PivotBuoy

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

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D2.5: Preliminary design for 10-20MW systems

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Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
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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INDEX

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ACRONYMS

DDR	Detailed Design Review
DNV	Det Norske Veritas
EHS	Environment, health and safety
ESM	Energie- und Schwingungstechnik Mitsch GmbH
FEA	Finite Element Analysis
FPSO	Floating Production Storage and Offloading platforms
FWT	Floating Wind Turbine
GBS	Gravity base system
HALT	High accelerated life test
HSE	Health and Safety Elements
IP	Intellectual Property
LCOE	Levelized cost of energy
NDA	Non-disclosure agreement
O&G	Oil and gas
O&M	Operations and maintenance
OTEC	Ocean Thermal Energy Converter
PDR	Preliminary Design Report
PLOCAN	Oceanic Platform of the Canary Islands
PTO	Power Take Off
ROV	Remotely operated vehicle
SCADA	Supervisory Control And Data Acquisition
SPM	Single Point Mooring
TEC	Tidal Energy Converter
TLP	Tension-leg Platform
TTA	Tower-Top Adaptor
UPC	Universitat Politècnica de Catalunya
WEC	Wave Energy Converter
WP	Work package

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1 EXECUTIVE SUMMARY

The *PivotBuoy® Project: An Advanced System for Cost-effective and Reliable Mooring, Connection, Installation & Operation of Floating Wind* (referred to as PivotBuoy project) is a project that will develop a prototype, which includes the PivotBuoy system, to reduce the levelized cost of energy (LCOE) of floating wind. The PivotBuoy is an innovative subsystem that aims to reduce the costs of mooring systems and floating platforms, allow faster and cheaper installation and a more reliable and sustainable operation. The system will be installed at PLOCAN test site to validate this concept, integrating a prototype of the mooring system in a downwind floating platform developed by X1 Wind.

Deliverable *"D2.5. Preliminary design for 10-20MW systems"* includes the learning to scale up the part-scale design into a full-scale PivotBuoy design for 10-20MW floating platforms.

This report also gathers the design requirements for other floating systems where the PivotBuoy can be applied to ensure its potential integration to other floating platforms.

The aim of this report is to share with the offshore wind and research community information about the PivotBuoy technology developed within this project, although detailed technical information and drawings cannot be shared due to IP protection. In case of interest, detailed technical information can be share upon NDA signature (please contact info@x1wind.com or info@pivotbuoy.eu).

Figure 1. PivotBuoy and floating platform moored at Las Palmas port

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2 INTRODUCTION

The PivotBuoy project is a demonstration project to develop a prototype of this new mooring system proposing the combination of the installation advantages of a single point mooring (SPM) with a tension-leg (TLP) mooring system to enable weight reduction compared to current systems.

Figure 2 shows the evolution of the floating platform from the concept design, defined during the proposal stage in April ’18 and starting point during the start of the project (April ’19) to the detailed design. This updated design was presented during March ’20 during the Detailed Design Review (DDR) when all parts were validated so that DEGIMA, the manufacturing partner, could start the manufacturing stage.

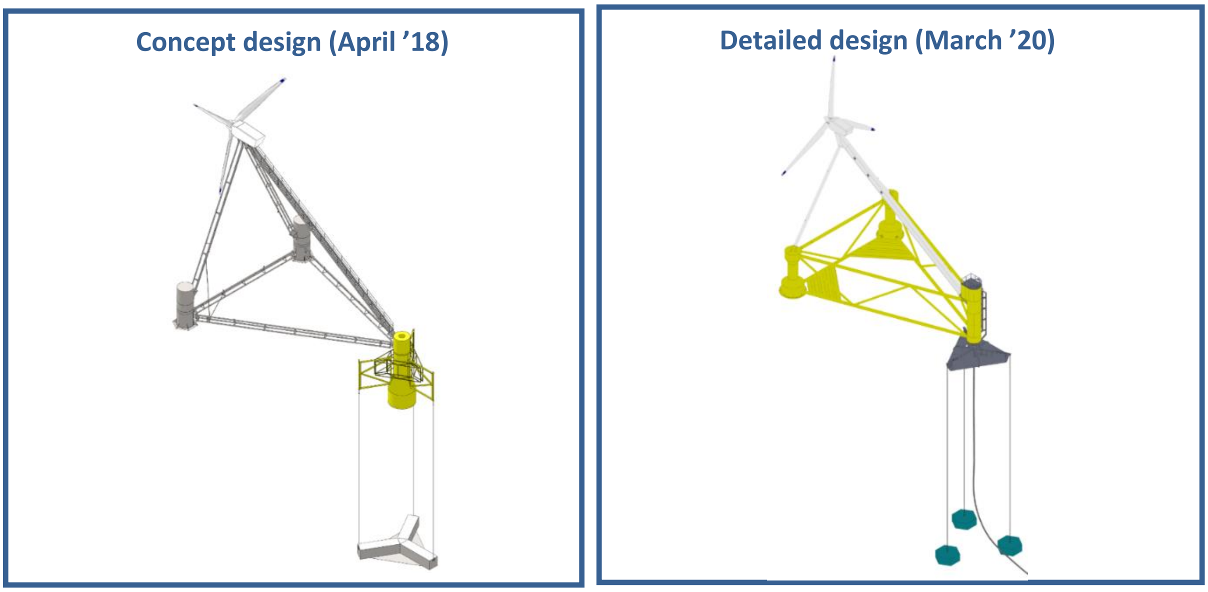

Figure 2. Concept design of PivotBuoy and floating platform defined at the proposal stage in April’18 (left) and its evolution to the Detailed Design Review in March’20 (right)

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. The outcome of that designing stage was shown in deliverable *“D2.3. Detailed design review”*, and its render is also shown in Figure 3.

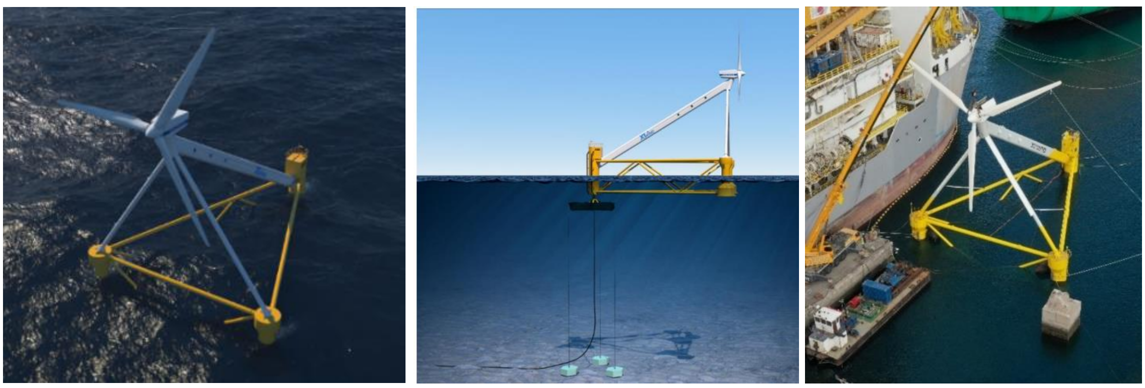

Figure 3. PivotBuoy render after Detailed Design Review (left and center). PivotBuoy picture from a drone (right)

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During the project development four deliverables related to work package 2 (WP2 - PivotBuoy Subsystems Design) have been developed and submitted to the European Commission so far. All these reports are confidential, so they are only for members of the consortium (including the Commission Services). Thus, deliverable *"D2.5 – Preliminary design for 10-20MW systems",* the last deliverable of the work package, gathers the knowledge of all the previous reports and it is the only one that can be published since the rest are confidential.

WP2 centralized the systematic concurrent design approach to integrate early in the design process elements of the product life cycle, such as manufacturing, assembly, installation, O&M and EHS considerations, shortening the total time compared to a traditional sequential design. The result of this development has been the following previous deliverables:

D2.1 – System requirements and design review

This deliverable provided a list of the main requirements for the key subsystems and components. This report also described the design review process and its criteria.

D2.2 – Preliminary design review

This deliverable included a summary of the preliminary design review, including minutes from preliminary design review meeting, presentations and drawings.

D2.3 – Detailed design review

This deliverable included a summary of the detailed design review, including minutes from detailed design review meeting, presentations and drawings.

D2.4 – Condition monitoring system

This deliverable included the full list of sensors, their location, expected normal values and the definition of warning and alarm levels.

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3 PRELIMINARY DESIGN FOR 10-20MW SYSTEMS

3.1 The X140 platform design using the PivotBuoy® system

This deliverable includes the preliminary design of the X140 platform using the PivotBuoy® technology developed within this project. The X140 platform is design to accommodate turbines in the range of 12 to 15MW. It also provides a preliminary design of the X90 platform (for a 6MW turbine) to show the positive scalability of this innovative solution.

Figure 4. Scalability from the current part-scale prototype (X30, left) to 6MW (X90, centre) and 14MW design (X140, right)

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.

PivotBuoy project developed the design, manufacturing, assembly, installation and operation of the X30 model, which is the part-scale model floating offshore wind platform prototype. In this platform it has been installed a 225kW downwind turbine. Afterwards, a full-scale model for 10-20MW systems

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has been designed. In this case, it features a 14MW turbine. The following table summarizes the main parameters for both models comparing its main characteristics.

Table 1. Main dimensions of the X30and X140 platform models (dimensions for X140 are approximate but not the actual dimensions with design optimization loops being carried out)

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

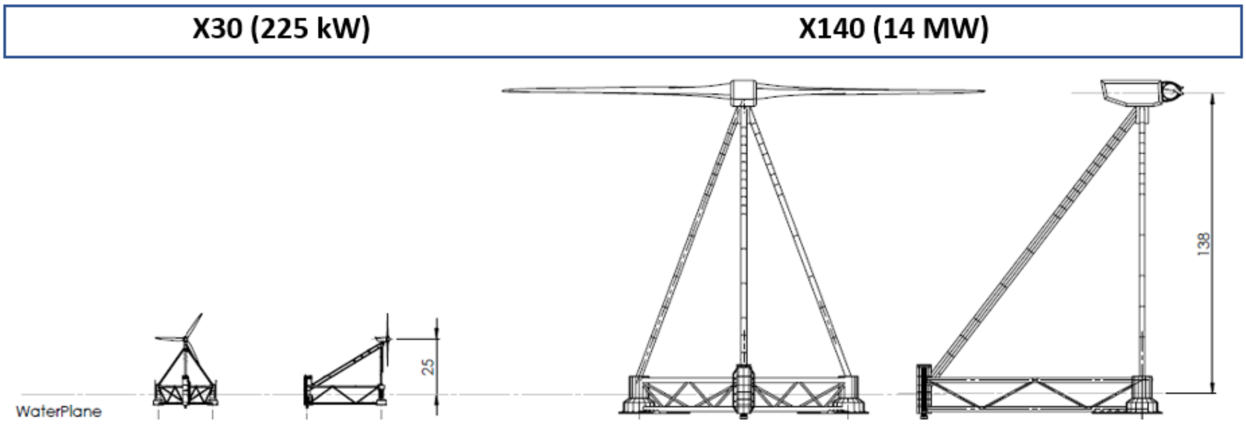

Figure 5. General assembly drawings of X30 (left) and X140 (right) concept designs

3.2 Scalability of the concept

Turbine power output is one of the main factors to reduce LCOE. The results of a recent NREL study[1] show that larger wind turbines and larger offshore wind projects alone can reduce a wind farm's LCOE by more than 23 per cent. Larger turbines are a good fit for FOW as they can withstand high wind-speeds and generate higher output per turbine. In the market, the capacity of offshore wind turbines is increasing rapidly. Wind turbines from 12MW to 16 MW have recently been announced for commercial use, therefore, it is crucial to upscale floater designs for such turbine sizes.

The X140 platform presented above is design for such purpose. While still at concept level, the design shows already very positive scaling factors when increasing the platform from a 6MW platform design (X90) to 14 MW (X140) as shown in the following table. While increasing rotor capacity by 133% (6MW to 14MW), the weight of the floater only increases by 67%, which results in a reduction of weight per **MW of 29%.** Similarly, the weight of the **tripod also shows good scalability** with an increase in weight of only 56% when jumping from 6 to 14MW (compared to the 133% capacity increase). The general dimensions also show good scalability, with an increase in length and width by only 25-60% showing the good scalability of the concept as previously mentioned (note the X140 design has not been optimized and further reduction in dimensions are expected). This is due to the platform rigid-body

[1] Matt Shields, et.al.Impacts of turbine and plant upsizing on the levelized cost of energy for offshore wind, Applied Energy,2021

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eigenmodes naturally having longer periods as the platform gets bigger, solving some of the challenges of the PivotBuoy 1:3 scale prototype in this regard simply by scaling up.

Parameter	% increase
Turbine capacity (MW)	133%
Turbine diameter (m)	57%
Turbine/RNA weight (tons)	47%
Hub height from water level (m)	53%
Tripod weight (tons)	56%
Floater length (between axes of columns & Pivot) (m)	25%
Floater width (between column's axes) (m)	60%
Floater draft (m)	50%
Floater weight (tons)	67%
Floater weight (tons/MW)	-29%

Figure 6. Scaling of the concept when upscaling from the X90 (6MW) to X140 (14MW)

The following figure shows how the floater relative weight (in tons per MW) decreases with size of the rotor, compared also with the state of the art of other floating systems that have been installed. Significant steel weight and cost reduction is expected due to its combination of lower weight and high degree of manufacturability. Note that the starting point is the small part-scale demonstrator X30, equipped with a Vestas V29 225kW, which a weight of 503 t/MW, very competitive at such a small scale (the small scale plays again the relative weight in this case).

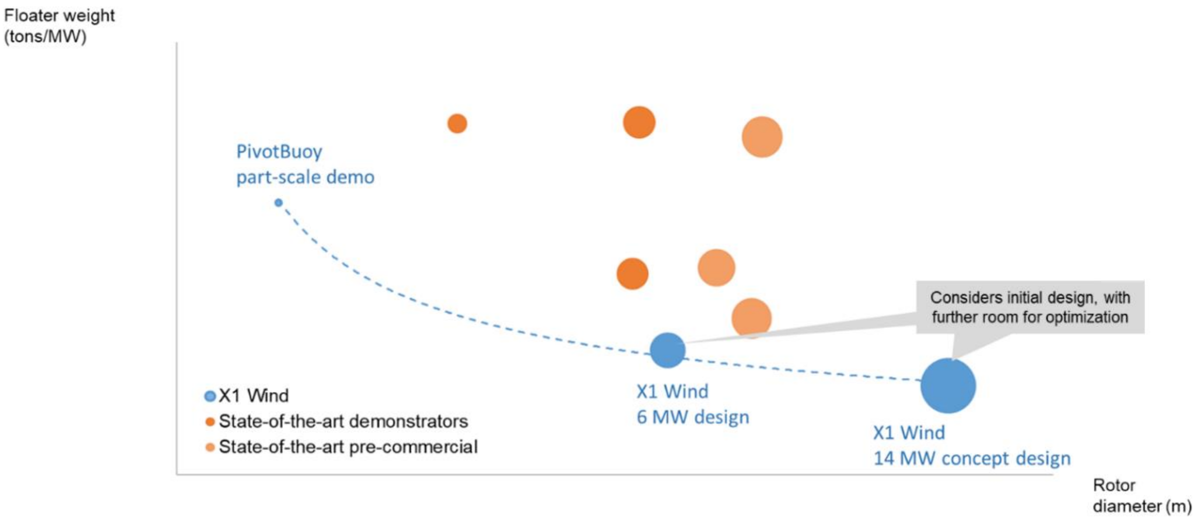

Figure 7. Floater weight[2] evolution in tons per MW compared to state-of-the-art projects. The bubbles represent the swept area of the turbine rotor.

Please note also that the design of both the X90 and X140 are not fully optimized (with 6 design loops and 3 design loops completed at this stage), with further potential for optimization expected.

[2] Floater weight does not include the tripod (only the floater) since other system weight do not include the tower weight (provided by the turbine OEM).

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In addition to this, results so far indicate that the tripod structure has no problem keeping up with the required stiffness in order to avoid structural resonance with the blade passing frequency. All structural frequencies can be kept above 3P (or 2P in this case, with a 2-Bladed turbine). This allows the floater to maintain the equivalent of a “stiff-stiff” tower, which is optimal, and avoid the added complications of soft-stiff and soft-soft tower designs that are quite problematic in case of most floaters that feature a standard tubular vertical tower at this power range.

3.3 Manufacturing considerations of the X140 floater design for industrialization

The design of the X140 floater is based on standard and readily available steel manufacturing. This section provides a summary of manufacturing considerations that have been taken in the design of the floating platform, but a specific deliverable (*D3.5 – Industrialization plan for serial production of large farms*) provides further details about the concept industrialization.

In order to facilitate the manufacturing process, some basic design concepts have been considered:

- Standard offshore steel
- Standard profiles and plate thicknesses
- Edge treatment can be done with conventional methods
- Welding with conventional methods
- Equilibrium between manufacturing simplicity and weight
- Cutting / rolling standard system (thickness below 50mm).

The manufacturing processes for the main structural elements of the platform are thought to be executed by several local suppliers working in parallel to supply each of the main elements in time. The dimensions and weights of each main element allows to manufacture all of them inside conventional steel workshops guaranteeing a proper working environment to ensure the quality of the manufacturing process.

It may be relevant to highlight that most of the tubular elements have small diameters so they can be manufactured by many local steel tube or onshore tower suppliers. The larger cylindrical elements, of higher diameter but less than 15-meter, can be manufactured in existing steel manufacturing facilities Europe.

The tripod is formed by three masts and the TTA (Tower-Top Adaptor). The two masts connecting the columns and supporting the TTA are tubular parts. The Pivot Mast that connects the Pivot Column and the TTA element has been designed to have an oval shape (currently conformed by two half-tubes separated by a "wall"), to allow the installation of an elevator inside the mast easing the access of personnel and transport of parts if needed up to the nacelle. Again, this is an early suboptimal design from a loads perspective but will be optimized taking into account manufacturing criteria.

The floater substructure is formed by three columns and the pontoons. Of the 3 column elements, two of them are bigger and symmetric: they have a lower section of higher diameter and a top section of a lower diameter (the section is variable for hydrodynamic behavior optimization and draft reduction, but further optimization is ongoing taking into account mass manufacturing factors). The third column is the Pivot Column and is considerably smaller, with a constant diameter. The pontoons are formed

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by a top and a lower chord and reinforced with diagonal braces. The 3 columns are connected by the pontoon elements, that keep the floater together and contribute to the buoyancy of the platform. The tubes of the front pontoon are generally smaller compared to the main horizontal chords (tubes) due to their lower loads.

For further details on industrialization please see deliverable *"D3.5 – Industrialization plan for serial production of large farms".*

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4 THE PIVOTBUOY® SYSTEM, LEARNING AND EXPERIENCE GATHERED WITH THE PART-SCALE PROTOTYPE

This section explains how the PivotBuoy® system is integrated within X1 Wind floating wind platform. It is worth clarifying that the PivotBuoy® refers to the patented single point mooring technology, which is integrated in X1 Wind's floating platforms but can also be applied to other systems (see section 5).

The following figure shows the different systems that integrate a floating wind unit, including the PivotBuoy® the single point mooring (SPM) system used to attach the floater to the seabed, which is the main focus of this project and this report:

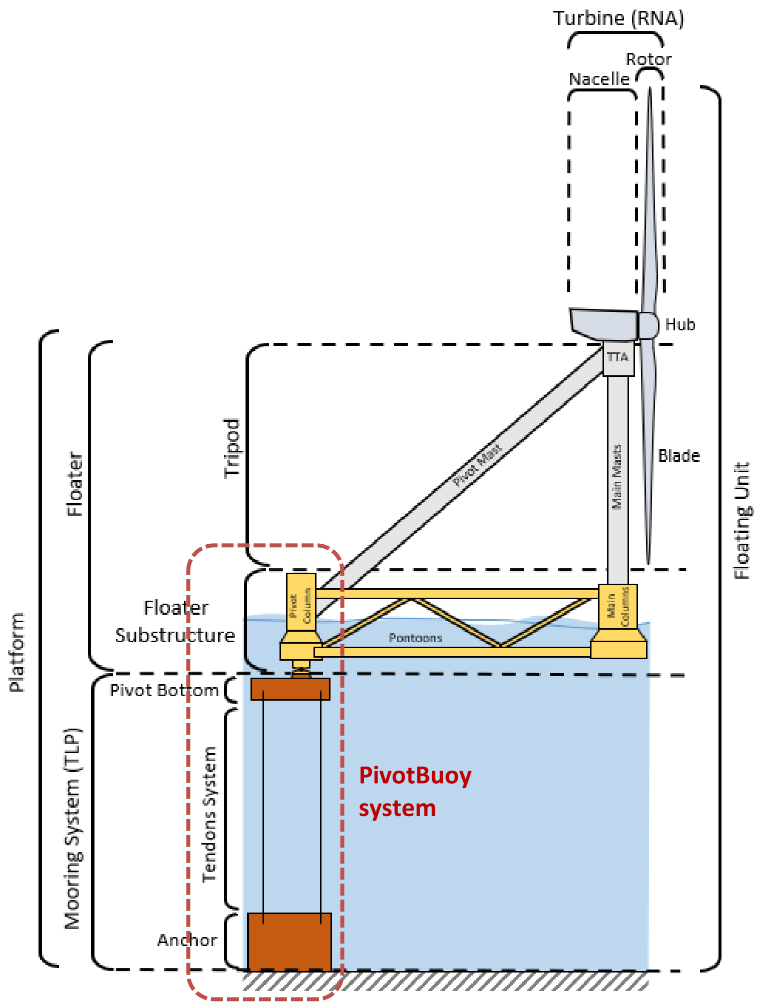

Figure 8. Floating wind unit and PivotBuoy® single point mooring system

While the PivotBuoy system can be applied also in traditional upwind systems, its full cost reduction potential is maximized in downwind systems. X1 Wind has developed an innovative platform design in a downwind configuration: to enable the possibility to use a more efficient isostatic structural design than the traditional tower design. The combination of the PivotBuoy system and X1 Wind downwind isostatic platform design results in an important reduction of the weight compared to current semi-sub and spar systems, they key driver of the costs of floating wind systems.

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The proposed floating platform is constituted by a small TLP and a floater. The TLP is fixed to the mooring system and provides the anchor point for the structure. The floater has a triangular base, shaped by three columns connected by pontoon elements. One of the columns, called the Pivot Column, is connected to the TLP below water, and is the point around which the platform pivots and weathervanes.

After the development of the X30 platform during the PivotBuoy project, a full-scale PivotBuoy system and its corresponding platform has been designed for 10-20MW systems. Thus, the learning and experience of the X30 platform has been applied for scaling up the design up to the current X140 proposed design model, for 14MW turbines.

Some of the most relevant achievements and lessons learned include:

- The creation of an internal process of structural optimization by interfacing a series of software systems, code check tools and in-house scripts.
- The usage of tubular shapes instead of trusses, in order to make the structure easier to manufacture and reduce the amount of welding, while increasing stiffness.
- The redesign of the lower pontoons to be split in a top and bottom pontoon connected through braves to ensure strength of the connection between the three columns and stiffness of the full structure.
- The optimization of the profiles of the steel elements, namely the columns, masts and SPM.
- Optimization of the relative position of the elastic coupling and tendon connections to minimize tendon loads.

4.1 The PivotBuoy® system

The PivotBuoy® is a novel system developed by X1 Wind that integrates the mooring and anchoring systems and the electric cable in a single point mooring (SPM), allowing faster connection of floating platforms. By using this SPM, the PivotBuoy system allows floating platforms to align itself passively with the wind, eliminating the need for an active yaw actuator and any active ballasts systems, reducing weight and the maintenance requirements in those systems. Moreover, one of the key innovations of the PivotBuoy is the combination of the advantages of SPM with a tension-leg mooring, enabling further weight reduction compared to systems using catenary moorings which require large weight or ballast to guarantee the platform stability.

The PivotBuoy combines the advantages of SPMs (pre-installation of the mooring and connection system using small vessels) with those of tension-leg systems (TLPs – weight reduction, reduced mooring length and enhanced stability), enabling a radical weight reduction of 50% to 90% in floating wind systems compared to current spar and semi-submersible systems but also enabling a critical simplification in the installation of traditional TLP systems.

The impact of the proposed innovations is sector wide: the system can be integrated not only in X1 Wind downwind platform but in any other floating platforms using single point mooring systems in the wind and other sectors such as wave energy, tidal and O&G industries. Further information on its integration in a downwind floating platform and other floating systems can be seen in chapter 5.

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PivotBuoy initial proposal

In the initial proposal, the PivotBuoy system was composed of a lower and upper body which could be easily plugged together through an innovative quick connection system (see figure below).

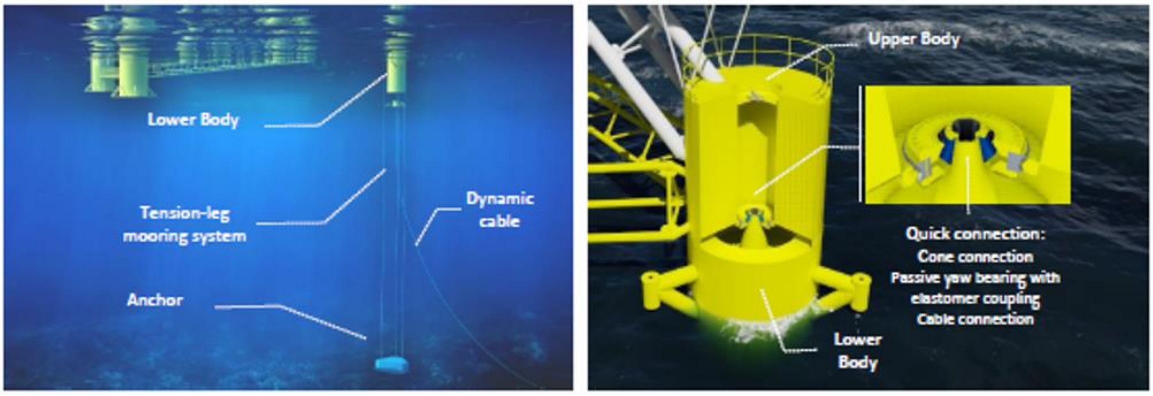

Figure 9. Initial proposal of the system. Substructure view (left) and topside view (right) of the PivotBuoy and its main components.

The lower body would be attached to the mooring system and cable connection. This lower body would be preinstalled to facilitate the platform installation. It included the following subcomponents:

i) The tension-leg mooring system with cables that connect the platform to the anchor.
ii) The anchor, using a concrete gravity base, suction or driven piles, depending on the seabed type.
iii) The dynamic cable to export the generated electricity.

Then upper body would be attached to the floating platform which would be towed and connected to the preinstalled lower buoy in a simple operation with a small local vessel. It includes the following subcomponents:

i) Cone connection that allows self-centering when installing.
ii) Passive yaw bearing with an elastic coupling to enable the platform to weathervane and allow certain axial misalignment to avoid high loads and bending moments and absorb potential impact loads.
iii) A novel coaxial cable connection with unroll mechanism to remove torsion from the cable that accumulates when weathervane.

Updated PivotBuoy system

However, during the design stage, the design evolved and the PivotBuoy connection point (connection between the floater and the single point mooring system) was no longer placed outside of the water, as originally planned, but submerged. This design change involves a much longer top body of the PivotBuoy, which now contributes significant buoyancy. This also enabled a much stronger configuration of the lower substructure of the floater, by splitting the pontoons, which now have 3 lower pontoons and 3 upper pontoons, all tubular, and connected by braces.

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Thus, the new layout with the submerged coupling system would have the elements stated in the following figure:

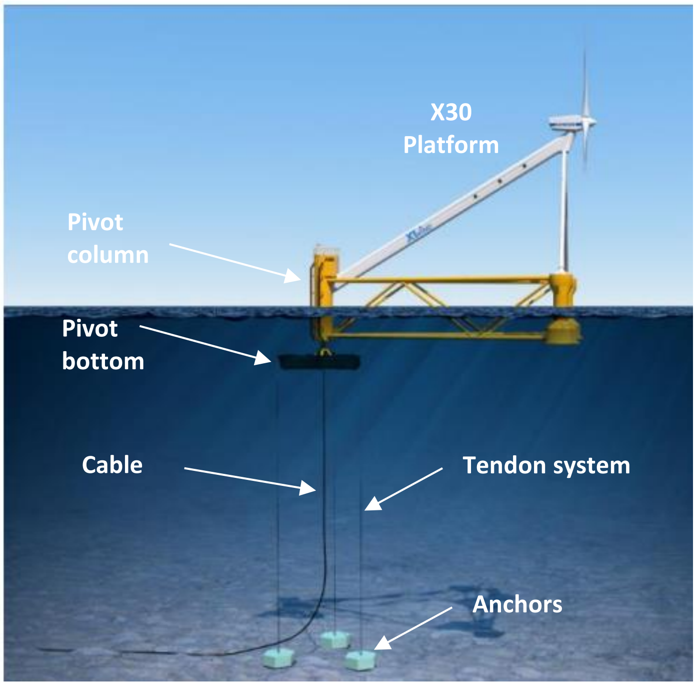

Figure 10. X1 Wind's floating wind X30 platform and PivotBuoy® single point mooring system. Several additional changes and optimizations are part of X1 Wind's protected IP and therefore cannot be shared in this report.

These updated elements have their equivalencies with respect to the former system, so the new nomenclature compared to the previous one can be seen in the following table:

Table 2. PivotBuoy system equivalencies

Initial PivotBuoy proposal	
Lower body	Tension-leg mooring system
	Anchor
	Dynamic cable
Upper body	Cone connection
	Passive yaw bearing with elastic coupling
	Coaxial cable connection with unroll mechanism

Equivalent to:

Updated PivotBuoy system	
TLP Mooring system	Pivot Bottom
	Tendon system
	Anchor
	Dynamic cable
Pivot Column	Quick connector
	Turret: yaw system with elastic coupling
	Slip ring

4.1.1 TLP mooring system

The TLP (tension-leg platform) mooring system is the name of the submerged part of the system. It would be the equivalent to the lower body from the initial proposal, although in this case the TLP mooring system would be completely submerged whereas the initial lower body was partly submerged and partly above the water surface. The TLP mooring system restricts motions of the PivotBuoy and provides the reacting force to counteract the turbine thrust, eliminating the need of additional weight or ballast required in semi-sub and spar systems.

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This system is composed of the following elements:

4.1.1.1 Pivot Bottom

The Pivot Bottom is a structural component that provides buoyancy. It is composed of three “legs” to which one or multiple tethers or cables are connected. Thus, this part integrates mooring, anchoring and electric cable system into a single point. It is embedded with the elastic coupling -through the quick connector- directly mounted at the bottom of the yaw system. This provides the Pivot Bottom upper connection with the semisubmersible part of the platform.

The Pivot Bottom should guarantee enough buoyancy to keep the mooring lines in tension, and it is meant to provide the single point mooring for the floating platform, with minimum sway, surge and yaw motions and almost no heave, pitch and roll motions.

Its structural design is based on the extreme loads coming from the elastic coupling system and the extreme effective tension of the mooring lines. It has been designed considering a balance between weight, manufacturing complexity and cost impact. In this way, the most suitable version has a triangular shape with tip legs, a central opening and the quick connector interface element on the top shell. The bottom shell is inclined upwards towards the end of each leg.

4.1.1.2 Tendon system

The tendon system consists in several vertical tensioned tendons, connected on the top end of the Pivot Bottom that restrain its vertical motions, as well as pitch and roll motions, connecting the Pivot Bottom to the anchor. Each tether or line is composed by three main elements: the bottom connector that connects the mooring line with the anchor, the top connector that connects the mooring line with the Pivot Bottom and the mooring line itself.

Depending on the number of the mooring lines considered, two main layouts can be considered for the system: 3 or 6 mooring lines. With 3 mooring lines it would be a non-redundant system with less number of elements, but those components would need to be larger. Whereas the 6 mooring lines configuration would be a redundant system with smaller components, but it would double the number of elements and operations, as well as adding some extra risks such as line clashing or possible line replacements that would add costs to the operational stage.

4.1.1.3 Anchor

The anchor is a component that provides a fixed connection to the seabed. The current manufactured part-scale model was a gravity base anchor, which is adequate for TLP systems in a seabed with clay or sand, such as the case of PLOCAN test site in the Canary Islands. Thus, the part-scale project used 3-concrete gravity blocks that were towed to the installation site.

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Figure 11. One of the three concrete gravity blocks built for the X30 part-scale prototype.

But the specific technology depends on the seabed characteristics and the connection with the seabed can be achieved in almost all types by means of a gravity base structure (GBS). For instance, in 10-20MW systems one considered option is to ballast a welded steel receptacle which later would be filled with rock, concrete or scrap materials. As in the case of the Pivot Bottom, attachment points to receive the connectors of the mooring lines would be located around the receptacle for the tether fixation.

Another advantage of having a TLP mooring system with GBS anchors is the low environmental impact on the seabed due to its small footprint, compared with the long spread and drag anchors used in catenary systems.

4.1.1.4 Dynamic cable

The dynamic cable is an umbilical power cable to export the generated electricity of the turbine to the substation or land.

Figure 12. Dynamic cable reel for X30 prototype stored at Las Palmas port

One of the advantages of using a TLP is that the dynamic cable is connected to a very stable platform, with very small motions and accelerations, compared to catenary systems where the cables are subject

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to larger motions and loads and require the use of special dynamic cables able to work in such fatigue-inducing conditions. The TLP enables the use of simpler cables working in quasi-static conditions, lowering fatigue and therefore costs on this key component.

4.1.2 Pivot Column

The Pivot Column is the central column that joins the system to the rest of the floater's structure (pontoons and masts). The Pivot Column provides buoyancy and houses the yaw system through which the connection to the mooring system is achieved.

Structurally it is a reinforced cylindrical column, made of two sections of different diameters. There are up to three watertight decks that subdivide the column into three main compartments.

The top compartment represents the machinery room of the platform, which will be fitted with the electrical and electronic systems, HVAC and the top bearing of the yaw system.

Figure 13. Pivot Column of X30 platform

The yaw system includes the yaw axis passes, bearing arrangement and slip ring.

4.1.2.1 Quick connector

The weathervane floating structure includes a quick connector that couples the turret yaw system to the pre-installed TLP mooring system. The quick connector comprises a base structure coupled to the outer body of the elastic coupling, a mooring interface attached to the TLP mooring system and a locking mechanism configured to couple and decouple the floating structure from the mooring interface.

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As described earlier, during the design phase, it was decided to make the connection system underwater instead of surface-piercing since it lowered significantly the loads, although it makes its design more complex to facilitate its installation and maintenance.

A 1:7 scale of the quick connector was designed and tested in the lab to de-risk this critical component, a preliminary design for this new quick connector is shared below. This includes some early results of early testing with a rapid-prototyping scaled model, which provided valuable input to refine its design.

Testing a prototype scaled model

As previously explained, a laboratory test was performed with a dummy solution of a quick connector for the full-scale size version. This was decided by the consortium, since the risk assessment showed that testing this novel quick connector already at the sea without ad-hoc lab testing was potentially putting the entire project at risk, should the connector fail during installation.

Thus the team launched the design of such a connector for a commercial-sized system, and downscaled it to 1:7 scale so that tests would be carried out at a reasonable cost. It is expected that the chosen size already reaches a good representation of the general function of the quick connector concept.

The selected facility for the tests was the elasticity and strength of materials lab, which belongs to the materials resistance and engineering structures department at university UPC-ETSEIB, located in Barcelona (Spain).

A large number of alternatives were evaluated for the quick connection system, some of them coming from O&G industry, related to FPSO's or vessel's connection to a floating buoy. Others related to risers and drilling systems. Also, the TLP's tendons bottom connection system was explored. Nevertheless, its associated costs were found excessive, and it would not perform well in the PivotBuoy environment and loads.

Hence, an internal brainstorming was performed and after a performance and cost evaluation a preferred solution was selected. First a preliminary CAD 3D model was designed and then it was structurally evaluated by means of finite element analysis (FEA). Afterwards, since the results were positive, a 1:7 scale prototype of the quick connector was manufactured for testing.

Some tests were performed between two periods: June '21 and November '21. The testing campaign was split into the following stages:

- Stage 1: components manufacturing and assembly
- Stage 2: endurance test
- Stage 3: ultimate limit loads verification

Stage 1: components manufacturing and assembly

The parts were manufactured between three suppliers depending on the part:

- Metallic parts, manufactured by DOILAN.
- Plastic parts, manufactured by CIM UPC.

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- Rubber parts, manufactured by ESM.

A second iteration of some of the plastic parts was tested afterwards using bronze, since the plastic elements were sustaining excessive plastic deformation.

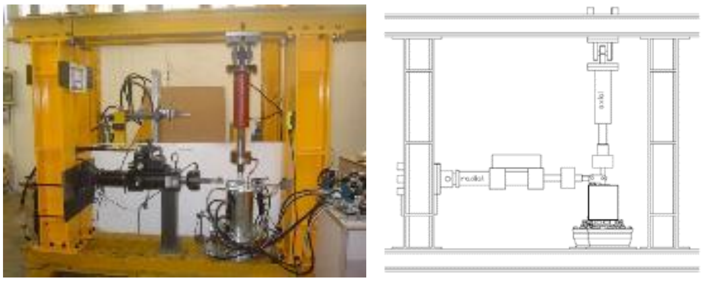

Figure 14. Quick connector and testing rig with radial and axial actuators.

The relative displacements of the TLP interface and the quick connector frame were measured and compared to the predicted values from the FEA model. The real displacements were registered by movement linear transducers.

Stage 2: endurance test

A high accelerated life test (HALT) was performed. Alternative bending moments were applied to the system a certain number of repetitions, representing a full year operation. Thus, the locking system was re-assembled and connected to the rig interface, equivalent to TLP interface.

Fatigue loads of the X30 prototype and their scaled values for the quick connecter were used, the cyclic load level was defined as a function of the number of repetitions. Thereby, an equivalent 19-years HALT was also performed.

Finally, the system was disconnected, and the parts disassembled for their inspection and measurement.

Stage 3: ultimate limit loads verification

Afterwards, the locking system was re-assembled again and connected to the equivalent TLP interface, so that the maximum axial and radial loads (weighted by the safety factors) were applied by the pistons.

Finally, the system was disconnected, and the parts disassembled for their inspection and measurement.

Results:

The testing campaign was very satisfactory. The manufactured model withstood the loads and the maximum displacements were measured. The parts were inspected and their wear checked. All these provided enough knowledge on the main areas to focus on to improve the quick connector design, tolerances and clearance to make some adjustments to improve its performance for the full-scale model.

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In general, the system showed excellent mechanical performance, as even the first test with some 3D printed parts successfully underwent a full fatigue test. Changing these to bronze reduced relative motion between cone and counter cone to sub-millimeter scale, even under extreme load. The geometry of these bronze parts could also be optimized looking at the deformation areas of the plastic parts, which provides a lot of insight and confidence going forward to have the best possible performance for this system.

Next steps in this regard after completion of the PivotBuoy project will entail the manufacture and testing of a full-scale unit at a much larger test site, to make sure there are no specific challenges or problems manufacturing and operating the system at full-scale, before it is deployed on a fully operational PivotBuoy commercial unit.

4.1.2.2 Turret: Yaw system with elastic coupling

The wind turbine floating structure is fitted with a turret mooring system to permit the buoyant structure to passively weathervane following the prevailing wind direction. The turret is in the Pivot Column, which is located in the upwind vertex of the triangular floating structure. From below, it connects to the mooring system which is connected to the seabed. The Pivot Column contains the shell, the internal structure and the yaw system; the latter being composed by the (i) yaw bearing and (ii) elastic coupling system.

The main function of the system is to link the floater to the Pivot Bottom while allowing the entire structure freely yawing around the azimuth axis, plus pitching and rolling small angles over the surface of the water.

Bearing function: the yaw axis connects the elastic coupling to the PivotTop structure through the bearing system.

Elastic coupling function: The elastic coupling has the function to enable the structure to pitch and roll small angles relative to the TLP, resisting all other loads. In this way it provides certain isolation to the connection between the yaw shaft and the connector of the TLP.

4.1.2.3 Slip ring

The slip ring is a kind of rotary electrical joint, electrical swivel and a collector ring. It is a device that can transmit power, electrical signals or data between a stationary component and a rotating one. This item substitutes the cable unwind system of the initial proposal. This is because during the preliminary design phase, risk assessment activities identified two issues with the cable unwind system:

- The first one was that it required a switchgear downstream from this system (that is, under it, either directly under but still on the floater, or at the PLOCAN platform. This is because a "hot" disconnection of the electrical cable by the cable unwind mechanism is not safe and can lead to premature failure of this lock mechanism and is also a fire hazard. So, a switchgear needs to remove voltage from the cable before the mechanism can physically disconnect it to proceed with the unwind operation. Having a Switchgear located at the lowest point of the

Pivot Column should be possible for the full scale, but the very limited space available for the part-scale prototype to be built as a part of the PivotBuoy project was unfeasible.

- The second issue has to do with a possible malfunction of any of the active systems in the cable unwind mechanism, be it the motor that unwind the cable, or the linear actuator that disengages the cable so it can unwind. Both require novel control systems as well, which could also be the origin of the failure. Regardless of the failure mode, the consequence would be to leave the platform without a grid connection until the system would be repaired, which could be weeks depending on the type of failure or just the weather conditions limiting access for the maintenance crew to proceed with the repair. This would mean losing both communication with the platform (through SCADA) and also the ventilation and dehumidifier systems, the latter being critical to keep the internal components from suffering accelerated corrosion which could lead to irreparable damage to the electrical systems onboard.

In parallel, further research into slip ring technology showed that the initial estimation of electrical losses for the slip ring at the beginning of the project were outdated, and current slip ring technology had an order of magnitude less losses of the order of 0.1%. This means that slip rings are actually viable, since these losses are acceptable. Slip rings being existing, proven technology reducing project risks, with acceptable costs, led the consortium to decide that it was not worth compromising the testing of the full platform functionality through a failure of the cable unwind mechanism, and to use a slip ring for the demonstration at PLOCAN.

For the full-scale system, the same slip ring philosophy is proposed. One of the main outcomes of the tests of the part-scale platform at PLOCAN is to measure the number of turns that the weathervaning platform actually does during this period, which will be very valuable input for the design of the commercial scale solution. The amount of control rings would remain the same so that the system can have a better structural design but the amount of fiber optics rings would be increased. As for the power rings, they will be adapted for the 10-20MW systems voltage and power.

There are specific challenges when scaling up from the voltage used in the PivotBuoy project (20 kV) to commercial units, which the latest research indicates will operate at 66 kV to reduce losses. At this voltage, air-insulated slip ring units become quite large in diameter, since they insulation distance required with air insulation are very large. The unit may then end up with diameters in excess of 4 m. While the upscaled PivotBuoy unit does have a larger diameter and can in theory accommodate such a large slip ring, it is not without issues. Fortunately, suppliers are already testing next generation designs using solid insulation, which should allow going back to more reasonable slip ring sizes. So this is not seen as a problem going forward.

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4.1.3 Installation method

One of the key advantages of the PivotBuoy is that there is part of the system which can be pre-installed. Thus, all the TLP mooring system can be installed and afterwards the rest of the platform (which includes the Pivot Column) is towed for connection to the submerged part, already installed, in a single operation.

As mentioned in the preceding sections. A different installation philosophy has been proposed for the PivotBuoy part scale prototype to de-risk the project, with the quick connector system being tested in the lab at 1:7 scale. For the X30 prototype to be tested at PLOCAN, the PivotBuoy Top and Bottom bodies (named Pivot Column and Pivot Bottom respectively) were assembled at the port in a controlled environment and towed to site together. The connection to the pre-installed tendons, which are deployed together with the GBS foundation, is performed through the top section of the tendon.

The following figure describes the proposed methodology for the commercial scale units to connect the two parts using a small vessel, which is used to tow the platform to the installation site. Once positioned, the platform (or the Pivot Column) can be submerged with water ballast until the system is connected and locked.

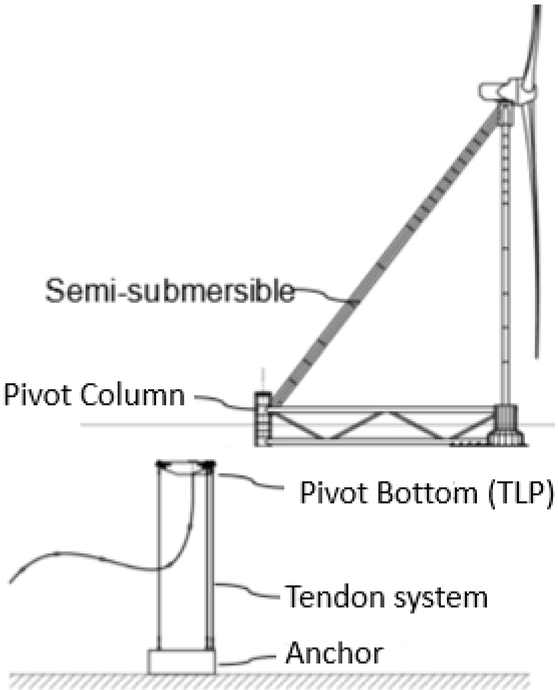

Figure 15. Pivot Column connection to Pivot Bottom

The full connection maneuver is divided in three steps. First, the mechanical quick connector is connected and locked to ensure the platform fixation. Then the umbilical cable is pulled in and mechanically attached to the yaw shaft head. Finally, the slip ring stator power and communications terminals are connected to the umbilical cable ones.

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5 PIVOTBUOY INTEGRATION IN OTHER FLOATING SYSTEMS

5.1 Design requirements for other floating systems

This subsection gathers the main requirements and characteristics that other floating systems need to implement the PivotBuoy system. These features are not only to ensure that the system is successfully applied but also that its potential integration to other floating platforms can enhance their performance because of some of the system characteristics.

Thereby, up to eight main features have been gathered. Below, those characteristics or requirements are briefly summarized:

Weathervaning. It benefits from or at least it would not be affected by it. Systems that have a need to stay aligned with either wind (e.g., wind turbines) or marine currents (e.g., tidal turbines) would benefit from it. Others, such as fish farms, do not need but it would not be a problem if it happens.

No vertical movements. It has either to be attached through a single point mooring system (SPM) to somewhere without vertical movements, or at least not being affected by those. For instance, WECs often need a fixed anchor point in the vertical direction to provide the reaction force to generate electricity.

Depth. It can be installed in deep waters, from 50 to 1000m range.

Electrical supply. It benefits from having electrical connection from 200kW to 20MW range (or even more if turbine size increase beyond 20MW). The PivotBuoy provides an integrated electrical connection plus swivel, which can be adapted for (e.g., tidal turbines).

Quick connector. It benefits from a fast connection and disconnection system. Enabling the platform to perform an easier and cheaper installation and a tow-to-port operation.

Low footprint. It benefits from having a small seabed footprint (~30x30m for the commercial unit) compared to the much longer mooring spread required when using catenary lines and drag anchors (around 900m in first pre-commercial projects).

Draft. the PivotBuoy system allows for a lower floater draft (<10m for the X140 floater) so that it can be assembled in many of the ports in Europe. As explained earlier, the TLP system is pre-installed and then the floater and turbine assembled at port and towed-to-site for its connection.

Low noise. The system fits applications that require low ambient noise underwater with tensioned cables with have lower noise than catenary systems using chain (results from noise levels will be obtained during tests at PLOCAN).

5.2 Feasibility evaluation of the integration in other potential systems

As a combined mooring and subsea power cable connection solution, the PivotBuoy system was designed to provide a quick, reliable, safe and cost-effective approach to connecting and disconnecting

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the X1 Wind's floating weathervaning offshore wind turbines. Still, such a quick-connection system may be found potentially applicable to other offshore platforms analysed in this sub-section.

As a TLP-based turret mooring system, the PivotBuoy system is optimized and most beneficial for single point mooring platforms, although in theory it may also be adapted for fixed-heading concepts. In the following sections, five main potential applications are considered: i) wave energy, ii) tidal energy, iii) other floating wind platforms, iv) offshore aquaculture, and v) typical O&G Floating Production Storage and Offloading (FPSO) systems. These potential end uses are evaluated and compared according to different metrics, such as the market size, technology development stage, potential benefits, and retrofit requirements. The list of metrics is presented in Table 3.

Table 3. Metrics for evaluating the potential applications of the PivotBuoy system

Metrics		Evaluation score		
		1	2	3
1	**Overall technology maturity**	Low maturity. A few prototypes have been developed and tested, but mostly still in a demonstration phase.	Intermediate maturity. Several prototypes have been developed and tested, and there are a few commercial projects in progress.	High maturity. There are several commercial projects.
2	**Potential benefits of implementing a PivotBuoy system**	Potential benefits of implementing a PivotBuoy system are negligible	Potential benefits of implementing a PivotBuoy system are moderate	Potential benefits of implementing a PivotBuoy system are significant.
3	**Requirement for retrofitting target concept**	Retrofitting requirement for target sector is large.	Retrofitting requirement for target concept is moderate.	Retrofitting requirement for target concept is minimal to none.
4	**Requirement for PivotBuoy design adjustments**	Implementing the PivotBuoy system in considered application would require extensive design effort	Implementing the PivotBuoy system in considered application would moderate design effort	PivotBuoy system could be applicable to the target concept with minimal design adjustments
5	**Current market size and expected sector growth**	Target market is relatively small (<$100 million). Moderate future growth is expected.	Target market size is moderate (between $100 million to $1 billion) and significant future growth is expected.	Target market size is large (> $1 billion) and significant future growth is expected.

The overall technology maturity was selected as a metric to compare different applications in respect to the readiness to market. The market size was selected as a metric to illustrate how much business potential exists in that specific sector. The potential benefits metric was included to quantify the positive impacts of implementing PivotBuoy system in a given project, namely on potential reductions on the levelized cost of energy. Finally, two metrics were considered to assess potential technical barriers to the implementation of PivotBuoy in the different sectors: the expected requirements for retrofitting an existing platform/concept, and internal research effort to redesign PivotBuoy to meet project the target platform requirements.

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5.2.1 Wave Energy

Wave energy converters (WEC) capture the energy of the ocean waves to generate electricity. Wave energy is an attractive renewable energy resource with the potential to become a major contributor to the global renewable energy generation mix [1]. Similar to floating offshore wind, floating wave energy converters can be deployed in further offshore locations where the wave energy resource is larger and space constraints are significantly lower. However, despite the development effort in the recent years, wave energy is still at an early stage of development when compared to other renewable energy technologies such as offshore wind, which translates into costs above grid-parity.

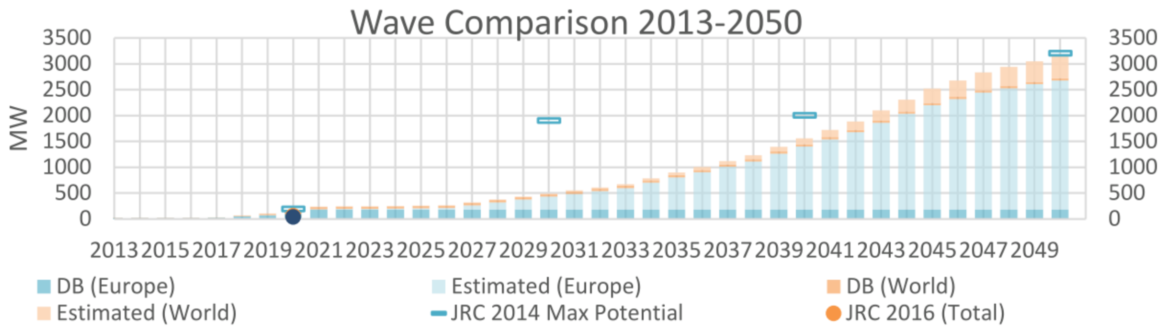

Figure 16. Wave energy future growth: optimistic scenario comparison with published forecasts for 2013-2050. Taken from [2].

The wave energy sector is expected to grow throughout the next decades. As shown in Figure 16, optimistic scenarios predict that the total cumulative installed capacity will reach 3000 MW by 2050. It is also expected that even though there will be a decrease in new installations, especially at low TRLs, the total operational capacity will be increasing, as projects from TRL 8 to 9 will be in operation for 10 to 25 years (see Figure 16) [2].

A clear sign that the sector has still not reached technology convergence is the wide range of wave energy technologies under development, for different water depths and locations (i.e. bottom-fixed or floating), different sizes, and operating principles. For floating wave energy converters, mooring systems can be divided into three categories: i) passive, when the only purpose of the mooring system is to ensure station keeping, and the device movements have limited impacts on the device efficiency, ii) active, when the mooring system stiffness has a strong influence on the hydrodynamic response of the WEC and hence on the power output of the device (mooring stiffness effects may induce resonance conditions which increase device's efficiency), and iii) reactive, when the mooring system provides the reaction force, and the Power Take Off (PTO) unit exploits the relative motion between the body and the fixed ground to produce energy [3].

Most proposed floating wave energy technologies fit into the active moorings category [3], which means that the design of the mooring system must be integrated in the design of the project as a whole. This also means that for these devices, the small dynamic responses of TLP mooring configurations such as PivotBuoy would significantly hinder their performance.

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Nonetheless, weathervaning attenuators with single point moorings are potentially suitable candidates for the PivotBuoy system, as the quick-connect mooring and cable interface may simplify the installation and tow-to-port maintenance of such devices [4], [5]. However, recent research in such WEC technologies has been very limited in the last few years.

Despite the large number of wave energy demonstration projects that failed spectacularly in the last two decades, resulting in a large number of companies filing for bankruptcy, many successful demonstration projects have proven their technical maturity [8]. Still, reducing the cost of energy remains a serious challenge for which PivotBuoy could potentially contribute.

Based on the compiled information, the wave energy sector was evaluated overall in respect to the potential suitability for implementing the PivotBuoy system.

Table 4. Evaluation of wave energy concepts as suitable applications for the PivotBuoy system

Metrics		Metric score	Comment
1	**Overall technology maturity**	**1**	Wave energy is at a relatively low maturity. There have been several prototypes that have been tested, but floating wave energy converters that could be compatible with the PivotBuoy system are not among the most developed ones. Most importantly, there has not been any commercial projects to date.
2	**Potential benefits of implementing a PivotBuoy system**	**1**	Not all floating wave energy concepts are suitable for a TLP-type mooring connector. Although a quick connection system would be beneficial for wave energy projects, in most cases, such TLP-based system may result in significant reductions of device energy production performance.
3	**Requirement for retrofitting target concept**	**1**	Most floating wave energy converter concepts are not weathervaning, which means that a significant level of retrofit of the target wave energy converter concept may be required.
4	**Potential requirement for PivotBuoy design adjustments**	**2**	Moderate PivotBuoy design adjustments may be expected due to lower power ratings, higher vertical motions and potentially slightly larger loads.
5	**Current market size and expected sector growth**	**1**	The wave energy sector is relatively small in comparison to other floating offshore applications.

5.2.2 Tidal Stream Applications

The high potential of the tidal energy resource coupled with successful demonstrations of full-scale tidal current technologies in the last decade have attracted private investors and governmental support for the technology and tidal project development [6].

Tidal stream devices, a subtype of tidal energy converters (TEC), are often considered the submerged equivalent to wind energy given that in both cases, energy is extracted from a moving fluid. Tidal stream is clean, powerful, but also exceptionally low in variability, highly predictable and capable of providing a stable output to the grid. In contrast to wave and wind, there are no extreme current speeds underwater that could potentially damage the PTO or force it to shut down, increasing farm

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availability [7]. However, there are presently techno-economic challenges associated with the manufacture, installation and maintenance of tidal stream energy farms in order to generate electricity at a large scale and at a competitive price [8].

In contrast to the wind industry, which has converged to the three-bladed axial-flow turbine for being more efficient at larger scales [9], there are multiple tidal stream technologies currently under development. Most tidal stream concepts consist of tidal turbines with aerofoil cross-sections that extract energy using through aerodynamic lift (axial-flow or cross-flow turbines), but there are also more unusual concepts such as tidal kites and oscillating hydrofoils [10]. However, in the context of PivotBuoy system, only floating tidal stream systems can be considered relevant.

In the last decade, the tidal stream sector has made significant progress. High potential technologies have been extensively tested and front running devices have been deployed at sea with a good degree of confidence about their future performance [11]. Current estimates suggest that tidal stream projects will grow in number at a faster pace than wave energy, reaching about 10,000 MW by 2050 (see Figure 17).

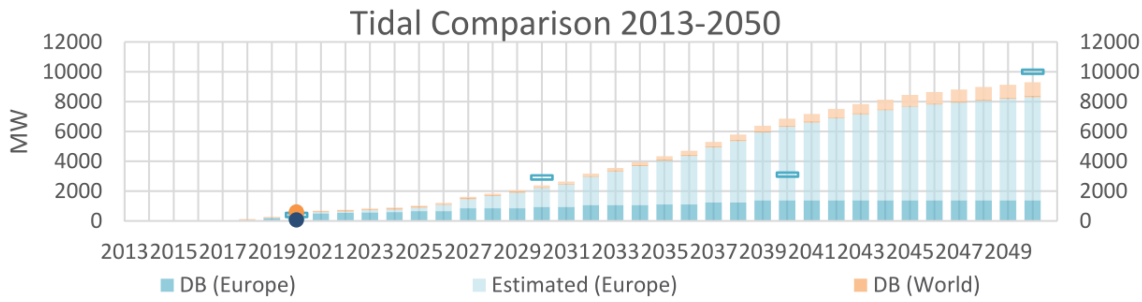

Figure 17. Tidal stream future growth: optimistic scenario comparison with published forecasts for 2013-2050. Source: [2]

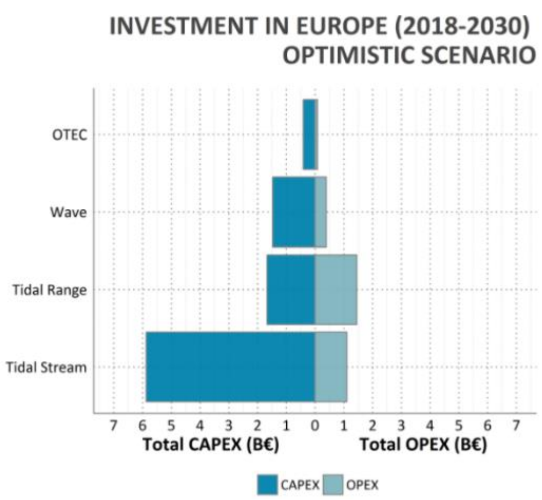

Figure 18. Future investment projections until 2030: optimistic scenario [2]

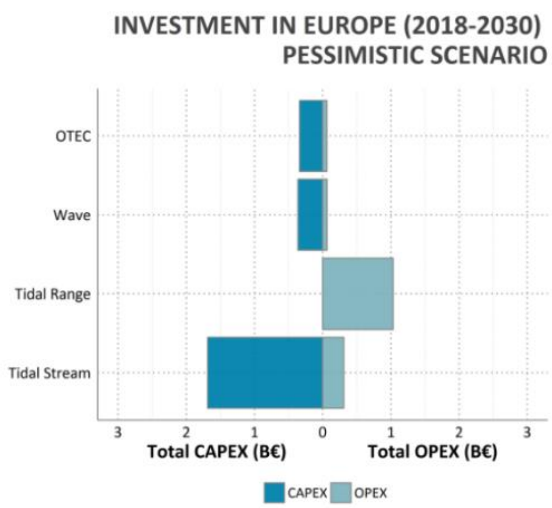

Figure 19. Future investment projections until 2030: Pessimistic scenario [2]

It can also be observed that out of the entire ocean renewables sector, for both optimistic and pessimistic projections (see Figure 18 and Figure 19, respectively), tidal stream projects will be the

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ones capturing the largest fraction of private and public investment in the next decade. This is reassuring for existing and new players in the tidal stream market.

Similarly to other renewable energy systems such as wave and offshore wind, floating tidal stream technologies have key advantages over bottom-fixed concepts, namely lower structural costs, simplified installation and maintenance work, as well as removing the need for heavy lift vessels. However, floating tidal stream technologies are typically exposed to rougher wave conditions, which result on additional off-axis loading on the turbine, as well as higher overturning moments which must be counteracted by the mooring system [8].

The development of advanced mooring systems and cable connectors, as well as innovations regarding the installation and O&M of tidal stream devices, are referred as key priorities for reducing the costs of tidal stream projects [11]. The mooring system must be capable of maintaining the optimal orientation of the turbine relative to the flow. Based on this, the tidal stream energy sector was evaluated overall in respect to the potential suitability for implementing the PivotBuoy system, shown in Table 5.

Table 5. Evaluation of tidal energy concepts as suitable applications for the PivotBuoy system

	Metrics	Metric score	Comment
1	**Overall technology maturity**	**2**	Several prototypes that have been developed and extensively tested. A few commercial projects are in construction.
2	**Potential benefits of implementing a PivotBuoy system**	**3**	Only a few tidal stream concepts are potentially compatible with TLP mooring system. However, for such concepts, the development of quick-connect connectors is considered a priority, due to their potential benefits in simplifying the installation and O&M.
3	**Requirement for retrofitting target concept**	**2**	Weathervaning systems are more common for tidal stream rather than wave energy technologies. However, further research in respect to potential challenges of constraining pitch motions of the tidal stream platform using a turret mooring system is required.
4	**Potential requirement for PivotBuoy design adjustments**	**3**	Low PivotBuoy design adjustments are expected when implementing the system on a weathervaning tidal stream platform. Mooring load profiles are likely to not be a problem.
5	**Market size**	**2**	The tidal stream sector is growing fast and expected to capture a major fraction of the total investment in ocean renewables until 2050. However, only a few tidal stream concepts are potentially compatible with TLP mooring system, reducing the total relevant market share.

5.2.3 Other floating offshore wind platforms

Floating offshore wind (FOW) is a fast-maturing sector, with the potential to satisfy a significant share of the global electricity demand. By 2050, it is expected that floating offshore wind farms will cover about 5% to 15% of the global offshore wind installed capacity, which is estimated to reach almost

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1,000 GW [12]. It is also expected, that in the next decades, the annual investments will significantly increase (see Figure 20).

Figure 20. Average annual investments for offshore wind deployment (USD billion/year). Source: [15]

Conventional floating offshore wind concepts are classified into three main groups according to the underlying stabilization principle of the platform: i) *buoyancy-stabilized platforms* such as the semi-submersible (e.g. Windfloat) and barge (e.g. IDEOL); ii) *ballast-stabilized platforms* such as the spar (e.g. Hywind), iii) *mooring line stabilized platforms* such as the TLP (e.g. Pelastar). According to the findings in [13], it is expected that semi-submersible FOWT concepts will dominate the market in the near-future, although significant design variations can still be expected.

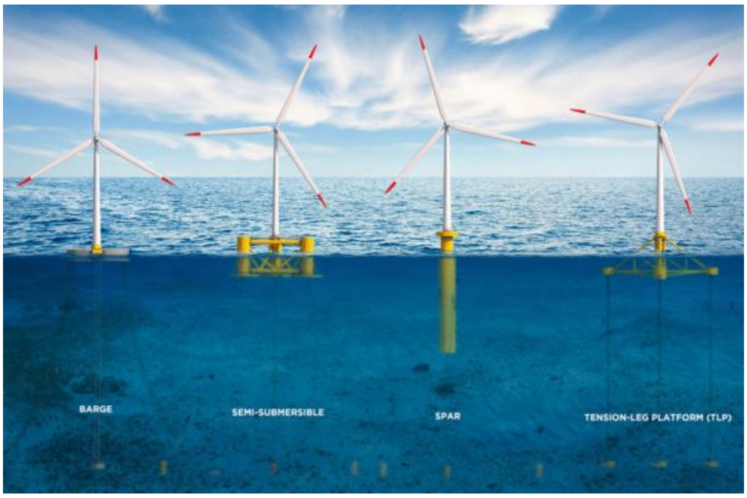

Figure 21. Traditional floating offshore wind foundations.

Conventional floating offshore wind projects have been progressing from pre-commercial stages to large-scale commercial deployment. Front-running floating offshore wind concepts have been designed as fixed-heading with multiple line mooring systems that ensure station keeping of the

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platform (see Figure 21). However, several alternative concepts are currently under development and prototype testing, featuring design variations such as multiple turbines per platform, alternative turbine designs, the integration of wind with other forms of renewable energy generation, as well as weathervaning platforms with single point mooring systems.

Given its design, the PivotBuoy system is naturally more suitable for the bespoke alternative weathervaning FOW concepts, designed with single point moorings. Some examples are SATH by Saitec Offshore Technologies, W2Power by EnerOcean, Nezzy by Aerodyn, Hexicon's concept and Eolink's concept by the French firm with the same name. In such cases, a quick-disconnect system such as PivotBuoy can be a particularly attractive concept for platforms that are expected to experience multiple connection and disconnection cycles throughout project lifetime. The overall evaluation in respect to the potential suitability for implementing the PivotBuoy system is shown in Table 6.

Table 6. Evaluation of weathervaning floating offshore wind concepts as suitable applications for the PivotBuoy system.

Metrics		Metric score	Comment
1	**Overall technology maturity**	**2**	Floating offshore wind is at an advanced development stage with pre-commercial wind farms in operation. Still, despite near-future plans for full-scale deployments, relevant FOW concepts with single-point mooring systems are still at TRLs of 6.
2	**Potential benefits of implementing a PivotBuoy system**	**3**	The disconnection and reconnection of FOW is a major logistic challenge, namely for concepts which are suitable for tow-to-port maintenance, which require multiple connection/disconnection cycles throughout project lifetime.
3	**Requirement for retrofitting target concept**	**3**	Although integrating the PivotBuoy system into conventional fixed-heading FOW turbines would impose significant retrofitting requirements, it is expected that the integration of PivotBuoy into alternative weathervaning FOW concepts would require low levels of retrofitting. However, further research is warranted.
4	**Potential requirement for PivotBuoy design adjustments**	**3**	Not all floating offshore wind concepts are suitable for a TLP-type mooring connector. Adapting PivotBuoy design for other single point moored FOW concepts appears to have the lowest level of design adjustment requirements. Still, further research is required to confirm this.
5	**Market size**	**2**	The FOW market is expected to rapidly expand in the next decades, providing opportunities for R&D and new projects. However, it must be noted that the number of suitable FOW candidates for the PivotBuoy system is much smaller, as it only includes those integrated with single point mooring systems.

5.2.4 Other

In addition to the offshore renewable energy applications described above, this solution could also be applied to other applications such as floating structures for aquaculture or for FPSOs floating vessels widely used in the offshore O&G industry for the production and processing of hydrocarbons. However, such applications would require significant adaptations of the design and it is not the scope of this project.

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5.2.5 Comparison

In the previous sections, four different offshore sectors were evaluated according to their potential for implementing the PivotBuoy system. Given their relevance to the offshore renewable energy industry, potential use cases in the wave energy, tidal stream and of course floating offshore wind were evaluated according to five metrics and scored from "1" (lowest) to "3" (highest), following the evaluation matrix presented in Table 3.

As depicted in Figure 16, wave energy is the least mature sector, as shown by its low market size, relatively low TRL, while having high costs of energy. Despite the very large number of existing technologies for extracting the energy of the waves, only a few are relevant contenders for implementing the PivotBuoy system. Additionally, depending on the operating principle of the device, a TLP mooring system such as PivotBuoy may hinder the performance of the device and ultimately affect the costs of energy. This may result in moderate research effort for adapting the PivotBuoy system to wave energy applications.

From the ocean energy sector, which includes wave, tidal, and Ocean Thermal Energy Conversion (OTEC), tidal stream is the most mature and the one expecting the highest amount of funding in the next decades. In contrast to wave energy, the energy capture performance of floating tidal stream technologies is not particularly affected by the implementation of a TLP mooring system, while single point moorings have been deployed in the past. Reducing the costs of energy is a current priority for the tidal stream sector, whilst the reduction of installation and maintenance costs has long been advocated as an important cost reduction pathway.

Floating offshore wind has the largest market size, showing considerable development progress in the last decade. However, most floating offshore wind concepts are not relevant contenders for the PivotBuoy system: tow-to-port maintenance is a key benefit of implementing a quick-disconnect system such as PivotBuoy but conventional spar and TLP platforms are not adequate for this type of maintenance without massive modifications in the platform design. Semi-sub and barge FOW platforms are potential candidates for the PivotBuoy system, but only when integrated with single-point mooring systems that allow weathervaning. For alternative floating offshore wind concepts with single point mooring systems, the expected platform retrofitting effort for integrating the PivotBuoy system is considered to be low. Even though fixed-heading floating offshore wind projects have been reaching pre-commercial stages in the last few years, alternative weathervaning concepts are still at lower maturity levels, representing a small share of the total FOW market size.

As illustrated in Table 7, floating wind exhibits the highest level of compatibility across the analysed metrics, while wave energy seems to be the least compatible.

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Table 7. Evaluation of the different potential applications for the PivotBuoy system according to the evaluation criteria.

Metrics		WAVE	TIDAL	FOW
1	Overall technology maturity	1	2	2
2	Potential benefits of candidate technology achieved by implementing a quick disconnect system	1	3	3
3	Requirement for retrofitting target concept	1	2	2
4	Potential requirement for PivotBuoy design adjustments	2	3	3
5	Market size	1	2	2

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6 CONCLUSIONS

This report is the completion of the project designing stage, since it's the last deliverable of its corresponding work package (*WP2 - PivotBuoy Subsystems Design*). In the first part of the report there is a brief introduction on the part-scale PivotBuoy® demonstration project and the evolution of the model through the designing stage, from its initial concept to its detailed design.

This deliverable shows the design evolution and scalability from concept to part-scale pilot to the preliminary design for a full-commercial unit. It also includes a brief explanation of the manufacturing considerations for its industrialization.

Then the document provides a description of the full-commercial floating offshore wind platform model developed by X1 Wind, called 'X140', that would fit a downwind 14MW turbine. It includes the updated PivotBuoy® system subcomponents and the installation philosophy. The section gathers all the lessons learned from the previous project stages. It also includes a subsection with the quick connector tests at the lab.

Last section collects the requirements for other floating systems where the PivotBuoy® can be applied to ensure its integration to other floating platforms, including a feasibility evaluation of the integration in other potential systems.

Please note that several designs as well as detailed features of the evolved models are part of X1 Wind's protected IP and therefore cannot be shared in this public report.

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