2023-12-14

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Edwards, E

https://pearl.plymouth.ac.uk/handle/10026.1/21793

10.24382/scvw-0t77

Supplementary information on early-stage floating offshore wind platform designs

Emma C Edwards[1,2,*], Anna Holcombe[1], Scott Brown[1], Edward Ransley[1], Martyn Hann[1], and Deborah Greaves[1]

[1] *School of Engineering, Computing and Mathematics, University of Plymouth, Drake Circus, Plymouth PL4 8AA, United Kingdom*
[2] *Department of Engineering Science, University of Oxford, Parks Rd Oxford OX1 3PJ, United Kingdom*
[*] *emma.edwards@eng.ox.ac.uk*

1 Introduction

This document serves as supplementary information to the authors' review paper on early-stage floating offshore wind turbine (FOWT) platform designs. The review paper is the second part in a study on FOWT platform designs, following Edwards et al. [1], which is a review of FOWT platforms which currently have or have previously had a prototype, demonstration, or farm scale project at-sea. The present review covers 86 past and current early-stage platform designs, ranging from early conceptual designs to platforms which have undergone lab tests simulating extreme conditions.

In the main body of the text, key trends in early-stage FOWT platform designs are identified and discussed. Four phases are identified to describe the evolution of FOWT platform designs and how changing design drivers have changed the FOWT platforms themselves. Furthermore, potential future trends are discussed. In this supplementary information document, more details are provided about all 86 platforms reviewed. For each device, the following is included (if available): (i) a description of the platform and its unique features, (ii) a rough timeline of development, (iii) design goals and constraints, (iv) evolution of the design, (v) lab testing information, and (vi) published dimensions. Summary tables of key parameters, such as 'type' of platform, projected turbine capacity, material, water depth limits, mooring set-up, other use (*i.e.*, hybrid device), and information about lab tests, can be found in the main body of the text, in Tables 1-4, separated by lab testing. In this document, Section 2 contains the platforms that are no longer in development (*i.e.* there has been no new development since 2018). Section 3 contains the platforms still in development today. Within each of those two sections, platforms designed to hold a single turbine are presented first, then platforms designed to hold multiple turbines, and finally hybrid platforms. Within each sub-section, the platforms are ordered roughly chronologically. The platforms in this review are all 'early stage' platforms because they do not have a prototype, demonstrator or farm-scale device at sea, but the 'early stage' designation spans a wide range of development, from early concept to tested in the lab simulating extreme conditions. This comprehensive review provides academics and developers with important information about the past and current status of the technology.

1.1 Abbreviations

FOWT: floating offshore wind turbine
GW: gigawatts
HAWT: horizontal axis wind turbine
kW: kilowatts
MW: megawatts
TLP: tension leg platform
VAWT: vertical axis wind turbine
WEC: wave energy converter

2 Early FOWT platform designs

2.1 Single turbine platforms

2.1.1 FLOAT

The FLOAT platform was developed in the early-mid-1990s by a consortium led by Tecnomare in the UK [2]. The overall goals of this proof-of-concept study, which was the first serious investigation of FOWTs, was to design two 12 MW wind farms, in two different locations. The study consisted of three phases: (i) consideration of platform designs, including conventional platform designs from the oil and gas industry as well as unconventional platform designs; (ii) numerical modeling; and (iii) lab testing [3]. After the first exploratory phase, a spar buoy was selected because it was already proven in the oil and gas sector. The platform was a concrete cylindrical spar with a heave plate, holding a 1.4 MW turbine, with eight mooring lines (either taut or catenary, depending on water depth) [4], [3]. The critical design goals for the platform and tower were to avoid resonance at 1P and 3P and to reduce weight. The final design was a compromise between minimizing cost, maximizing stability, and minimizing dynamic motion response. Concrete was chosen because of its cost effectiveness [3]. For the lab testing, 1:48 scale model tests of the 1.4 MW system were performed in a towing tank, including survival sea states, though wind conditions were not modeled satisfactorily due to scaling difficulties [2], [3], [4]. Though there was no further development on this platform after the initial study, the insights from this study were instrumental in early FOWT research.

2.1.2 ELOMAR

ELOMAR was a platform developed in the early-mid-1990s by AIOM and ENEL. The initial proof-of-concept study consisted of an investigation of a few different designs for the substructure of the TLP and then some lab testing. The submerged structure was originally a lenticular shape, to distribute pressure evenly, with a single column attaching to the tower above water, but the design changed so that the submerged structure was toroidal in shape, with three columns attaching to the tower. Originally, concrete was to be used, but it was decided to use steel instead because of its flexibility to shape the structure more freely and its more common use in offshore structures. The structure was designed for water depths 30-100 m, and six taut diagonal mooring lines connected the submerged shape to three anchors. Two configurations were tested for the columns attaching the substructure to the tower above the water surface: one in which the three columns were diagonal, and one in which the columns were vertical. 1:50 scale model tests (with undisclosed power for full-scale) were performed, testing the performance in waves only. These lab tests concluded that mooring load distribution needed to be developed further. Additionally, installation was shown to be of concern since, although it was designed to float on its own for towing, the platform was unstable in heave and pitch while being ballasted but before connecting to the mooring [2], [5]. There have been no further studies or development on the platform since the mid-1990s.

2.1.3 Doris TLP

Doris and Marseille Engineering University designed and tested a three-leg star TLP in the early-2000s. Doris used its experience in floating offshore oil and gas to design the platform. 1:49 scale model tests (with undisclosed power for full-scale) were performed in BGO-First at La Seyne [2], [6]. There have been no signs of further development since 2004.

2.1.4 Arcadis TLP

Arcadis developed and patented a steel TLP platform with concrete gravity anchors, but there was limited published information about the platform, and there has been no news since the mid-2000s about it [7].

2.1.5 MIT/NREL platforms

MIT and NREL developed multiple platforms in the mid-late-2000s, including a TLP, a taut-leg buoy, and a barge. The goals of this collaboration were to explore different platform designs and to develop coupled numerical codes to accurately represent FOWT dynamics. The TLP platform was designed for use in 10-200 m water depth. The critical design condition of the structure was to be neutrally buoyant during tow-out, and they found that this static performance of the system drove the design. It was decided at the time to not look at spars because of their unsuitability for shipyards. The platform size and shape were determined to constrain steady-state pitch to below 10°, and the mooring system was designed to ensure that (i) the mooring lines provided sufficient restoring force in surge, (ii) the windward tether tension did not exceed the allowable amount, and (iii) the leeward tether did not go slack. The platform, designed to hold a 5 MW turbine, consisted of a cylindrical body with a cross at the bottom, of diameter 22 m and draft 20 m [8].

A taut leg buoy (TLB) was also designed, consisting of a cylindrical spar buoy with eight semi-taut mooring lines connected to four anchors [9], [10], [11].

Finally, a barge was designed, consisting of a steel cylinder with concrete ballast, with 36 m diameter and 5 m draft [8]. None of these platforms were developed past the initial concept stage.

2.1.6 Concept Marine Associates TLP

Concept Marine Associates developed a TLP platform in the early-mid-2000s, with a lowerable anchor. The gravity anchor was to be used as a barge during tow-out, and then at the site of installation it would be filled with gravel and ballast water to be lowered to the seabed [9]. There is no record of any tank testing or development further than an initial design.

2.1.7 Hua barge

Hua [12] designed a barge platform in the early-2010s. The platform, which was designed to hold a 5 MW turbine, was made with reinforced concrete. The structure consisted of a wide, vertical cylinder at the waterline, an elliptical sphere below the waterline, and a narrower cylinder above the waterline. The design allowed for good hydrostatic stability during operational conditions due to the large waterplane area. During a severe storm, the structure would increase its ballast to lower down so that the narrower cylinder was at the waterline to decrease extreme motions [12]. There is no record of any tank testing or development further than an initial design.

2.1.8 HiPRWind

HiPRWind was a three-column semi-sub platform developed by Dr. techn. Olav Olsen in the early-2010s. During the initial parts of the study, TLP and spar platforms were also considered, but a constraint of the study was to develop a platform design that could be fabricated and installed at a standard port, so it was decided that a three-column steel semi-sub was the most technically and economically feasible option. The platform was designed to hold a 1.5 MW turbine, and it consisted of three columns with heave plates at the bottom of each column, connected by braces to each other and to the tower in the center. The draft of the structure was 15.5 m and the columns were 35 m apart [13]. There is no record of any tank testing or development further than an initial design. However, Dr. techn. Olav Olsen proceeded to design a different platform, the OO-star (3.1.9).

2.1.9 Ocean Breeze

The Ocean Breeze TLP platform was developed in the early-2010s. The main platform structure consisted of four outer steel columns, connected via trusses to each other and a central column carrying the tower and turbine. The gravity base was made of concrete and steel and towed out separately to the main buoyant hull. The design goal of the platform, which was designed for water depths 60-200 m, was to minimize cost, including manufacturing, installation, maintenance, operation and removal. The mooring system, connecting the hull to the gravity base, consists of four taut lines, made of spiral steel bridge strand wires with silicon based anti-fouling coating [14], [15]. There is no record of any tank testing or development further than an initial design.

2.1.10 VertiWind

VertiWind was a platform developed in early-mid-2010s. The platform was a semi-sub with three outer columns with hexagonal heave plates and a central column holding a 2 MW Darrieus VAWT [16], [17]. According to the developers, compared to a HAWT, the VAWT would (i) be cheaper and more reliable, (ii) save material, (iii) have an easier turbine installation, (iv) avoid power production being affected by motion of the platform, (v) have a lower center of gravity, reducing structural cost and visual impact, and (vi) not be sensitive to wind direction [18], [19]. The mooring system consisted of three catenary lines made of chains with clump weights [18]. A 35 kW onshore prototype of the VAWT was in operation, but the turbine was redesigned due to blade fatigue concerns. There has been no record of any tank testing or further development for the platform.

2.1.11 FAWT-S and FAWT-C

The FAWT-S and FAWT-C were concepts developed by KAIST in the early-mid-2010s. These concepts used two different types of VAWTs on top of the same spar platform. Inspired by the DeepWind concept, the entire floater rotated with the turbine, but for this design, the generator was located in a supporting float at the water surface, instead of submerged at the base of the spar, which was where the generator was located for the DeepWind design. The FAWT-S turbine had straight blades, and the FAWT-C had curved blades [20]. The spar platform, designed for a 3 MW turbine, had a draft of 30 m and diameter of 5 m. The mooring system consisted of two catenary mooring lines attached to the supporting float containing the generator [21]. There is no record of any tank testing or development further than an initial design.

2.1.12 Winflo

The Winflo platform was a semi-sub developed in the early-2010s. The semi-sub consisted of three outwardly-inclined columns, connected by pontoons at the bottom and a truss at the top to a central column holding the tower and turbine. There were plans for a 1 MW demonstrator in 2013 off the coast of France, but it never went through, and there have been no signs of further development [22].

2.1.13 TLPWind

TLPWIND was a TLP platform developed in the mid-2010s by Iberdrola Engineering and Construction, in collaboration with the Offshore Renewable Energy Catapult and the University of Strathclyde which underwent a few rounds of lab testing. The platform was made of four square-sectioned pontoons, forming a cross with a column in the center holding the tower and turbine [23]. The platform was not stable when being towed, so a semi-sub barge was developed for towing [24]. The mooring consisted of two taut lines on each of the four sections made of steel or synthetic material, ensuring complete redundancy [25]. The 5 MW system had a draft of 35.5 m, the pontoons were 4.4 m by 5.5 m, and the central column had a 8.2 m diameter [26]. 1:40 scale model tests of the 5 MW system were done at the CEHINAV (UPM) model basin and CEHIPAR ocean basin, including regular waves, operational, survival, failure and transport conditions. It was found that the platform response was small in all modes except surge, as is typical for a TLP [25]. 1:36 scale model tests of the 5 MW system were also done in the Kelvin Hydrodynamics Lab at the University of Strathclyde, including decay tests, tests in regular wave, irregular waves, and failure and accidental load cases for a North Sea location. It was found that wind had a significant contribution to overall platform response, and that wave conditions had a small contribution [26]. There is no record of development beyond these tank tests.

2.1.14 SSTLWT

The SSTLWT was a combination semi-sub-TLP platform developed in the mid-2010s. It was designed so that the platform could be towed, with tower and turbine installed, to the location of deployment. There, it would be connected to either catenary or taut mooring lines. The structure had three outwardly-inclined surface-piercing columns, coming together at the base below the water surface, with a vertical central column holding the tower and turbine [27]. There is no record of any tank testing or development further than an initial design.

2.1.15 Aerogenerator

The Aerogenerator X was a platform designed in the mid-2010s to carry 5-10 MW VAWTs. Multiple designs were considered, including barges (circular or square, with and without heave plates) and semi-subs (four columns, with two or four pontoons). The final design consisted of a four-column semi-sub with four pontoons connecting the columns at the bottom in a square, and a deck attached to the top, with the VAWT in the center. The largest driving requirement for the platforms was found to be a good response to wave excitation, not an ability to counteract wind overturning moment [28], [29]. There are no records of any tank testing or development further than an initial design.

2.1.16 Pusan University alternative spar

An 'alternative spar' design developed from an optimization study by researchers at Pusan National University in the mid-2010s, and some lab tests were done on the resulting design. The study aimed to optimize a spar-type buoy, holding a 3 MW turbine, by minimizing body motion in all six degrees-of-freedom, as well as platform weight. Design parameters to optimize were diameter, draft, weight of concrete, and weight of water ballast. A standard cylindrical spar was compared with a truss spar (a spar in which the middle section is made from trusses), and it was found that hydrostatic stability was similar between the two designs, and motions in heave, roll and pitch were smaller for the truss spar [30], [31]. 1:75 scale model tests of the 2.5 MW system were performed, using a clump mass for the wind turbine and testing the response to waves only [32]. There have been no further developments since these tests in 2015.

2.1.17 Tetrafloat

The Tetrafloat was a tetrahedral semi-sub developed in the mid-2010s that underwent a few rounds of lab tests. The motivation for the design of the platform was to utilize the structural efficiency of a tetrahedron. Three cylindrical buoys connected above the waterline in a triangle. Instead of a typical wind turbine tower, three masts extended from the top of each buoy to the turbine nacelle, forming the tetrahedron [33], [34]. Each of the three buoys consisted of a smaller-diameter cylinder at the waterline (for favorable heave motion response), a larger-diameter cylinder below the waterline (for sufficient buoyancy), and a hanging heave plate. The mooring system consisted of a single catenary line which divided into two segments close to the platform and attached to the two front buoys to allow for weathervaning of the platform [33]. 1:120 scale model tests were performed at the Cranfield University wave tank. In the experiments, the configuration with the suspended heave plates was tested, as well as a configuration in which the heave plates were attached to the bottom of the buoy. Decay tests, regular waves and irregular waves were tested, and it was found that suspended heave plates suppress heave motion but increase surge motion in large swell waves [34]. Additionally, 1:30 scale model tests of the 10 MW system were performed at IFREMER [35]. There were plans to build a prototype in 2018, but there has been no news on the platform for a few years.

2.1.18 5MW-CSC

The 5MW-CSC was a platform designed in the mid-late-2010s which underwent some lab tests. The platform was a braceless steel 5 MW semi-sub, designed for use off the coast of Norway in the North Sea. Inspired by the OO-star platform (described in 3.1.9), the design goal centered around making the platform without braces, to avoid the necessary complex, expensive welding and the fatigue common in brace-column joints. The platform consisted of three outer columns, connected on the bottom via three pontoons to a central column holding the tower and turbine. The draft of the platform was 30 m and each pontoon was 45.5 m long. The design constraints included (i) ensuring that the area under GZ/area heeling curve is greater than 1.3, and (ii) ensuring that the resonant periods of the structure and vibration modes avoid first order wave loads (3-25 seconds), 1P (5-8.7s for 5 MW turbine) and 3P (1.7-2.9s for 5 MW). To satisfy these constraints, sufficient added mass and mass are required. Heave plates would satisfy this goal but are more costly for construction, so instead the structure was made larger and pontoons were utilized [36]. The mooring system consisted of three catenary lines, designed for 50-200 m water depth. The effects of changing geometry and stiffness of mooring lines on line tension were investigated, and it was determined that heavier mooring lines with longer lines on the seabed should be used for shallower water [37], [38], [39]. 1:30 scale model tests of the 5 MW system were performed at the SINTEF ocean basin for moderate conditions. It was found that low frequency motions were dominated by wind loads, second (and higher) order wave loads and restoring stiffness, and resonant/ wave motions were dominated by damping forces. Loads were measured on the structural components, and it was determined that the interface between the pontoons and the central column was the most critical part of the structure [36], [37]. There has been no known further development since the experiments in 2018.

2.1.19 TripleSpar

The Triple Spar was a platform designed and developed within the project INNWIND.EU in the mid-late-2010s that underwent some lab tests. The platform consisted of three concrete cylinders with heave plates connected on top by a steel truss above the surface, with the tower and 10 MW turbine in the center. The platform had a draft of 54.5 m, each outer column had a 15 m diameter, and the platform was 65 m long. The mooring was connected above the surface. 1:60 scale model tests of the 10 MW system were performed for operating wave conditions, using three different turbine control strategies: fixed blade pitch, using a land-based controller, and using a tuned controller. The purpose of the experiments was to look at the instability of the motion above rated wind speeds associated with land-based controllers [40].

2.2 Multi-turbine platforms

Bill Heronemus had the first conceptual FOWT idea in 1972. Not much is known about the floater, but his idea was to hold up to 20 turbines on one floating platform [2].

2.2.1 MUFOW

Multiple Unit Floating Offshore Wind Farm (MUFOW) was a research project in the 1990s to investigate the feasibility of designing a floating platform which could hold multiple turbines. The stated advantages of such a platform were cheaper installation per machine and increased stability due to the larger platform. Challenges/ disadvantages were also discussed, including turbine spacing to avoid wake interference, weathervaning techniques, economics of such a large structure, and the lack of feasibility of building the structure at a normal port [41], [42], [43], [2]. There is no record of any tank testing or development further than an initial design.

2.2.2 WindSea

The WindSea platform was a three-turbine semi-sub platform developed by FORCE Technology Norway, Statkraft, and NLI in the early-mid-2000s. The platform was a three-column semi-sub with 3.2 MW turbines on each of the three columns. The front two turbines were angled out to avoid wake interaction with the third rear turbine. The tow-out draft was 8 m and the operational draft was 22 m. Mooring was connected from a turret in the center of the triangular platform to enable the platform to weathervane. 1:64 scale model tests were performed in wind and waves. There has not been any activity from the company since mid-late-2000s [44].

2.3 Hybrid platforms

2.3.1 ITI energy barge

The ITI Energy Barge was a barge platform, designed to hold a 5 MW wind turbine and an Oscillating Water Column Wave Energy Converter (OWC WEC), developed by ITI Energy, NREL, and the Universities of Glasgow and Strathclyde in the mid-2000s. The platform was square with a moonpool, which is where the OWC WEC was located. The platform dimensions were 40 m x 40 m x 10 m for the barge and 10 m x 10 m x 10 m for the moonpool, with draft 4 m, and the mooring system consisted of eight catenary lines, two from each corner [45]. There are no records of any tank testing or development further than an initial design.

2.3.2 WindWaveFloat

In the early-2010s, Principle Power investigated incorporating WECs into their WindFloat platform, with three possible designs. The three designs underwent lab tests, but none of them were deemed worth pursuing further. The WindWaveFloat 1 consisted of the 5 MW WindFloat system fitted with three flap-type WECs. The flaps were 16 m long and 11 m wide, with a 4.75 m draft. The flaps were connected to each side of the triangular platform, and it was found that the flap in front extracts significantly (up to 10x) more power than the other two if the wave direction is head-on. Of all three configurations considered, this was the one that affected the platform motion the most, compared to the stand-alone WindFloat platform. A maximum power of 150 kW/m-sq was obtained from the WECs. 1:78.5 scale model tests of the 5 MW (wind) system were performed, including regular waves with two different wave headings [46], [47].

The WindWaveFloat 2 had a spherical point-absorber WEC (called the SWEDE) in the center of the platform. The spherical WEC was chosen because it does not pitch and roll much and responds well in heave. A maximum power of 50 kW/m-sq was obtained from the WEC. 1:78.5 scale model tests were performed [48], [47].

Finally, the WindWaveFloat 3 had an Oscillating Water Column (OWC) on one of the two columns without the turbine. The OWC was made of a 18 m diameter, 9 m draft cylinder around the 10 m column, which had a draft of 17 m. A maximum power of 139 kW (with regular wave height 2 m) was obtained. 1:78.5 scale model tests were performed [49], [47].

2.3.3 SKWID

SKWID (Savonius Keel and Wind Turbine Darrieus) by MODEC Inc was a spar platform holding a VAWT, with a counter-rotating submerged Savonius water current turbine developed in the early-2010s [50], [16]. A VAWT was chosen because it was less top-heavy than a HAWT, and the water turbine was chosen to reduce reaction torque, alleviating tension in mooring lines [16]. The two turbines were decoupled from the floating structure in pitch so that the VAWT could tilt [50]. In 2013 a prototype was built but sank during the installation, and there has been no news on further development of the platform since this prototype [16].

2.3.4 THyP and C-HYP

There were a few wind-wave hybrid platforms designed in the early-2010s by Ecole Centrale de Nantes and INNOSEA. The THyP was a five column semi-sub, with heave plates below each column. The columns were connected by trusses to each other, with the 5 MW turbine and tower held by one of the columns. 12 pitching wedge WECs were attached to the truss above the water surface, each with a 9 m width, resulting in a total capacity of 5 MW for the WECs. The overall platform had a 22.5 m draft and 120 m width [51].

The C-HYP was a circular barge with 100 m diameter, with 20 Oscillating Water Column WECs covering half of the outer surface of the platform, totaling up to 5 MW of capacity from the WECs. It was determined that this platform was not feasible because of difficulties to build a platform of this size at a port [52]. There is no record of any tank testing or development further than an initial design for either of these platforms.

2.3.5 STC

Several hybrid platforms were designed and tested by NTNU as part of the MARINA Platform project in the 2010s. The Spar Torus Combination (STC) was one of the platforms designed during this project that underwent some lab tests. The STC was inspired by the Hywind spar platform and the Wavebob WEC, and thus it is a spar buoy with a torus (donut-shape) WEC around the spar [53]. The platform was designed to be used in deep water and is insensitive to wave direction. For a platform holding a 5 MW turbine, the spar had a draft of 120 m, 6.5 m diameter at the water level, and 9.4 m diameter at the bottom, with a torus of 2 m draft, 8 m height, and 20 m outer diameter. Permanent ballast was included inside the spar, along with active ballast inside the torus to tune to the incident sea state and optimize the extracted power [54]. The mooring system consisted of three catenary mooring lines with clump weights and delta connections [53]. Bearings between the spar and torus allowed the bodies to move freely in heave, and there were end stops above the torus [53]. Compared to a stand-alone spar, the STC configuration resulted in 6% higher wind

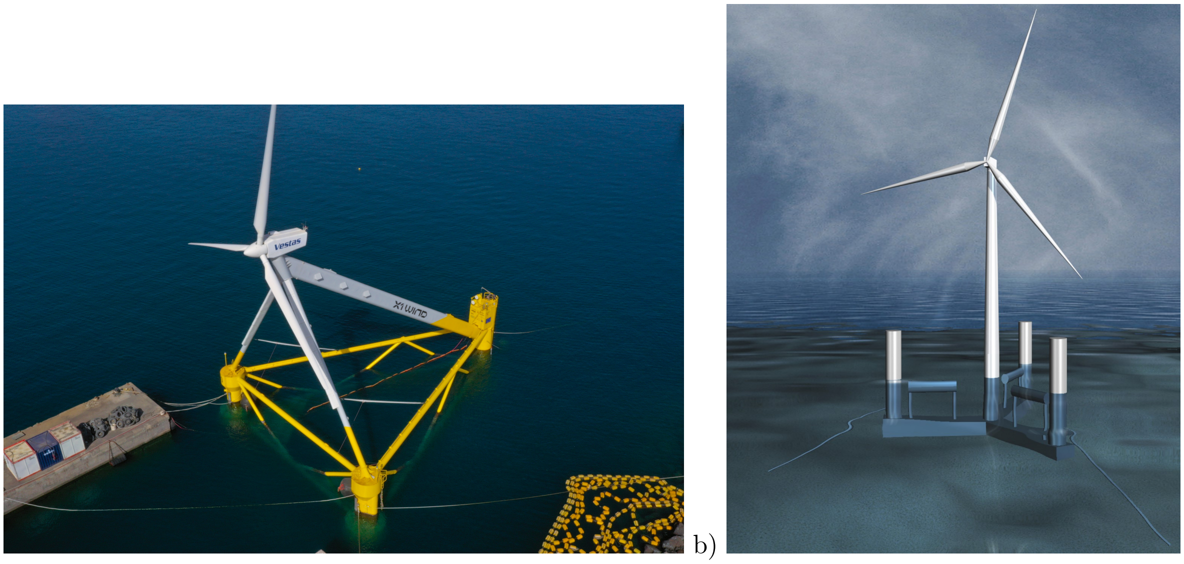
a) b)

Figure 1: a) X1Wind, courtesy of X1Wind; b) SFC, courtesy of NTNU

power for wind speeds below rated wind speed and 10-15% higher power in total. The mean displacement was slightly increased with the torus, but the standard deviation of surge and pitch motion decreased, due to the additional waterline stability that the torus adds. Mooring line tension was slightly increased with the addition of the torus [53]. 1:50 scale model tests were completed, including decay tests, regular waves, irregular wave-only, and irregular wave plus wind. Two survival modes for the WEC were tested: one in which the torus is fixed to the spar, and one in which the torus is fully-submerged. When the torus was at the waterline, slamming and green water were observed, but when the torus was fully submerged no severe wave load occurred [55]. There has been no news of further development on this platform since these test results in 2014.

2.3.6 SFC

The semi-sub-flap combination (SFC) platform, shown in Figure 1b, was another platform design by NTNU to come out of the MARINA project in the mid-2010s which also underwent some lab tests. The platform was the 5MW CSC semi-sub platform, discussed in 2.1.18, with two or three flap-type WECs attached to the pontoons [56], [57]. The WECs were inspired by optimized bottom-fixed flap-type elliptical WECs [56]. Each WEC was 20 m long and 7 m high, with the top being 2 m from the surface. Compared with the 5MW-CSC platform with no WECs attached, the response was not significantly affected; it was found that natural periods were not influenced significantly by adding the WECs, the mooring line tension increased by 5.4% and the tower bending moment increased by 5.6%. Adding the WECs did not affect the wind power, and the total power was increased by 1-8% [57]. 1:50 scale model tests were performed for the 5 MW system, including decay tests and regular waves to test operational conditions, and irregular waves with wind loads to test extreme environmental conditions [58], [59]. There has been no news of further development on this platform since these test results in 2016.

2.3.7 TLPWT+PA

The TLPWT + PA was another hybrid wind-wave platform developed by NTNU as part of MARINA project. It consisted of a TLP platform holding a 5 MW wind turbine and three spherical point absorber WECs. Two options were considered: one where point absorbers were restricted to motion in heave only and one where the point absorbers were allowed to move in heave, surge and pitch. In case of an extreme sea state, the power take-off would be turned off, and three scenarios were considered for the WEC: (i) freely moving, (ii) submerged and (iii) submerged with locks. Through numerical modeling it was determined that, compared to the wind-only platform, in operational conditions the hybrid platform had a lower platform response in surge and pitch and reduced tendon tension and tower base bending moment variation. In survival reductions, the hybrid platform had smaller surge and yaw motions but significant increases in pitch motions and tendon tension variations [60]. There have been no developments since this initial design concept in 2013.

2.3.8 OWCHyP

The OWCHyP was a very large barge, developed in mid-2010s, with 20 Oscillating Water Column (OWC) WECs. The platform, which was designed to hold a 5 MW turbine, had a 300 m width, 150 m length, and 12 m depth. Each OWC chamber was 24 m x 8 m [61]. There has been no news on development for this concept since 2014.

3 Early-stage FOWT platforms in development

3.1 Single turbine platforms

3.1.1 Dutch Tri-floater

The development of the Dutch Tri-Floater started in the early-2000s, and the platform is still in development today. The platform has undergone at least three design iterations. The aim of the preliminary project was to assess the technical and economic feasibility of a FOWT. Originally, multi-turbine floaters were considered, due to benefits in terms of shared maintenance and infrastructure, but it was determined that such a floater would need to be impractically large. During the initial exploratory studies, several types of platform design were considered: (i) a single cylindrical floater (barge) with spread or tension leg mooring, (ii) an inverted spar with pre-tension, (iii) a spar with spread mooring, (iv) a triple floater (semi-sub) with and without damping plates, (v) a quadruple floater (semi-sub), and (vi) a four leg jack-up (fixed). The tri-floater was chosen because, among the platforms considered, it required the least steel. Heave plates were included since without them the heave natural frequency of the device would be within the wave exciting frequency range. At the end of this initial study, the platform consisted of three outer cylinders connected to each other via braces, and the tower was connected above the surface in the center of the platform [62], [63], [64], [2].

The design had changed by 2014, with the columns only connected at the top by thick beams, instead of the truss, and the heave plates changed from circular to rectangular. 1:50 scale model tests of the 5 MW system were performed at MARIN [65], [66].

Since these tests, the platform design has evolved again. The outer columns are now hexagonal, and there is now a fourth, smaller column on one of the sides of the triangular structure, which holds the tower and turbine, instead of being located in the center of the platform. The heave plates are also hexagonal, and there is a passive ballast system. For a 15 MW system, the operational draft is 20 m (towing draft 8.5 m), the length is 94 m and the beam is 104 m. The mooring is a catenary system attached above the surface [67]. 1:50 scale mode tests of the 15 MW system were performed at the Oceanide wave basin, including extreme conditions (13.5 m significant wave height, 190 km/h wind speed) [68].

3.1.2 Pelastar

The Pelastar platform, shown in Figure 2a, has been under development since the mid-2000s by Glosten [69]. The platform is a TLP, which was originally chosen because of low material weight and suitability for a wide range of water depths. The platform consists of five arms connected to high vertical load anchors via synthetic fiber cables [69], [70]. 1:50 scale model tests of the 5 MW system were performed at MARIN in 2015 [71]. In 2022, the SENSE Pelastar project was funded by the UK government to build a 2 MW demonstrator off Scotland in 2023. The SENSE technology is a self-erecting nacelle, to eliminate the need for a special floating crane [72].

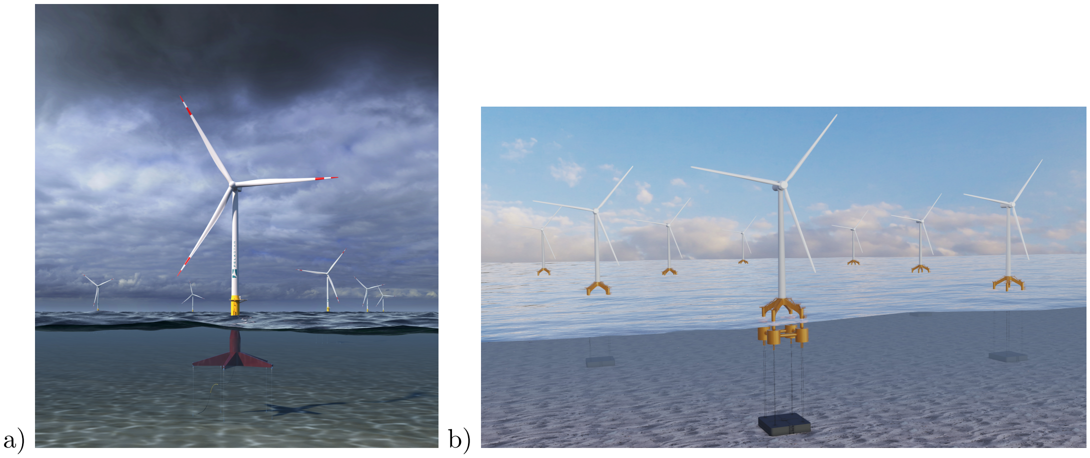

Figure 2: a) Pelastar TLP, courtesy of Glosten; b) SOF, courtesy of ©GICON ® group

3.1.3 GICON SOF

GICON's SOF platform, shown in Figure 2b, has been in development since the late-2000s. The TLP platform design has undergone a few different iterations throughout its lifetime [73]. The first iteration consisted of three steel legs with a concrete buoyancy body at the end of each leg. The second iteration consisted of a four-leg truss structure with buoyancy bodies along the legs, the third iteration consisted of a square truss-type structure with buoyancy bodies around the square, and the fourth iteration consisted of a square shell-type structure [74], [73]. The current design of the platform, which is shown in Figure 2b, consists of four submerged vertical cylinders attached to the tensioned mooring lines below and to thinner vertical columns above, which extend above the water and then join together to hold the tower. A lowerable gravity anchor acts as a barge for tow-out and is lowered at the location of installation [75], [76].

1:50 scale model tests of the 5 MW system were done at ECN to validate numerical models [77]. In 2017, 1:50 scale model tests of the 6 MW system were performed at MARIN, including for extreme seas, and the transportation process (tow-out and lowering gravity anchor) was tested at SSPA Maritime Dynamics Laboratory [75] [78] [79].

3.1.4 Windcrete

The Windcrete structure is a spar platform that has been under development since late 2000s by UPC-BarcelonaTech [80], [81]. The platform is made of a single concrete cylindrical piece that extends from the nacelle to below the water surface. This design was developed to avoid the fatigue common in the transition between a concrete substructure and steel tower [80], [82]. The platform is towed out horizontally until at sufficiently deep water. Seawater is added to upturn the structure and ballast it, until the top of the tower is only 20 m above the surface, when the turbine is installed. Then, the seawater is pumped out and aggregates are added for permanent ballast. This installation procedure does not require a very tall floating crane, but it does require deep water [80]. In mid-2010s, 1:100 scale model tests were performed for the 5 MW system in the CIEM wave flume facility at the UPC, including extreme sea states [83], [84].

As part of the H2020 project COREWIND, the platform is now being scaled-up to 15 MW [85], [86], [87]. The design goals for the platform during the up-scaling are to ensure that (i) the static pitch due to maximum thrust is less than 4°, (ii) the natural periods of heave, surge and pitch are greater than 30 seconds, and (iii) the mean pitch angle for rated thrust is 3.2°[86], [85]. The platform has a 155 m draft with a hemisphere at the base, to distribute hydrostatic pressure, and a truncated cone section at the waterline. The below-surface diameter is 18.6 m and the diameter at and above the water surface is 13.2 m. This diameter for the tower is larger than fixed-bottom towers because the tower base experiences higher moments when the platform is floating [85], [86]. The mooring system consists of three 165 mm diameter catenary lines with delta connections, with three fairlead depth locations being considered [85], [87]. 1:100 scale models tests of the 15 MW system have been performed in a wind tunnel, imposing harmonic platform motions in surge, sway, roll, pitch and yaw with an actuator [88].

3.1.5 Sea Reed

Sea Reed is a semi-sub platform, which has been under development by Naval Energies since the early-2010s. Little is published about its evolution, but the platform currently consists of three outer columns, connected via pontoons to a central column holding the tower. It can be made of steel, concrete or a hybrid of the two materials [89], [90]. It has been certified by DNV and there are plans to use it for the Groix & Belle-Ile project, consisting of three 9.6 MW turbines in 60 m depth off the coast of France. For this project, the platform will be made of steel and the mooring will consist of five catenary lines for each platform [91], [92].

3.1.6 Cobra SEMI-SPAR

The Cobra SEMI SPAR is a concrete structure with three outer columns connected by pontoons to a central column which holds the tower and turbine. During tow-out, the structure acts as a semi-sub, but when it reaches the location of installation, the structure is ballasted so that the center of gravity is lower than a typical semi-sub, using spar stability techniques. There is a planned demonstrator at PLOCAN in Spain [93].

3.1.7 Nerewind

NereWind is a semi-sub, developed by the DORIS Group since early-mid-2010s, with either three or four outer columns plus a central one holding the tower and 10-15 MW turbine. The platform can be made of steel, concrete, or a hybrid of both materials [94].

3.1.8 X1Wind

X1Wind, shown in Figure 1a, is a platform which can be split into two sections: (i) the TLP platform called the PivotBuoy, installed first, and (ii) the rest of the platform, which is self-floating and looks like a small semi-sub, subsequently towed and connected to the PivotBuoy. The semi-sub platform consists of three small outer columns, with heave plates connected to two of the columns, and the third column connects to the PivotBuoy. The mooring is a single-point taut mooring system. The wind turbine is not on a standard tower, but instead three masts extend from the three columns to the nacelle. The turbine is a downwind turbine, to enable the system to weathervane to avoid an active yaw system in the nacelle. The platform benefits from the stability and lightness typical of a TLP, but it is also self-floating and stable during tow-out and installation [95], [96]. The 15 MW platform has a draft of 9 m and mass (including turbine) of 5429 t [95].

In 2018, 1:64 scale model tests of the 5 MW system were performed at CIEMLAB wave flume to determine the hydrodynamic coefficients [96], [97]. In 2019, 1:50 scale model tests of the 5 MW system were performed at ECN, including wind and extreme sea states [96], [97].

There is now a prototype of the platform, called the X30, which was installed at the PLOCAN test site (Gran Canary, Spain) in late 2022. The main goals of the prototype are to test the single-point mooring and downwind turbine [96]. A Vestas V29 turbine (225 kW) has been altered to a downwind configuration. There are plans to build a 6 MW demonstrator platform through the EU-funded X1 ACCELERATOR project.

3.1.9 OO-Star

The OO-Star is a semi-sub platform which has been under development by Dr. techn. Olav Olsen since the mid-2010s. The platform has been part of two large research projects for up-scaling the platform, though the substructure design has not changed during these up-scaling studies. It has undergone multiple lab tests throughout its development. The platform consists of three cylindrical outer columns with heave plates, connected via pontoons to a central column which holds the tower and turbine. The platform can be made from steel, concrete or a hybrid of the two materials [98]. The mooring system consists of three catenary lines with clump weights. Developers claim that the platform is well suited for modular fabrication [98].

The platform was originally designed for a 6 MW turbine. 1:40 scale model tests of the 6 MW system were performed for operational irregular waves in the mid-2010s [99]. The LIFES50+ project's objective was to optimize the substructure design for a 10 MW turbine in water depth larger than 50 m [100], [101]. The platform used in this study was adapted from their commercial design. The draft for the 10 MW system was 22 m, and the DTU 10 MW turbine controller was altered to avoid negative damping above rated wind speeds [100], [101]. 1:36 scale model tests of the 10 MW system were performed, including wave tank tests and wind tunnel tests, in 2017 and 2018 [100], [98], [102], [103].

The ongoing FLAGSHIP project's objectives are to reduce the levelized cost of energy of the OO-Star platform and to up-scale the platform again to hold an 11 MW turbine. For the 11 MW system, the platform draft is 21 m, the length is 71 m, and the width is 78 m. The columns do not connect to each other or to the central column above the water surface, to avoid beams in the splash zone, to lower the center of gravity, and to ensure easier fabrication. A passive ballast system is used [104] [103].

3.1.10 AWC

The Articulated Wind Column (AWC) is a spar platform with a tension rod attached to a gravity base via an articulated joint. The technology has been used in the oil and gas industry as an offloading column since the 1960s. The platform is a cylindrical spar, made of concrete [105]. The platform is suited for water depths of 70-250 m, with better performance and efficiency in deep water. The size of the platform is determined to allow for a maximum inclination angle of 5°. 1:42.5 scale model tests of the 8 MW system were tested at BGO FIRST in the mid-2010s, including extreme storms, operating and maintenance weather conditions [106]. There are plans to use the platform in demonstration farms in the Celtic Sea off the coast of England, with capacity 98 MW for phase I and 300 MW for phase II [105].

3.1.11 Telwind

Telwind is a concrete spar platform with lowerable ballast, which has been in development since the mid-2010s with two main design iterations. The platform was developed to use a self-erecting telescopic tower [107]. The design goals for the platform in its first design phase were to (i) enable serial production, (ii) achieve simple and reliable installation by avoiding reliance on floating heavy lift vessels, (iii) adhere to size constraints for assembly: low draft (<9 m), low height (<60 m) and low width (<40 m), (iv) allow for scalability to 10 MW+ turbines, (v) limit static tilt angle to less than 10°, (vi) ensure natural periods in heave and pitch to be greater than 25 seconds, and (vii) ensure metacentric height to be greater than 1 m [107], [108]. The resulting design consisted of two cylinders: a wide, shallow cylinder at the waterline, as the main source of buoyancy, with a suspended cylinder with smaller diameter and larger height, as the main source of ballast. The developers have classed the platform as a spar, but it also has stability from a large waterplane area [108]. Cables between the two bodies form a triangular system, so that the whole body moves as one, and the system is designed so that it never moves enough for any cables to become vertical (which would cause other cables to lose tension). The mooring system is a traditional catenary mooring made of chain, fibers or mixed. The tow-out and installation procedure is as follows: the two bodies are towed out separately, the lower structure is ballasted, the mooring lines are attached to the upper structure, the upper structure is ballasted, and finally the tower is installed by the telescopic lift device [107]. For the 5 MW system, the draft is 60 m, the upper body has 32 m diameter and 10 m height, and the lower body has 15.3 m diameter and 16.5 m height. For the 10 MW system, the draft is 92.25 m, the upper body has 44.5 m diameter and 10 m height, and the lower body has 23 m diameter and 22.5 m height [107], [109].

Adding a Tuned-Mass-Damper (TMD) in the nacelle to mitigate dynamic response was investigated, and it was shown that tensions in the tendons decreased with its addition [109]. 1:45 scale model tests of the 5 MW system were tested in 2017 at CCOB lab at IHCantabria [110], [108]. The suspension tendons were also tested for fatigue loading at Technische Universitat Munchen [108].

Since 2018, the platform has evolved, whereby the upper body now looks like a 'typical' semi-sub, with three cylindrical columns connected at the bottom via pontoons to a central column holding the wind turbine. The lower body is now triangular [111].

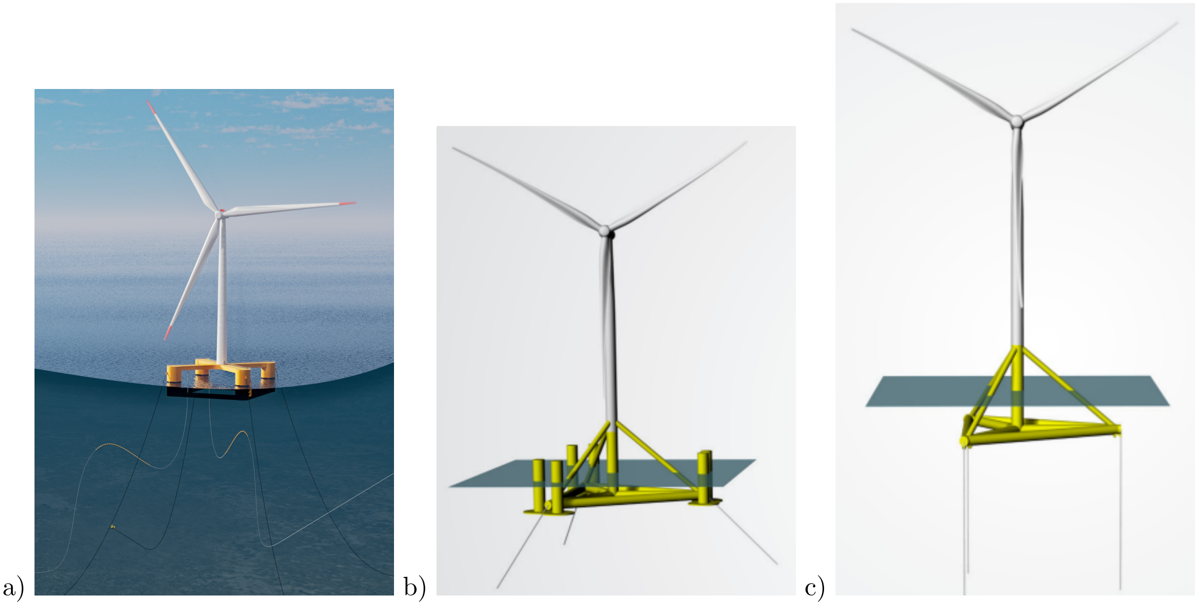

Figure 3: a) NAUTILUS, courtesy of Nautilus Floating Solutions; b) TetraSub, courtesy of Stiesdal; and c) TetraTLP, courtesy of Stiesdal

3.1.12 NAUTILUS

The NAUTILUS platform is a four-column semi-sub, shown in Figure 3a. The platform is symmetric to reduce sensitivity to wind-wave misalignment [112]. Four cylindrical columns are connected at their base to a square pontoon structure and at their top with beams forming a cross, with the wind turbine at the center of the cross [100], [113]. The platform is made with modular elements to ensure ease of manufacturing [112]. The 10 MW platform has a 62.5 m width/breadth and 18.3 m draft with four catenary mooring lines [113], [114]. There was a central heave plate in the 5 MW system but was taken out when up-scaling to the 10 MW system [100], [114]. There is an active water ballast system [114], [100]. 1:36 scale model tests of the 10 MW system have been performed for operational and extreme sea states [113], [114]. Optimization of the platform has been done to understand the sensitivity of different parameters to the performance of the platform [115].

3.1.13 SBM TLP

The SBM TLP is a TLP platform developed by SBM Offshore and IFP Energies Nouvelles [116]. There have been two generations of the platform design: one from the mid-late 2010s, and the second announced in early 2022. For the first generation, the main design goals for the structure were to (i) minimize weight, (ii) minimize operation and maintenance, and (iii) minimize motion at the nacelle [117]. The structure consisted of three outer buoys connected via a truss to a central buoy holding the tower and 5 MW turbine. The main purpose of the central buoy was to support the weight of the turbine, and the main purpose of the outer buoys was to provide stability during towing [116], [117]. The platform for the 5 MW system had a 6.5 m draft during tow-out and 25 m draft once installed [117]. The mooring system consisted of three bundles of two lines, made of chains, inclined to allow for compliance in roll and pitch but minimize surge motion and acceleration at the nacelle [117], [116]. Minimizing surge acceleration allowed for control strategies in the turbine to be standard [117]. 1:40 scale model tests of the 5 MW system were tested at MARIN in operational conditions.

The second generation of the platform, announced in early 2022, consists of three horizontal cylinders connected to a single central vertical cylinder holding the tower and turbine. The design goals of this platform are (i) ease of industrialization by using a simple design, and (ii) scalability to larger wind turbines with no modification of the control strategies of the turbine [118].

3.1.14 DTI-F

The Deep Turbine Installation Floating (DTI-F) by FWT Ltd is a concrete or hybrid-material spar platform developed for a 7 MW turbine, but with flexibility to scale-up to 15 MW. The platform consists of a cylinder with 15 m diameter and 62 m draft, with a heave plate of diameter 40 m and height 2 m at the base. The cylinder is hollow so that the tower can be lowered into it during installation and towing. Three mooring configurations are considered: three standard catenary lines, four standard catenary lines, and three catenary lines with delta connections. The dimensions of the platform are chosen to (i) keep natural periods of the structure outside of the range of wave excitation periods, and (ii) minimize motions. Two constraints were imposed: (i) the pitch and roll motions are constrained to be less than 10°, and (ii) the horizontal acceleration at the nacelle is constrained to be less than $3\,\mathrm{m/s^2}$. Due to the unique feature of raising and lowering the tower into the substructure, the platform and tower can be towed vertically with draft 23.82 m to a deeper assembly point, when the platform is ballasted and the nacelle and blades are installed [119]. 1:45 scale model tests of the 7 MW system were performed, for waves only [120].

3.1.15 Stinger Keel

The Stinger Keel by Floating Energy Systems, shown in Figure 4, was developed to use strengths from different types of FOWT platforms in a single platform [121]. The platform has undergone several design iterations, but it has always included a semi-sub-like upper structure with a lowerable ballast. The platform was first developed in the mid-late-2010s. For the first design iteration, the upper structure consisted of three cylinders, connected via a truss to a central column holding the tower and turbine, and there were hanging keels/ heave plates suspended from each of the three columns [121]. For this design, 1:50 scale model tests of the 10 MW system were performed at the University of Strathclyde's Kelvin Hydrodynamics Laboratory, including decay tests, regular waves and irregular waves of extreme sea states [122], [121]. The platform design changed, so that it now consists of a single truss-like structure holding the ballast weight, suspended from the main semi-sub structure. As shown in Figure 4, the truss and ballast weight are towed horizontally behind the structure and lowered once at the location of installation. The semi-sub structure also changed, now consisting of three sets of two horizontal cylinders, connected via horizontal cylindrical pontoons and cylindrical braces to a central column holding the tower and turbine. 1:67 scale model tests (of undisclosed full-scale power) were done at the HR Wallingford Fast Flow Facility, including decay tests, regular and irregular wave conditions [123]

3.1.16 Nihon VAWT barge

The VAWT barge developed by Nihon University is a barge with four moonpools, holding a VAWT. The platform has a 6.8 m draft, 90 m length and 40 m width, and it holds either one or two VAWTs [124], [125]. Moonpools were added to reduce heave and roll motion of the structure. Four moonpools were considered, as opposed to one, to shift sloshing modes to high frequencies [125], [124]. 1:100 scale model tests were performed for the 2 MW system in regular waves only. The focus of the experiments were to consider gyroscopic effects of the turbine rotation on the motion response of the platform. It was shown that first-order sway and roll motions near resonant frequencies were reduced by the gyroscopic forces, but second-order motions may be significantly amplified by gyroscopic forces [125].

3.1.17 Sherbuoys TLP

The Sherbuoys TLP is a TLP structure with buoys connected halfway down the taut mooring lines. The main structure consists of a central cylindrical section which holds the tower, with four rectangular pontoons extending horizontally. For a 5 MW system, the central cylindrical section has diameter 20 m and height 10 m, the pontoons are 20 m long and 4 m wide, and the structure's draft is 30 m. The cylindrical buoys connected to the mooring lines are 10 m tall for the 5 MW system, and they are added to reduce surge motion. Experiments have been done to test the platform and buoys separately, both in waves only [126].

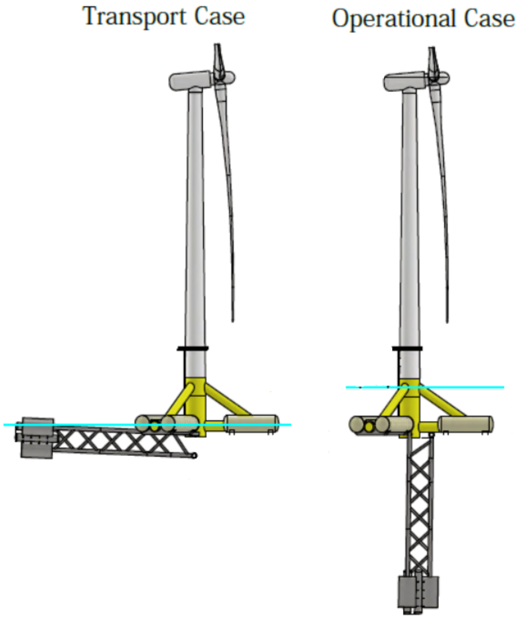

Figure 4: StingerKeel, courtesy of Floating Energy Systems Ltd

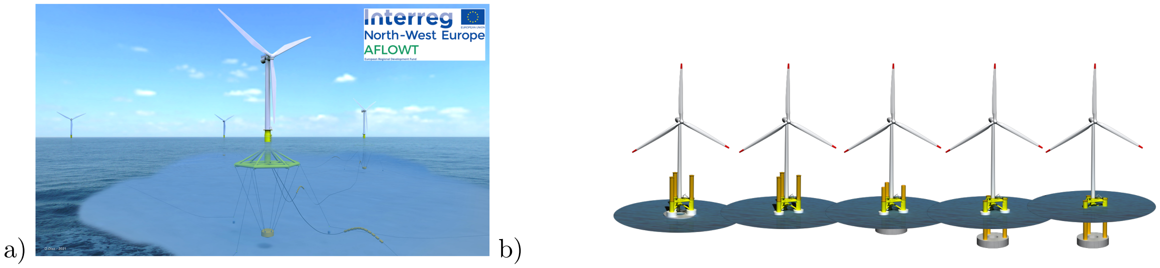

Figure 5: a) Hexafloat, courtesy of Saipem; b) MSPAR, courtesy of MONOBASE Wind

3.1.18 Huazhong University of Science and Technology inclined columns semi-sub

Liu et al. [127] developed a semi-sub platform consisting of three inclined columns connected to each other and a central vertical column via braces. It was found that inclining the towers decreases heave motion. Mooring arrangement was also considered, and it was found that surge motion was decreased by using a ‘connection node,’ which connects the mooring lines between the columns, and a normal catenary line extends down to the seafloor from the connection node [127].

3.1.19 Hexafloat

Hexafloat, shown in Figure 5a, is a platform, developed by Saipem, consisting of a submerged hexagonal structure, a suspended weight and six taut and/or catenary mooring lines. The hexagonal structure is submerged and connects via braces to the central column holding the tower and turbine. The weight is suspended with six tendons. According to the developers, a main advantage of the platform is that up-scaling (from 2 to 15 MW) results in a very similar platform with slight changes to the diameter of the structure and depth of ballasted weight [128]. For a 10 MW turbine, the platform is 78 m wide and the suspended weight is 120 m below the surface. A scaled 12 MW system (at undisclosed scale) was tested at ECN, including extreme sea states [129]. The platform is being used for the planned AFLOWT project, which will deploy the platform off the coast of Ireland [130].

3.1.20 CT-bos

CT-bos, developed by Bluenewables, is a concrete TLP platform. The floating platform is a 45 m x 45 m square, with a 17.6 m draft, and it is designed to hold a 15MW turbine. The mooring setup consists of four sets of two steel rod tendons connected to suction cans [131]. The platform is self-stable for transport and installation [132].

3.1.21 S-bos

S-bos, developed by Bluenewables, is a concrete semi-sub platform. It consists of four columns connected to each other at the bottom via pontoons forming a square. The turbine is attached to one of the columns [132].

3.1.22 WIND-bos

WIND-bos, developed by Bluenewables, is a semi-sub-spar combination platform. The platform is made up of two main bodies connected by three legs. The upper body, which consists of a central vertical cylindrical column and three pontoons, is made of steel, the lower body, which is made of three pontoons forming a triangle, is made of concrete, and the legs are made of steel. 1:40 scale model tests of the 10 MW system were performed at Oceanide, including decay tests, wave-only tests and combined wind and wave tests [133]. At the port and during tow-out, the platform acts as a semi-sub with a shallow draft [132].

3.1.23 MARLIN

The MARLIN Modular Floating Platform for Offshore Wind, developed by Frontier Technical, is a three-column semi-sub platform. Specifically designed for Small Islands Developing States (SIDS) and coastal communities, the platform is designed to hold a smaller turbine (50 kW-2 MW) with small modular components which can fit into a standard shipping container. Requiring no large marine construction yard or heavy lift crane vessels, the platform utilizes subsea construction by Frontier Technical [134].

3.1.24 TetraSub

The TetraSub, shown in Figure 3b, is a semi-sub developed by Stiesdal for water depths 50-200 m [135]. The platform consists of three sets of two vertical cylinders, each with hexagonal heave plates, connected to each other via pontoons in a triangular shape. On one side of the triangle, there is another vertical column holding the tower and turbine, which is also attached to the corners of the outer columns by braces. The wind turbine is placed on the side like this to ease installation, due to crane limits, but the configuration does complicate coupling between different modes compared with having the turbine in the center [136]. A focus of the platform design is on ensuring that the structure is modular, so the tetrahedral structure is made from 4-5 types of steel braces [135]. The mooring system consists of three catenary lines. 1:60 scale model tests of the 10 MW system were performed at the Danish Hydraulic Institute as part of the FloatStep research project, which aimed to optimize floating foundations and tower designs. The purpose of the experiments were to test control strategies to avoid pitch instabilities that occur in conventional control strategies. Operational and extreme sea states were tested [136].

3.1.25 Y-shaped semi-sub

Differences between steel and concrete platform dynamics were studied by Li et al. [137] from Harbin Institute of Technology. A Y-shaped semi-sub was designed for the comparison. The underwater geometry was the same in both semi-subs, but two different materials were used. The semi-sub consists of three cylindrical columns with heave plates, connected at the bottom via pontoons in a Y-shape to a central hexagonal column with smaller diameter holding the tower and 5 MW wind turbine. The platform draft is 20 m and the heave plates have a height of 5 m. Less ballast is used for the concrete platform to achieve the same draft, because it is heavier than steel. 1:60 model scale tests of the 5 MW system were performed, and it was shown that the concrete structure has a higher pitch natural period (further from energetic wave frequencies), and the steel structure has a smaller average platform pitch motion and smaller tower base loads at the pitch natural frequency [137].

3.1.26 MSPAR

The MSPAR, shown in Figure 5b, is a floater which utilizes spar and semi-sub stabilization techniques. It is made of three cylindrical columns with heave plates, connected on the top and bottom with a truss structure, and the tower is at the center. Below the floater, columns extend down to attach to a lowerable concrete ballast. It is designed for the 15-20 MW systems to have a draft of no more than 70 m to work in water depths of 90 m and deeper. 1:44 scale model tests were performed in March 2022 at Oceanide in Seyne sur Mer, France. Stability and behavior in transport, installation, operational and extreme sea states were tested [138].

3.1.27 INO WINDMOOR

The INO WINDMOOR platform by Inocean and Equinor is a semi-sub with three vertical cylindrical columns, connected to each other on the bottom via pontoons and on the top via thick beams. The tower and turbine are connected to the downwind column [139], [140]. The mooring system consists of three hybrid chain and polyester catenary lines. For the 12 MW system, the platform draft is 15.5 m and the pontoon length is 61 m [139]. 1:40 scale model tests of the 12 MW system were performed at the SINTEF ocean basin for moderate sea states and varying wind conditions [140].

3.1.28 ActiveFloat

The ActiveFloat platform, developed by COBRA, is a concrete semi-sub platform being developed as part of the H2020 project COREWIND. The platform consists of three outer columns with heave plates, connected via pontoons to a central column which holds the turbine and tower. The transport draft for the platform holding a 15 MW turbine is 11-13 m with an operational draft of 26.5 m. The outer columns have a diameter of 17 m, and the pontoons are each 34 m long. An active ballast system is used. The mooring system is designed so that at the maximum thrust value, the maximum surge is 15 m, and so that there is never vertical force on the anchors [86]. 1:100 scale model tests of the 15 MW system were performed in a wind tunnel, using an actuator to provide harmonic motion in surge, sway, pitch, roll and yaw [88], [141].

3.1.29 Trivane

The Trivane platform is a trimaran, with a long central hull and two shorter hulls along each side to provide stability. The motivation for the platform is to utilize a turret mooring system, to enable the structure to weathervane. Other designs, such as a single hull or a catamaran, were considered, but for these configurations the hulls needed to be very long to provide favorable motion responses and were thus too expensive. For the 10 MW system, the draft is 6 m, the central hull has diameter 8 m and is 150 m long, and the outer hulls have diameter 5 m. 1:50 scale model tests of the 10 MW system were performed at the University of Plymouth COAST lab ocean basin to validate motion. A 1 MW demonstrator is in planning now [142].

3.1.30 JMU semi-sub

The JMU semi-sub consists of four columns with heave plates, connected at the bottom via pontoons in a cross formation. The tower and turbine are connected to one of the four columns, and the mooring system consists of four catenary lines connected to two of the columns. The development of this platform was informed by JMU's experience designing and building Fukushima Hamakaze. 1:64 scale model tests of the 12 MW system have been performed for waves only [143], [144].

3.1.31 SEALIFT

SEALIFT by Nautica Windpower is a structure that 'folds' to fit under bridges for towing. The main structure consists of three columns, one of which connects to a pre-installed rod fixed to the sea floor, and the structure weathervanes about that point [145].

3.1.32 PelaFlex

PelaFlex is a TLP platform developed by Marine Power Systems. The platform consists of only ten steel components to enable fast manufacturing. The mooring consists of six taut lines from three points on the structure, and the platform has a 5 m draft while towing. A demonstration-scale platform is planned off the coast of northern Portugal [146].

3.1.33 W.SEMI

W.SEMI, developed by Wison Offshore & Marine, is a steel semi-sub with three cylindrical columns with heave plates, connected to each other with braces. The turbine and tower are connected to the downwind column, and the mooring system consists of 3-8 catenary lines. There is an active ballast system, whereby water ballast is pumped to the upwind columns in times of high wind, to trim the heel angle. The platform has been designed to be modular [147].

3.1.34 BT Wind

BT Wind is a steel truss spar platform developed by Wison Offshore & Marine. The tower is lowered into the truss substructure during tow-out, and the whole platform is towed horizontally. At the site of installation, the platform is turned vertically, the turbine is installed while the tower is still lowered, and then finally the tower is lifted to operational height. The 8 MW system can be used in water depths of 80-200 m [147].

3.1.35 Gazelle

Gazelle Wind Power have designed a platform with three tripodal arms with a central counterweight. The tower and turbine are attached at the center. The developers claim that the design requires 75% less mooring length, when compared to a semi-sub, and 50% less mooring loads, when compared to a TLP. The platform is designed so that it moves horizontally and vertically but pitch motion is constrained to be less than 5°. The platform is designed to be modular. Scale model tests of the 10 MW system (with undisclosed scale) were performed at IHCantabria Environmental Hydraulics Institute, including decay tests and separate wind- and wave-only tests [148].

3.1.36 ECO TLP

The Eco TLP is a concrete platform designed for 100-3000 m water depths, consisting of a cylindrical concrete floater and cylindrical concrete gravity anchor. The platform is designed to be an artificial reef marine habitat [149].

3.1.37 FLOTANT barge

The FLOTANT platform is a hybrid concrete-plastic barge-like structure. It is being designed to hold a 12 MW turbine and to operate off the coast of Gran Canaria, Spain and West of Barra, United Kingdom. The structure consists of a central concrete tower, connected to an exterior cylindrical concrete shell by concrete braces, between which are filled with extruded polystryene (XPS) foam close to the central tower and water ballast tanks close to the outer shell. There is a heave plate at the bottom of the structure. The structure has a 12 m draft, and the main structure has diameter 48 m, with the heave plate having a diameter of 55.2 m. The mooring systems for the two locations are distinct: for the Gran Canaria site, it is a four-line semi-taut system using wire rope, and for the West of Barra site it is a five-line chain catenary system [150].

3.1.38 Braceless TLP

Zhou et al. [151] proposes a 10 MW Braceless-TLP. The platform is based on the 5 MW-CSC design, but the catenary mooring setup is replaced by six taut lines. The platform has a 26 m draft, each pontoon is 36.4 m long and 9 m wide, and each column has a 8.3 m diameter. The platform is designed for intermediate water depths (approximately 60 m) [151].

3.1.39 Wind Semi

The Equnior Wind Semi is a three column semi-sub, connected at the base with pontoons in a triangle, and at the top with thick beams also in a triangle, with the tower and turbine on one of the three columns. The mooring system consists of three catenary lines. A passive ballast system is used. The harbor draft is 10 m. The developers created the simple design without braces or heave plates, which they claim are prone to fatigue cracking [152].

3.1.40 Truss Float

The TrussFloat by Dolphines is a steel three column semi-sub connected with braces on the top and bottom of the columns, with heave plates below each column. The platform has undergone four rounds of tank testing. Developers claim that the benefits of the structure include the lightweight and modular structure and high deck capacity [153].

3.1.41 XCF

XCF by MAREAL is a concrete semi-sub designed for 15 MW+ turbines. The platform consists of four vertical cylindrical columns, connected at the base via horizontal cylindrical pontoons to a larger central column which holds the tower and turbine. The design goals include (i) using concrete to increase life span, (ii) putting the wind turbine at the center of the structure to decrease tilt angles to less than 10°, (iii) limiting the width of the structure to be less than 60 m, (iv) limiting tow-out draft to be 8-9 m, (vi) using static ballast to increase robustness, (vii) having two axes of symmetry to be more stable in all directions, (viii) using circular columns to avoid impacts from high current velocity, and (ix) making it modular for simple production lines [154].

3.1.42 T-Floater/ D-Floater

The D-Floater and T-floater are semi-subs designed by Bassoe Technology. The design motivation for these floaters is to be able to fit many platforms onto a transport pontoon before the turbine and tower are installed. The D-Floater consists of three cylindrical columns, one of which holds the tower and turbine. The column holding the tower is attached to the other columns via pontoons at the base and thin beams at the top. The two columns which do not hold the tower are not connected to each other, so that the structures nestle into each other, to enable many platforms to fit onto a transport barge. For this structure, the tow-out draft is 8 m for a 20 MW system [155].

The T-Floater also consists of three cylindrical columns, one of which holds the tower and turbine. The columns are attached at the base by a T-shaped pontoon, and at the top via triangular thin beams [155].

3.1.43 INO12TM

The INO12TM is a semi-sub designed by Technip Energies. There is not much information published about the design, but it seems to be a semi-sub consisting of three columns, with pontoons connecting in a triangle at the base, with the tower and turbine over one of the columns [156].

3.1.44 TetraTLP

The TetraTLP, shown in Figure 3c, is a TLP platform designed by Stiesdal for water depths 80-500 m. The platform looks like the main platform from the TetraSpar (see Edwards et al. [1]), but instead of the hanging weight, taut mooring lines are added [135].

Figure 6: BRUNEL, courtesy of Fred. Olsen 1848

3.1.45 BRUNEL

BRUNEL by Fred. Olsen 1848, shown in Figure 6, is a semi-sub platform consisting of three columns. One of the columns is a vertical cylinder which is attached to a single-point mooring system. The other two columns incline in toward each other, and two masts extend from these columns to meet at the nacelle, instead of using a standard wind turbine tower. The columns are connected at the base via pontoons in a triangle, with added braces to the columns holding the masts. The design goals are to ensure (i) manufacturability, (ii) low weight, (iii) low draft, (iv) low acceleration, (v) feasibility in range of geographic locations, (vi) scalability to different sizes and locations, and (vii) good hydrodynamic response. Tank tests were completed at SINTEF Ocean in February 2022 [157].

3.1.46 OSIRenewables TLP

OSIRenewables TLP is a TLP platform consisting of a small truss-structure above the surface connected to nine tendons which extend to the seabed and connect to a seabed structure. There are diagonal taut mooring lines connected to the above-surface structure. It is designed for up to 20 MW turbines and for suitability in 50-150 m water depth [158].

3.1.47 Deepsea Semi

Deepsea Semi, developed by Odfjell Oceanwind, is a semi-sub platform for use in water depths 60-1300 m. Not much is published about the platform, but it looks like it has three columns connected by braces [159].

3.1.48 NASA Floater

The NASA floater is a platform being developed by NASA, University of Maine, NREL and Atkins. The platform is being designed to utilize NASA motion mitigation systems, which were originally used to minimize vibrations in rockets. The concrete platform is being developed to hold a 15 MW turbine, and it is designed with many sensors and controls to monitor different parts of the turbine and platform including tower base moment, platform heel angle, and tuned mass damper damping ratio. The platform can then control its tower base movement, heave motion, heel motion and fairlead tension [160].

3.2 Multi-turbine platforms

3.2.1 Flowocean

Flowocean is a two-turbine platform, shown in Figure 7a. The platform consists of three vertical cylindrical columns. One of these columns attaches to the single-point mooring, and the other two hold the two towers and turbines. The two columns holding the turbines are connected at the bottom and top, and a long truss section runs through the middle to connect to the other column. Tensioned wires connect from

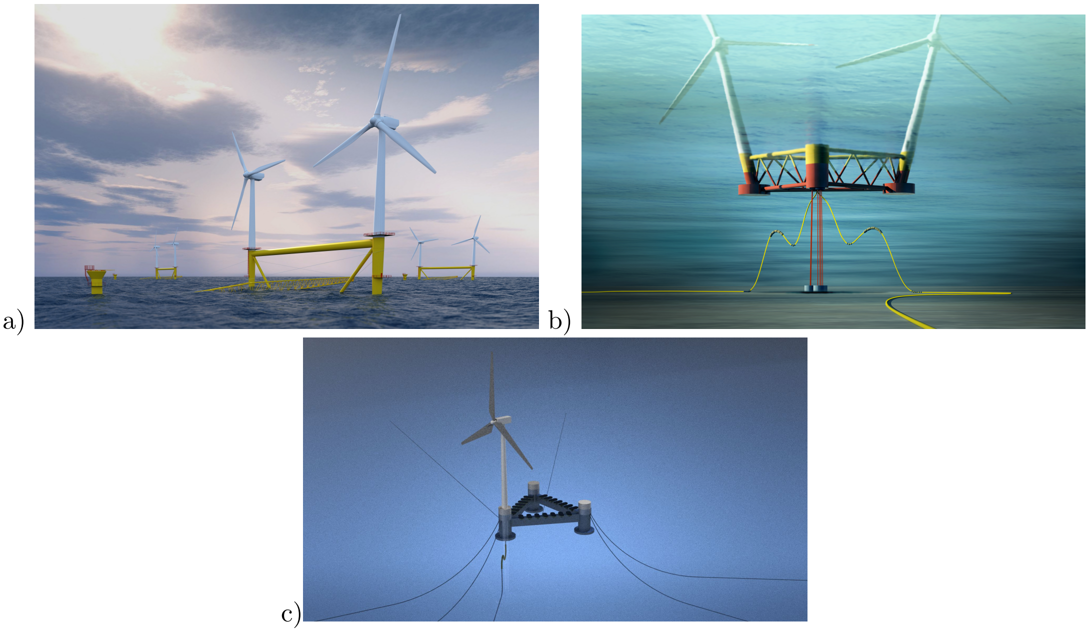

Figure 7: a) Flowocean, courtesy of Flowocean AB; b) TwinWind, courtesy of Hexicon; c) InSPIRE, courtesy of Bombora Wave

the third column to the towers. 1:50 scale model tests (at undisclosed full-scale power) have been performed in extreme conditions [161].

3.2.2 TwinWind

TwinWind, developed by Hexicon and shown in Figure 7b, is a two-turbine system. The platform is a three column semi-sub, connected by trusses. The two towers, which incline away from the center of the platform, are attached to two of the columns. There is a single-point taut mooring system attached to the third column, to allow for the system to weathervane. The platform has undergone multiple design iterations; for example, in 2015 the platform held three turbines [162]. A full-scale demonstrator is being developed for deployment off the coast of Norway, and there are plans to develop a farm in the Celtic Sea [163].

3.3 Hybrid platforms

3.3.1 PelaGen/ PelaFlex

Marine Power Systems have developed their TLP platform as a wind-only platform (PelaFlex, as mentioned in 3.1.32) or as a hybrid platform, by adding a WEC, called the PelaGen. The system consists of two top-hinged WECs attached above the surface, so that the entire device can be lifted out of the water in storms, and the entire device yaws to the incoming wave direction. The company have been developing WECs since 2008 and have done some at-sea testing. The PelaGen is their latest generation, announced in March 2022. There are plans for a multi-megawatt array of WECs at the European Marine Energy Centre (EMEC) in Scotland in 2025-2026 [146].

3.3.2 TWWC

The TWWC (TLP-Wind Turbine-WEC Combination) is a TLP platform with a heaving torus WEC around the central tower. It is inspired by the STC system described in 2.3.5, but this platform is a TLP, in contrast to the spar used in the STC. The torus has a 3 m draft and 8 m height, with outer diameter 20 m. The TLP platform has a 30 m draft. 1:50 scale model tests of the 5 MW system were performed [164].

3.3.3 Sea Flower

SeaFlower is a six-column semi-sub platform, connected at the bottom by a solid plate, with an additional column in the center to hold the 5 MW wind turbine. Gyroscopic stabilizers are added to damp the motion and produce power. The platform has a 12 m draft, the float diameter is 63 m, and the mooring system consists of six catenary lines. Numerical models show that adding the gyros decrease pitch motion by 37% and decrease nacelle acceleration by 10% [165].

3.3.4 Semi-sub + heaving torus

Wang et al. [166] developed a semi-sub platform with a heaving torus on the central column. The platform is a three-column semi-sub, connected at the bottom with pontoons to a central column holding the tower and 5 MW turbine. The columns have a 6.5 m diameter and 30 m draft, and the WEC has an 8 m inner diameter, 16 m outer diameter, and 3.5 m draft. The shape of the torus was investigated, and a concave shape was determined to be optimal [166], [167].

3.3.5 InSPIRE

The InSPIRE platform, developed by TechnipFMS and Bombora and shown in Figure 7c, is a semi-sub platform with submerged flexible-membrane WECs. mWave is the WEC technology by Bombora, which is an air-filled rubber membrane that forces air through a duct when the wave passes over. A demonstrator is planned, consisting of a platform with a 4 MW wind turbine and 2 MW of wave energy capacity. Subsequently, series 1 will include a 8 MW wind turbine and 4 MW of wave energy capacity, and series 2 will be a 12 MW wind turbine and 6 MW of wave energy capacity [168].

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