news (El Pais, La Vanguardia ...),Specialized media (Recharge, El Periódico de la Energía, Offshore Wind biz...)
Nr. of appearances in TV and radio	3 by M36	1 TV + 2 radio	
News Articles	6 by M36	5	News in the PivotBuoy webpage and excel log register

Figure 44. Performance Indicator Log

Audio-visual materials

Task 8.5 aimed at producing and developing audio-visual materials that were able to contribute to the overall objective of WP8 "Communication and Dissemination of Results". Therefore, the videos created for this project were essential to promoting and disseminating the project's goals and achievements.

The two videos produced, in which PivotBuoy's consortium has invested significant efforts, provide comprehensive insights into the project's core objectives, technological innovations, and challenges.

The first video was launched in the project's M12 and was specifically created to introduce the project's mission and objectives to a wider audience and showcase the ground-breaking technology that was being developed. It served as a powerful tool for promoting the project to stakeholders and other interested parties. The video emphasizes the significance of the project and the innovations being presented, and the platform's working principle. The video, which was uploaded to YouTube two years ago, has, at the moment, 14k views and can be assessed through the following link: https://www.youtube.com/watch?v=3rp_0F8_5g4.

The second video was produced towards the end of the project to present the results and achievements obtained throughout the project's duration. The video's objective was to provide the interested public with an overview of the project's accomplishments, while also showcasing the innovative technology developed through the project. This video results from PLOCAN's efforts, with the support of other partners, to create a comprehensive project summary video showcasing various phases of the project to allow a visual representation of the project's development and progress. It includes footages of the manufacturing at DEGIMA's facilities, the transportation and discharge of the pieces to the Las Palmas Port, the assembling in the shipyard of the different components, the launching of the prototype into the water, the wind turbine rotor assembling, the gravity-based anchor transportation, the cable installation from the platform to the deployment location, the prototype installation, and the turbine operating. Video link: https://www.youtube.com/watch?v=irKMu1JwLBI

WP8 Conclusion

Concluding, the main objectives defined at the beginning of the project for Work Package 8, which focuses on the Communication & Dissemination of Results within the PivotBuoy project, were successfully obtained.

A communication plan was created to define who was going to be our targeted audience, to establish the important messages to be delivered and to guide the partners on how to use the tools and channels available to successfully disseminate and promote the project.

Several communication materials (a logo, Word and PowerPoint templates, a website, social media, leaflets and roll-ups, and press releases) were produced to obtain a consistent design in the different documentation formats and communication materials so the project could have a visual identity easily recognised by the targeted audience.

A data management plan was set early in the project, several abstracts were submitted, and X1 Wind attended technical conferences.

Two workshops, attended by high-level professionals from the offshore wind industry, were organised (November 2021 and March 2023).

The audio-visual materials produced were also powerful tools for promoting the project and its mission to a broader audience, especially the two videos released at the start and end of the project.

Work Package 8 has thus served its purpose, and by communicating and disseminating the results of the project, it has contributed to the overall success of the PivotBuoy project.

3 CONCLUSIONS

This deliverable compiles the extensive work developed over the four years of the PivotBuoy project. The summary is divided by work packages, each covering a given stage or aspect of the project, from the design, a variety of numerical modelling, risks assessment, manufacturing, assembly and installation, environmental impacts, carbon emissions, LCoE, and results communication and dissemination. Each work package presents the specific tasks and objectives, the challenges, results and lessons learned. The experience assimilated during the project is certainly fruitful for the direct participants in the project, but it is also interesting for the offshore wind sector in general. Some of the resultant reports have been made available, either on the European Commission's portal and on the project's website. The reader is invited to visit the website and consult each public deliverable in more detail:

https://pivotbuoy.eu/

Overall, the consortium managed to accomplish the main objectives of this ambitious project. The X30 prototype was designed, built, installed and demonstrated in a real operational environment reaching TRL6, obtaining valuable data from multiple sensors showing excellent hydrodynamic and self-aligning performance and exporting electricity into PLOCAN's Smart Grid via a dynamic cable, as well as surviving several significant storm conditions given its part-scale, presenting a very promising response.

The project suffered some delays due to Covid-19 pandemic and how it affected the manufacturing phase as well as constraints in the availability of local vessels for the installation phase, which resulted in a one-year extension which led to the obtention of the excellent data and results mentioned above.

Altogether, the partners consider it a very successful project which will now be followed up with the scaling up of the technology into a commercial-scale pilot (NextFloat Project).

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