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Review article

Evolution of floating offshore wind platforms: A review of at-sea devices

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ABSTRACT

Using floating platforms to support offshore wind turbines will be necessary for many countries to reach their Net-Zero targets, since much of the wind resource is located at water depths at which fixed offshore wind turbines are uneconomic or technologically unfeasible. However, floating platforms for wind turbines are still at an early stage of development, and there are a wide range of platform designs. This paper reviews the current state-of-the-art of floating offshore wind turbine platform designs which currently have or have previously had a prototype, demonstration, or farm scale project at sea. The most common design goals for the platforms and the corresponding design features of platforms used to achieve those goals are reviewed. Past, current and projected future levelized cost of energy values for floating offshore wind are reviewed and discussed. The development of each platform design is described, including evolving design goals and resulting changes in platform features. Finally, overall trends in platform designs are discussed and divided into three phases, defined by changing goals: (i) influences from the offshore oil and gas industry, (ii) specialization to floating offshore wind, and (iii) further specialization to local environment.

1. Introduction

Net-Zero goals for many countries rely on a massive and rapid expansion of offshore wind. The Global Wind Energy Council (GWEC) predicts an increase from the current (2022) 35 GW of global capacity to 380 GW by 2030 [1]. At present, most offshore wind turbines are ‘fixed’ – they are supported by a structure that extends from the bottom of the turbine tower to the seabed. Wind energy is stronger and more consistent in areas with deep water: 80% of the practical offshore wind energy resource is contained in water deeper than 60 m [1]. However, fixed structures are infeasible to build in such water depths, and therefore, floating offshore wind turbines (FOWTs) are required.

At the current time of writing, the installed capacity of FOWTs is 121 MW, however it is anticipated that this will increase to 18.9 GW by 2030 [1] and to 264 GW by 2050 [2]. Fig. 1 shows the historical (dark blue) and projected (light blue) global capacity of floating wind, as well as the breakdown of current and projected capacity by country. The first significant research on FOWT platforms started in the 1990’s, and the first prototype of a FOWT was built in 2007. Since then, there has been a rapid expansion in FOWT research and development. In turn, this has led to a massive increase in the number of platform designs which are being developed and tested. A timeline of the development of these devices is given in Fig. 2, which includes at-sea prototypes, demonstration projects and pilot farms. There are two platform designs that have been deployed at the pilot farm stage: (i) Equinor’s Hywind Spar, which is used at Hywind Scotland (United Kingdom, 30 MW), installed in 2017, and (ii) Principle Power’s WindFloat, which is used at WindFloat Atlantic (Portugal, 25 MW), installed in 2019, and Kincardine (United Kingdom, 50 MW), installed in 2021. There are a further 20 platform designs that have reached the stage of testing at-sea prototypes or demonstrators and over 80 other platforms at earlier stages of development.

Looking at the range of FOWT designs, it is evident that there has not yet been convergence in platform design, rather the range of designs has expanded rapidly, as is expected in the early stages of technology development. Engineering convergence on a smaller number of designs is likely to lead to cost reductions, which are crucial for the enormous number of planned future deployments of floating offshore wind. Therefore, in this paper an up-to-date review is presented on the state-of-the-art of FOWT platform designs at farm, prototype and demonstration scale. The purpose of this review is to examine the predominant design goals of the platforms and their drivers, along with the corresponding design features used to achieve those goals. Where platform designs have available information over multiple iterations, for example, through multiple stages of lab and/or at-sea testing, trends in the design goals and features are discussed. After reviewing each individual platform design, overall trends in platform designs, drivers and features are compared. It is observed that there has been a

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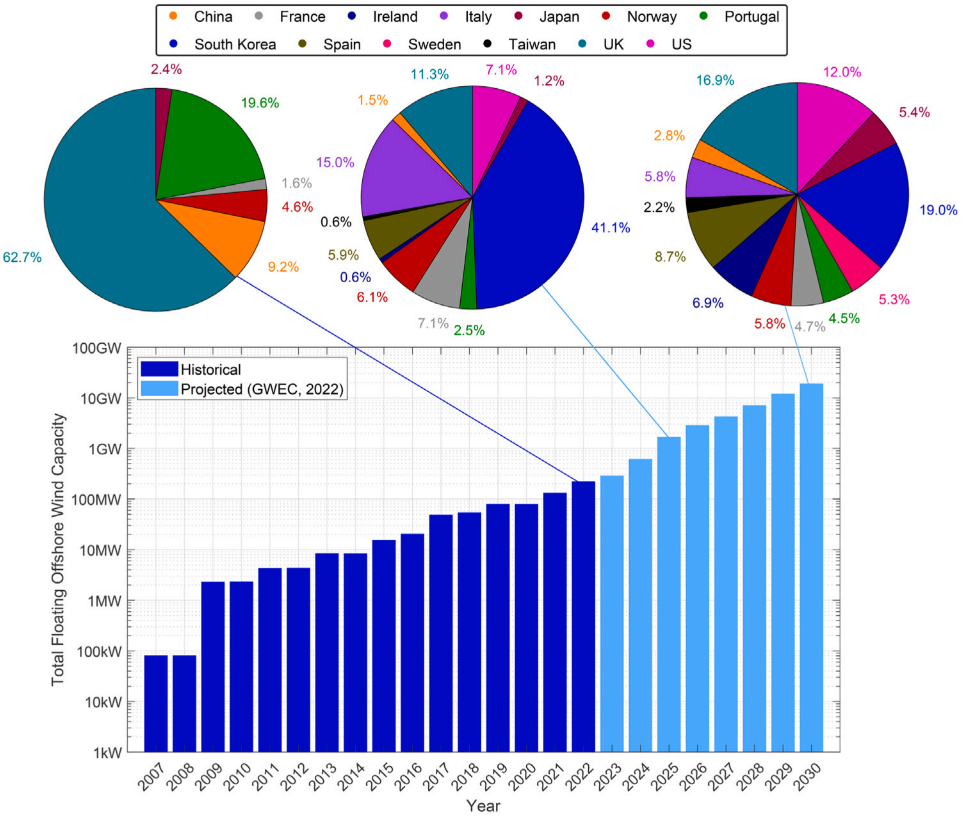

Fig. 1. Historical (dark blue) and projected (light blue) global floating offshore wind capacity, with percentages of current (2022) installed and projected (2025 and 2030) capacity by country (top). Projected capacity from GWEC [1]; historical capacity tallied from our research (see Table 4 for references for each device).

List of abbreviations

FOWT	Floating offshore wind turbine
GW	Gigawatts
HAWT	Horizontal axis wind turbine
kW	Kilowatts
LCOE	Levelized cost of energy
MW	Megawatts
O&G	Oil and gas
O&M	Operation and maintenance
TLP	Tension leg platform
TRL	Technology readiness level
USD	United States Dollar
VAWT	Vertical axis wind turbine
WEC	Wave energy converter

shift in design priorities, starting from initial designs motivated to use experience from the oil and gas industry, moving to designs specialized to the specific needs of a floating offshore wind platform, and most recently, to designs which are specialized to specific environments.

Up to now, there have been several previous reviews on FOWT platforms. Henderson and Witcher [3] wrote a review in 2010 of research on floating wind platforms and the state-of-the-art at the time, when there were two prototypes in the sea. Cruz and Atcheson [4] wrote a book in 2016 on floating offshore wind turbines, which included a history of early platform development and a review of the four prototypes in the sea at that time. Leimeister et al. [5] wrote a critical review of FOWT platforms in 2018, which focused on determining the best type of platform using a multi-criteria decision analysis. These previous reviews all provide valuable learning, however there has not been a review focusing on the platform design drivers, their corresponding features, and design trends across a wide range of FOWT platform designs. Therefore, this review provides new and valuable insights in these areas, in addition to providing a much-needed update on the hugely expanded state-of-the-art. The information in this paper is based on publicly available data only. This review covers single turbine platforms, as well as multi-turbine and hybrid (*i.e.*, multi-energy) platforms.

It is important to note that the purpose of this paper is not to pick ‘winning’ devices, rather it is motivated by the need for researchers, developers and other stakeholders to understand the important design characteristics of FOWT platforms, their drivers and the differing ways of achieving design goals. The review will be helpful to policy makers in understanding the current status of FOWT platforms, particularly since it is a very promising but still developing technology which needs government support. Furthermore, it will be useful to the FOWT industry, not only for platform designers, but also port developers, supply chain developers, and developers of other aspects of the technology such as dynamic power cables and floating power substations. It will also be useful to give a current state-of-the-art of the technology to a range of academic researchers, from those researching FOWT platform designs to marine scientists researching the impacts of these devices on marine life, wind turbine developers, structural engineers looking at platform design, and those interested in wake effects in floating offshore wind farms. In this way, the wealth of information available from the range of existing FOWT designs can aid the sector in ultimately working towards low-cost, high-performance devices. In a further paper this review will be extended to platform designs at earlier stages of development, however it was opted to preserve the important distinction between more proven technologies and more conceptual designs. Therefore, in this paper the focus is solely on FOWT designs which have a Technology Readiness Level (TRL) of 5 or above.

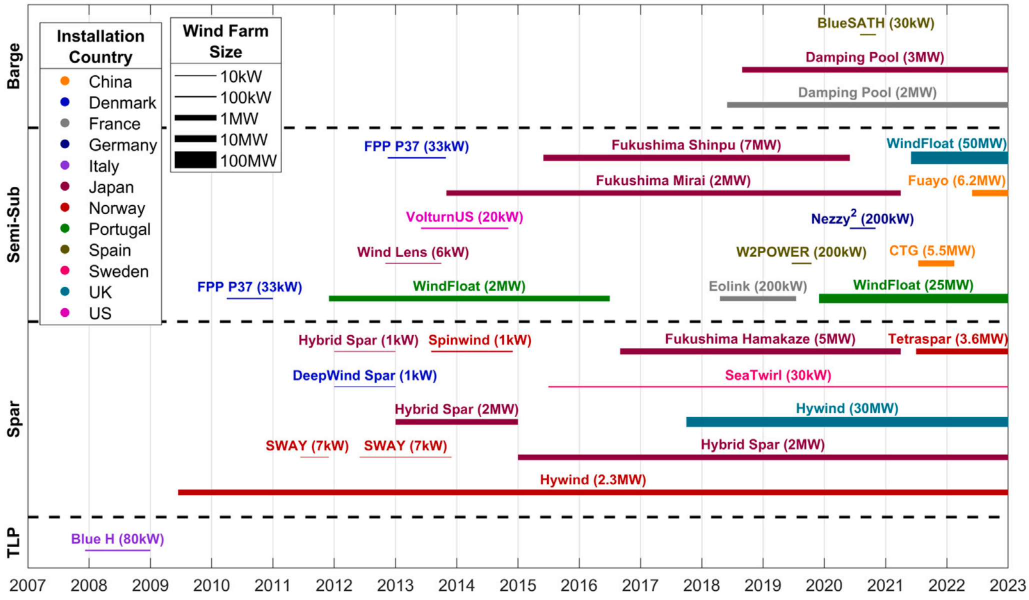

Fig. 2. Timeline of floating offshore wind turbine deployments, including prototypes, demonstrators, and farms. See Table 4 for references for each device.

This paper is structured as follows. Section 2 specifies the broad categories of FOWT platforms and their general advantages and disadvantages. This section also includes an introduction to and review of typical design goals and drivers, and the most common design features used to achieve those design goals. Additionally, levelized cost of energy (LCOE) for FOWTs is discussed, and studies which define LCOE values and factors which influence LCOE are reviewed. Section 3 details the two platform designs in operation at farm scale and their respective design histories. Section 4 lists the 20 live or decommissioned prototype/demonstration-scale devices, including multi-turbine and hybrid platforms. More detail on these 20 designs, including design evolution, design goals, lab tests programs, and prototype or demonstration projects, can be found in the Appendix. Section 5 provides a discussion of the main trends in platform designs, the respective goals and the corresponding design features.

2. Design goals and features of floating offshore wind turbine platforms

In this section the most common design drivers and features of FOWT platforms are reviewed. The four general 'types' of platforms are introduced first. Although these categories are important to define and discuss, the type of platform will not be the focus of this paper. This is due to the recent divergence of platform designs which has resulted in many designs which cannot easily be categorized in this way. The most common platform design goals are then introduced, followed by a brief discussion on the typical platform features that are used to meet the stated design goals.

2.1. Platform types

One of the most important aspects of any FOWT platform is the need to maintain stability. Therefore, the platform must counteract the thrust and inertial forces from the wind turbine, centered up to 150 m above the platform. Furthermore, limiting or minimizing pitch motion will improve the performance of the wind turbine. There are three main methods of increasing stabilization in pitch: (i) increase the distance between the vertical center of buoyancy and the vertical center of gravity ('gravity-stabilized'), (ii) increase the pitch second moment of the waterplane area ('waterplane-stabilized'), and (iii) use taut moorings ('mooring-stabilized') [6]. Due to the importance of stabilization, platforms are often categorized into one of four main types, dependent on the method by which they achieve stability. These four types are: (1) spar, (2) barge, (3) semi-submersible ('semi-sub') and (4) tension leg platform ('TLP'). Examples of each type are shown in Fig. 3. Spars use gravity stabilization, and the 'typical' spar platform is a single vertical cylinder with ballast at the bottom, with the wind turbine tower connected directly to the vertical cylinder. TLPs use mooring stabilization, and the 'typical' TLP consists of a submerged body connected to the mooring lines, with a central column connecting the submerged body to the wind turbine tower above the surface. Barges use waterplane stabilization, and the 'typical' barge consists of a floating shallow, wide platform. Semi-subs use waterplane and gravity stabilization, and the 'typical' semi-sub consists of three to five vertical cylinders connected together, with the turbine in the center or above one of the columns. However, not all platforms fit into these distinct types, with many designs using a combination of stabilization mechanisms and thus spanning across categories. Recently, there has been an increase in these combination-type platforms and generally an increase in platforms diverging from these four categories.

Table 1 presents the typical advantages and disadvantages of the platform types. It is generally accepted that there is no one 'best' category of platform. Rather, different categories may be optimal depending on the water depth at the location of installation, port limitations, seabed conditions, manufacturing costs, and the relevant wave, tidal and wind climate.

2.2. Design drivers for FOWT platforms

There are many design goals stated by platform developers which generally fit under two overarching design drivers: (i) to ensure platform stability (and thus reduce platform motions) and (ii) to reduce costs.

2.2.1. Platform stability and motion reduction

Ensuring platform stability and decreasing platform motions are important to reduce the risk of failure in extreme events and to increase performance of the wind turbine in operational conditions. For the former, developers often look to design standards by international classification societies, such as DNV [7] and IEC [8].

Many platform developers state a design goal to limit pitch motion or, similarly, nacelle acceleration, for an extreme event such as a 100-year storm. Other platform developers state that their design goal is

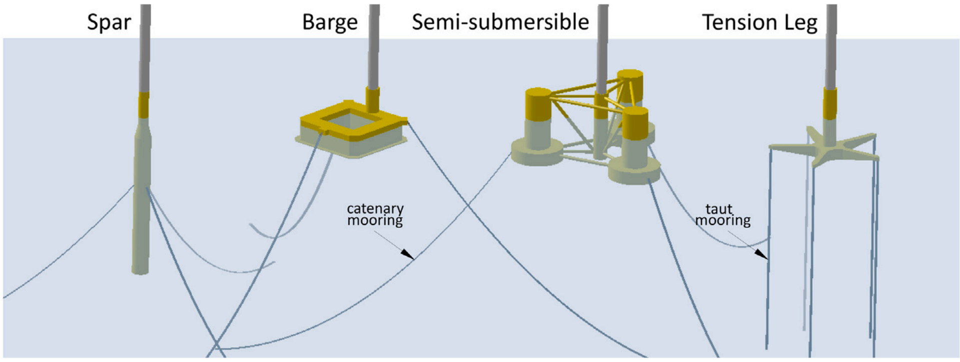

Fig. 3. Types of platforms used for floating offshore wind turbines.

Table 1
Typical advantages and disadvantages of different types of FOWT platform.

	Advantages	**Disadvantages**
TLP	• Small heave and pitch motion • Small seabed footprint • Can work in many water depths • Light and small structure, meaning lower material costs	• Usually requires special purpose-built vessel to install because unstable under tow • Expensive mooring lines and anchors with high vertical load • If one mooring line fails, it could be catastrophic • Currently has a low TRL; not a proven technology for FOWTs • Low/no deck space (for maintenance) • Difficult to use in an area with large tidal range
Spar	• Usually relatively simple to make and manufacture • Proven technology (30 MW in operation using this type of design today) • Small heave motion	• Hard to tow out and install: Requires a deep dock or sheltered area and large offshore crane to install turbine • Requires deep operational water, especially for larger turbines • Heavy and large structure • High fatigue load on base • Large seabed footprint • Larger pitch and roll motion (relative to others) • Low deck space (for maintenance)
Semi-sub/barge	• Does not require deep dock or specialist equipment for tow-out and installation • Proven technology (70 MW in operation using this type of design today) • Less material than spar • Not dependent on water depth • Lower pitch and roll motions (relative to spar) • More deck space (for maintenance)	• More difficult to manufacture than spar • Large seabed footprint • Larger heave motion (relative to others)

to limit or minimize pitch motion in operational conditions or at rated thrust.

Though there is much focus on pitch motion of the device, there is also interest in limiting or minimizing platform motions in all six degrees of freedom. In particular, the platform is designed so that its natural frequencies in all degrees of freedom (with particular emphasis on heave, pitch and roll) avoid critical regions. These critical ranges are defined by the range of exciting wave frequencies (usually 4–30 s, depending on the location), the frequency at which a blade passes the tower (called 1P) and the third harmonic of that frequency (called 3P) for three-bladed turbines.

2.2.2. Cost reduction

Minimizing or limiting motion also helps to reduce cost; if the platform moves less and experiences lower fatigue and extreme loads, the material of the structure need not be as thick, thus reducing material and manufacturing costs. Additionally, wind turbine performance increases, lowering LCOE. However, there are also design goals focused on reducing costs but not aimed at platform stability and motion.

For example, some platform developers state an explicit desire to reduce material weight or increase power to weight ratio. Other design goals aim at improving manufacturability, for example by using a modular design to enable serial production or avoiding braces due to welding difficulties and high fatigue. Some developers use a ‘plug and play’ approach for mooring systems and turbines; that is, platforms are designed around conventional systems already developed.

On the other hand, some platforms are designed for applicability to specific locations or types of locations. An example of this is where platform developers use materials which can be sourced through local supply chains and adopt manufacturing processes based on local capability. The proliferation of designs which use concrete rather than steel is a result of this since concrete is cheaper than steel in many locations, and using it avoids the need to import steel. Furthermore, some platform developers have draft constraints to be usable in ‘intermediate’ water depth (*i.e.*, water that is too deep for fixed turbines

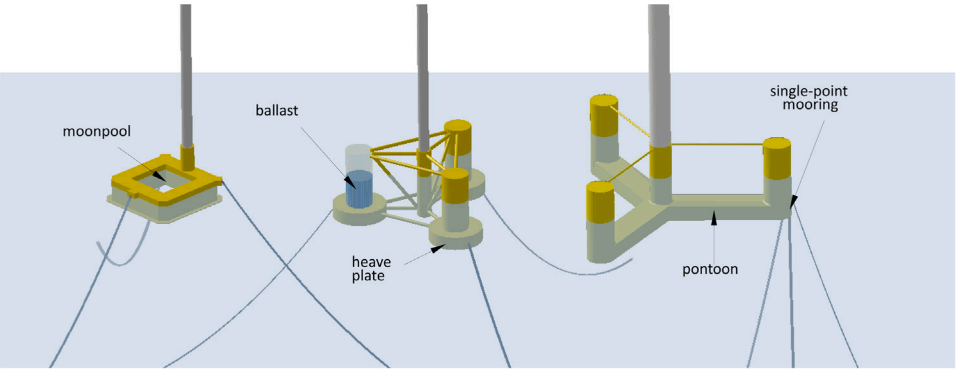

Fig. 4. Common design features of floating offshore wind turbine platforms.

but not very deep, 40–80 m). Numerous design goals pertain to ports and installation. Platforms are often designed to fit at a ‘standard’ port, and this requirement introduces width, height, and draft limits. Furthermore, another common design requirement is to avoid reliance on specialist installation vessels to reduce cost, which means the turbine must be installed at the port and towed-out in an upright position.

2.3. *Design features of FOWT platforms*

Many of the typical design features used in FOWT platforms have multiple benefits for the platform. In this section the features are grouped by those features which are primarily geared towards increased stability and/or reduction of platform motion and those design features whose main function is to decrease cost. The design features reviewed in this section are summarized in Table 2.

2.3.1. *Platform stability and motion reduction*

Following on from the introduction to the different platform types in Section 2.1, the features for achieving stability are discussed herein. Hydrostatic analysis can provide information about stability and how to achieve it. The restoring equation in pitch is

$$\left(\rho g S_{55} + F_b z_{CB} - F_w z_{CG}\right)\sin\theta_5 = F_t\left(h_{\text{hub}} + f_b + z_{CB}\right) - M_m \tag{1}$$

where ρ is water density, g is gravitational acceleration, S_{55} is the pitch second moment of waterplane area, F_b is buoyancy force, z_{CB} is the vertical center of buoyancy, F_w is weight force, z_{CG} is vertical center of gravity, θ_5 is the pitch displacement angle, F_t is aerodynamic thrust force, h_{hub} is the hub height, f_b is the freeboard, and M_m is the external moment from mooring [9]. It can be seen from this equation that there are multiple ways to achieve and/or increase stability. It is also apparent that as aerodynamic thrust and hub height increase, stability becomes more difficult: the restoring forces must get larger to avoid an increase in pitch inclination.

For a barge, increasing stability requires increasing the pitch second moment of the waterplane area, S_{55}—that is, increasing waterplane area far from the center of gravity. For a TLP, stability is achieved by tensioned mooring lines, M_m. For spars, increasing stability is achieved by increasing the distance between center of buoyancy (z_{CB}) and center of gravity (z_{CG}), usually by lowering the center of gravity. For semi-subs, increasing stability is achieved by increasing pitch second moment of area – usually by moving columns further from the center of gravity – and/or lowering the center of gravity. For semi-subs and spars, to lower the center of gravity, ballast is used. Ballast, as shown in Fig. 4, is weight at the base of the structure which can be solid or fluid (usually sea water).

Limitation or reduction of surge or sway motion is usually achieved by the mooring lines. There are two main types of mooring, shown in Fig. 3: (i) taut lines which are connected from the platform to a high-load vertical anchor, and (ii) catenary lines which have a characteristic freely-hanging shape, extending horizontally on the seafloor with drag anchors at the ends. Taut lines are used for TLPs, and catenary lines are used for semi-subs, spars and barges. For taut lines, diagonal lines may be included to reduce surge motion.

Spar platforms are particularly prone to yaw motion. To reduce this motion, a crow-foot or delta connection is commonly implemented, whereby the mooring line splits into two near the platform and attaches to two connection points on the platform. Other techniques for yaw suppression include radial fins/plates or connecting the mooring to the widest section of the platform. Though not part of the platform, blade pitch control techniques are an important feature of the system to reduce platform motion. For suppressing yaw motion, individual blade pitch control is used, especially for large turbines where there is more wind field variation across the blades.

TLPs inherently do not have high motion response in heave because of the taut mooring. For spars or semi-subs, a common design feature is to have a small waterplane area (with the diameter of the spar or columns often increasing below the waterline) which decreases wave loads, especially in heave. For semi-subs, common design features to decrease heave motion are heave plates and/or pontoons. In this paper, a heave plate, shown in Fig. 4, is defined to be any thin (relative to the other platform dimensions) plate or section at the base of a column which is wider than the column itself. They are often circular but are sometimes hexagonal to use flat plates instead of rolled material. Heave plates increase viscous damping forces, decreasing platform motions. They also increase heave added mass, which increases the heave resonant period, ensuring it is above the critical ranges discussed earlier, or enabling the platform to be smaller for the same resonant period. Pontoons, shown in Fig. 4, are long, thin (relative to the other platform dimensions) sections at the base of a structure, connecting columns. Pontoons also increase viscous drag, and furthermore increase buoyancy of the structure. For barges, a common design feature to decrease heave motion is a moonpool, which is a cut-out in the platform, as shown in Fig. 4.

In general, TLPs do not have high motion response in pitch because of the taut mooring. For spars, reduction of pitch motion is usually achieved by ensuring a low ballast. For semi-subs, heave plates and pontoons also help dampen motion in pitch and increase pitch added mass. Another technique used to decrease pitch motion in semi-subs is an active ballast system. These systems pump water between different columns; in high winds, water is transferred to the downwind column(s) to trim the heel angle.

Again, though not part of the platform, blade pitch control techniques are important in reducing pitch motion. If control strategies typically used for land-based or fixed offshore wind turbines are used in floating applications, negative damping will occur above the rated wind speed as thrust decreases, causing a high motion response [10,11]. Therefore, the platform must be designed to deal with this negative damping, or floating-specific control strategies, specific to the platform design, can be adopted to optimize the whole system.

Table 2
Common design goals and associated common features used to achieve the goal. Note that some features are associated with multiple design goals.

Design goal	Related design features used to achieve goal
Increase platform stability/reduce platform motion	• Ballast • Heave plates • Pontoons • Tuned-mass-damper in nacelle • Different blade-pitch control to fixed/land-based turbines • Diameter smaller at the waterline and increases below • Mooring attached wide • Motion suppression fins • Moonpool • Wave energy converter locked in storms (for hybrid platforms) • Vertical and diagonal taut lines • Delta connections for mooring • Individual blade pitching • Active ballast
Cost reduction	• Pontoons • Moonpool • Tilt towers out for multi-turbine • Lowerable ballast/keel • Lowerable gravity anchor • Weathervaning (with/without single point mooring) • Active ballast

Most of the FOWT platforms are designed for horizontal axis wind turbines (HAWTs), in which the main rotor shaft is horizontal, but there are also vertical axis wind turbines (VAWTs), in which the main rotor shaft is vertical. VAWTs are attractive for floating applications since they have a lower vertical center of gravity compared to HAWTs.

2.3.2. Cost reduction

Some design features originate from the desire to decrease complexities in installation and maintenance. For example, using water as ballast enables the ballasting to be done at the location of installation. Before the ballast has been added, the platform has a shallow draft, enabling construction at a standard port. Some spars have a separate lowerable keel, and some TLPs have a lowerable gravity anchor. These features are towed out before ballasting, and then ballast is added at the location of installation. The keel or gravity anchor are sometimes used as barges for tow-out, allowing for construction at a standard port without the need for special installation vessels, but the stability benefits are still achieved once installation is complete. Another design feature related to installation is connecting the mooring lines on the platform above the water surface, avoiding the need for diving.

Other design features center around increasing capacity factor of the turbines and decreasing downtime, with the overarching goal to lower LCOE of the system. An example of this is using a single-point mooring. A single-point mooring system (shown in Fig. 4 on the right) is a taut or catenary system attached to a single part of the structure. This configuration allows the platform to swing about this point to passively face the wind turbine to the prevailing wind. This is called ‘weathervaning’ and is used for TLPs, semi-subs or barges, and is particularly common for multi-turbine platforms. Other platforms use active ballast to orient platforms with the prevailing wind, or to stabilize platforms in the case of misaligned wind and wave directions, allowing the turbine to be more effective in power capture.

Multi-turbine platforms are attractive due to the use of more established technologies (smaller turbines), the use of shared infrastructure such as mooring and dynamic power cables, and potential wake loss advantages. Tilting the towers outward enables the platform to be smaller without the turbines negatively interfering with each other.

2.4. Levelized cost of energy

Levelized cost of energy (LCOE) is the average price of electricity required to cover the lifecycle cost of a project. LCOE for FOWTs depends on environmental surveys and consent, the turbine, transmission cabling and substations, mooring, the platform, installation, operations and maintenance, and decommissioning [12]. While LCOE is currently over 200 $/MWh (∼183 €/MWh) due to small sizes of farms and immaturity of the technology and supply chain, it is forecast to fall to less than 100 $/MWh (∼92 €/MWh) by 2025 and less than 40 $/MWh (∼37 €/MWh) by 2050 [2]. DNV [2] predict that in the next few years, as more information becomes available about day-to-day operations, turbine performance and component replacements, more accurate values of LCOE can be predicted. Compared to fixed offshore platforms, the aspects of FOWTs which are currently proving challenging to the goal of reducing LCOE include an increase in mass (floating platforms require twice the steel mass as a fixed structure for the same turbine size), an increase in design and fabrication complexity, and additional maintenance required for the floating structure, turbine and mooring system due to motion. Key ways to decrease LCOE include increasing turbine size and size of farm, decreasing the platform cost (which is currently five times that of a fixed platform, due to earlier level of development), and decreasing the operating cost (which is also currently five times that of a fixed platform, due to uncertainty and smaller farm size).

There have been a number of studies discussing and reviewing LCOE for FOWTs. In 2014, Myhr et al. [13] compared three platforms with demonstrators/prototypes at the time (Hywind, SWAY and Windfloat) to an early-concept TLP (TLWT) and two early-concept Tension-Leg-Buoys (TLB X3 and TLB B). To calculate costs, 100 5 MW turbines were assumed to be installed 100 km from shore. LCOE was calculated to be 82–237 €/MWh, and the factors which significantly affected the LCOE included distance to shore, availability and water depth [13]. It was found that Windfloat had the most expensive LCOE, followed by Hywind, TLWT, SWAY, TLB X3 and finally TLB B.

In 2017, Heidari [14] performed a comparison of a semi-sub (Windfloat), TLP (Pelastar) and spar (Hywind). Information on the cost of the Hywind and Windfloat platforms came from Bjerkseter and Ågotnes [15], whereas cost of Pelastar came from the developer. It was found that the LCOE for the semi-sub was highest, followed by TLP and finally spar, but as turbine capacity increased, LCOE decreased and the difference between the LCOE for the three concepts decreased [14].

In 2019, Stehly et al. [32] conducted a study comparing two reference wind farm projects: one fixed and one floating. Each project had 100 6.1 MW turbines operating for 25 years. The fixed wind farm was located at 34 m depth 50 km from the shore in the North Atlantic (USA), and the floating wind farm was located at 739 m depth 36 km from

Table 3
Platform designs in operation at farm-scale, with current parameter values (not including maximum possible turbine capacity rating, other material options, and water depth limits).

Platform design name	Technology developer	Type	WTG rating in operation (MW)	Material	Water depth (m)	Mooring	References
Hywind	Equinor	spar	2.3, 6	steel	95–120	3 catenary lines (steel chain)	[4,5,16–21]
WindFloat	Principle Power	semi-sub	2, 8.4, 9.5	steel	60–80, 100	3 to 4 line catenary lines	[4,22–31]

the shore in the Pacific (USA) using a semi-sub platform. The LCOE for the floating project was 132 \$/MWh (~121 €/MWh), compared to 85 \$/MWh (~78 €/MWh) for the fixed project. It was found that the substructure for the floating project represented 29.5% of the total CAPEX cost, compared to 13.5% for fixed. Furthermore, it was shown that operation and maintenance would account for 30% of total LCOE cost (and 34.3% for fixed) [32].

In 2020, Ioannou et al. [9] performed a study to compare the mass and cost of standard barge, spar and semi-sub platforms. Specifically, material and manufacturing costs were considered, using manufacturing complexity factors obtained through a survey among experts. Platform sizes were determined based on hydrostatic laws. It was found that steel semi-subs were the most expensive option due to their complex geometry and amount of steel required, and the barge had the lowest cost [9].

In 2021, GWEC [33] presented a report on a heatmapping study performed to assess competitiveness of FOWTs in certain markets. Based on a 2030 time-frame, and thus accounting for technology development of the turbine and substructure, the techno-economic offshore wind performance model calculates total project cost and lifetime power generation. The model predicts LCOE to be 95–170 €/MWh for the Philippines, 84–153 €/MWh for Italy, 52–75 €/MWh for Ireland, and 64–161 €/MWh for California (USA). These ranges show the dependence on location, even within one country, due to wind resource, distance to port, and water depth [33].

In 2022, Martinez and Iglesias [12] performed a spatial variation analysis of LCOE for the European Atlantic, considering 100 10 MW turbines on the same semi-sub platform and found that the LCOE varies from 95 €/MWh to 135 €/MWh at different locations. It was found that LCOE is very dependent on the location of the wind farm; the wind resource is the most important determining parameter, and next is the distance to port [12]. In contrast to Myhr et al. [13], Martinez and Iglesias [12] found that water depth does not significantly affect cost.

Due to the dependence of LCOE on many factors other than the substructure itself, particularly the location of deployment, in this study cost or LCOE values for specific substructures are not discussed or reported, since if a developer has chosen to share this information it is very rarely with sufficient detail about assumptions used to calculate the value.

3. Platform designs in operation at farm scale

There are currently two platform designs in operation at farm scale: Equinor's Hywind spar and Principle Power's WindFloat. In this section, the design development of these platforms is discussed. Parameters of the platforms are summarized in Table 3. Section 5 will summarize the platforms' evolutions and compare the platforms.

3.1. Hywind Spar

The Hywind Spar, shown in Fig. 5, has been developed by Equinor (formerly Hydro Oil & Energy and Statoil) [4,20]. It is a 'traditional' spar platform, consisting of a continuous cylindrical structure. Development started in 2001, the demonstration platform was deployed in 2009 in Norway [4], and the pilot farm has been in operation since 2017.

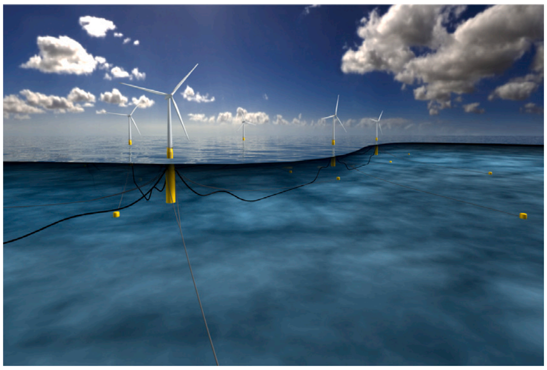

Fig. 5. Hywind, courtesy of Equinor. Note that this figure has been computer generated to show the design of the platform.

3.1.1. Early development and design drivers

Development of this platform started in 2001 by Hydro Oil & Energy, and a spar platform was chosen, to benefit from relatively low production costs for the simple structure, the relatively simple stability mechanism, and the moderate wave loads. During the initial concept stage, the platform was to be made of concrete and was designed for a 5 MW turbine. One of the stated key design challenges was to avoid negative pitch damping above rated wind speed, so blade pitch control strategies differing from land-based ones were developed simultaneously. In 2005, 1:47 scale model tests of the 5 MW system were completed at MARINTEK Ocean Basin Laboratory, including 100-year wave conditions and above-rated wind speeds. In these tests, their new blade pitch control system was tested and shown to considerably reduce platform motions [4,20]. After these successful tests, the platform progressed to a demonstration scale device.

3.1.2. Demonstration platform

The Hywind Demo was installed off the coast of Norway in June 2009 [18]. The demonstration platform holds a 2.3 MW Siemens turbine and was the first multi-megawatt FOWT installed in the world. There were some updates for the demonstration platform from their original design. The focus for the re-design was to avoid natural periods within the range of wave periods in the North Sea (5 to 20 s), as well as the 1P and 3P periods of the rotor. It has a 100 m draft, which was known to be conservative as it was the largest one built at the time. The platform's diameter at the waterline is 6 m, increasing to 8.3 m below the surface [4]. The natural periods of the platform are 125 s in surge, 27.4 s in heave, 23.9 s in pitch, and 23.9 s in yaw [18]. Another change from the original design was a change from concrete to steel.

The main focuses for design of the mooring system were to prevent the platform from drifting too much and to provide stiffness in yaw. The mooring system consists of catenary lines made of steel chain and wires with added clump weights. A crow-foot configuration is used, and after three years the largest yaw motion on the demonstration platform was 1.5° [18].

To install the demonstration platform, the platform was towed horizontally to a sheltered deep-water fjord, where it was upended to

Fig. 6. Photo of the Kincardine Offshore Wind Farm project, courtesy of Principle Power.

vertical by adding water. Then, the nacelle and rotor were installed and finally the platform was towed to its final location where anchors had been pre-installed. The average capacity factor for the first three years of the demonstration was 40%, and in 2011 it was 50.1%, producing 10.1 GWh [19]. The demonstrator was in operation for eight years, and in 2019 Unitech Offshore took ownership of the device. It is now being used for research and technology development [34]. The success of the demonstrator lead to the development of the world's first commercial floating wind farm, the Hywind Pilot Park.

3.1.3. *Pilot farm and future planned development*

In 2017 the Hywind Pilot Park was built and connected to the grid off the coast of Aberdeenshire, Scotland, United Kingdom [19]. This FOWT farm is 29 km offshore, where the water depth is 95–120 m, and it consists of five platforms with 6 MW Siemens turbines on each, totaling 30 MW capacity. The steel platforms have a 78 m draft with a diameter of 10 m at the waterline and 14 m diameter below the surface. Compared to the demonstration platform, the diameter is increased but draft is decreased, and the developers claim that the capital cost per MW is reduced by 70% [16].

Because larger turbines were used in this farm than the demonstration project, spatially distributed wind forces were observed, leading to noticeable yaw motion, despite the crow-foot mooring configuration still used. Therefore, the active damping strategy was updated to include individual blade pitching to damp yaw and roll motion, in addition to the collective blade pitching to damp pitch motion [19].

Hywind Tampen will be the second farm to use the Hywind spar and is expected in 2023 off the coast of Norway [21]. It will include 11 6.6 MW Siemens turbines for a total capacity of 95 MW. The structures will be made of concrete. The water depth at the farm's location is 260–300 m. The expected capital cost per MW is expected to decrease by a further 40% [16]. There are additional plans to use this platform at farms in Norway (Utsira Nord) and South Korea (Firefly Floating Wind Farm Project) [16].

3.2. *WindFloat*

The WindFloat platform, shown in Fig. 6, has been developed by Principle Power (originally by Marine Innovation & Technology). It is a 'traditional' three-column semi-sub with the turbine mounted on one of the columns. At the base of each column is a heave plate, and the columns are connected via braces. Development started in 2006 [25], the demonstration project was installed in 2011 in Portugal, the first farm, WindFloat Atlantic, was installed in 2019 in Portugal, and the second farm, Kincardine, was installed in 2021 in Scotland, United Kingdom.

3.2.1. *Early development and design drivers*

The platform stemmed from the MiniFloat, a semi-sub developed by Marine Innovation & Technology in California, originally for use in the oil and gas industry for hydrocarbon production [25–28]. The MiniFloat platform had three rectangular columns with one continuous plate attached to the bottom of the columns [28]. Zambrano et al. [25] first proposed using the platform for floating wind turbines in 2006, performing a numerical investigation to fit three small wind turbines on a resized platform.

The platform was renamed WindFloat in 2009 when floating wind turbines became the main aim of the platform. The stated design goals for the WindFloat were to (i) minimize weight of the structure, (ii) optimize power to weight ratio, (iii) ensure ease of manufacturability, (vi) ensure a shallow draft, (v) be able to use any turbine, (vi) avoid reliance on a special installation vessel (and therefore complete all assembly, erection and commissioning of wind turbines at quayside), (vii) have reversible ballast, mooring and cable hook-up so that it can be towed back to quayside for maintenance, (viii) maintain stability while being towed, and (ix) use conventional mooring [4]. The main motivation for developing a semi-sub was due to the reduced cost for tow-out and installation, compared to spar and TLP platforms.

The first iteration of the platform was designed to support a single 5 MW turbine, and the platform design differed from the MiniFloat platform by separating the plate at the bottom of the columns into three separate heave plates, and the columns became cylindrical rather than rectangular. The platform now held a single turbine, instead of three, which was connected on top of one of the three columns. The mooring system consisted of four catenary lines from the column which held the tower and turbine and one from each of the other two columns, totaling six lines. The platform had three 10.7 m diameter columns, 56.4 m apart with heave plates of diameter 27.4 m, and the operational draft was 22.9 m. Additionally, an active ballast system was designed [4,22–24,27].

Two lab test campaigns were completed at 1:105 scale of the 5 MW system, testing the 100-year wave and moving lead to simulate the active ballast based on changing wind direction [4,24]. After the completion of these lab tests, the demonstration platform, WindFloat 1, was designed and built.

3.2.2. *Demonstration platform*

WindFloat 1 demonstration platform was installed in 2011 off the coast of Northern Portugal [4,31], and it was in operation for 5 years. The platform held a 2 MW Vestas turbine, had four mooring lines, and the project was located 6 km offshore at a water depth of 49 m. During its demonstration period, the turbine operated in sea states with a maximum wave height of 12 m and survived storms with a maximum wave height of 20 m. Analysis of data from the demonstrator showed for the first time that the motion of the platform impacts the turbine response, and large aerodynamic forces affect the motion of the platform. After the demonstration, the goals for further development were to minimize steel weight, adapt the design for larger turbines, minimize downtime, and allow for fabrication in series [31]. The success of the demonstrator paved the way for the two pilot farms.

3.2.3. *Pilot farms and future planned development*

WindFloat Atlantic was built and commissioned in 2019. The farm is 20 km off Northwest Portugal in 100 m water depth. The three platforms hold 8.4 MW Vestas turbines to total 25 MW capacity [29]. Kincardine Offshore Wind Farm was commissioned in 2021. This farm is 15 km off the coast of Aberdeenshire, Scotland, United Kingdom in 60–80 m water depth. The five platforms hold 9.5 MW Vestas turbines. Together with the relocated 2 MW WindFloat 1 platform, the total farm capacity is 50 MW. The platform design used in these farms looks similar to the demonstration platform, with no noticeable changes in the platform design. One of the platforms from Kincardine is shown in Fig. 6. In this figure, which shows the platform at the port, everything

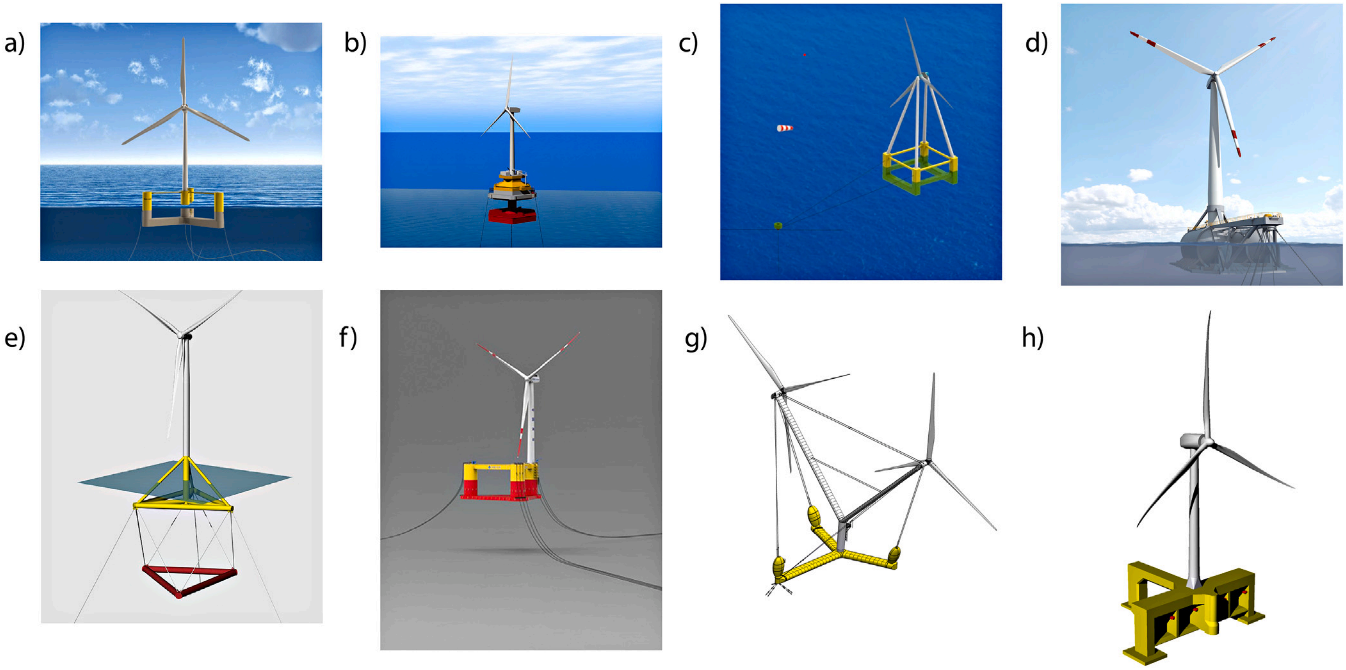

Fig. 7. (a) VolturnUS, courtesy of the University of Maine. (b) Fukushima Hamakaze/Advanced Spar, courtesy of Japan Marine United Corp. (c) Eolink, courtesy of Eolink. (d) SATH, courtesy of Saitec. (e) TetraSpar, courtesy of Stiesdal. (f) Fuyao, courtesy of CSSC Haizhuang Windpower. (g) Nezzy2, courtesy of aerodyn engineering gmbh/EnBW Energie Baden-Württemberg AG. (h) Floating Power Plant, courtesy of Floating Power Plant A/S. Note that these figures have been computer generated to show the design of the platform.

shown in yellow is above the mean water surface line. The three columns, heave plates and trusses are visible, as well as the turbine connector on the top of the left column.

There are future projects planned with this platform, including Les Eoliennes Flottantes du Golfe du Lion (France, 30 MW, 2023), Korea Floating Wind (South Korea, 1000 MW, 2026), Redwood Coast Offshore Wind Project (USA, 100–150 MW, 2026), and Erabus (UK, 96 MW, 2027) [30].

4. Platform designs with a live or decommissioned demonstration or prototype project

Platform designs which currently have a demonstration or prototype project, or had one that has now been decommissioned, are detailed in Appendix. These 20 platform designs are summarized in Table 4. Note that the table presents the demonstration/prototype scale wind turbine capacity, the material and mooring used in the project, and the water depth at the site of the demonstrator/prototype. Full-scale capacity, material options, water depth limits and mooring designs are discussed in Appendix. Fig. 2 shows a timeline of the projects, with information about their location and turbine rating. Fig. 7 shows eight of these platform designs. Section 5 will summarize the platforms' evolutions and compare the platforms.

5. Discussion

In this section, the evolution of FOWT platform designs, the dominant design goals, and the resulting features are summarized and discussed. The discussion is broken into three themes, broadly as follows. (i) Reviewing the timeline of FOWT development, it is clear that the focus of early designs was predominantly on platform stability, using experience from the oil and gas industry. (ii) Subsequently, driven by the need to reduce costs while maintaining stability, designs specialized towards floating wind have evolved. (iii) Most recently, developers are taking a holistic view of the local environment, including aspects such as local economy, infrastructure, and particular marine environment, leading to further specialization.

It is important to note that floating offshore wind is a rapidly developing sector, and this review can only provide a snapshot of the state-of-the-art. Promising technologies and important factors now could change if a particular platform is given significant capital investment to develop the ability to be mass-produced. Furthermore, there are many other aspects of floating offshore wind that are not discussed in this review, such as dynamic power cables, installation methods, operation and maintenance, control systems, radar, marine life impact, and structural design. These aspects affect the platform design and are affected by platform design, and to build a better floating offshore wind industry, these different areas must all be considered. To this end, this review can serve as a resource for academic researchers, industry players and policy makers to understand the current state-of-the-art of platform designs.

5.1. *Influences from oil and gas platforms*

The first FOWT prototypes and demonstrators were developed by directly applying experience gained from the oil and gas industry to the floating offshore wind industry. This natural starting point arose from the common goal of reducing platform motions. For example, the first FOWT prototype, the Blue H TLP, was an oil and gas platform design upon which a wind turbine was mounted [35,36]. Following this, the Hywind Spar [4], WindFloat [25] and SWAY [4] platforms have all been developed by companies in the oil and gas industry. Furthermore, many platforms which did not originate from an oil and gas background have used these early designs as 'standards', giving them an initial point from which to develop and subsequently optimize, rather than starting from completely new designs. The VolturnUS platform, shown in Fig. 7(a), is an example of this, having evolved from its predecessor, the OC4/DeepCWind Semi, which was developed as a reference standard semi-sub at the time [106].

5.2. *Specialization of platforms to floating wind and co-evolution of platforms and turbines*

As floating wind has developed, platform designs have begun to diverge from their oil- and gas-based predecessors, with the emergence

Table 4
Platform designs with a live or decommissioned prototype/demonstration project.

Platform name	Years active	Technology developer	Type	WTG rating for demonstrator (MW)	Material	Water depth (m)	Mooring	Other use	References
Blue H	2007–2008	Blue H Engineering	TLP	0.08	steel	113	taut	N/A	[35,36]
SWAY	2011	Inocean	spar-TLP	0.007	steel	25	tension rod	N/A	[4,37,38]
DeepWind Spar	2011	DeepWind Consortium	spar	0.001	steel	4	3 catenary lines	N/A	[5,17,39–47]
Hybrid Spar	2012–2013, 2013–2015	Toda corporation	spar	2,0.001	steel and concrete	100	3 catenary lines (steel chains, 2 equipped with clump weights)	N/A	[4,48–57]
VolturnUS/VolturnUS-S	2013–2014	New England Aqua Ventus/University of Maine	semi-sub	0.02	concrete	45	3 chain catenary lines	N/A	[58–64]
Fukushima Mirai	2013–2021	Mitsuit Engineering and Shipbuilding Co., Ltd.	semi-sub	2	steel	120	6 chain catenary (diameter 132 mm)	N/A	[65–68]
Spinwind	2013–2014	Gwind	spar	0.001				N/A	[39,69,70]
SeaTwirl S1	2015	SeaTwirl	spar	0.03	steel	35		N/A	[17,39,71–73]
Fukushima Shinpu	2015–2018	Mitsubishi Heavy Industries	semi-sub	7	steel	120	8 chain catenary lines	N/A	[66–68,74]
Fukushima Hamakaze (Advanced Spar)	2016–2021	Japan Marine United Corp.	spar	5	steel	120	6 line chain catenary (diameter 132 mm)	N/A	[67,68,75–78]
Damping Pool	2018-present	BW Ideol	barge	2,3	steel or concrete	28	chain or nylon catenary lines	N/A	[79–82]
Eolink	2018–2019	Eolink	semi-sub	0.2	steel	35	3 synthetic lines to single point mooring	N/A	[83–85]
SATH	2020	Saitec	barge	0.03	concrete		3 catenary lines to single point mooring	N/A	[86–90]
TetraSpar	2021-present	Stiesdal	spar	3.6	steel	120	3 catenary lines (chain and synthetic rope and clump weights)	N/A	[91–93]
China Three Gorges	2021–2021	China Three Gorges	semi-sub	5.5				N/A	[94]
Fuyao	2022-present	CSSC Haizhuang Wind Power	semi-sub	6.2		50	6 catenary lines	N/A	[95,96]
W2Power	2019	Enerocean	semi-sub	2 x 0.1	steel		catenary	N/A	[97–100]
Nezzy2	2020	EnBW	semi-sub	2 x 0.1	concrete		6 catenary lines	N/A	[101]
FPP	2010, 2012–2013	Floating Power Plant	semi-sub	3 x 0.011		7	catenary lines to a single-point mooring	10 x 14 kW WECs (flap-type)	[102–104]
Hakata Bay Scale Pilot Wind Lens	2012–2013	Kyushu University	semi-sub	2 x 0.02	concrete			solar PV	[105]

of specialized design goals and their corresponding features. Examples of these features are active ballast (used for WindFloat [24], Advanced Spar [75], shown in Fig. 7(b), and Eolink [83], shown in Fig. 7(c)), the use of heave plates (WindFloat [22], Fukushimma Mirai [65]) or pontoons (VolturnUS [59], Fukushima Shinpu [74], Fuyao [95], shown in Fig. 7(f)) instead of continuous flat plates, and using single-point mooring (Eolink [83], Floating Power Plant [102], shown in Fig. 7(h), SATH [90], shown in Fig. 7(d), W2Power [100]) to weathervane the system. These features have largely arisen due to the fact that the forces on FOWTs differ substantially from those experienced by oil and gas platforms, due to a considerable increase in pitch moments, a high center of gravity, and a smaller payload. Furthermore, cost reduction is a much stronger driver in FOWT designs than for oil and gas platforms and has therefore heavily influenced FOWT designs.

Though some platforms have been designed to be suitable for any conventional turbine (*e.g.*, WindFloat [4], Advanced Spar [75]), other platform developers have opted to modify the standard turbine control and design for enhanced suitability with their platform. For platforms such as Hywind [20] and VolturnUS [59], developers have upgraded floating-specific blade pitch control algorithms for the wind turbine simultaneously with designing their platform. This synchronized development of both platform and turbine enables further optimization, since the platform need not be designed to overcome the negative damping above rated wind speed associated with standard blade pitch control. Other platforms have varied even further from conventional land-based/fixed turbines. Designing platforms to hold VAWTs (*e.g.*, DeepWind [107], Spinwind [69], SeaTwirl [108]) was a popular area of research in the period 2010–2015, due to the benefits of a lower center of gravity and a lower generator height to lessen maintenance difficulties, compared to a HAWT. While there have been no further at-sea prototypes or demonstrators of floating VAWTs, interest for the applicability of VAWTs for offshore wind is still prevalent, as evidenced by the recent X-ROTOR project [109].

DampingPool [79] and Floating Power Plant [103] use two-bladed turbines, which may be better for floating applications due to being lighter and easier to install with a crane. While the majority of designs still use a traditional tower to connect the platform to the turbine nacelle, some developers have opted for specialized tower designs integrated with their platforms. For example, Eolink uses four masts to enable the installation of larger turbines by allowing for more flexibility in the blades [83]. SWAY [37] and Nezzy2 [110], shown in Fig. 7(g), designed their tower to be streamlined to reduce loads, enabled by their weathervaning systems.

5.3. Further specialization to local environment

As evidenced by the wide range of platform designs and their emergence and evolution over time, there has not been a convergence in FOWT platform designs. Rather, platforms have diverged to give a higher degree of specialization to particular environments. This trend is widely observed and extends beyond the turbine operation, covering specialization to the relevant economy, the particular marine environment, and the available port characteristics.

On the construction side, driven by a desire to use local materials, there has been a noticeable increase in use of concrete for the platform structure. Hywind and WindFloat both use steel in their current farm scale platform designs, but Hywind is moving to a concrete-based platform in their upcoming farm, Hywind Tampen [21]. SATH has been developed specifically for ease of manufacturing in concrete [86]. DampingPool [80] and VolturnUS [111] have two distinct platforms, one made from steel and one from concrete. These two design options enable the use of local content and increase the degree of local manufacturability in different countries (*e.g.*, concrete is cheaper and more prevalent in Europe, whereas steel is considered more cost-effective in Asia).

Environmental characteristics, for example water depth, at the location of installation also impact the platform designs. There are many locations where fixed wind is uneconomic and/or technologically unfeasible but where spar platforms would be too deep when supporting a large (10 MW+) turbine. This is often the case with water depths in the range 40–100 m which are common for potential locations in the UK, France, and the east coast of USA. Therefore, with the trend towards larger turbines, it is likely that spars will not be suitable in these locations and hence shallower platform designs are emerging (TLP, semi-sub and barge). However, there are other locations (*e.g.*, Norway, west coast of USA, Japan) where water depth is large enough to allow for spars. Mooring also greatly depends on location as it is strongly influenced by the seabed conditions and water depth (*e.g.*, DampingPool uses different mooring systems in their two locations of their demonstrators [81]). Due to difficulties associated with tensioned mooring lines, areas where there is a large tidal range will likely not favor TLPs. Furthermore, wind and wave characteristics impact the optimal design for a location. For example, there are an increasing number of platforms (Eolink [83], Floating Power Plant [102], SATH [90], W2Power [100]) that employ single-point mooring systems to weathervane the system to face prevailing winds. However, if a location is prone to wind-wave misalignment, there may be stability issues that must be considered in the design.

Another example of specialization to a particular location is an increased influence from port requirements, especially as wind turbine sizes increase. Standard ports are shallow, which precludes deep spars to be built unless they are towed horizontally. Some locations, for example Norway, have sheltered deep-water fjords where a spar can be towed to upend it and install the turbine; hence spars continue to be popular there. For most locations, however, the turbine must be installed at the port. Sergiienko et al. [112] has shown that for platforms holding larger turbines, their width dimensions increase with increasing turbine size, but their draft does not (*e.g.*, VolturnUS). The reason for this trend is most likely a combination of stabilization and port requirements. The Tetraspar, shown in Fig. 7(e), deployed off the coast of Norway, enables the devices to be installed at a standard port but still take advantage of spar stabilization techniques in deep water [92]. Furthermore, some platforms (WindFloat [25], Shinpu [74], DampingPool [81], Fuyao [95]) have their turbine on the side of the platform, rather than at the center, reducing the distances in crane-based installations. This trend is particularly important as turbines get larger, but this configuration does add challenges with stability. It seems likely that these location-specific drivers may continue to be the main influence on platform designs going forward.

5.4. Potential design drivers in future

Into the future, there are a number of other themes which have the potential to have a major influence on FOWT platform designs. Co-location of platforms with energy storage mechanisms has been identified [113] as a potentially important driver (*i.e.*, batteries, electrolysers for hydrogen, or storage facilities for thermo-mechanical energy storage). Operation and maintenance (O&M) accounts for 30% of life-cycle costs for floating offshore wind [32]. Therefore, this may become a major design driver, particularly since increased standardization tends to decrease the costs associated with O&M. Furthermore, O&M safety has the potential to be highly influential.

6. Conclusion

This paper reviews floating offshore wind turbine (FOWT) platform designs which currently have or have previously had a prototype, demonstration, or farm scale device at sea. The common design goals and corresponding features of platforms used to achieve those goals are reviewed. Levelized cost of energy values for FOWTs are reviewed and discussed, including projected decreases in cost per MWh in the near future due to size of turbines, scale of farms, maturity of the technology, and improvements in operation and maintenance. Farm-scale and prototype-/demonstration- scale devices are reviewed, and evolution of design goals and features are explained. Finally, trends in design drivers and resulting platform designs are explained. There are strong influences from the oil and gas industry, which are evident in early FOWT designs. Specialization to the floating offshore wind industry has driven evolution and the emergence of features unique to floating offshore wind. Finally, further specialization to particular local environments have resulted in a wide range of platform designs.

There are two platform designs that have reached farm-scale deployment: Hywind Spar, a cylindrical spar platform, and WindFloat, a three-column semi-sub. Three-column semi-subs are clearly a promising design direction for the industry, evidenced by the fact that eight of the 22 platforms which have reached at-sea deployment are of this design. There have also been four additional cylindrical spars, in addition to the Hywind spar, though most of the spar designs that have been designed recently have not been traditional cylinders but rather had lowerable ballast or been advanced spars, using more than one stability mechanism. There has also been an emergence recently of more innovative platforms which diverge from these two traditional platform types. Examples include SATH, DampingPool, TetraSpar and Eolink, which include features such as horizontal weathervaning about a single-point mooring to increase the efficiency of the turbine and avoid the need for active yaw control, a moonpool to suppress wave-induced motion, a lowerable ballast to enable spar stability mechanisms but still have the ability to be erected at port, and multiple masts instead of a single tower to use less steel and allow for larger blades.

These innovative platform designs show that there has been a divergence in platform design recently. This divergence is a result of platform developers aiming to lower cost by specializing their platform to a particular environment, enabling their platform to be adaptable to multiple locations, or relying on a novel, innovative feature which allows the platform to be smaller and/or cheaper while still adhering to stability requirements. While there may be different designs better suited for particular locations, and a single solution may not be optimal for the entire industry, the wide range of designs being tested at sea, particularly recently, suggests that more research in this sector can further reduce costs and improve performance. The information in this review can be used by policy-makers to establish sufficient government support is given to ensuring the continuation of advancement for this technology. Furthermore, industry and academic researchers can use this summary of the state-of-the-art to focus their research, including research on structural designs, port infrastructure, installation methods, wind turbine farm design, and marine life impacts.

Overall, FOWT platform technology has advanced considerably in a short space of time and is strongly positioned for the further progress required to meet targets in the next 7–30 years. Moving forward, it is likely that the (sometimes competing) objectives of further standardization (*e.g.*, to ease towing and O&M requirements, ensure safety considerations are met, and standardize supply chains) and further specialization (*e.g.*, to optimize a solution to a particular environment and best match local supply chain) will continue to be influential to the design space, and compromises will need to be reached. There are likely to be other design drivers emerging, such as co-location with energy storage. FOWT platforms that do not fit into one of the four traditional types of floating platform, multi-turbine platforms, hybrid (multi-use) platforms, and platform which accommodate multi-mast turbines all have promising advantages and thus are likely to be explored more in future.

This review includes only those platforms that have reached at-sea deployment, but to understand more about the evolution of and, in particular, the future of the industry, trends in early concept devices must be explored as well. Therefore, in a further review, platforms at an earlier stage of development will be reviewed and discussed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix. Detailed description of platform designs with a live or decommissioned demonstration or prototype project

In this appendix, platform designs which currently have a demonstration- or prototype-scale system, or had one that has now been decommissioned, are detailed. Appendix A.1 presents the platforms designed for a single turbine; Appendix A.2 presents those designed for multiple turbines; and Appendix A.3 presents the hybrid platforms. Within each of the sections, the platforms are ordered by the year that their first prototype/demonstrator was installed. For some of the decommissioned platforms, future development of the platform is unclear or unlikely, which is clarified, if possible, from publicly available information.

A.1. Single turbine platforms

A.1.1. Blue H

The Blue H prototype was the first floating wind turbine [36]. A disconnected 80 kW turbine was mounted on a TLP platform which had been developed for the oil and gas industry [35]. The location of the prototype was 22 km off the coast of Italy, where the water depth was 113 m. The project ran from the end of 2007 to the end of 2008. After this prototype, the company changed their design to a ‘self-installing TLP’ with lowerable gravity anchors, but there has been no news on the platform for a few years [35].

A.1.2. SWAY

The SWAY platform consists of a spar with a tension rod connected to a gravity platform, originally designed for the oil and gas sector in the North Sea for depths of 100–400 m. The design goals of the platform were to limit maximum pitch in operating conditions to be 8° and maximum pitch for the 100-year storm to be 15° [4]. A downwind turbine is used, with ‘spreader beams’ attached to the tower and tension cables attached from the top of the tower to the bottom of the underwater structure. This setup allows the structure to weathervane, enabling an aerodynamically-streamlined profile to be used for the tower. Furthermore, using a downwind turbine enables the rotor to tilt in a more optimal way for maximum alignment with the wind, meaning that the structure can be smaller for a given size turbine because the blades will not hit the tower. The spreader beams and tension cables stiffen the tower and reduce fatigue loads [4,37]. The full size platform is designed to hold turbines with rated power 2.5–10 MW [37], and the draft for a platform holding a 5–7 MW turbine would be 60–80 m. Stability is achieved by ballasting in the spar and the tension rod fixed to the seabed [4].

In 2007, 1:45 scale model tests of a 5 MW system were performed at MARIN [4]. In March 2011, a 1:6.5 scale prototype was built and deployed off the coast of Norway until the end of that year. The water depth of the location was 25 m, the draft of the spar was 16 m, and a 7 kW turbine was used. In December 2011, the prototype was hit with a wave height which scaled-up exceeded 40 m. This was outside the design conditions and the tower flooded. The prototype was redeployed in 2012 until Autumn 2013. The aim of the prototype was to demonstrate and verify tower motions, stability, downwind rotor, yaw bearing, yaw control and individual blade pitch control [4]. There has been no news since 2016 on this platform.

A.1.3. DeepWind Spar

The DeepWind Consortium, with lead partner DTU in Denmark, consisted of industries and universities with the aim to develop a novel 5 MW floating vertical axis wind turbine (VAWT) platform [39]. The structure consists of a floating continuous cylindrical body that spins with the VAWT.

The design requirements for the platform are to ensure that (i) heave, pitch and roll periods are above the energetic wave period range, (ii) Mathieu instability is unlikely, (iii) there is enough buoyancy for the mass of the payload and mooring, (iv) there is enough stability to limit the pitch angle to 15° [107], and (v) acceleration of the nacelle is limited [40]. The diameter of the cylinder at the waterline is smaller than the diameter below the surface to decrease wave loads on the structure and ensure that the heave resonance period is above the energy wave period range [40]. The spar has a draft of 107 m and maximum diameter of 8.3 m [107]. The VAWT blades are designed to reduce the gravitational loads [107]. The design goal of the mooring system is to ensure that the restoring force is sufficient to balance the yaw moment caused by the rotating structure [40,43]. Challenges identified for this design included submerging the generator at a significant water depth and designing the mooring to withstand significant torque [41]. Furthermore, compared to a reference spar (OC3) holding a HAWT of the same capacity, the power variation increases more with wind speed for this system [43].

An experimental campaign of a 1 kW three-bladed VAWT was performed in a wind tunnel to look at the sensitivity of the VAWT’s performance to tilting, and it was found that efficiency does decrease as it tilts [39,114]. The full structure, using the 1 kW VAWT, was tested at the Maritime Research Institute in the Netherlands, and it was found that viscous drag from the rotating spar underwater decreases the power output [39]. The 1 kW system was tested in the Roskilde Fjord in Denmark. During this test period, the configuration was changed so that the rotor could only move in three degrees of freedom, and seawater ballast was added to the spar. This change resulted in the whole system lowering so that, in case of high wind when the system tilts excessively, the blades hit the water and thus slow down, avoiding the most extreme tilting [47]. There has been no news on developments of this platform since this prototype.

A.1.4. Hybrid Spar

The Hybrid Spar by Toda corporation, also called the Goto Island Project, is so-called ‘hybrid’ because it includes a section of concrete and a section of steel. The platform is a cylindrical spar of varying diameter, with the upper section made of steel and the lower section made of concrete. Concrete is used for the platform to lower the center of gravity and decrease costs. Seawater and ballasting solids are also added to the bottom of the spar to aid in lowering the center of gravity. The mooring system consists of three catenary lines, with two on the weather-side which also have clump weights. The platform design development started in 2008, and the platform design has undergone four iterations and several experimental campaigns.

As a first step in the platform development, 1:100 scale model tests of a 2 MW system were done in 2008 for (i) a simple cylindrical floater and (ii) a ‘stepped’ cylindrical floater, with a cylinder of smaller radius at the waterline on top of a cylinder with a larger radius below. It was concluded that a stepped spar would be more suitable for a FOWT [4].

The second iteration of the design consisted of a cylinder with three sections: the top section of diameter 4.8 m, located at the waterline and above and made of steel, the middle section of diameter 8.4 m, located below the waterline and made of steel, and the lowest section of diameter 12 m and height 8 m, located at the base and made of concrete. The design also included a ‘motion suppressing device’ just below the waterline, consisting of four vertical flat plates protruding radially from the spar, to suppress motion in yaw, with perpendicular plates at the ends of each plate to suppress motion in surge, sway, roll and pitch. 1:22.5 scale model tests were performed of the 2 MW system at the National Maritime Research Institute. It was concluded that the motion suppression device was unsuccessful in reducing body motion [49].

The third iteration of the design returned to just two diameters, but still made of the two materials. The upper cylinder with smaller diameter was made from steel. The lower cylinder with larger diameter was made of three sections: a hollow section where the shell was made from steel, a hollow section where the shell was made of prestressed concrete (PC), and a section made of solid concrete at the bottom. A 1 kW wind turbine was installed on a 1:10 scale prototype of the 2 MW system and tested at sea. The goal of the at-sea testing was to demonstrate construction, towing and installation, generation of electricity, and removal of the platform [4,56].

The fourth iteration of the design consisted of two cylinders (still with the smaller diameter at the waterline and larger diameter below) with a sloped interface connecting the two sections. Four long vertical fins were added to the lower half of the bottom cylinder to suppress yaw motion. 1:34.5 scale model tests were performed, with a focus on mooring line tension to ensure it would not snap in extreme storm conditions [55].

This design remained for the 1:2 scale prototype of the 2 MW system, which was installed in 2012 in southern Japan. A 100 kW Subaru turbine was used but the maximum power was altered to 30 kW, to increase the time where wind speed was above-rated, to test blade pitch control. The platform survived a severe typhoon (wave height 9.5 m, wind speed 36.8 m/s), and no negative damping was observed from the control strategy used in the turbine [4,50].

Finally the full-size demonstrator, called Haenkaze, was installed in 2013 off the coast of Nagasaki, Japan. A 2 MW downwind Hitachi turbine is installed on the platform [54], which has a draft of 75 m, diameter at the waterline of 4.8 m, and a diameter of the lower section of 7.8 m [48]. The design remains the same as the 1:2 scale prototype, except that the fins have been removed. The demonstrator has survived a typhoon with maximum wind speed 52.2 m/s and maximum significant wave height 6.9 m [57]. In 2015 the demonstrator was moved to Sakiyama Fuke Island. There are plans to use this platform design for the Goto Pilot Farm Project, using eight 2.1 MW Hitachi turbines, to be installed in 2024. Further research is also being done to develop the platform for use with larger turbines.

A.1.5. VolturnUS/VolturnUS-S

The VolturnUS/VolturnUS-S, shown in Fig. 7(a), is a semi-sub with three outer columns and a central column holding the tower and turbine. The concrete platform is called the VolturnUS, and the steel version is called the VolturnUS-S. The platform design has undergone several iterations.

The platform design development started with the OC4-DeepCWind consortium, made up of 30 members including universities, national labs, and companies, with the aim to study FOWTs, get experimental data and validate numerical models. The consortium developed reference platforms for each type (spar, semi-sub, and TLP) for a 5 MW turbine [62]. The design goals for these platforms were to (i) have sufficient positive buoyancy and restoring stiffness to stabilize the body when excited by wind and/or waves, (ii) ensure that the natural periods of the platform were outside the range of energetic wave periods (4–20 s period) and (iii) ensure that the natural periods of the platform did not correspond to the 1P and 3P periods of the wind turbine [62]. Each platform was designed to be a ‘generic’ version of the type of platform. The semi-sub had three outer columns with heave plates at the bottom of each, with a narrower column in the middle to hold the turbine and tower. The four columns were connected with braces, and the total draft of the device was 30 m. The outer columns were 28.87 m from central column and had diameter 12 m with heave plates of 24 m diameter and 6 m height. Ballast water was in each of the outer columns [106]. In 2011, a 1:50 scale test of the 5 MW system was performed at MARIN [106].

The University of Maine (the lead university of the DeepCWind consortium) used information from the DeepCWind consortium and resulting tests to develop the VolturnUS platform, a concrete semi-sub. In 2013, 1:50 scale model tests of a 5 MW VolturnUS system were performed [64]. From 2013–2014 during an 18-month period, a 1:8 scale prototype of their 6 MW system was deployed off the coast of Maine (USA) and was the first offshore wind turbine in the US [58]. The platform consisted of three outer rectangular columns connected on the bottom by pontoons, at the top by beams, and by a brace to the central column holding the tower and a 20 kW turbine [61]. The 20 kW turbine was chosen to correctly scale the aerodynamic force. The goals of this intermediate-scale prototype were to test the manufacturing of concrete, validate numerical modeling, and test deployment, installation, and instrumentation [60,61]. The platform was built dock-side and towed at shallow draft. The site was chosen for high probability of scaled sea states of interest being realized in a short time, and indeed numerous storm events did occur during this 18-month period, including a scaled 500-year wave, with a scaled wave height of 20.8 m [60].

The platform design was updated, and 1:52 scale model tests of the 6 MW system were performed in the W2 facility at the University of Maine [64]. In July 2020, the VolturnUS-S reference platform specifications were released. This platform is an open-source steel version of the VolturnUS platform. The platform consists of three cylindrical columns connected at the bottom by pontoons, and at the top by thin beams, to a central column holding the tower and 15 MW turbine. The outer columns have diameter 12.5 m and are 51.75 m from the central column, which has a diameter of 10 m. The structure’s draft is 20 m [59]. There is a planned demonstrator, called the New England Aqua Ventus I, that will be an 11 MW turbine on the VolturnUS concrete platform [111]. Subsequently, the plan is to build a research array farm with 50–200 MW capacity [58].

A.1.6. Fukushima Mirai

The Fukushima FORWARD Wind Farm Demonstration Project was a consortium involving industries and the University of Tokyo, and three demonstration projects were deployed near Fukushima, Japan, 20 km from the shore at a water depth of 120 m [66,68]. The first design installed was the 2 MW Fukushima Mirai in November 2013 [65,66]. The platform is a semi-sub with three outer columns with heave plates, connected via pontoons, braces and upper-deck beams to a central column which holds the tower and turbine [65]. The design goals for the platform were to develop a compact semi-sub and to minimize platform motions using turbine controls and ballast [68]. The platform is 64.2 m wide with a 16 m draft [65], held in place by a 6-line catenary mooring made of 132 mm diameter chains. Before deployment, a 1:60 scale model was tested in the Akishima lab [65]. It was decided in 2021 that the platform and project would be dismantled as it was not profitable enough to continue [67].

A.1.7. Spinwind

Spinwind is a gyro-stabilized VAWT on a spar buoy with a heave plate [39]. The platform design underwent tank testing at the Stadt Towing Tank in 2013 [69], and later that year a prototype was launched off the coast of Norway [70]. There has been no news since the launch, and the website is now offline.

A.1.8. SeaTwirl

The SeaTwirl platform is a spar buoy holding a VAWT. The buoy and turbine spin together, with a generator housing above the surface with three mooring lines attached [71]. The platform is currently using steel as the material but future designs may use concrete [17,108].

In 2015, a 30 kW prototype, called S1, was deployed in West Sweden and has since been generating electricity to the grid. The prototype extends 13 m above the sea surface and has an 18 m draft [108]. A 1 MW system, called S2x, is scheduled for completion in 2023. The device will extend 55 m above the sea surface and have an 80 m draft. It has been designed for extreme wind speeds up to 50 m/s and is being targeted at niche markets: remote islands and coastal regions, marine aquaculture farms, and to be integrated with offshore oil and gas platforms [71].

A.1.9. Fukushima Shinpu

The second platform as part of the Fukushima FORWARD was the 7 MW Fukushima Shinpu, installed in September 2015 [66,67,74]. The platform, developed by Mitsubishi Heavy Industries, is a semi-sub with three rectangular columns with a V-shape pontoon structure, with the tower and turbine connected to the column at the base of the V. The design goals were to make sure the platform was self-stable and that the construction could be done in Japan with a simple shape that could be mass-produced. Other aspects that the developers thought about were maintenance, critical failures, response in waves, and crane capacity to install the turbine. To minimize platform motions, a motion reduction device called ‘MS-Board’ is installed at the base of each column. The columns are each 14 m wide, the pontoons are 106 m long, and the draft of the structure is 17 m [74]. The mooring system consists of eight chain catenary lines [66,68]. Before deployment, 1:64 scale model tests were done in the Seakeeping & Maneuvering Basin [74], and it was found that using the MS-Board shifted the pitch natural period higher. Wind tunnel tests were also performed [74]. It was decided in 2018 that it would be dismantled due to low availability and expensive operation and maintenance costs [67].

A.1.10. Fukushima Hamakaze/Advanced Spar

The final platform as part of the Fukushima FORWARD was the 5 MW Fukushima Hamakaze (also called the Advanced Spar), installed in July 2016 [75]. This platform, shown in Fig. 7(b), is a spar, but instead of one continuous hull, it is separated into multiple discrete hulls. The platform has undergone two design iterations. The design goals for this platform were to (i) reduce material, (ii) enable the structure to stand on its own at the port, (iii) have a small enough diameter/width to be constructed at a normal port, (iv) enable the platform to be towed in the upright position, (v) be able to support 2–10 MW turbines, (vi) have small pitch motion, (vii) have a small draft, making construction, transportation and installation possible for more ports (note: the operating draft was 39 m), and (viii) have low impact to the environment and ocean life [75].

The first design iteration was made up of three hulls: one at the waterline, and two submerged beneath it. The purpose of the hull located at the waterline was to suppress heave motion at low wave frequencies. The middle hull’s purpose was to raise the center of buoyancy and to attach the mooring. The mooring consisted of four catenary lines, and because the middle hull was wider than the highest hull, connecting to the middle enabled more yaw motion suppression. The lower hull’s purpose was to lower the center of gravity, and it also included motion suppression fins to decrease pitch and yaw motion, especially in low frequency motion. There was also an active ballast system to move water between the hulls. This platform’s natural periods were well above the wave excitation periods, and high viscous damping forces helped to overcome the negative damping force from the wind turbine above the rated wind speed [75].

The platform design changed between 2013–2015 to the current design, which includes just two hulls: one at the waterline and one submerged. This change was implemented to make construction easier and improve motion performance [78]. The goal of the redesign was to reduce the load in the tower base [77]. The upper hull is wider to increase the waterplane area, with a wider plate attached under the water surface to increase viscous forces. The mooring system consists of six catenary lines, made of 132 mm diameter chains, which are attached to the widest section of the top hull to increase yaw motion suppression. The operating draft is 33 m, and the width of the structure is 51 m [77]. The demonstrator was installed from 2016–2021, when it was decided that the demonstrator would be dismantled due to low capacity factor. The Fukushima FORWARD project also developed a floating substation structure (Fukushima Kizuna) [66].

A.1.11. DampingPool

DampingPool by Ideol is a square barge with a moonpool in the center. The stabilization in pitch is achieved by a large waterplane area, with most of the area far from the centerline. Wave excitation is damped by the moonpool, as well as a horizontal skirt at the base of the platform [81]. The shape of the hull was chosen for ease of manufacturing (large flat plates on every side). Mooring and cable connections are above the sea surface so that no diving is required to connect these cables. Mooring material and layout depend on the location of operation: intermediate depths favor chain-only mooring systems, and shallower depths favor mixed cable and chain systems, but polyester mooring systems are best if wave conditions are high. In shallow water polyester mooring systems need buoys along the lines to prevent seabed chafing [81].

Ideol have designed two similar but distinct platforms: one using concrete and one using steel [80]. Several model tests were performed in the lab, including combined wind-wave conditions [81]. It was also determined that micro-cracks that occur in concrete remain sufficiently small as to not let water through or corrode [81].

There are two demonstrators in operation (one of each material). Floatgen is a concrete demonstrator 22 km off the coast of France in water depth of 33 m, which has been in operation since 2018. It holds a 2 MW Vestas turbine, and in the month of February 2020 the capacity factor reached more than 66% and survived wave heights of 11 m. Concrete is used to enable use of local content, and chain mooring is used [82].

Hibiki is the other demonstrator of the DampingPool. It has been in operation since 2018 and off the coast of Kitakyushu, Japan, at a water depth of 55 m. It is made of steel with nylon mooring. It holds a 3 MW two-bladed turbine and has survived three super-typhoons just after installation. It has a draft of 7.5 m and a width of 36 m [79].

The platform holding a 10–12 MW turbine will be 55 m long. Future projects using this platform design include Eolmed (France, 30 MW, 2024), Scotwind (UK, 940 MW), and South Brittany (France, 240–270 MW) [79].

A.1.12. Eolink

The Eolink platform, shown in Fig. 7(c), is a semi-sub with four vertical cylindrical columns, connected at the base with four horizontal pontoons forming a square and at the top with beams forming a square. Instead of a singular tower to hold the wind turbine nacelle, a pyramid structure is used, whereby four masts connect each corner of the platform to the nacelle. The developer claims that this configuration uses 30% less steel than other semi-sub platforms with three columns and a single tower, by distributing forces more evenly throughout the structure. Using four columns instead of three reduces the length and width dimensions of the platform by 20%. Using four masts instead of a single tower enables the use of more flexible blades because of the increased space between the blades and tower. The developers claim that the flexibility of the blades results in blades being able to be longer without increasing the mass, resulting in a 6%–11% increase in energy extracted. Furthermore, it enables larger turbines (20 MW), with the 1P and 3P frequencies far from the platform and tower natural frequencies. The towing draft is 3 m and the operating draft is 15 m for the 15 MW system, and a single-point mooring system is used so that the turbine weathervanes. If wind and current are misaligned, a dynamic ballast system is used to orient the wind turbine up to 120° [83].

In 2016 a 1:50 scale model of a 12 MW system was tested in the IFREMER tank, with regular and irregular waves with aligned and orthogonal wind [83,85]. In 2018, a 1:10 prototype of a 12 MW system was deployed and connected off the coast of France. Two testing periods were performed in 2018 and 2019. During these tests, the prototype withstood scaled 63 m/s wind and wave elevation of 8 m. Furthermore, the single-point mooring system was tested to ensure it can withstand tidal forces [83,84]. A 5 MW demonstration project (3:4 scale of a 12 MW system) is planned to be installed at the SEM-REV site in France in 2022 [83].

A.1.13. SATH

The SATH (Swinging Around Twin Hull) platform by Saitec, shown in Fig. 7(d), is a unique platform which consists of two horizontal cylindrical stability hulls with a flat heave plate below. This platform is an example of a platform which does not definitively fit into one of the four traditional 'types' of floating platform. A frame connects the two hulls above the sea surface and extends upwind of the turbine to connect to a single-point mooring system [90]. This platform was designed based on the need to build a platform using concrete [86].

In August 2020, a 1:6 prototype of the 10 MW system, called Blue-SATH, was installed off the coast of Spain [86]. The system consisted of a 30 kW wind turbine [90]. The prototype completed its testing campaign and survived what it was rated for (up to a scaled-up 30 m wave), but capsized during a hurricane, when a scaled-up 60 m wave hit in November 2020 [89].

In 2021, a 1:49 scale model of the 10 MW system was tested in the Deep Ocean Basin in the Lir National Ocean TF [87]. A 2 MW demonstrator is being built, called DemoSATH, off the coast of the Basque Country, Spain, and is expected to be deployed and connected in 2022. It is being installed 2 miles off the coast at a water depth of 85 m, and the plan is to test the platform over two years [90]. Further plans for this platform include GEROA (45 MW, Spain, 2025), Medfloat (50 MW, Spain, 2025), and CADEMO (60 MW, California) [90].

A.1.14. TetraSpar

The TetraSpar is a spar platform by Stiesdal, shown in Fig. 7(e). The platform achieves a low center of gravity by a suspended keel, which is only suspended once the platform reaches its location of installation. This configuration enables the tower and turbine to be installed at the port, and the whole platform to be towed out with the keel attached to the base of the upper hull, avoiding the need for a floating crane or a deep dock. The platform uses a modular arrangement, with just 4–5 types of braces. The design goal is to use modules that have dimensions no larger/heavier than a wind turbine tower so that the foundation is no more difficult to deliver than the turbine itself. Furthermore, nodes are used to connect steel modules to avoid welding at the port [91,92].

1:43 scale model tests were completed before building the demonstrator, to confirm that there was no slack line events in the lines between the keel and the upper hull in 50-year and 2000-year load conditions [92].

The demonstrator was towed to test site and fully commissioned in 2021 at the Marine Energy Test Centre, 10 km off Norway. The platform holds a 3.6 MW Siemens turbine. The keel is suspended 50 m below the floating platform with six taut lines. The upper hull and keel have an unballasted draft of 8–10 m, before water is added to the keel at the final location. There is catenary mooring connected to radial braces which is made of synthetic rope and chain with clump weights [91,92].

A.1.15. China Three Gorges

China Three Gorges (CTG) installed a 5.5 MW demonstrator floating wind platform in July 2021 off the coast of Yangjiang City, China for a 6-month trial. Little is published about the platform or its performance over the intended test period. The wind turbine used is the 'MySE5.5MW' 'typhoon-resistant' turbine by MingYang Smart Energy [94].

A.1.16. Fuyao

Fuyao, shown in Fig. 7(f), is a three cylindrical-column semi-sub developed by CSCC-Haizhuang Wind Power, connected to each other at the bottom via pontoons in a triangle and at the top with beams in a triangle. The tower and turbine are connected to one of the columns, and the mooring consists of six catenary lines, two connected to each of the three columns [95].

Scale model tests were completed (at undisclosed scale) [95], and the demonstrator was installed in May 2022 off the coast of the island of Luodousha, China. The wind turbine is a 6.2 MW 'typhoon-resistant' turbine. For the 6.2 MW system, the platform has a draft of 33 m, a 72 m length and a 80 m width [96].

A.2. Multi-turbine platforms

A.2.1. W2Power

W2Power by Enerocean is a semi-sub platform with two turbines. The platform development started in 2009, when Pelagic Power wanted to combine their wave energy converter designs (which had been tested at 1:3 scale in the sea in 2008 [100]) with a floating wind turbine [99,100]. At the time, the combined wind-wave platform consisted of a triangular semi-sub with three cylindrical columns, with two counter-rotating 3 MW turbines on two of the columns and wave energy converters (totaling an additional 3 MW) connected between the columns. The platform mooring was connected to the column with no turbines so that the whole system could weathervane [100].

That original platform design had natural frequencies in heave and pitch which would have required heavy construction to ensure survivability. Therefore, a 4-stage design revision was completed to optimize hydrodynamics, limit fatigue load, and reduce steel [99]. One design change was to tilt the wind turbine towers outward by 15°, to enable the platform to be smaller while still avoiding the blades crossing. A brace system was also added between the columns and heave plates under each column. For a 2 × 3 MW system, the columns have a 9 m diameter and heave plates with 27 m diameter and height 1.5 m. The columns are 90 m apart, and the structure has a 15 m operating draft. The mooring consists of five catenary lines made of chains or steel wire rope [99].

In the re-design, the wave energy converters were removed, but the company is still considering adding wave energy converters onto the platform in the future [97]. The current design consists of two 6 MW turbines. There have been eight testing campaigns in four laboratories [97]. At 1:100 scale, tests were carried out in Edinburgh (Nov 2012, twice in 2013) and Cork (April 2014), and at 1:30 scale, tests were carried out in June 2014 in Cork. A 1:6 scale prototype was installed in 2020 at PLOCAN [97].

A.2.2. Nezzy2

The Nezzy2 platform is a precast concrete semi-sub with two turbines, shown in Fig. 7(g). The platform consists of three outward-inclined columns connected via a Y-shaped pontoon system. At the cross of the Y, there is a vertical column which extends above the surface and holds two masts which extend outward to two nacelles. The mooring consists of six catenary lines connected to the column at the base of the Y so that the system can weathervane. Tensioned cables connect the nacelles to the platform columns. A 1:10 scale prototype of a single-turbine platform was tested in Japan in 2018. Then, a 1:36 scale system of the multi-turbine design was tested in Cork, Ireland. A 1:10 scale prototype was built and tested in 2020 in a gravel pit in Hymendorf, Germany to examine the weathervaning aspect of the platform where waves or current would not contribute. It was then moved to the Baltic Sea and tested for two months in 2020. During this test period, it withstood a storm which, scaled-up would have been equivalent to a category 4 hurricane. There are plans for a full-scale demonstrator in China, using two 8.3 MW downwind turbines [101,110].

A.3. Hybrid platforms

A.3.1. Floating Power Plant

The Floating Power Plant, shown in Fig. 7(h) is a hybrid semi-sub platform with wave energy converters in addition to the wind turbine. The history of the technology goes back to 1998, when it started as a floating wave energy converter idea. It continued as a wave energy converter until 2010, by which time the wave energy converter platform had been tested offshore from 2008–2009 [104]. In 2010, wind turbines were added to the floating structure and connected to the grid. In 2012–2013, the P37 prototype was connected to the grid for two years off the coast of Denmark, 3 km from the shore in 7 m water depth. It was a 37 m long platform, consisting of ten 14 kW wave energy converters (WECs) and three 11 kW two-bladed downwind wind turbines. The platform underwent two testing periods, from November 2012 to January 2013 and from September 2013 to October 2013 [103].

In 2013 1:50 scale model tests were performed of the current platform design, called the P80. The T-shaped semi-sub platform, which holds a single wind turbine at the cross of the T, is made of three rectangular columns with square heave plates at the base of each. Flap-type wave energy converters are installed underneath the top of the T, with flat plates underneath the WECs to trap waves to increase efficiency of the WECs [102,103]. The platform can hold a 4–15 MW turbine and 1–4 MW of WECs [102]. The WECs are locked in storms to avoid slamming and extreme motions [104]. A single-point catenary mooring system allows the entire platform to weathervane. This feature also enables easier access for maintenance boats due to a calm sea behind the platform due to the WECs. The wind turbine also has a yaw system in case of wind-current misalignment [102]. There are plans to install a demonstrator at PLOCAN in Gran Canaria [102].

A.3.2. Hakata Bay Scale Pilot Wind Lens

The Hakata Bay Scale Pilot Wind Lens was built to test a new type of wind turbine called the Wind Lens. Two 3 kW turbines were put on the platform, along with 2 kW of solar PV. The prototype was an 18 m wide hexagonal concrete platform, and it was operational from November 2012 to October 2013. The purpose of the prototype was to compare the performance of offshore wind to an onshore turbine very nearby. It was shown that the offshore turbines produced significantly more power than the onshore ones. There were plans to build a second pilot study consisting of three 300 kW turbines on a 70 m wide semi-sub with solar panels on the structure between the turbines (totaling 1 MW power capacity), but the second pilot study was cancelled [105].

References

[1] GWEC. Global offshore wind report 2022. 2022, https://gwec.net/wp-content/uploads/2022/06/GWEC-Offshore-2022_update.pdf.

[2] DNV. Floating offshore wind: The next five years. Technical report, DNV; 2022.

[3] Henderson AR, Witcher D. Floating offshore wind energy—a review of the current status and an assessment of the prospects. Wind Eng 2010;34(1):1–16.

[4] Cruz J, Atcheson M. Floating offshore wind energy: The next generation of wind energy. Springer; 2016.

[5] Leimeister M, Kolios A, Collu M. Critical review of floating support structures for offshore wind farm deployment. J Phys Conf Ser 2018.

[6] Collu M, Borg M. 11 - Design of floating offshore wind turbines. In: Ng C, Ran L, editors. Offshore wind farms. Woodhead Publishing; 2016, p. 359–85.

[7] DNV. DNV-ST-0119 floating wind turbine structures. 2021, https://www.dnv.com/energy/standards-guidelines/dnv-st-0119-floating-wind-turbine-structures.html. [Accessed 04 October 2022].

[8] IEC. IEC TS 61400-3-2:2019 wind energy generation systems- Part 3-2: Design requirements for floating offshore wind turbines. 2019, https://webstore.iec.ch/publication/29244. [Accessed 04 October 2022].

[9] Ioannou A, Liang Y, Jalón M, Brennan F. A preliminary parametric techno-economic study of offshore wind floater concepts. Ocean Eng 2020;197:106937.

[10] Jonkman J. Influence of control on the pitch damping of a floating wind turbine. In: 46th AIAA aerospace sciences meeting and exhibit. 2008, p. 1306.

[11] Larsen TJ, Hanson TD. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. J Phys Conf Ser 2007;75.

[12] Martinez A, Iglesias G. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. Renew Sustain Energy Rev 2022;154.

[13] Myhr A, Bjerkseter C, Ågotnes A, Nygaard TA. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Renew Energy 2014;66:714–28.

[14] Heidari S. Economic modelling of floating offshore wind power: Calculation of Levelized cost of energy. 2017.

[15] Bjerkseter C, Ågotnes A. Levelised costs of energy for offshore floating wind turbine concepts. Norwegian University of Life Sciences, Ås; 2013.

[16] Equinor. Floating wind. 2022, https://www.equinor.com/energy/floating-wind. [Accessed 10 May 2022].

[17] Mathern A, von der Haar C, Marx S. Concrete support structures for offshore wind turbines: Current status, challenges, and future trends. Energies 2021;14(7):1995.

[18] Skaare B, Nielsen FG, Hanson TD, Yttervik R, Havmøller O, Rekdal A. Analysis of measurements and simulations from the Hywind Demo floating wind turbine. Wind Energy 2015;18(6):1105–22.

[19] Skaare B. Development of the Hywind concept. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2017.

[20] Nielsen FG, Hanson TD, Skaare B. Integrated dynamic analysis of floating offshore wind turbines. In: International conference on offshore mechanics and Arctic engineering. 2006, p. 671–9.

[21] Equinor. Hywind Tampen. 2022, https://www.equinor.com/energy/hywind-tampen. [Accessed 29 April 2022].

[22] Roddier D, Cermelli C, Weinstein A. WindFloat: a floating foundation for offshore wind turbines—Part I: Design basis and qualification process. In: International conference on offshore mechanics and Arctic engineering. 2009, p. 845–53.

[23] Cermelli C, Roddier D, Aubault A. WindFloat: a floating foundation for offshore wind turbines—Part II: Hydrodynamics analysis. In: International conference on offshore mechanics and Arctic engineering. 2009, p. 135–43.

[24] Roddier D, Cermelli C, Aubault A, Weinstein A. WindFloat: A floating foundation for offshore wind turbines. J Renew Sustain Energy 2010.

[25] Zambrano T, MacCready T, Kiceniuk Jr T, Roddier DG, Cermelli CA. Dynamic modeling of deepwater offshore wind turbine structures in Gulf of Mexico storm conditions. In: International conference on offshore mechanics and Arctic engineering. 2006, p. 629–34.

[26] Aubault A, Cermelli C, Roddier D. Parametric optimization of a semi-submersible platform with heave plates. In: International conference on offshore mechanics and Arctic engineering. 2007, p. 471–8.

[27] Aubault A, Cermelli C, Roddier D. WindFloat: A floating foundation for offshore wind turbines—Part III: Structural analysis. In: International conference on offshore mechanics and Arctic engineering. 2009, p. 213–20.

[28] Cermelli CA, Roddier DG. Experimental and numerical investigation of the stabilizing effects of a water-entrapment plate on a deepwater minimal floating platform. In: International conference on offshore mechanics and Arctic engineering. 2005, p. 517–25.

[29] PrinciplePower P. Windfloat Atlantic. 2022, https://www.principlepower.com/projects/windfloat-atlantic. [Accessed 12 May 2022].

[30] PrinciplePower. WindFloat projects. 2022, https://www.principlepower.com/projects. [Accessed 12 May 2022].

[31] Roddier D, Cermelli C, Aubault A, Peiffer A. Summary and conclusions of the full life-cycle of the WindFloat FOWT prototype project. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2017.

[32] Stehly T, Beiter P, Duffy P. 2019 cost of wind energy review. Technical report, Golden, CO (United States): National Renewable Energy Lab (NREL); 2020.

[33] GWEC. Floating Offshore Wind – A Global Opportunity. 2022, https://gwec.net/wp-content/uploads/2022/03/GWEC-Report-Floating-Offshore-Wind-A-Global-Opportunity.pdf.

[34] METCENTRE. Unitech Zefyros (Hywind Demo). 2023, https://metcentre.no/project/unitech-zefyros-hywind-demo/. [Accessed 17 April 2023].

[35] Blue H Engineering. Historical development, https://www.bluehengineering.com/historical-development.html. [Accessed 27 April 2022].

[36] Huber F. The first floating wind turbines. In: Proceedings of the 2nd international conference on ocean energy. 2008, p. 15–7.

[37] Koh J, Robertson A, Jonkman J, Driscoll F, Ng E. Building and calibration of a fast model of the sway prototype floating wind turbine. Technical report, Golden, CO: National Renewable Energy Lab (NREL); 2013.

[38] Koh JH, Robertson AN, Jonkman JM, Driscoll F, Ng EYK. Validation of SWAY wind turbine response in FAST, with a focus on the influence of tower wind loads. In: The twenty-fifth international ocean and polar engineering conference. OnePetro; 2015.

[39] Hand B, Cashman A. A review on the historical development of the lift-type vertical axis wind turbine: From onshore to offshore floating application. Sustain Energy Technol Assess 2020;38.

[40] Berthelsen PA, Fylling I, Vita L, Paulsen US. Conceptual design of a floating support structure and mooring system for a vertical axis wind turbine. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2012, p. 259–68.

[41] Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F. A novel floating offshore wind turbine concept. In: European wind energy conference and exhibition. 2009, p. 16–9.

[42] Paulsen US. Sizing of a spar-type floating support structure for DeepWind. Technical report, DTU Wind Energy; 2013.

[43] Paulsen US, Borg M, Madsen HA, Pedersen TF, Hattel J, Ritchie E, et al. Outcomes of the DeepWind conceptual design. Energy Procedia 2015;80:329–41.

[44] Vita L, Paulsen US, Madsen HA, Nielsen PH, Berthelsen PA, Carstensen S. Design and aero-elastic simulation of a 5MW floating vertical axis wind turbine. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2012, p. 383–92.

[45] Vita L, Paulsen US, Pedersen TF. A novel floating offshore wind turbine concept: new developments. In: European wind energy conference and exhibition. 2010.

[46] Vita L, Zhale F, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F. A novel concept for floating offshore wind turbines: recent developments in the concept and investigation on fluid interaction with the rotating foundation. In: International conference on offshore mechanics and Arctic engineering. 2010, p. 389–96.

[47] Pedersen T, Paulsen U, Vita L, Madsen H, Nielsen P, Kragh K, et al. Design and manufacture of an offshore concept wind turbine–the DeepWind demonstrator. Tech. Rep. E-0030, DTU Wind Energy; 2013.

[48] Toda Corporation. The first grid connected floating wind turbine in Japan. 2022, https://haenkaze.com/en/. [Accessed 13 May 2022].

[49] Utsunomiya T, Sato T, Matsukuma H, Yago K. Experimental validation for motion of a spar-type floating offshore wind turbine using 1/22.5 scale model. In: International conference on offshore mechanics and Arctic engineering. 2009, p. 951–9.

[50] Ishida S, Kokubun K, Nimura T, Utsunomiya T, Sato I, Yoshida S. At-sea experiment of a hybrid spar type offshore wind turbine. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2013.

[51] Utsunomiya T, Sato I, Yoshida S, Ookubo H, Ishida S. Dynamic response analysis of a floating offshore wind turbine during severe typhoon event. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2013.

[52] Utsunomiya T, Yoshida S, Ookubo H, Sato I, Ishida S. Dynamic analysis of a floating offshore wind turbine under extreme environmental conditions. J Offshore Mech Arct Eng 2014;136.

[53] Utsunomiya T, Yoshida S, Kiyoki S, Sato I, Ishida S. Dynamic response of a spar-type floating wind turbine at power generation. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2014.

[54] Utsunomiya T, Sato I, Shiraishi T, Inui E, Ishida S. Floating offshore wind turbine, Nagasaki, Japan. In: Large floating structures. Springer; 2015, p. 129–55.

[55] Kokubun K, Ishida S, Nimura T, Chujo T, Yoshida S, Utsunomiya T. Model experiment of a SPAR type offshore wind turbine in storm condition. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2012, p. 569–75.

[56] Utsunomiya T, Matsukuma H, Minoura S, Ko K, Hamamura H, Kobayashi O, et al. On sea experiment of a hybrid spar for floating offshore wind turbine using 1/10 scale model. In: International conference on offshore mechanics and Arctic engineering. 2010, p. 529–36.

[57] Tanaka K, Sato I, Utsunomiya T, Kakuya H. Validation of dynamic response of a 2-MW hybrid-spar floating wind turbine during typhoon using full-scale field data. Ocean Eng 2020;218.

[58] University of Maine. VolturnUS floating concrete hull technology. 2022, https://composites.umaine.edu/research/volturnus/. [Accessed 19 May 2022].

[59] Allen C, Viscelli A, Dagher H, Goupee A, Gaertner E, Abbas N, et al. Definition of the UMaine VolturnUS-S reference platform developed for the IEA Wind 15-megawatt offshore reference wind turbine. Technical report, Golden, CO: National Renewable Energy Lab (NREL); 2020.

[60] Viselli AM, Goupee AJ, Dagher HJ, Allen CK. Design and model confirmation of the intermediate scale VolturnUS floating wind turbine subjected to its extreme design conditions offshore Maine. Wind Energy 2016;19(6):1161–77.

[61] Viselli AM, Goupee AJ, Dagher HJ. Model test of a 1: 8-scale floating wind turbine offshore in the Gulf of Maine. J Offshore Mech Arct Eng 2015;137(4).

[62] Robertson AN, Jonkman JM, Goupee AJ, Coulling AJ, Prowell I, Browning J, et al. Summary of conclusions and recommendations drawn from the DeepCwind scaled floating offshore wind system test campaign. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2013.

[63] Young AC, Hettick S, Dagher HJ, Viselli AM, Goupee AJ. VolturnUS 1: 8-scale FRP floating wind turbine tower: Analysis, design, testing and performance. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2014.

[64] Fowler MJ, Goupee AJ, Allen C, Viselli A, Dagher H. 1: 52 scale testing of the first US commercial scale floating wind turbine, VolturnUS: Testing overview and the evolution of scale model testing methods. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2017.

[65] Yamaguchi H, Imakita A. Learning from field test regarding damping of a floater motion-2MW FOWT "Fukushima Mirai". In: Grand renewable energy proceedings Japan Council for Renewable Energy. Japan Council for Renewable Energy; 2018, p. 177.

[66] Public Relations Office, Government of Japan. The world's largest floating wind farm. 2016, https://www.gov-online.go.jp/eng/publicity/book/hlj/html/201609/201609_03_en.html. [Accessed 17 June 2022].

[67] The Mainichi. Failure of world's 1st offshore floating wind farm in Fukushima disappoints 3.11 survivors. 2021, https://mainichi.jp/english/articles/20210305/p2a/00m/0na/034000c. [Accessed 17 June 2022].

[68] Ishihara T, Taki S. Fukushima floating offshore wind farm demonstration project (Fukushima FORWARD). 2016, http://www.fukushima-forward.jp/english/pdf/pamphlet3.pdf. [Accessed 17 June 2022].

[69] Offshore-Energybiz. Floating gyro-stabilized VAWT to be tested in Norway (VIDEO). 2013, https://www.offshore-energy.biz/floating-gyro-stabilized-vawt-to-be-tested-in-norway-video//. [Accessed 27 July 2022].

[70] OffshoreWINDbiz. VIDEO: sea launch of Gwind turbine- floating gyro-stablized VAWT. 2013, https://www.offshorewind.biz/2013/09/02/video-sea-launch-of-gwind-turbine-floating-gyro-stabilized-vawt/. [Accessed 27 July 2022].

[71] SeaTwirl. SeaTwirl: The future of offshore wind. 2022, https://seatwirl.com/. [Accessed 14 June 2022].

[72] Akel N. Grid stability benefits with Seatwirl vs horizontal shaft windpower plant. Chalmers University of Technology; 2017.

[73] Budesinsky M. CFD simulation of hydrodynamic loads on a floating vertical axis wind turbine. Chalmers University of Technology; 2019.

[74] Ohta M, Komatsu M, Ito H, Kumamoto H. Development of a V-shaped semi-submersible floating structure for 7MW offshore wind turbine. In: Proceedings of the international symposium on marine and offshore renewable energy. 2013, p. 28–30.

[75] Yoshimoto H, Awashima Y, Kitakoji Y, Suzuki H. Development of floating offshore substation and wind turbine for Fukushima FORWARD. In: Proceedings of the international symposium on marine and offshore renewable energy. 2013, p. 28–30.

[76] 4COffshore. Fukushima floating offshore wind farm demonstration project (FORWARD)-phase 2. 2021, https://www.4coffshore.com/windfarms/japan/fukushima-floating-offshore-wind-farm-demonstration-project-(forward)---phase-2-japan-jp13.html. [Accessed 17 June 2022].

[77] Yoshimoto H, Kamizawa K. Validation of the motion analysis method of floating offshore wind turbines using observation data acquired by full scale demonstration project. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2019.

[78] Matsuoka R, Yoshimoto H. Verification of precision concerning the design of advanced spar type structure. In: Conference proceedings the Japan Society of Naval Architects and Ocean Engineers 20. The Japan Society of Naval Architects and Ocean Engineers; 2015, p. 1–4.

[79] Ideol BW. Floating offshore wind. 2022, https://www.bw-ideol.com/en. [Accessed 12 May 2022].

[80] Choisnet T, Geschier B, Vetrano G. Initial comparison of concrete and steel hulls in the case of Ideol's square ring floating substructure. In: Proceedings of the 15th world wind energy conference and exhibition, vol. 31. 2016.
[81] Choisnet T, Favré M, Lyubimova M, Rogier E. A robust concrete floating wind turbine foundation for worldwide applications. In: Proc grand renewable energy conference. 2014.
[82] Floatgen. Floatgen wind power going further offshore. 2022, https://live.floatgen.eu/en. [Accessed 13 May 2022].
[83] Eolink. Floating offshore wind energy. 2020, http://eolink.fr/en/. [Accessed 19 May 2022].
[84] Guyot M, De Mourgues C, Le Bihan G, Parenthoine P, Templai J, Connolly A, et al. Experimental offshore floating wind turbine prototype and numerical analysis during harsh and production events. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2019.
[85] Connolly A, Guyot M, Le Boulluec M, Héry L, O'Connor A. Fully coupled aero-hydro-structural simulation of new floating wind turbine concept. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2018.
[86] Baita-Saavedra E, Cordal-Iglesias D, Filgueira-Vizoso A, Morató À, Lamas-Galdo I, Álvarez-Feal C, et al. An economic analysis of an innovative floating offshore wind platform built with concrete: The SATH® platform. Appl Sci 2020;10(11):3678.
[87] Vittori F, Azcona J, Eguinoa I, Pires O, Rodríguez A, Morató Á, et al. Model tests of a 10 MW semi-submersible floating wind turbine under waves and wind using hybrid method to integrate the rotor thrust and moments. Wind Energy Sci. Discuss. 2021;1–20.
[88] Marijuán R. Offshore floating platforms: Analysis of a solution for motion mitigation. KTH Royal Institute of Technology; 2017.
[89] OffshoreWindbiz. BlueSATH floating wind prototype capsizes during Hurricane Epsilon. 2020, https://www.offshorewind.biz/2020/11/04/bluesath-floating-wind-prototype-capsizes-during-hurricane-epsilon/. [Accessed 21 July 2022].
[90] Saitec. SATH technology. 2022, https://saitec-offshore.com/sath/. [Accessed 21 June 2022].
[91] Stiesdal. The TetraSpar full-scale demonstration project. 2022, https://www.stiesdal.com/offshore-technologies/the-tetraspar-full-scale-demonstration-project/. [Accessed 12 May 2022].
[92] Borg M, Walkusch Jensen M, Urquhart S, Andersen MT, Thomsen JB, Stiesdal H. Technical definition of the TetraSpar demonstrator floating wind turbine foundation. Energies 2020.
[93] Borg M, Viselli A, Allen CK, Fowler M, Sigshøj C, Grech La Rosa A, et al. Physical model testing of the TetraSpar Demo floating wind turbine prototype. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2019.
[94] OffshoreWINDbiz. China's first floating wind turbine heads offshore. 2021, https://www.offshorewind.biz/2021/07/13/chinas-first-floating-wind-turbine-heads-offshore/. [Accessed 09 November 2022].
[95] CSSC-HZ. Floating wind power. 2021, http://cssc-hz.com/?en/Technologies/Floating/. [Accessed 03 October 2022].
[96] OffshoreWINDbiz. CSSC installing largest floating wind turbine in China. 2022, https://www.offshorewind.biz/2022/05/30/cssc-installing-largest-floating-wind-turbine-in-china/. [Accessed 03 October 2022].
[97] Enerocean. W2Power. 2022, https://enerocean.com/w2power/. [Accessed 28 July 2022].
[98] Legaz MJ, Coronil D, Mayorga P, Fernández J. Study of a hybrid renewable energy platform: W2Power. In: International conference on offshore mechanics and Arctic engineering. American Society of Mechanical Engineers; 2018.
[99] Hanssen JE, Margheritini L, O'Sullivan K, Mayorga P, Martinez I, Arriaga A, et al. Design and performance validation of a hybrid offshore renewable energy platform. In: 2015 tenth international conference on ecological vehicles and renewable energies. IEEE; 2015, p. 1–8.
[100] Pelagic Power. W2Power. 2010, http://www.pelagicpower.no/index.html. [Accessed 28 July 2022].
[101] EnBW. Floating wind turbine: Nezzy2. 2022, https://www.enbw.com/renewable-energy/wind-energy/our-offshore-wind-farms/nezzy2-floating-wind-turbine/. [Accessed 28 July 2022].
[102] Floating Power Plant. Floating power plant. 2022, https://www.floatingpowerplant.com/. [Accessed 29 July 2022].
[103] Yde A, Larsen TJ, Hansen AM, Fernandez M, Bellew S. Comparison of simulations and offshore measurement data of a combined floating wind and wave energy demonstration platform. J Ocean Wind Energy 2015;2:129–37.
[104] Yde A, Bellew SB, Clausen RS, Nielsen AW. Experimental and theoretical analysis of a combined floating wave and wind energy conversion platform. DTU Wind Energy; 2014.
[105] Ohya Y, Karasudani T, Nagai T, Watanabe K. Wind Lens technology and its application to wind and water turbine and beyond. Renew. Energy Environ. Sustain. 2017;2:2.
[106] Robertson A, Jonkman J, Masciola M, Song H, Goupee A, Coulling A, et al. Definition of the semisubmersible floating system for phase II of OC4. Technical report, National Renewable Energy Lab (NREL); 2014.
[107] Paulsen US, Vita L, Madsen HA, Hattel J, Ritchie E, Leban KM, et al. 1St DeepWind 5 MW baseline design. Energy Procedia 2012;24:27–35.
[108] Willén E, Schou P. SeaTwirl: A game-changer in offshore wind. 2020, https://seatwirl.com/content/uploads/LCoE-SeaTwirl-1.pdf. [Accessed 14 June 2022].
[109] Leithead W, Camciuc A, Amiri AK, Carroll J. The X-Rotor offshore wind turbine concept. J Phys Conf Ser 2019.
[110] de Vries E. In: WINDPOWER Monthly, editor. Exclusive: Radical 16.6MW Nezzy2 twin floating offshore wind platform takes shape in China. 2022, URL: https://www.windpowermonthly.com/article/1797699/exclusive-radical-166mw-nezzy%C2%B2-twin-floating-offshore-wind-platform-takes-shape-china, Online; posted 1-September-2022.
[111] Maine Aqua Ventus. Aqua Ventus Maine. 2019, https://maineaquaventus.com/.
[112] Sergiienko N, da Silva L, Bachynski-Polić E, Cazzolato B, Arjomandi M, Ding B. Review of scaling laws applied to floating offshore wind turbines. Renew Sustain Energy Rev 2022.
[113] Garvey SD, Eames PC, Wang JH, Pimm AJ, Waterson M, MacKay RS, et al. On generation-integrated energy storage. Energy Policy 2015;86:544–51.
[114] Battisti L, Benini E, Brighenti A, Castelli MR, Dell'Anna S, Dossena V, et al. Wind tunnel testing of the DeepWind demonstrator in design and tilted operating conditions. Energy 2016;111:484–97.