2024-04

Trends in floating offshore wind platforms: A review of early-stage devices

Edwards, EC

10.1016/j.rser.2023.114271
Renewable and Sustainable Energy Reviews
Elsevier BV

Renewable and Sustainable Energy Reviews 193 (2024) 114271

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review article

Trends in floating offshore wind platforms: A review of early-stage devices

Emma C. Edwards [a,b,*], Anna Holcombe [b], Scott Brown [b], Edward Ransley [b], Martyn Hann [b], Deborah Greaves [b]

[a] Department of Engineering Science, University of Oxford, Parks Rd, Oxford, OX1 3PJ, United Kingdom
[b] School of Engineering, Computing and Mathematics, University of Plymouth, Drake Circus, Plymouth, PL4 8AA, United Kingdom

ARTICLE INFO

Keywords:
Floating offshore wind
Floating offshore wind turbine platform design
Hybrid floating wind-wave platform
Multi-turbine platform

ABSTRACT

This study reviews early-stage floating offshore wind turbine (FOWT) platform designs. The review covers 86 past and current early-stage platform designs, ranging from early conceptual designs to platforms which have undergone lab tests simulating extreme conditions. The evolution of FOWT platforms is described, and it is shown how FOWT platforms were originally influenced by floating platforms typically used in the oil and gas industry, but FOWT platforms have deviated away from these conventional floater designs to suit the specific needs of the technology. Four phases are defined to characterize chronological shifts in design thinking. There has been a number of alternative cost reduction strategies recently, including (i) specializing the platform to a particular location or environment, (ii) increasing manufacturability, and (iii) designing an innovative platform which diverges further from conventional designs. For the latter strategy, there has been an emergence of multi-turbine platforms, hybrid platforms, platforms which use a combination of stability mechanisms, and hydrodynamically specialized platforms. Finally, potential future trends are discussed, and it is shown that competing priorities for platform designers in the future will likely mean that the design space must compromise between increasing standardization and increasing specialization.

Abbreviations

FOWT	Floating offshore wind turbine
GW	Gigawatts
HAWT	Horizontal axis wind turbine
kW	Kilowatts
MW	Megawatts
O&G	Oil and gas
TLP	Tension leg platform
VAWT	Vertical axis wind turbine
WEC	Wave energy converter
WTG	Wind turbine generator

1. Introduction

Increasing global offshore wind energy capacity is paramount to achieving Net-Zero goals. There are predictions that offshore wind will increase from the 2022 global capacity of 56 GW, to 370 GW by 2030 and to 2000 GW by 2050 [1]. To accomplish this enormous expansion, wind turbines must be deployed in water depths at which fixed foundations for wind turbines are uneconomic or unfeasible, so floating platforms become necessary. Floating offshore wind is still a relatively nascent technology, with only 121 MW of installed capacity globally as of 2022 [2], but a rapid scale-up is predicted, to an installed capacity of 18.9 GW by 2030 [1]. Allowing wind turbines to float introduces new challenges due to the platform moving in response to waves and wind. Wind turbines have mostly converged in design, but, as identified in Edwards et al. [2], floating offshore wind turbine (FOWT) platform designs are still evolving and diverging in design. Due to the recent rapid expansion in number and diversity of FOWT platforms, an up-to-date review is needed.

In Edwards et al. [2], the authors reviewed the 22 FOWT platforms that have deployed a prototype, demonstrator, or farm-scale device at sea. In this work, the review is extended to 86 additional platforms either currently in the early (pre-deployment) stage of development or which never made it past this stage and are no longer being developed. The analysis of the platforms that have reached at-sea deployments yielded useful learning, highlighting design features and philosophies which are relied upon in commercial or near-commercial projects. However, larger-scale engineering necessarily becomes more

---

* Corresponding author at: Department of Engineering Science, University of Oxford, Parks Rd, Oxford, OX1 3PJ, United Kingdom.
E-mail address: emma.edwards@eng.ox.ac.uk (E.C. Edwards).

https://doi.org/10.1016/j.rser.2023.114271
Received 8 March 2023; Received in revised form 15 December 2023; Accepted 21 December 2023

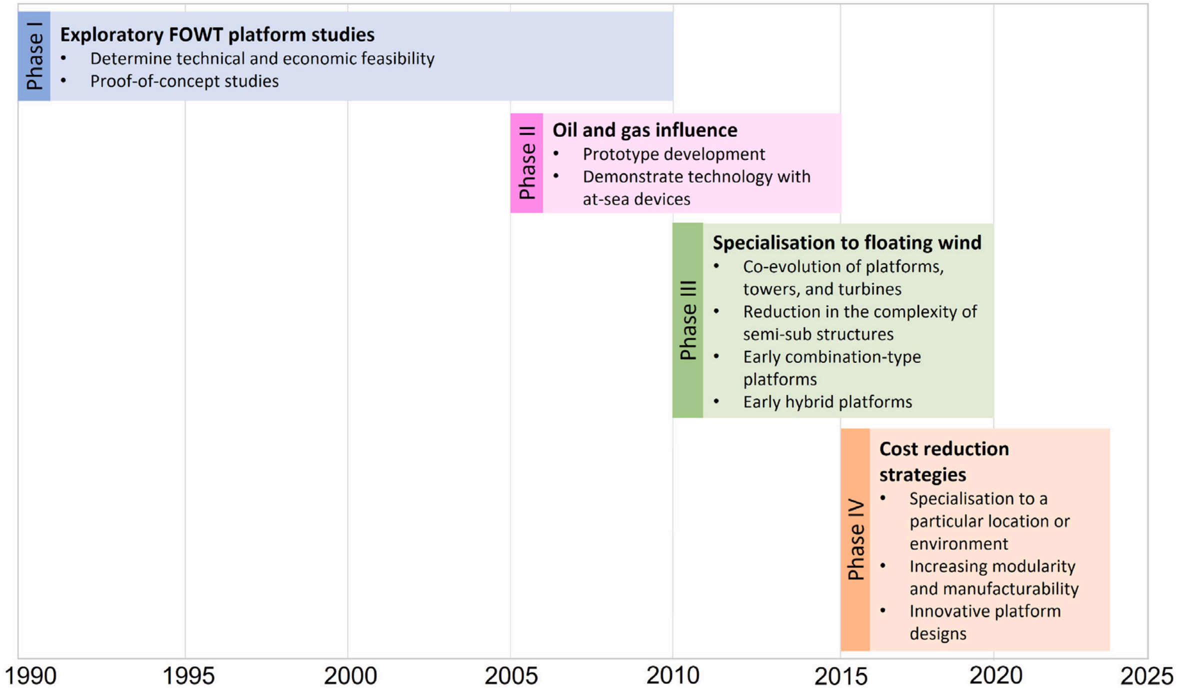

Fig. 1. Timeline of the four phases of FOWT platform design development.

risk averse, and therefore it is informative to look at the evolution of early-stage devices. Trends in early-stage devices provide insights into the industry's past, current and future priorities which cannot be seen from solely considering at-sea devices. To better understand these priorities, it is important to consider past early-stage trends which never made it to a larger-scale device, and how relative success, or lack thereof, in larger-scale devices has led to positive or negative feedback in early-stage devices. Furthermore, trends in recent early-stage devices ultimately help to predict future design directions and priorities.

Floating offshore wind has been studied since the 1990s. There have been a few review articles on platform designs during this time (*e.g.*, Henderson and Witcher [3], Cruz and Atcheson [4], and Leimeister et al. [5]). However, there has not been a recent review on this subject, and, over recent years, there has been a significant growth in the number and diversity of platform designs (for example, there have been at least 35 new platform designs in the past four years). Therefore, this review has been performed to provide an up-to-date summary of early-stage devices. Moreover, this review resolves the underlying reasons for why platform designs have been diverging in recent years, and what that might mean for the future of the wider FOWT industry. This divergence affects individuals involved in the FOWT system other than platform developers, including academic and industrial researchers looking at environmental monitoring and surveying, environmental geotechnics, materials and composites, wind turbine array modeling, and many others. Therefore, understanding and characterizing these trends is a crucial step to advancing the viability of the floating offshore wind industry as a whole.

To examine the divergence of platform design recently, 86 early-stage platform designs, from the past 30+ years of research, have been studied and characterized. Analysis of trends in these platforms has been performed, and four phases in the evolution of FOWT platform designs have been identified, which are discussed in this review. As depicted in Fig. 1, these phases characterize changing design priorities throughout the timeline of FOWT research and explain the resulting change in design features. Additionally, potential future trends are discussed, which have been identified as a result of this study, to give insight into the direction of the industry.

The four phases defined to characterize the evolution of early-stage devices, as shown in Fig. 1, generally reflect the chronological shifts in design thinking, though some temporal overlap is present. Phase I (1990–2010) is characterized by proof-of-concept studies, comparing 'conventional' platforms to 'unconventional' ones. Typically, these studies highlighted proven designs as the ones to develop further. Phase II (2005–2015) is characterized by influence from the oil and gas (O&G) industry, wherein floating platforms from the O&G industry were studied carrying a wind turbine with limited platform modifications. A natural progression, Phase III (2010–2020) is characterized by the emergence of platform designs to suit the unique needs of floating wind. This phase saw the emergence of specialized FOWT platforms to deal with the differing forces of FOWTs and a greater drive for cost reduction. Finally, Phase IV (2015-present) is characterized by a number of alternative cost reduction strategies, which has resulted in a recent divergence in platform designs. In particular, there have been three main areas of focus to drive down cost: (i) specializing platforms to a particular location or environment, (ii) increasing modularity and manufacturability, and (iii) innovating the platform further from convention.

The structure of this work is as follows. Sections 2–5 describe Phases I–IV. Summary tables tabulate all platforms studied in this work. The tables are separated by lab testing: Table 1 summarizes those that have completed lab tests of extreme conditions, Table 2 summarizes those that have completed some lab tests, and Tables 3 and 4 summarize those that have either not completed lab tests or not published information about lab tests. In these tables, key parameters are included for each platform, such as 'type' of platform, projected turbine capacity, material, water depth limits, mooring set-up, other use (*i.e.*, hybrid device), and information about lab tests (if they have been done). These tables summarize some of the analysis done to compare and characterize FOWT platform designs. Finally, Section 6 discusses potential future trends.

2. Phase I: Exploratory FOWT platform studies (1990–2010)

Phase I is characterized by exploratory studies on FOWT platforms, including both 'traditional' floating platforms, based on those in the O&G industry, as well as new, innovative platform designs. Traditional floating platforms from the O&G industry typically include spars, semi-submersibles ('semi-subs'), tension leg platforms (TLPs) and barges.

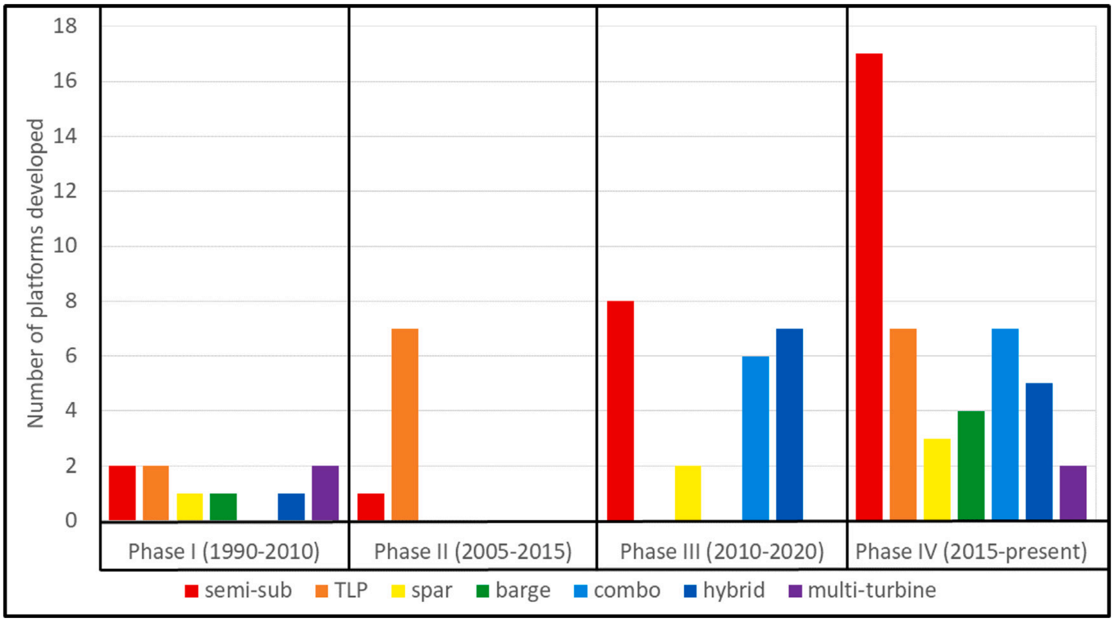

Fig. 2. Number of each 'type' of platform, separated by the four phases.

These four types of platforms, discussed more in Edwards et al. [2], are characterized by their stability mechanism: spars use a low center of gravity, TLPs use taut moorings, barges use a large waterplane area, and semi-subs use both a large waterplane moment and low center of gravity. Fig. 2 shows the number of each platform type, separated by the four phases.

The purpose of the FLOAT [6], MUFOW [7], ELOMAR [8], MIT/NREL [9], HiPRWind [10], and Dutch Tri-Floater [11] projects, which all took place in the 1990s or early 2000s, was to consider traditional and non-traditional platform types to determine the technical and economic feasibility of a FOWT (*i.e.*, how to ensure stability, manufacturability, ability to be built at and towed from a standard port, and how to reduce motion of the structure). The result of most of the exploratory studies from Phase I was to pick the more 'typical' platform that they considered; it was determined in each study that the most proven technology would be lowest risk and fastest to progress to a prototype scale. For example, FLOAT chose a spar because it was already proven in the O&G industry [12]. As another example, originally concrete was to be used for the ELOMAR platform, but this was changed to steel because it was more commonly used in offshore structures [8].

Due to the early nature of the technology, more 'adventurous' ideas were also considered, such as multi-turbine platforms (*e.g.*, MUFOW [7], WindSea [13]) and hybrid platforms (*e.g.*, ITI energy barge [14]). While none of these studies lead to further testing or a prototype, they laid some of the groundwork for future adventurous designs. As shown in Fig. 2, a wide range of types of platforms were developed during this phase.

3. Phase II: Oil & Gas influence (2005–2015)

Phase II is characterized by influence from the O&G industry. After the first exploratory studies in Phase I, the focus shifted to getting a device in the sea, to demonstrate the technology. A natural first step was to use known technology that had been working for O&G floating platforms for decades. Furthermore, likely due to the emerging success of fixed offshore wind and the recognition that floating platforms were a logical progression, a number of O&G companies were interested in getting involved in developing the technology. These companies were well-placed because of their experience in floating offshore platforms and their investment availability. This has strongly influenced the set of at-sea FOWTs [2], since many of the first prototypes/demonstrators were built by companies in the O&G industry (*e.g.*, Blue H [15], SWAY [16], Hywind Spar [17], and WindFloat [18]). However, there are additional trends apparent only in early-stage platforms. For example, there were a significant number of TLPs developed during this time period, as shown in Fig. 2, mostly by O&G companies. It was believed that, among the existing O&G platforms, a TLP was the best option for a FOWT, due to its low material weight and suitability for a wide range of water depths. For example, Doris [19], Ocean Resource [20], Glosten (shown in Fig. 3a [21]) GICON (shown in Fig. 3b [22]), Arcadis [3], Concept Marine Associates [23], and Iberdrola [24] all developed TLP concepts. However, none of these concepts ever made it to at-sea trials. Due to a lack of documentation, the exact reasons for this are difficult to ascertain. However, likely explanations are that installation costs of the TLP, which are higher than other types of platforms, outweighed the advantages, or that the high pitch moments and higher center of gravity, due to the wind turbine, meant that the O&G TLP setups were not well-suited at the time for FOWTs.

This phase was also an important stepping stone in the evolution of FOWT platforms: influence from O&G's decades' worth of experience shaped early FOWT platforms, including both those at early stages of development and those that made it to the sea. This influence makes sense, owing to the common goal of minimizing platform motion, shared between FOWT platforms and O&G floating platforms. However, early concept designs give us insight to the fact that forces and objectives also differ significantly between the two uses of floating platforms. The fact that none of the early-stage TLP designs from this phase ever went to at-sea trials highlights that the sector needed to adapt to floating wind specific needs.

Physical modeling of FOWTs was also started to be developed during this phase. FOWTs are an inherently difficult system to model at scale due to the scaling mismatch between Froude scaling (to correctly scale wave effects) and Reynolds scaling (to correctly scale wind effects). Otter et al. [25] provide a review of physical modeling techniques and studies performed. There are two main types of laboratory techniques, done in a wave tank: software-in-the-loop and blown wind. In software-in-the-loop tests, the wind turbine is replaced by a thruster, controlled in real-time based on numerical simulations to produce the correctly Froude-scaled aerodynamic thrust force. In blown wind tests, fans blow wind on blades that have been geometrically distorted to produce the correctly Froude-scaled forces.

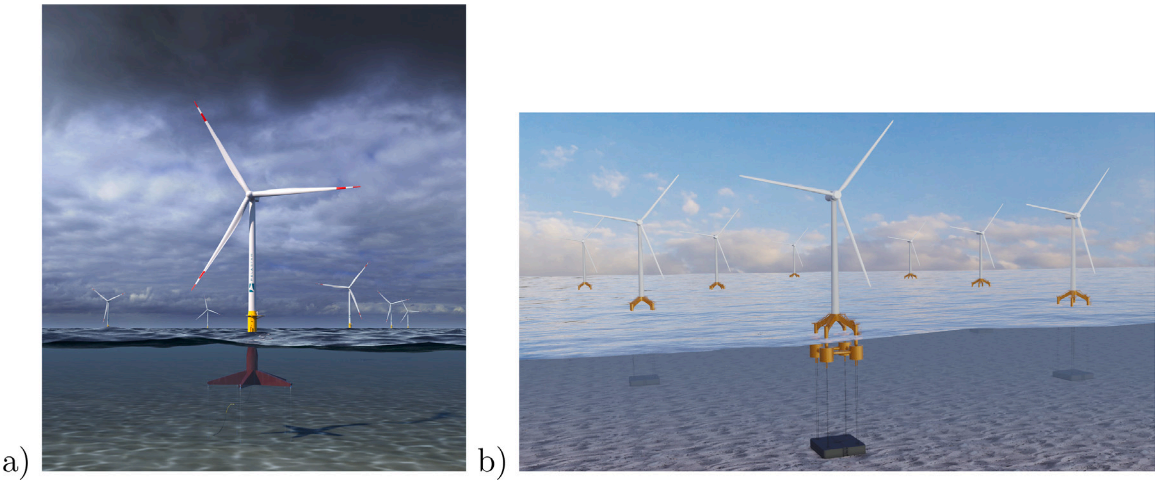

Fig. 3. (a) Pelastar TLP, courtesy of Glosten; (b) SOF, courtesy of ©GICON® group.

Tables 1–4, which list all 86 platform designs studies in this review and compare important parameters, also detail lab tests which have been completed for each platform, if applicable. The tables are separated by degree of lab tests. Table 1 includes all platforms that have completed lab tests simulating extreme environmental conditions. Table 2 includes all platforms that have completed some lab tests but not yet survival conditions. Finally, Tables 3 and 4 include all platforms that have not yet completed lab tests or do not provide any information about lab tests. While these categories are aligned with Technology Readiness Level (TRL), these values are not assigned in this work, due to the fact that a number of developers claim a particular TRL level on their website but do not show their lab test results.

4. Phase III: Specialization to floating wind (2010–2020)

Phase III is characterized by a shift in FOWT platform designs away from O&G influence and towards platforms specifically designed to meet the needs of floating wind. FOWT platforms have significantly different forces than O&G floating platforms: there are substantial aerodynamic thrust forces high above the sea surface, the center of gravity of the whole structure is higher, and the payload is smaller. Furthermore, cost reduction is a stronger driver than for the O&G industry. Therefore, it is natural that FOWT platforms evolved away from early designs influenced by O&G. Some of the trends discussed in this section have influenced at-sea development [2], but the evidence base for the influence of these factors in early-stage devices is wider. This phase also demonstrates how at-sea designs influence early-stage development — there is feedback from the earliest at-sea prototypes that filtered down to influence early-stage devices during this phase. There are four main ways that the specialization to floating wind needs manifest in the designs during this phase: (i) a co-evolution of platforms, towers, and turbines, (ii) a reduction in the complexity of semi-sub platforms, (iii) early combination-type platforms, and (iv) early hybrid platforms.

4.1. Co-evolution of platforms, towers, and turbines

Many of the first FOWTs designed in the early stages, including at-sea prototypes, used wind turbines and towers typically designed for fixed offshore wind applications. However, it has been shown that, without changing the blade pitch control strategy, using a turbine designed for a fixed application can lead to an unfavorably large response of the floating structure above rated wind speeds [26,27]. This revelation led to control strategies of the wind turbine to be developed alongside the platform development (*e.g.*, TetraSub [28], OO-star [29]). Though there are still some platforms (*e.g.*, SBM TLP [30]) that are designed to use a 'standard' fixed offshore wind turbine, most developers now adopt floating-specific control strategies (*e.g.*, VolturnUS-S reference platform includes a floating-specific correction to the control strategy of the IEA 15 MW turbine [31,32]).

Compared to fixed wind turbines, the tower used for a FOWT experiences different forces due to the motion of the floating platform. Early-stage devices have come up with a number of different methods to cope with these forces. For example, WindCrete is a structure which consists of a single cylindrical piece acting as tower and floating spar platform. The continuous structure avoids the fatigue common at the point where the steel turbine tower and concrete floating platform would typically attach [33]. As another example, several developers (*e.g.*, Tetrafloat [34], X1Wind [35], Eolink [36]) use multiple masts, instead of a solitary tower, to hold the wind turbine (for example, see X1Wind in Fig. 4a). This configuration distributes structural forces among the multiple masts and reduces the overall steel needed, and it means that the tower natural frequencies are not close to the blade passing frequency or wave excitation frequency ranges, even for larger blades and turbines [36].

Another example of turbines evolving with platforms is evident when considering the popularity around 2010–2015 of attaching a Vertical Axis Wind Turbine (VAWT) to a floating structure. This idea was popular due to the lower center of gravity of a VAWT compared to a typical Horizontal Axis Wind Turbine (HAWT). Early-concept designs with VAWTs included VertiWind [37], FAWT-S/C [38], and Aerogenerator [39]. There were also a number of small prototypes that made it to the sea (DeepWind Spar [40], Spinwind [41], and SeaTwirl [42]).

Since the mid-2010s there has been more limited interest in VAWTs in early-stage designs. While there are projects which are still looking at the potential of VAWTs for offshore wind (*e.g.*, the X-ROTOR project [43], Nihon VAWT barge [44]), the waning interest suggests a shift in the industry's perspective towards this technology. While the reason for this shift may be partially technological (*i.e.*, most floating VAWTs are deep spars, challenging for installation), it is likely mostly due to desires for standardization. HAWT wind turbines have mainly converged to three-bladed designs and are much more prevalent in onshore and fixed offshore wind than VAWTs. Therefore, many developers opt for a 'plug-and-play' approach with already-proven wind turbine technology.

While control, towers and VAWTs are not part of the platform, they do impact platform design. For example, optimizing the control in the wind turbine means that platforms can be more efficiently designed. Using multiple masts as opposed to a single tower to hold the wind turbine will result in a different distribution of forces on the platform. Finally, using a VAWT, compared to a HAWT, increases gyroscopic forces on the platform but reduces pitch overturning moments.

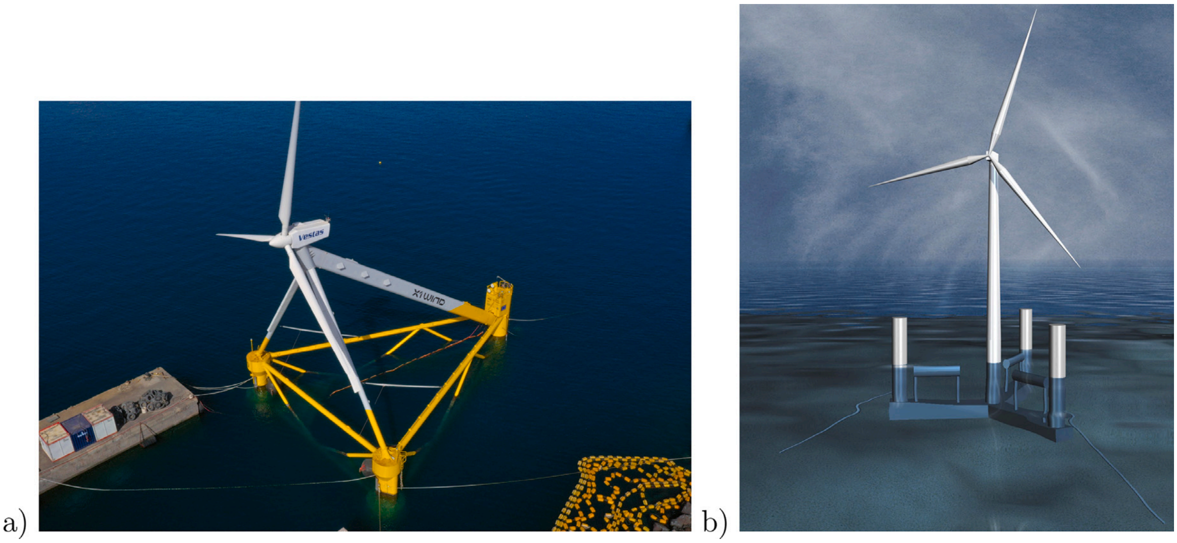

Fig. 4. (a) X1Wind, courtesy of X1Wind; (b) SFC, courtesy of NTNU.

4.2. Reduction in the complexity of semi-sub structures

As shown in Fig. 2, during phase III, there is an increase in popularity of semi-sub structures, which is likely due to the success of early semi-sub prototypes and demonstrators (*e.g.*, WindFloat [18], VolturnUS [45]). In fact, since the first WindFloat demonstrator was deployed in 2012, there have been at least 26 other three-column semi-sub platform concepts that have been designed, which is a clear example of platforms that have made it to the sea significantly impacting the space of early-stage devices.

A trend in semi-sub structures during this time is that the structures became less complex. That is, they were made with fewer parts, and manufacturability was more emphasized. For example, the semi-subs developed at the beginning of this phase typically included multiple braces, heave plates and/or pontoons. However, those developed at the end of the phase trended towards more material weight with fewer parts. Some platforms (*e.g.*, OO-Star [46], 5MW CSC [47]) were designed to avoid braces, since fatigue cracking was common in those parts and complex, expensive welding was necessary in brace-column joints [47]. This trend is illustrated in Fig. 5. The platform on the left of Fig. 5 shows what some of the platforms designed at the start of this phase looked like, whereas the middle platform shows what the platforms designed at the end of this phase look like. These figures were made loosely based on the 5 MW OC4 Semi-sub [48] and the 6 MW VolturnUS 1:8 prototype [45]. This figure serves as a visual representation of the design progression (the figure is not to scale). The shift illustrated in this figure suggests that the industry realized that material weight is not a sufficient measure of cost and efficiency, but rather manufacturability is also important. Furthermore, it shows that the additional forces from the wind turbine, that are not seen in the O&G industry, result in different design priorities, and consequently different resulting designs.

4.3. Early combination-type platforms

Another trend seen in this phase is the emergence of FOWT platforms that are a combination of the four commonly-defined ‘types’ of platforms (spar, semi-sub, TLP, barge). These four types of platforms are defined mainly by their stability mechanism, whereas a ‘combination-type’ platform uses multiple stability mechanisms. For example, the Cobra Semi-Spar is a combination semi-sub-spar platform. It acts as a semi-sub and uses semi-sub stabilization techniques during tow-out, but when the platform has reached its location of installation, water is added to the columns so that the platform has a lower center of gravity than most semi-subs, using both spar and semi-sub stability techniques [49]. Telwind is another combination semi-sub-spar platform. It acts as a semi-sub during tow-out, but when the platform has reached its location of installation, a weight is lowered, connected with taut tendons to the waterline structure, thus using spar stabilization techniques only during operation [50]. SSTLWT was a combination semi-sub-TLP platform. It was designed such that the platform, with turbine installed, was self-stable during tow-out, and then was connected to taut mooring lines to further increase stabilization at the location of installation [51]. Finally, AWC is a spar with an articulated joint, so it uses stabilization from the fixed joint in addition to the spar stabilization [52]. As shown in Fig. 2, there was a clear increase in these combination-type platforms during this phase, suggesting that the platform types that had been well-defined from the O&G industry were potentially not the only (or optimal) types for floating offshore wind.

4.4. Early hybrid platforms

Hybrid platforms combine another form of renewable energy on the same floating platform as the FOWT. Most commonly, it is a wave energy converter (WEC) that is added. These platforms seek to increase energy yield while sharing infrastructure between the WEC and FOWT. Additionally, some hybrid platforms aim to reduce platform loads and/or increase stability of the platform. Emerging as a trend during Phase III, a number of hybrid platform concepts have been developed in early stages. Principle Power (one of two developers with a farm-scale device) investigated the possibility of adding a WEC to their WindFloat design. Their early-stage designs were called WindWaveFloat 1, 2, and 3, and they consisted of three different types of WECs [53–55]. However, none of these made it to an at-sea prototype device.

Several other wind-wave hybrid platform concepts were designed in the early 2010s by Ecole Centrale de Nantes and INNOSEA: the THyP was a semi-sub with pitching WECs [56], and the C-HYP was a barge with Oscillating Water Columns [57]. The MARINA project also looked at different hybrid concepts. These concepts, developed at NTNU, were based on different ‘known’ FOWT platforms and WECs, to understand which combination of FOWT platform type and WEC would be most promising. The Spar-Torus Combination (STC) was inspired by the Hywind spar and Wavebob WEC [58]. The Semi-sub-Flap Combination (SFC, shown in Fig. 4b) was the 5MW CSC with 2–3 flap-type WECs attached to the pontoons [59]. The TLP and Point-Absorber (TLPWT+PA) was a TLP platform with three spherical point-absorbers

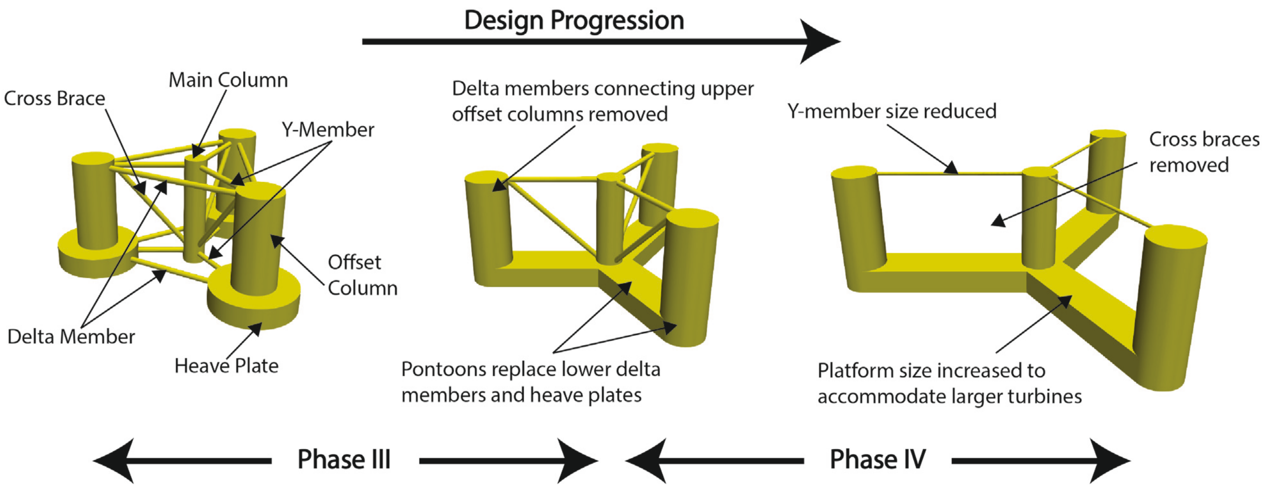

Fig. 5. Design progression of semi-sub platforms, showing how the platform has become less complex with fewer parts. These platforms are loosely based on the 5 MW OC4 Semi-sub [48], the 6 MW VolturnUS 1:8 prototype [45] and the 15 MW VolturnUS-S [32].

[60]. At the time of writing, the Floating Power Plant (FPP) is the only hybrid wind-wave platform to have made it to at-sea testing (which started in 2010) [61]. One benefit of this trend is that the development of hybrid platforms has brought expertise from wave energy into the FOWT platform industry.

5. Phase IV: Cost reduction strategies (2015-present)

Phase IV is characterized by cost-reduction strategies and contains the largest number of platforms (44). Only a few platforms developed during this phase have made it to the at-sea prototype stage, so many of the trends from this phase can only be seen from early-stage devices. There are three main strategies platform developers are taking to achieve cost reduction, which are sometimes conflicting: (i) specialization to a particular location or environment; (ii) increasing manufacturability/modularity of the platform; and (iii) designing an innovative platform which diverges further from conventional designs. In Edwards et al. [2], the first strategy (specialization to a particular environment) was observed in at-sea devices. Here, this category is expanded to cover the multitude of unique ways early-stage platforms are being designed to achieve this goal. The second category (modularity) is also emerging in at-sea devices, but an expanded set of designs are found in early-stage devices. The final category (innovative designs) is mostly seen only in early-stage designs.

5.1. Specialization to a particular location or environment

In both early-stage devices as well as at-sea prototypes and demonstrators [2], a trend to reduce costs by specializing a FOWT platform for a particular location or environment can be observed. This trend materializes in different aspects of the platform design, including unique ways to tow a platform out to its location of installation and/or fit in available ports, using a particular material due to its local availability and cost, or specializing the platform to a particular type of location at sea (in terms of water depth, wind, tidal, wave, and geotechnical characteristics).

5.1.1. Creative ways to tow-out/fit at a standard port

Water depth at most ports means there are installation and tow-out draft limits. This requirement favors semi-subs and barges, but early-concept modified spars and TLPs have been developed to work around these limits. For spars, one way to adhere to port depth constraints is to use a lowerable ballast technique, which turns the platform into a combination semi-sub-spar. For example, Telwind [97], Hexafloat (shown in Fig. 6a [109]), and TetraSpar (which deployed a demonstrator in 2022 [2]) use this technique by lowering a ballast weight from taut lines once at the location of installation. The MSPAR (shown in Fig. 6b) also uses a lowerable ballast, which is similarly raised during installation and tow-out, but then it is lowered using columns instead of taut lines [113]. The Stinger Keel (shown in Fig. 7) uses similar ideas, but instead of a suspended weight, it uses a truss spar. During tow-out and installation, the waterline structure is stable in isolation and the truss spar is towed behind, so that it adheres to draft limits. Then, at the location of installation the truss section is lowered to increase stability [107]. For all these semi-sub-spar combinations, the wind turbine is installed at port, avoiding the need for a floating crane (which is usually needed for conventional spar designs).

In addition to the lowerable ballast spars, other techniques have emerged for towing spars out to the location of installation. For example, Windcrete have developed a method whereby the spar is towed horizontally, then once it has reached the location of installation the structure is righted and ballasted until the top of the tower is only 20 m above the surface. Then, the turbine is installed, and finally ballast is pumped out until it is the correct height. This procedure requires deep water at the location of installation, and still requires a floating crane for the installation, but crane size is reduced [77]. Similarly, BT Wind lowers the tower into a truss-spar and tows the structure horizontally. Once at the location of installation, the structure is upturned and the turbine is installed while the tower is still lowered in the truss-spar. Finally, the tower is raised [121]. For the DTI-F system, the wind turbine tower is lowered into the spar substructure at the port for tow-out. This arrangement is towed vertically, with draft less than 25 m to a deeper assembly area where the nacelle and blades are added [122]. Finally, in addition to the lowerable ballast, Telwind also uses a self-erecting telescopic tower, which lowers the center of mass and increases stability during tow-out [50].

TLPs also typically have challenges associated with installation and tow-out, since usually the platform is unstable during tow-out, meaning a special installation vessel must be designed to tow it to the location of installation. To overcome this usually restrictively expensive and difficult barrier, GICON's SOF and the ECO TLP use a lowerable gravity anchor, whereby the concrete gravity anchor is used as a barge for tow-out, and ballast is added at the location of installation [71,123]. Pelastar uses a 'self-erecting nacelle' called the SENSE, whereby the turbine is installed to a track-and-carriage design at the base of the tower and erected at the location of installation, which eliminates the need for a floating crane or installation vessel [124]. X1Wind is a semi-sub-TLP combination platform. The single-point TLP portion is towed out and installed separately. Then, the rest of the platform, which uses

Table 1

Platform designs with lab testing completed for extreme conditions, including multi-turbine and hybrid platforms. The order (within each sub-category) is roughly chronological. For more information about a particular platform, see matching section in Edwards et al. [62].

Platform design name	Technology developer	Type	WTG rating for full-scale (MW)	Material	Water depth (m)	Mooring	Other use	More details about test	References
Single-use and single-turbine platforms									
FLOAT	Tecnomare	Spar	1.4	Concrete	75–500	8 lines: catenary or taut depending on water depth	N/A	1:48 scale of 1.4 MW	[4,6,12]
Dutch tri-floater	GustoMSC and NOV	Semi-sub	15	Steel		6 chain catenary lines (2 from each column)	N/A	1:50 scale of 5 MW, 1:50 scale of 15 MW	[4,11,63–68]
PelaStar	Glosten	TLP	15	Steel		5 taut lines		1:50 scale of 5 MW	[21,69–72]
GICON	GICON	TLP		Concrete		8 taut to gravity base	N/A	1:50 scale of 5 MW, 1:50 scale of 6 MW	[22,71,73–76]
Windcrete	UPC-BarcelonaTech and Windcrete	Spar	15	Concrete		3 catenary lines with delta connections	N/A	1:100 scale of 5 MW, 1:100 scale of 15 MW in wind tunnel	[33,77–84]
X1Wind	X1wind	TLP-semi-sub	15	Steel	40–500	Taut single point mooring	N/A	1:64 scale of 5 MW, 1:50 scale of 5 MW	[35,85–87]
OO-Star	Dr.Techn.Olav Olsend and Floating Wind Solutions AS	Semi-sub	11	Concrete, steel, or hybrid	50+	3 line catenary chains [162 mm in top 50 m, 142 mm lower]	N/A	1:40 scale of 6 MW, 1:36 scale of 10 MW	[29,46,88–91]
TLPWind	Iberdrola Engineering and Construction	TLP	5	Steel		8 taut mooring lines made from steel or synthetic material	N/A	1:36 scale of 5 MW, 1:40 scale of 5 MW	[24,92–94]
Articulated Wind Column (AWC)	AWC Technology	Spar-TLP	8	Concrete	80–200	Tension rod	N/A	1:42.5 scale of 8 MW	[52,95]
TELWIND	ESTEYCO	Spar-semi-sub	10	Concrete	100+	3 catenary lines	N/A	1:45 scale of 5 MW	[50,96–100]
NAUTILUS	Nautilus Floating Solutions	Semi-sub	10+	Steel		4 catenary lines	N/A	1:36 scale of 10 MW	[88,101–106]
Stinger Keel	Floating Energy Solutions	Semi-sub-spar	10	Steel and concrete			N/A	1:50 scale of 10 MW	[107,108]
Hexafloat	Saipem	Spar-TLP	12	Steel	130+	3–6 catenary lines with clump weights or 3–6 taut lines	N/A	1:? scale of 12 MW	[109,110]
TetraSub	Stiesdal	Semi-sub	15	Steel	50–200	3 catenary lines	N/A	1:60 scale of 10 MW	[28,111]
Li Y-shaped semi-sub	Harbin Institute of Technology	Semi-sub	5	Steel or concrete			N/A	1:60 scale of 5 MW	[112]
MSPAR	MonoBase Wind	Spar-semi-sub	15–20	Steel and concrete	90+		N/A	1:44 scale of ? MW	[113]
Multi-turbine platforms									
Flowocean	Flowocean	Semi-sub-TLP				Single-point mooring	N/A	1:50 scale of ? MW	[114]
Hybrid platforms									
STC (Spar-Torus Combination)	NTNU	Spar	5			3 catenary mooring lines with clump weights and delta connections	Wave power (one heaving torus)	1:50 scale of 5 MW	[58,115–118]
SFC (Semi-submersible Flap Combination)	NTNU	Semi-sub	5	Steel		3 catenary mooring lines	Wave power (three flap-type WECs)	1:50 scale of 5 MW	[59,118–120]

semi-sub stabilization techniques during tow-out, is connected. Therefore, the platform uses both semi-sub and TLP stabilization techniques during its lifetime, but no special installation vessel or floating crane is required [85]. As shown in Fig. 2, there has been a resurgence in the popularity of TLPs recently, which is possibly due to advancements in their tow-out techniques.

Fig. 6. (a) Hexafloat, courtesy of Saipem; (b) MSPAR, courtesy of MONOBASE wind.

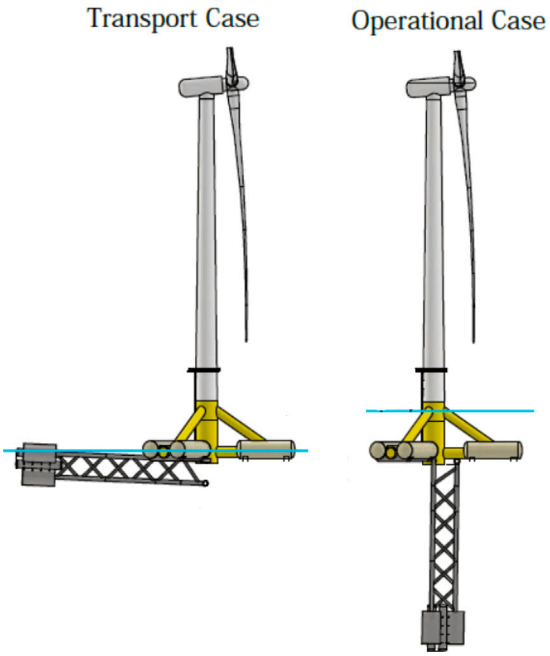

Fig. 7. StingerKeel, courtesy of Floating Energy Systems Ltd.

Though barges and semi-subs do not usually have the same water-depth and stability challenges during installation and tow-out as spars and TLPs, the width of the platform, especially for platforms supporting large turbines, can be limiting. Crane limits can influence the design, since it can be difficult, expensive or impossible for the crane to reach the middle of a very wide semi-sub or barge platform. Therefore, there has been an increase in the number of platforms where the turbine is on the side, instead of in the middle (*e.g.* Dutch Tri-Floater [64], TetraSub [111], INO WINDMOOR [125], W.SEMI [121], Wind Semi [126], T-Floater/D-Floater [127], INO12TM [128], Deepsea Semi [129], S-bos [130]). However, this configuration creates challenges for stability, especially in wind-wave misaligned seas. The success of WindFloat's design, which has the turbine on the side, may have influenced subsequent early-stage thinking. However, many early-stage semi-subs still opt for a central turbine, suggesting that the stability challenges are significant. Another way in which port size has affected semi-sub design is seen in platforms (*e.g.*, XCF [131], Telwind [50]) that restrict their width to be able to fit in a standard port. Additionally, there are platforms (*e.g.*, D-Floater and T-Floater [127]) designed for ease of substructure transport from the place of construction to the port of installation, with designs that can be stacked easily on a transport barge.

5.1.2. Material and specialization to a particular location at sea

Material availability is also an important consideration for a platform, to adapt the platform to the local supply chain to reduce costs, reduce embedded carbon, or to fulfill government targets on local content. The trend of platforms offering designs in multiple materials (*i.e.*, concrete or steel options) that has recently emerged in at-sea platforms (*e.g.*, DampingPool [132], VolturnUS [32]) is more expansive in early-stage devices (*e.g.*, Sea Reed [133], Nerewind [134], OO-star [46]) with a wider diversity of materials. For example, the FLOTANT barge uses a combination of concrete and plastic [135]. In contrast to the dominance of steel in earlier phase designs, the increased prevalence of other materials suggests that FOWT platform design has become much more multi-disciplinary, and the importance of circular economy is having an impact on the design space.

A location's particular sea-state (tidal, wind and wave characteristics), sea floor geology, and water depth are all aspects which have influenced platform designs. Sea-floor geology affects the type of platform that can be used in a particular location. For example, TLP anchors may not be well-suited for certain types of sediment. Even among platforms that use catenary moorings with anchors, some platforms may not be well-suited for particular locations due to the forces the mooring lines and anchors need to withstand. Some platforms (*e.g.*, FLOTANT [135], Hexafloat [109]) design different types of mooring systems for different locations.

Wind and wave characteristics clearly affect the loads the platform needs to withstand regularly (fatigue) and during extreme events (survivability). These requirements affect the structural strength needed in the platform and tower. Furthermore, wind-wave misalignment in a location can affect the platform design. For example, NAUTILUS (shown in Fig. 8a [101]) and XCF [131] are symmetric four-column semi-subs, with reducing sensitivity to wind-wave misalignment and increased stability listed as primary design drivers. Tidal characteristics can also significantly affect the type of platform. For example, TLPs may not be best suited for locations with large tidal ranges, due to large difference in the resulting forces in the taut mooring lines. Another unique platform concept designed for a particular location is the Eco TLP, whose substructure is designed to also be an artificial reef [123]. The MARLIN platform is designed for use in coastal communities, off-grid locations and Small Islands Developing States [136].

Early-stage designs specialized to specific depth ranges are also emerging. This is particularly the case for 'intermediate-depth' locations, *i.e.*, where fixed wind is uneconomic, but spars designed to hold large (10 MW+) turbines would be too deep (*i.e.*, 40–100 m water depth). Therefore, platforms that are optimal for locations with water depth less than 100 m may be different from those optimal at deeper water sites. This is likely why both shallow-draft platforms (semi-subs and barges) and spars (particularly lowerable ballast spars) continue to be popular in early-stage designs.

5.2. Increasing manufacturability and modularity

There is a clear trend in early-stage devices to decrease costs by increasing platform modularity. For example, NAUTILUS [101], Gazelle [156], Truss Float [159], XCF [131], Brunel [160], Telwind [50], SBM TLP [146], W.SEMI [121], and PelaFlex [161] all mention modularity and/or serial production in their design goals or benefits of their

Table 2
Platform designs with some lab testing done, including multi-turbine and hybrid platforms. The order (within each sub-category) is roughly chronological. For more information about a particular platform, see matching section in Edwards et al. [62].

Platform design name	Technology developer	Type	WTG rating for full-scale (MW)	Material	Water depth (m)	Mooring	Other use	More details about tests etc	References
Single-use and single-turbine platforms									
ELOMAR	AIOM and ENEL	TLP		Steel	30–100	6 taut lines	N/A	1:50 scale of ? MW, waves only	[4,8]
Doris TLP	Marseille Engineering University and Doris	TLP				Tensioned	N/A	1:49 scale of ?, MW	[4,19]
Pusan National University alternative spar	Pusan National University	Spar	3	Concrete		Catenary	N/A	1:75 scale of 2.5 MW, waves only	[137–139]
Tetrafloat	Tetrafloat	Semi-sub	10		30+	Single anchor; one catenary line that divides into two	N/A	1:120 scale of ? MW, 1:30 scale of 10 MW	[34,140, 141]
5MW-CSC	NTNU	Semi-sub	5	Steel	50–200	3 catenary lines	N/A	1:30 scale of 5 MW in operational conditions	[47,142–144]
SBM TLP	SBM	TLP	15	Steel	50+	3 sets of 2 taught chain lines	N/A	1:40 scale of 5 MW in operational conditions for 1st generation	[30,145, 146]
Triple spar	INNWIND	Semi-sub-spar	10	Concrete and steel		3 catenary lines	N/A	1:60 scale of 10 MW, operational wind and waves	[147]
DTI-F	Universities of Edinburgh, Strathclyde and Exeter	Spar	15	Concrete	60+	3 or 4 catenary lines	N/A	1:45 scale of 7 MW, waves only	[122,148]
Nihon University Moonpool VAWT	Nihon University	Barge	2			Modeled as linear springs	N/A	1:100 scale of 2 MW, regular waves only	[44,149]
Serbuoys-TLP	Dalian University	TLP	5			Taut with buoys halfway down lines	N/A	Platform and buoys tested separately in waves	[150]
WIND-bos	Bluenewables	Semi-sub-spar	10	Steel and concrete		Catenary	N/A	1:40 scale of 10 MW	[130,151]
INO WINDMOOR	SINTEF and Inocean	Semi-sub	12	Steel		3 hybrid (chain + polyester) catenary lines	N/A	1:40 scale of 12 MW in operational sea states w/extreme wind	[125,152]
Activefloat	COBRA and ESTEYCO	Semi-sub	15	Concrete		3 catenary lines	N/A	1:100 scale of 15 MW in wind tunnel using actuator	[81,84,153]
Trivane	Trivane	Barge	10	Steel		3 or 6-line catenary	N/A	1:50 scale of 10 MW	[154]
JMU Semi-sub	Nihon Shipyard and JMU	Semi-sub	12			4 catenary lines	N/A	1:64 scale of 12 MW, waves only	[155]
Gazelle	Gazelle Wind Power	Semi-sub-TLP	2	Steel	≤400 m		N/A	1:? scale test of 10 MW, decay tests, separate wind- and wave-only	[156]
Multi-turbine platforms									
WindSea	FORCE Technology, Statkraft, NLI	Semi-sub	3 × 3.2			Turret mooring	N/A	1:64 scale of ? MW	[13]

(*continued on next page*)

platforms. A focus on modularity is likely due to the relative success in early at-sea demonstrators. The industry has accepted that platforms can be stable, so focus has now shifted to practicalities of scaling the technology to commercial levels. Climate-related/Net-Zero targets for many countries for 2030 or 2035 goals rely on a very quick up-scale of floating wind, and modularity can enable these shifts in production capacities.

An example of the shift to modularity can be seen in the shift from the initial design to the current design of the SBM TLP. For the first design iteration, the goals were to minimize motion and minimize weight, and the result was three buoys connected via a truss to the central tower. However, for the current design iteration, the main goal was to increase industrialization, and the result was to use three horizontal cylinders connected directly to the central tower [146]. As another example, consider the Tetra platforms TetraSub (shown in Fig. 8b), TetraTLP (shown in Fig. 8c) and TetraSpar (discussed in Edwards et al. [2]). All three platforms use the same components and use the same 4–5 different types of braces. The platforms are designed so that no part of the platform is larger or heavier than the wind turbine tower, to ensure that the platform components are no more difficult to transport than the

Table 2 (*continued*).

Hybrid platforms									
WindWaveFloat 1 (flapping plates)	Principle Power/Marine Innovation and Technology	Semi-sub	5	Steel	40 m+	6 catenary lines	Wave power (three flapping plates)	1:78.5 scale of 5 MW with regular waves	[53,157]
WindWaveFloat 2 (point absorber)	Principle Power/Marine Innovation and Technology	Semi-sub	5	Steel	40 m+	6 catenary lines	Wave power (one spherical point-absorber)	1:78.5 scale of 5 MW with regular waves	[54,157]
WindWaveFloat 3 (OWC)	Principle Power/Marine Innovation and Technology	Semi-sub	5	Steel	40 m+	6 catenary lines	Wave power (one OWC)	1:78.5 scale of 5 MW with regular waves	[55,157]
TWWC	Hainan University	TLP	5			Tensioned with 4 lines	Wave power (one heaving donut-shape)	1:50 scale of 5 MW	[158]

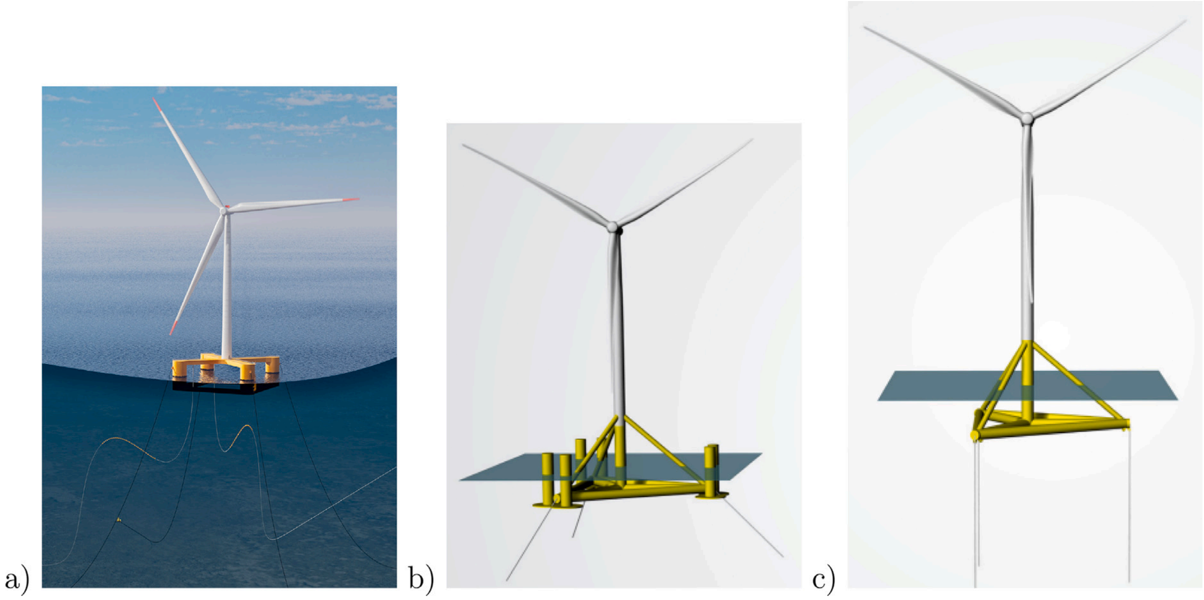

Fig. 8. (a) NAUTILUS, courtesy of Nautilus Floating Solutions; (b) TetraSub, courtesy of Stiesdal; and (c) TetraTLP, courtesy of Stiesdal.

tower [111]. In a similar approach, the MARLIN platform is designed so that each modular part is no larger than a standard shipping container, so that the platform can be shipped to remote communities and built without the need for a large marine construction yard or heavy lift vessel [136]. Some platforms (*e.g.*, Dutch Tri-floater [64]) are shifting to using flat plates, to form hexagonal columns, instead of rolling metal to form cylindrical columns. As another example, consider the evolution of Telwind: at first, the lowerable ballast spar platform was made of two cylinders (one wide, flat cylinder at the waterline and a taller, narrower one for the ballast). However, this platform has evolved to now look like a 'typical' three-column semi-sub at the waterline with a triangular ballast weight [98].

Related to increasing manufacturability, there is also a continuation of the trend mentioned in Phase III of decreasing the complexity of semi-subs. Of the four main 'types' of platforms, semi-subs are usually the most complex to manufacture, so streamlining these platforms by avoiding many different parts and difficult welding jobs eases the manufacturing process. Another advantage of avoiding parts like heave plates and braces is that those parts are more prone to high fatigue and are more costly for construction [47,126]. This trend is shown in Fig. 5: the platform in the middle shows what the platforms at the start of this phase looked like, and the platform on the right shows what they tend to look at the end of this phase. These figures are loosely based on the 6 MW VolturnUS 1:8 prototype [45] and the 15 MW VolturnUS-S [32]. It is clear that the platforms designed near the end of the phase have fewer parts. However, heave plates and braces are certainly not universally avoided, with many recent platforms (*e.g.*, Truss Float [159], W. SEMI [121], TwinWind [162], Deepsea Semi [129] and InSPIRE [163]) choosing to still include these features due to their advantages (reduction of weight and increase of added mass and viscous damping).

5.3. Innovative platform designs

The final main way that developers are trying to reduce platform costs is by developing an innovative substructure platform design, diverging further from conventional wisdom. Four main categories of such innovation are discussed here: hybrid platforms, multi-turbine platforms, combination-type platforms, and hydrodynamically innovative platforms.

5.3.1. More hybrid platforms, multi-turbine platforms and more combination-type platforms

As described in Section 4.4, combining a WEC with a FOWT has considerable advantages. The FOWT and WEC can share infrastructure (mooring, installation, operations and maintenance), and the overall

Table 3
Single turbine platform designs at early concept or with limited published information about testing. The order is roughly chronological. For more information about a particular platform, see matching section in Edwards et al. [62].

Platform design name	Technology developer	Type	WTG rating for full-scale (MW)	Material	Water depth (m)	Mooring	References
Single-use and single-turbine platforms							
Arcadis TLP	Arcadis	TLP		Steel with concrete gravity anchors		Taut with gravity anchors	[3]
MIT/NREL TLP	MIT/NREL	TLP	5	Steel and concrete	30–150	Taut	[9,164,165]
MIT/NREL SDB	MIT/NREL	Semi-sub (barge)	5	Steel and concrete	30–150	Catenary	[164]
Concept Marine Associates TLP	Concept Marine Associates	TLP				Taut	[23]
Hua concrete barge	Jianbo Hua	Barge	5	Concrete		Catenary	[166]
HiPRWind	Dr. techn. Olav Olsen	Semi-sub	1.5	Steel		3 catenary lines	[10]
Ocean Breeze	Xanthus Energy and Ocean Resource	TLP		Concrete and steel	60–200	4 taut lines	[20]
Sea Reed	Saipem and Naval Energies	Semi-sub	9.5	Steel, concrete, or hybrid	60	5 catenary lines	[133,167,168]
VertiWind	Nenuphar	Semi-sub	2	Steel		3 catenary lines with clump weights on each	[37,169–171]
FAWT-S/FAWT-C	KAIST	Spar	2	Steel with concrete ballast		2 catenary lines	[38,172]
Cobra SEMI SPAR	Cobra	Spar	5	Concrete		Catenary	[49]
Winflo	Nass & Wind, Saipem and DCNS	Semi-sub	1				[173]
SSTLPWT and TLPWT	I.D.E.A.S. Inc	TLP-semi-sub	5	Steel	50+	Catenary or taut	[51]
Aerogenerator X/NOVA	University of Cranfield/Grimshaw	Semi-sub	10	Steel	50–100	Catenary	[39,174]
NereWind	DORIS Group	Semi-sub	15	Steel, concrete or hybrid	70–250	Catenary	[134]
Inclined columns semi-sub	Huazhon University	Semi-sub	5			3 catenary lines with connection nodes	[175]
CT-bos	Bluenewables	TLP	20	Concrete		4 sets of 2 steel rod tendons connected to suction cans	[130,176]
S-bos	Bluenewables	Semi-sub	15	Concrete		Catenary	[130]
MARLIN	Frontier Technical	Semi-sub	2				[136]
SEALIFT	Nautica Windpower	Semi-sub-TLP				Pivot around fixed tension rod	[177]
PelaFlex	Marine Power Systems	TLP		Steel		6 taut lines from three corners	[161]
W.SEMI	Wison Offshore & Marine	Semi-sub	15	Steel		3–8 catenary lines	[121]
BT Wind	Wison Offshore & Marine	Spar	8	Steel	80–200		[121]
ECO TLP	DBD systems	TLP		Concrete	100–3000	Tensioned from floater to concrete base	[123]
FLOTANT barge	FLOTANT	Semi-sub (barge)	12	Concrete and plastic		Either 4-line semi-taut or 5-line catenary	[135]
Braceless-TLP	Huaneng Clean Energy Research Institute	TLP	10	Steel		6 taut lines	[178]
Wind Semi	Equinor	Semi-sub				3 catenary lines	[179]
TrussFloat	Dolphines	Semi-sub		Steel		Catenary	[159]
XCF	MAREAL	Semi-sub	15	Concrete		Catenary	[131]
T-floater/D-floater	Bassoe Technology	Semi-sub	20			Catenary	[127]
INO12TM	Technip Energies	Semi-sub	12				[128]
TetraTLP	Stiesdal	TLP	15	Steel	80–500	Taut	[111]
BRUNEL	Fred. Olsen 1848	Semi-sub	15	Steel		Single point mooring	[160,180]
OSIRenewables TLP	OSIRenewables	TLP	16	Steel	50–150	Tendons and taut mooring	[181]
Deepsea Semi	Odfjell Oceanwind	Semi-sub	15		60–1300		[129]
NASA floater	NASA, University of Maine, NREL, Atkins		15	Concrete			[182]

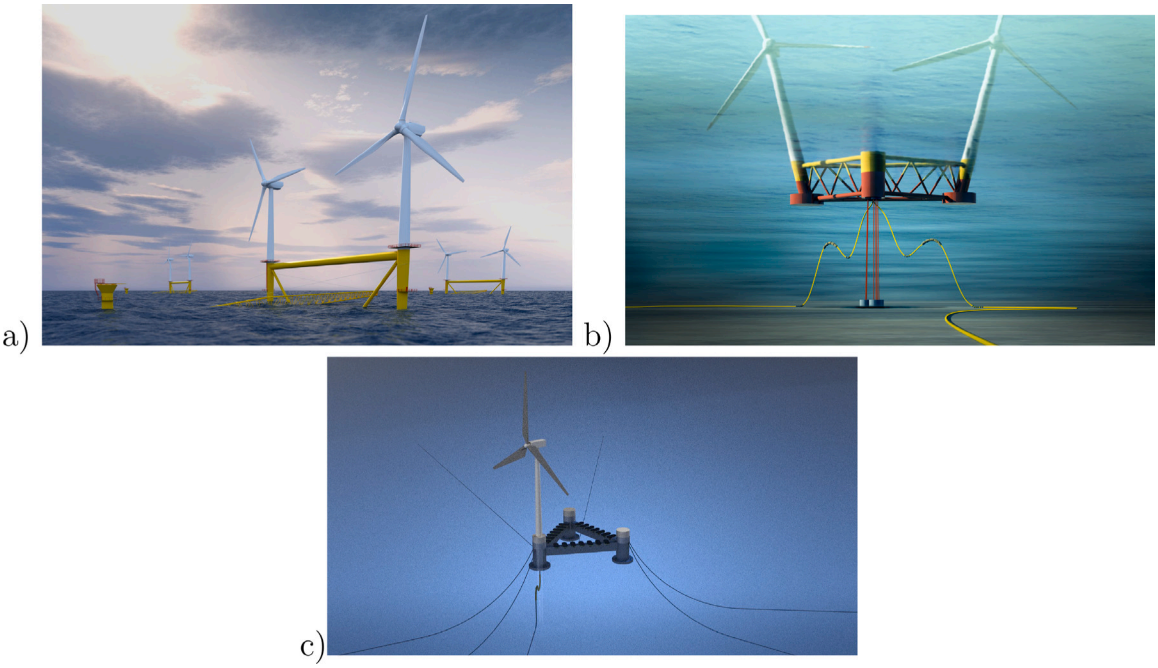

Fig. 9. (a) Flowocean, courtesy of Flowocean AB; (b) TwinWind, courtesy of Hexicon; (c) InSPIRE, courtesy of Bombora Wave.

energy yield can increase with the addition of the WEC. Phase IV has seen a continuation of the development of hybrid platforms. Some of these platforms are being developed by companies that were originally WEC developers (*e.g.*, PelaFlex/PelaGen [161] and InSPIRE [163]). Typically, these developers are seeking ways to incorporate their WEC design onto a FOWT platform. There have also been a number of feasibility studies of combining a certain type of FOWT platform with a certain type of WEC. For example, the TWWC (TLP-Wind turbine-WEC Combination) is a torus WEC on a TLP platform [158], and a semi-sub with a heaving torus has been considered, too [183].

While there are clearly considerable potential advantages to hybrid platforms, there are few that have completed lab tests in extreme conditions and only one prototype-scale device at-sea. The main reasons for the lack of commercialization of this system, compared to a stand-alone FOWT, are that (i) from research studies thus far, it seems that the WEC is likely to produce much less energy than the FOWT, (ii) there are concerns for the survivability of the WEC during extreme sea-states. However, there are plans for more hybrid platforms to be tested at-sea in the near future, suggesting that as yet the technology has been too nascent for at-sea trials, but development could help realize the great potential this technology has. In particular, now that stand-alone FOWTs are better understood and are reaching commercial success, there is more space and understanding to develop hybrid platforms.

Multi-turbine platforms have also seen early-stage development since the earliest days of FOWT platform design, but there has been a noticeable increase in their popularity recently, as shown in Fig. 2 (*e.g.,* Flowocean (shown in Fig. 9a [114]) and TwinWind (shown in Fig. 9b [162])). Installation, operations and maintenance account for a significant proportion of a platform's lifecycle cost. Multi-turbine platforms offer a way to decrease the number of total platforms, without decreasing yield. This could lead to reduced installation and operational costs, and the turbines would also share infrastructure, such as dynamic power cables and mooring lines. Additionally, some multi-turbine platforms diminish risk by relying on two smaller turbines instead of one larger turbine. Challenges with multi-turbine platforms include manufacturing a platform large enough for multiple turbines and designing for the situation when one of the turbines fails.

Introduced in Phase III (Section 4.3), there has been a continuation in the popularity of combination-type platform concepts, as shown in Fig. 2. In addition to the semi-sub-spar and semi-sub-TLP platforms discussed in Section 5.1.1, there have also been other combination-type platforms. For example, the Triple Spar is a semi-sub-spar combination, whereby the platform acts as a semi-sub during tow-out, but at the location of installation, ballast is added to lower the center of gravity, so that it uses mostly spar stabilization techniques during operation. The platform's operational draft is 54.5 m for a 10 MW turbine, shallower than most spars, due to the additional stability gained from the increased waterplane area moment [147]. Similarly, the MSPAR is designed to use both stability mechanisms and thus be not as deep as a typical spar (limited to 70 m for 15–20 MW systems) [113]. As another example of a combination-type platform, SEALIFT uses semi-sub stability, particularly during tow-out, but is then connected to a fixed rod at the location of installation to provide increased stability [177].

5.3.2. *Hydrodynamically innovative platforms*

A number of early-stage designs seek to design a hydrodynamically specialized substructure, which may look different than the four conventional types of platforms, to exploit hydrodynamic forces to minimize platform motion, which in turn improves wind turbine performance. These platforms range in status from early-concept level to pre-deployment (*i.e.* there is a planned demonstrator), though most fall into the former category. The platforms discussed in this section are particularly interesting because though perhaps not as likely to be built in the first phase of FOWT platform construction before 2035, they may have significant impact on the next generation of FOWT platforms. As is typical for a new technology, the first generation of FOWT platforms may not have reached engineering convergence, and there may be a way to design FOWT platforms that are smaller, and thus cheaper, but still stable.

There have been a number of academic studies that design a platform by considering the hydrodynamic response of particular aspects of the platform, which suggest that, theoretically, there could be significant improvements to current platform designs. For example, the Nihon VAWT barge, which has four moonpools and holds a VAWT, is designed this way to reduce heave and pitch motion of the barge, but it was found that second-order motions of the platforms may be significantly amplified by the gyroscopic forces of the VAWT [44].

Table 4
Multi-turbine and hybrid platform designs at early concept or with limited published information about testing. The order is roughly chronological. For more information about a particular platform, see matching section in Edwards et al. [62].

Platform design name	Technology developer	Type	WTG rating for full-scale (MW)	Material	Water depth (m)	Mooring	Other use	References
Multi-turbine platforms								
MUFOW	UCL, ECN, W.S. Atkins	Semi-sub		Concrete		Catenary chains	N/A	[4,7,185, 186]
TwinWind	Hexicon	Semi-sub		Steel	50+	Single-point mooring	N/A	[162,187]
Hybrid platforms								
ITI Energy Barge	ITI Energy	Barge	5			8 catenary lines (2 from each corner)	Wave power (OWC)	[14]
PelaGen/PelaFlex	Marine Power Systems	TLP		Steel	60 m+	Tensioned	Wave power (2 top-hinged)	[161]
SKWID	MODEC Inc	Spar				Catenary	Ocean current	[169,188]
THyP	LUNAM Université and INNOSEA	Semi-sub	5	Steel			Wave power (12 pitching)	[56]
C-HYP	LUNAM Université and INNOSEA	Semi-sub (barge)	5	Steel			Wave power (20 OWSCs)	[57]
TLPWT + PA	NTNU	TLP	5	Steel and concrete		Tensioned with 3 lines	Wave power (3 point absorbers)	[60]
OWCHyP	UCC	Semi-sub (barge)	5	Steel or concrete		20 catenary mooring lines	Wave power (20 OWCs)	[189]
SeaFlower	Fincantieri and Polytechnic of Turin	Semi-sub	5			6 catenary lines (1 from each corner)	Wave power (gyro)	[190]
Semi-sub + heaving torus	Dalian University	Semi-sub	5			3 catenary lines	Wave power (torus point absorber)	[183,191]
InSPIRE	TechnipFMC and Bombora	Semi-sub	12				Wave power (flexible membranes)	[163]

Another early-concept platform idea came out of Huazhong University of Science and Technology, who used inclined semi-sub columns to reduce heave response and mooring lines connected between columns to reduce surge motion [175]. Harbin Institute of Technology designed a Y-shaped semi-sub and compared how different materials changed the platform response, using the same underwater geometry. Their concrete platform, which required less ballast, had a higher pitch natural period (further from energetic wave frequencies), while the steel structure, which required more ballast, had a smaller average platform pitch motion and smaller tower base loads at the pitch natural frequency [112]. Pusan National University did an optimization of a spar-type platform and found that, compared to a standard cylindrical spar, a truss spar reduces heave, roll and pitch response [137]. The Hua barge is a single-piece structure that adapts to the incident sea-state. During storms, ballast is added to the structure to change the underwater geometry and waterline area [166].

Not just of academic interest, hydrodynamically innovative platforms also exist in the industry. Trivane is a trimaran platform, which was designed this way to utilize turret mooring [154]. Gazelle uses a central counterweight system, which means the platform is allowed to move horizontally and vertically, but pitch motion is minimized [156]. Another way in which developers are trying to make platforms smaller while still minimizing platform motion is by using active ballast (*e.g.*, NAUTILUS [88], ActiveFloat [81], W.SEMI [121]) or passive ballast (*e.g.* OO-Star [184], Dutch Tri-Floater [64], Wind Semi [126]). NASA, in collaboration with University of Maine, NREL and Atkins, are developing a floating platform using their motion mitigation system, which was originally used to minimize vibration in rockets [182].

6. Discussion of potential future trends

To understand what platform designs will look like in the future, it is important to consider potential future motivations. There are likely to be multiple, competing priorities for platform designers in the future, which will mean that the design space is pulled between increasing standardization and increasing specialization. For example, safety and operations and maintenance work will be important and difficult for FOWTs. To streamline and ensure reliability in the training of workforce and/or autonomous systems for operations and maintenance and installation of platforms, standardization of FOWTs and their platforms will be preferred, as opposed to needing multiple training for different types of FOWT platforms. Furthermore, it is the opinion of multiple industry players that research and innovation of FOWT platforms should stop now to allow for supply chains, ports, and workforces to be able to assemble and operate in such a way to reach 2030 and 2035 Net-Zero goals.

However, encouraging diversity in FOWT platforms will encourage better, more optimized solutions and could be better for local economies. Specializing platforms to a particular location may be more aligned with policy interests and be more beneficial to the industry as a whole. Considering the increasing need for a circular economy, there may be a greater push towards specializing based on local content, manufacturing, and workforce. Furthermore, considering future uses for the platform after it has been decommissioned and/or recyclability of materials may also influence future platform designs.

There have been some platforms designed recently which adapt certain aspects of their design to better suit a particular location. This trend is a sensible way to specialize to a particular location while standardizing certain aspects of the design. For example, some platforms (*e.g.* DampingPool [192], Sea Reed [133], Nerewind [134], OO-star [46]) have designed their platforms to be made from steel, concrete, or sometimes a hybrid of the two materials. As another example, some platforms (*e.g.*, FLOTANT [135], Hexafloat [109]) design multiple mooring configurations to suit different locations. The Stiesdal platforms (TetraSpar, TetraTLP and TetraSub, [111]) have the same components and parts but can be used in different locations based on which type of platform is most applicable. This trend of designing a platform to be adaptable will most likely continue in the future.

The innovative platform designs mentioned in Section 5.3.2, whereby the substructure is being designed to favorably take advantage

Fig. 10. BRUNEL, courtesy of Fred. Olsen 1848.

of hydrodynamic forces dependent on the substructure's geometry to reduce the entire structure's motion and/or forces, suggest that platform designs could change drastically. Subsequently, their performance could significantly improve and/or their cost could significantly decrease. While these more drastic changes may not influence platform designs in the very near future, platform development for later Net-Zero goals, such as those for 2050 and beyond, may be strongly influenced by these early-concept and/or academic studies. There have been a few more innovative designs of platforms with demonstrators in the past few years (*e.g.*, DampingPool [192], TetraSpar [193], Eolink [36], X1Wind [35], SATH [194]), and the relative success or otherwise of these platforms will likely influence whether industry move away from the current established designs (cylindrical spar and three-column semi-sub).

Larger turbines may also influence further FOWT platform design changes. As shown in Sergiienko et al. [195], as turbines are getting larger, the trends in how FOWT platforms are changing are not clear, suggestive of the nascent technology. Additionally, as turbines are getting larger and blade diameters are increasing, the blade passing (1P and 3P) frequency ranges are decreasing. Fixed wind turbine towers are designed so that their natural frequencies are between the 1P and 3P frequency range, but FOWT towers cannot be designed in this way for large turbines since this would mean that the tower natural frequency is within the wave excitation range. Therefore, FOWT towers must be built such that the natural frequency is above the 3P range, resulting in thicker steel and increasing the cost. Another option, already being explored by a few developers (*e.g.*, Eolink [36], X1Wind (shown in Fig. 4a [35]), Brunel (shown in Fig. 10) [160]) is to use multiple towers to connect the platform to the nacelle, instead of a single tower. In this configuration, the natural frequencies of the towers are not near the critical 1P and 3P ranges, meaning the steel need not be as thick as for a single tower and thus may be easier and cheaper to make. As more platforms are designed for 10 MW+ wind turbines, using multiple masts may become more common, which will most likely influence platform load distribution and, consequently, platform design.

The specific nature of how platforms will change with larger turbines is as yet unknown. Fig. 11 plots dimensions of early-stage platforms as functions of their wind turbine generator (WTG) capacity. Spar draft, semi-sub draft, and semi-sub width all show very weak correlation to WTG capacity, suggesting that the platforms are changing each time they up-scale. Though the correlations are weak, spar draft and semi-sub width are generally increasing with WTG capacity, and semi-sub draft is generally staying pretty constant, reflecting their respective stability mechanisms. If semi-sub platforms do get wider with larger turbines, this could cause more difficulties in adhering to constraints due to port requirements, such as width and draft limits and crane reach limits.

Considering the vast range of early-stage FOWT platforms presented in this study, predicting the most successful FOWT platforms in the future is a difficult task. It seems clear that one focus of the sector is on three-column semi-subs. Most likely due to the success of the Windfloat platform, many other companies have looked to design their own version of it, each with its own unique aspect. However, it also seems like there are other designs with advantages that could be promising directions for the technology. For example, multi-turbine and hybrid (especially wind-wave) platforms have the significant advantage of saving on infrastructure, installation and maintenance costs. Furthermore, multi-mast platforms are an interesting solution with clear advantages. Also, it seems clear that combination-type platforms, which utilize multiple benefits from the four classical types of floating platform, provide stability and cost-reduction benefits. TLPs have seen a resurgence in popularity recently. Their low-weight has always been an advantage, and their recent resurgence could be due to advancements in tow-out procedures. The conceptual academic studies and industry designs discussed in Section 5.3.2 suggest that platforms can be significantly improved by using a drastically different, hydrodynamically specialized design. Finally, platforms which allow for certain aspects (*i.e.* material, mooring) to be adaptable have a definite advantage, to allow for the platform to be specialized to a particular location but still standardizing certain aspects of the design.

This review focuses solely on FOWT platform designs, but the entire system of a FOWT, including the turbine, tower, mooring, dynamic power cable, and anchoring, is connected and coupled. To better understand the loads on and global motions of FOWT platforms, it is necessary to look at the interaction of these elements with the platform. However, this review can be a useful resource to summarize the current state-of-the-art of FOWT platform designs, for academic and industrial researchers focused on this subject area, but also for those researching the mentioned connected aspects of the FOWT system.

7. Conclusion

In this work, 86 early-stage FOWT platforms are reviewed, ranging from those at the early concept stage to those that have undergone lab testing simulating extreme conditions. Detailed information about all 86 early-stage FOWT platforms have been prepared to complement this paper for interested readers [62]. In the document, the design evolution of each platform design is summarized. For each device, the following is included (if available): (i) a description of the platform and its unique features, (ii) a rough timeline of development, (iii) design goals and constraints, (iv) evolution of the design, (v) lab testing information, and (vi) published dimensions. The purpose of this review was to examine and characterize the recent divergence in FOWT platform design, and to determine potential future trends in the industry based on evolution of and trends in early-stage designs. Four phases in the evolution of platform design have been identified, and trends within each phase have been explained.

Phase I is characterized by proof-of-concept studies and exploratory concepts. Phase II is characterized by O&G influence, wherein O&G companies used their industry experience to design FOWT platforms very similar to floating O&G platforms. A trend has been observed that TLP platforms were popular in this phase, but interest in the platform decreased after this phase, suggesting a shift in industry interest or technological problems encountered. Phase III is characterized by platforms changing to be more specialized to the specific needs of floating wind. For example, there is a trend towards reduction of the complexity of semi-sub platform substructures, *e.g.*, through removing components such as braces and heave plates. This phase also saw the emergence of combination-type platforms, which adopt stability mechanisms from multiple of the four traditional types of floating offshore platforms (spar, tension leg platform, barge and semi-sub), and hybrid platforms, which also include a wave energy converter (WEC) in addition to the FOWT. The trends shown in early-stage devices from Phase III have already influenced devices which have reached the sea.

By the start of Phase IV, the earliest at-sea demonstrators had proven that FOWT platforms could be manufactured and be made

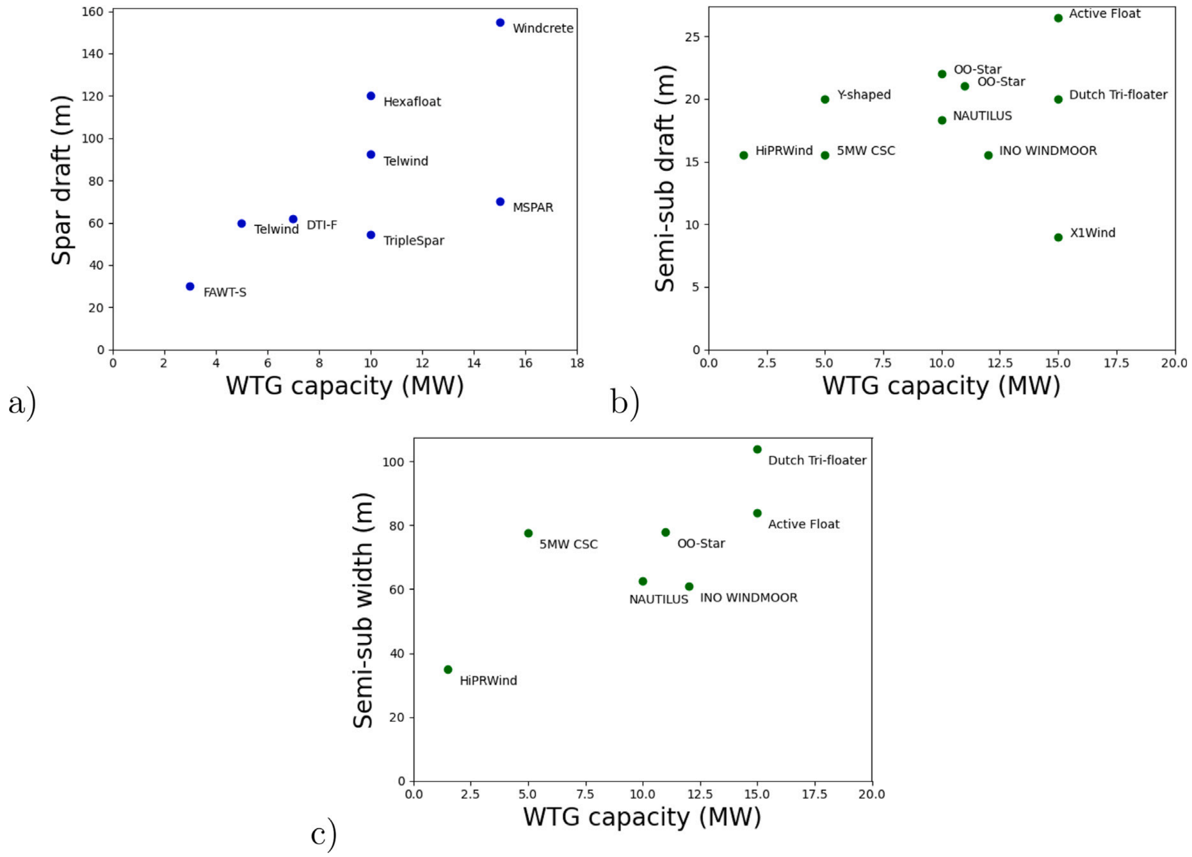

Fig. 11. Dimensions of platforms (y-axis), including (a) spar draft, (b) semi-sub draft, and (c) semi-sub width, compared to their wind turbine generator capacity (x-axis). For each device, see matching section in Edwards et al. [62] for references.

stable, so the most important and influential design driver switched to be cost reduction. The platforms in this phase are characterized by the following cost reduction strategies. (i) Some platforms are highly specialized to a specific location/environment, for example designs adhering to port/tow-out requirements and/or deployment location. (ii) There is an increasing focus on modularity/manufacturability of platforms, which allow for an increased ability to up-scale. (iii) There is an increase in innovative platform designs that deviate further from conventional designs. For example, there is an increase in multi-turbine platforms, combination-type platforms, hybrid platforms, and platforms aiming to exploit the hydrodynamic forces on the platform to reduce the structure's motion and/or forces.

By extrapolating recent observed trends in FOWT platforms, especially from Phase IV, potential future trends in the technology can be conjectured and discussed. Looking forward, there is likely to be an interplay and/or compromise between standardization (*i.e.*, platforms should have similar port/towing requirements, safety considerations and supply chains) and specialization (leading to more optimized solutions and better integration with local supply chains). The future balance of these two (sometimes competing) areas is uncertain, but it could plausibly be that standardization constrains the space in which specialization takes place (for example, through specific port requirements) or that platforms become more adaptable to be able to specialize to more than one location. It seems likely that FOWT platforms will further blur the lines between the four traditional floating offshore platform types in the search of more optimal designs for FOWTs. The hybrid platform design space also offers several advantages, though it is relatively nascent still. Likewise, multi-turbine platforms could offer advantages in future, though challenges must be explored and researched more. Finally, the predicted desire for larger turbines will likely be a major driver for FOWT platforms and could significantly impact platform design.

Overall, while early FOWT platform design was heavily influenced by the O&G industry, there has been a consistent trend, especially in early-stage platform designs, away from these conventional platforms used for floating offshore structures, to platforms better suited for FOWTs. Though overall design drivers of ensuring platform stability and reducing costs have stayed consistent, novel strategies for cost reduction have resulted in an incredibly wide and diverging range of platform designs.

Floating offshore wind is becoming commercialized, and it has been identified as a vital technology to meet NetZero goals. Therefore, the recent divergence in FOWT platform design, the focus of this review, is pertinent to the relevant industries and policy makers. It suggests that there will likely be a set of preferred platforms for the first set of Net-Zero goals which will change for later goals as the technology is developed and optimized further. This conclusion is optimistic, because while more research is clearly required to determine the optimal solutions for FOWT platform designs, it suggests that there is likely still much improvement to be seen for the technology.

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.

Acknowledgments

This study has been produced under the resources of the Cornwall FLOW Accelerator Project, which is led by Celtic Sea Power and delivered in partnership with the University of Plymouth, the University of Exeter and the Offshore Renewable Energy (ORE) Catapult. The Cornwall FLOW Accelerator Project has been supported by a grant from the European Regional Development Fund, project number O5R19P03188. The authors gratefully acknowledge that this work was partly funded by the Engineering and Physical Sciences Research Council, UK, through the “Supergen ORE Hub” grant (EP/S000747/1), and “Extreme Loading on Floating Offshore Wind Turbines (FOWTs) under Complex Environmental Conditions” grant (EP/T004177/1). We are also grateful to the companies who provided illustrative Figures for this manuscript (all credited individually in respective image captions). Dr E Barbour is gratefully acknowledged for his help with many aspects of the manuscript.

References

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

[2] Edwards EC, Holcombe A, Brown S, Ransley E, Hann M, Greaves D. Evolution of floating offshore wind platforms: A review of at-sea devices. Renew Sustain Energy Rev 2023;183.

[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. In: Journal of physics: conference series. IOP Publishing; 2018.

[6] Tong K, Cannell C. Technical and economical aspects of a floating offshore windfarm. Wind Eng 1993;108–12.

[7] Barltrop N. Multiple unit floating offshore wind farm (MUFOW). Wind Eng 1993;183–8.

[8] Bertacchi P, Di Monaco A, De Gerloni M, Ferranti G. Elomar—A Moored platform for wind turbines. Wind Eng 1994;189–98.

[9] Sclavounos PD, Lee S, DiPietro J, Potenza G, Caramuscio P, De Michele G. Floating offshore wind turbines: tension leg platform and taught leg buoy concepts supporting 3-5MW wind turbines. In: European wind energy conference (EWEC). 2010, p. 20–3.

[10] DrtechnOlav Olsen. HYPRWIND: Development of a column stabilized floater for 1.5MW test wind turbine. Technical report, Dr.techn. Olav Olsen; 2011.

[11] Henderson AR, Bulder B, Huijsmans R, Peeringa J, Pierik J, Snijders E, van Hees M, Wijnants GH, Wolf MJ. Feasibility study of floating windfarms in shallow offshore sites. Wind Eng 2003;27(5):405–18.

[12] Tong K. Technical and economic aspects of a floating offshore wind farm. J Wind Eng Ind Aerodyn 1998;74:399–410.

[13] FORCE Technology. Windsea - an offshore wind concept designed for the future. 2022, Accessed: 2022-07-28. https://forcetechnology.com/no/cases/offshore-wind-for-the-future.

[14] Jonkman J, Buhl M. Development and verification of a fully coupled simulator for offshore wind turbines. In: 45th AIAA aerospace sciences meeting and exhibit. 2007, p. 212.

[15] Blue H Engineering. Historical development. 2022, Accessed: 2022-04-27. https://www.bluehengineering.com/historical-development.html.

[16] 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, National Renewable Energy Lab (NREL), Golden, CO; 2013.

[17] 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.

[18] 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.

[19] Molin B, Remy F, Facon G. Etude expérimentale du comportement hydro-aéro-elastique d’une eolienne offshore sur ancrages tendus. In: Ocean energy conference, brest, france. 2004.

[20] Ocean Resource. Ocean breeze - floating offshore wind. 2020, Accessed: 2022-07-22. http://www.oceanresource.co.uk/Ocean-Breeze.html.

[21] Glosten. PELASTAR. 2022, Accessed: 2022-09-22. https://glosten.com/project/pelastar/.

[22] Adam F, Myland T, Dahlhaus F, Großmann J. GICON®-TLP for wind turbines—the path of development. In: The 1st international conference on renewable energies offshore (RENEW). 2014, p. 24–6.

[23] Butterfield S, Musial W, Jonkman J, Sclavounos P. Engineering challenges for floating offshore wind turbines. Technical report, National Renewable Energy Lab (NREL), Golden, CO (United States); 2007.

[24] Zamora-Rodriguez R, Gomez-Alonso P, Amate-Lopez J, De-Diego-Martin V, Dinoi P, Simos AN, Souto-Iglesias A. Model scale analysis of a TLP floating offshore wind turbine. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[25] Otter A, Murphy J, Pakrashi V, Robertson A, Desmond C. A review of modelling techniques for floating offshore wind turbines. Wind Energy 2022;25:831–57.

[26] 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.

[27] Larsen TJ, Hanson TD. A method to avoid negative damped low frequent tower vibrations for a floating, pitch controlled wind turbine. In: Journal of physics: conference series, Vol. 75. IOP Publishing; 2007.

[28] Gandia Santaya A. Experimental study of novel control strategies for a 10 MW tetrasub floating wind turbine (Master’s thesis), DTU; 2021.

[29] Pegalajar-Jurado A, Bredmose H, Borg M, Straume JG, Landbø T, Andersen HS, Yu W, Müller K, Lemmer F. State-of-the-art model for the LIFES50+ OO-star wind floater semi 10MW floating wind turbine. In: Journal of physics: conference series. IOP Publishing; 2018.

[30] Melis C, Caille F, Perdrizet T, Poirette Y, Bozonnet P. A novel tension-leg application for floating offshore wind: Targeting lower nacelle motions. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2016.

[31] Gaertner E, Rinker J, Sethuraman L, Zahle F, Anderson B, Barter G, Abbas N, Meng F, Bortolotti P, Skrzypinksi W, Scott G, Feil R, Bredmose H, Dykes K, Shields M, Allen C, Viselli A. Definition of the IEA 15-megawatt offshore reference wind. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States); 2020.

[32] Allen C, Viscelli A, Dagher H, Goupee A, Gaertner E, Abbas N, Hall M, Barter G. Definition of the umaine volturn US-S reference platform developed for the IEA wind 15-megawatt offshore reference wind turbine. Technical report, National Renewable Energy Lab (NREL), Golden, CO; 2020.

[33] Vázquez D’andrea JM. Study of the motions and nacelle accelerations of the Windcrete floating offshore wind turbine according to the IEC 64100-3 procedure (Master’s thesis), Universitat Politècnica de Catalunya; 2020.

[34] Simpson M, Davenne T, Garvey S. Dynamic response of a tetrahedral floating wind turbine platform. In: Offshore energy stroage symposium. 2016.

[35] X1Wind. X1wind: disrupting offshore wind. 2022, Accessed: 2022-06-23. https://www.x1wind.com/technology/.

[36] Eolink. Floating offshore wind energy. 2020, Accessed: 2022-05-19. http://eolink.fr/en/.

[37] Tjiu W, Marnoto T, Mat S, Ruslan MH, Sopian K. Darrieus vertical axis wind turbine for power generation II: Challenges in HAWT and the opportunity of multi-megawatt darrieus VAWT development. Renew Energy 2015;75:560–71.

[38] Akimoto H, Tanaka K, Uzawa K. Floating axis wind turbines for offshore power generation—A conceptual study. Environ Res Lett 2011;6.

[39] Collu M, Brennan F, Patel M. Conceptual design of a floating support structure for an offshore vertical axis wind turbine: the lessons learnt. Ships Offshore Struct 2014;9(1):3–21.

[40] Pedersen T, Paulsen U, Vita L, Madsen H, Nielsen P, Kragh K, Enevoldsen K, Sørensen S, Rasmussen M, Kjaersgaard R, et al. Design and manufacture of an offshore concept wind turbine–the deepwind demonstrator. Tech. Rep. E-0030, DTU Wind Energy; 2013.

[41] OffshoreWINDbiz. VIDEO: sea launch of Gwind turbine- floating gyro-stablized VAWT. 2013, Accessed: 2022-07-27. https://www.offshorewind.biz/2013/09/02/video-sea-launch-of-gwind-turbine-floating-gyro-stabilized-vawt/.

[42] Willén E, Schou P. SeaTwirl: A game-changer in offshore wind. 2020, Accessed: 2022-06-14. https://seatwirl.com/content/uploads/LCoE-SeaTwirl-1.pdf.

[43] Leithead W, Camciuc A, Amiri AK, Carroll J. The X-Rotor offshore wind turbine concept. In: Journal of physics: conference series. IOP Publishing; 2019.

[44] Ikoma T, Tan L, Moritsu S, Aida Y, Masuda K. Motion characteristics of a barge-type floating vertical-axis wind turbine with moonpools. Ocean Eng 2021;230.

[45] 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.

[46] Landbø T. OO-star wind floater: The future of offshore wind?. 2018, Accessed: 2022-06-21. https://www.sintef.no/globalassets/project/eera-deepwind-2018/presentations/closing_landbo.pdf.

[47] Luan C. Design and analysis for a steel braceless semi-submersible hull for supporting a 5-MW horizontal axis wind turbine (Ph.D. thesis), NTNU; 2018.

[48] Robertson AN, Jonkman JM, Goupee AJ, Coulling AJ, Prowell I, Browning J, Masciola MD, Molta P. 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.

[49] COBRA. Cobra’s developments in floating offshore wind. 2016, Accessed: 2022-07-28. https://www.eu-japan.eu/sites/default/files/imce/seminars/2016-09-27-WindEnergy/10_cobra.pdf.

[50] Dankelmann S, Visser B, Gupta N, Serna J, Counago B, Urruchi A, Fernández C, Garcia RG, Jurado A. TELWIND- integrated telescopic tower combined with an evolved spar floating substructure for low-cost deep water offshore wind and next generation of 10 MW+ wind turbines. In: Wind europe. 2016.

[51] Copple RW, Capanoglu C. Conceptual design of an offshore wind tower (OWT) support structure stable to transport with hybrid in-place tethering system. In: The Twenty-Fourth international ocean and polar engineering conference. OnePetro; 2014.

[52] Rousse B, Langeard O, Broughton P, Davies RL. AWC, a new concept of offshore wind turbine derived from oil & gas technology. In: XIVèmes journées nationales génie côtier - génie civil. 2016.

[53] Peiffer A, Roddier D. Design of an oscillating wave surge converter on the windfloat structure. In: Proceedings of the 2012 4th international conference on ocean energy (ICOE), Dublin, Ireland. 2012, p. 17–9.

[54] Peiffer A, Roddier D, Aubault A. Design of a point absorber inside the WindFloat structure. In: International conference on offshore mechanics and arctic engineering. 2011, p. 247–55.

[55] Aubault A, Alves M, Sarmento A, Roddier D, Peiffer A. Modeling of an oscillating water column on the floating foundation WindFloat. In: International conference on offshore mechanics and arctic engineering. 2011, p. 235–46.

[56] Soulard T, Babarit A, Borgarino B. Preliminary assessment of a semi-submersible floating wind turbine combined with pitching wave energy converters. In: 10th european wave and tidal energy conference (EWTEC2013). 2013.

[57] Soulard T, Babarit A, Borgarino B, Wyns M, Harismendy M. C-HyP: A combined wind and wave energy platform with balanced contributions. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2013.

[58] Muliawan MJ, Karimirad M, Moan T. Dynamic response and power performance of a combined spar-type floating wind turbine and coaxial floating wave energy converter. Renew Energy 2013;50:47–57.

[59] Luan C, Michailides C, Gao Z, Moan T. Modeling and analysis of a 5 MW semi-submersible wind turbine combined with three flap-type wave energy converters. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[60] Bachynski EE, Moan T. Point absorber design for a combined wind and wave energy converter on a tension-leg support structure. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2013.

[61] Yde A, Bellew SB, Clausen RS, Nielsen AW. Experimental and theoretical analysis of a combined floating wave and wind energy conversion platform. Technical report, DTU Wind Energy; 2014.

[62] Edwards EC, Holcombe A, Brown S, Ransley E, Hann M, Greaves D. Supplementary information on early-stage floating offshore wind platform designs. 2023, http://dx.doi.org/10.24382/scvw-0t77.

[63] NOV. Tri-floater floating offshore wind turbine foundation. 2022, Accessed: 2022-06-23. https://www.nov.com/products/tri-floater-floating-offshore-wind-turbine-foundation.

[64] GustoMSC, NOV. Tri-floater floating offshore wind turbine foundation: robust and cost-effective. Technical report, GustoMSC and NOV; 2021, Accessed: 2022-06-23.

[65] de Ridder E-J, Otto W, Zondervan G-J, Huijs F, Vaz G. Development of a scaled-down floating wind turbine for offshore basin testing. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[66] Huijs F, de Bruijn R, Savenije F. Concept design verification of a semi-submersible floating wind turbine using coupled simulations. Energy Procedia 2014;53:2–12.

[67] Bulder B, Henderson A, Huijsmans R, Peeringa J, Pierik J, Snijders E, van Hees MT, Wijnants G, Wolf M. Floating offshore wind turbines for shallow waters. In: EWEC 2003. 2003.

[68] Bulder B, van Hees M, Henderson A, Huijsmans R, Pierik J, Snijders E, Wijnants G, Wolf M. Study to feasibility of and boundary conditions for floating offshore wind turbines. In: ECN, MARIN, TNO, TUD, MSC, lagerway the windmaster, Vol. 26. 2002, p. 70–81.

[69] SENSEwind. Sensewind: Engineering to reduce the cost of wind energy. 2022, Accessed: 2022-06-22. https://sensewind.com/.

[70] Vita L, Ramachandran G, Krieger A, Kvittem MI, Merino D, Cross-Whiter J, Ackers BB. Comparison of numerical models and verification against experimental data, using Pelastar TLP concept. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2015.

[71] GICON. The GICON-SOF. 2022, Accessed: 2022-06-22. http://www.gicon-sof.de/en/sof1.html.

[72] GICON Group. GICON group. 2022, Accessed: 2022-09-22. https://www.gicon.de/gicon-group.

[73] Adam F, Steinke C, Dahlhaus F, Großmann J. GICON®-TLP for wind turbines–validation of calculated results. In: The Twenty-Third international offshore and polar engineering conference. OnePetro; 2013.

[74] Adam F, Myland T, Dahlhaus F, Groß mann J. Scale tests of the GICON®-TLP for wind turbines. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[75] Hyland T, Adam F, Dahlias F, Großmann J. Towing tests with the GICON®-TLP for wind turbines. In: The Twenty-Fourth international ocean and polar engineering conference. OnePetro; 2014.

[76] Walia D, Schünemann P, Hartmann H, Adam F, Großmann J. Numerical and physical modeling of a tension-leg platform for offshore wind turbines. Energies 2021;14(12).

[77] Windcrete. Windcrete: concrete floating platform for wind turbines. 2022, Accessed: 2022-07-01. https://www.windcrete.com/.

[78] Mahfouz MY, Molins C, Trubat P, Hernández S, Vigara F, Pegalajar-Jurado A, Bredmose H, Salari M. Response of the international energy agency (IEA) wind 15 MW WindCrete and activefloat floating wind turbines to wind and second-order waves. Wind Energy Sci 2021;6(3):867–83.

[79] Campos A, Molins C, Gironella X, Trubat P, Alarcón D. Experimental RAO's analysis of a monolithic concrete spar structure for offshore floating wind turbines. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2015.

[80] Campos A, Molins C, Gironella X, Trubat P. Spar concrete monolithic design for offshore wind turbines. In: Proceedings of the institution of civil engineers-maritime engineering, Vol. 169. Thomas Telford Ltd; 2016, p. 49–63.

[81] Mahfouz MY, Salari M, Hernández S, Vigara F, Molins C, Trubat P, Bredmose H, Pegalajar-Jurado A. Public design and FAST models of the two 15MW floater-turbine concepts. Technical report, COREWIND; 2020, Accessed: 2022-07-01.

[82] Matha D, Sandner F, Molins C, Campos A, Cheng PW. Efficient preliminary floating offshore wind turbine design and testing methodologies and application to a concrete spar design. Phil Trans R Soc A 2015;373.

[83] Trubat P, Molins C, Alarcon D, Arramounet V, Mahfouz MY. Mooring fatigue verification of the WindCrete for a 15 MW wind turbine. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2021.

[84] Fontanella A, Facchinetti A, Di Carlo S, Belloli M. Wind tunnel investigation of the aerodynamic response of two 15 MW floating wind turbines. Wind Energy Sci Discuss 2022;1–25.

[85] PivotBuoy. PivotBuoy: An advanced system for cost-effective and reliable mooring, connection, installation & operation of floating wind. 2022, Accessed: 2022-06-23. https://pivotbuoy.eu/.

[86] Urbán AM, Voltà L, Lio W, Torres R. Preliminary assessment of yaw alignment on a single point moored downwind floating platform. In: Journal of physics: conference series. IOP Publishing; 2021.

[87] Maximiano A. D5.4 benchmark of pivotbuoy compared to other floating systems. Technical report, PivotBuoy; 2019, Accessed: 2022-06-22.

[88] Yu W, Müller K, Lemmer F. D4.2 public definition of the two LIFES50+ 10MW floater concepts. Technical report, University of Stuttgart; 2018.

[89] LifeS50+ consortium. Innovative floating offshore wind energy. 2022, Accessed: 2022-06-21. https://lifes50plus.eu/.

[90] Bayati I, Belloli M, Bernini L. D3.2 Wind turbine scaled model. Technical report, Politecnico di Milano; 2016.

[91] Anderson H, Dufseth E, Straume J, Madsen M, Laukeland L, Landbø, Alveberg H-K, Birkeland G. D1.2 concept description report. Technical report, FLAGSHIP; 2021, Accessed: 2022-06-22.

[92] Amate J, Sánchez GD, González G. Development of a semi-submersible barge for the installation of a TLP floating substructure. tlpwind® case study. In: Journal of physics: conference series. IOP Publishing; 2016.

[93] Oguz E, Day AH, Clelland D, Incecik A, Dai S, Lopez JA, González G, Sánchez GD. Experimental study of a TLP offshore floating wind turbine. In: ICMT 2014. 2016.

[94] Oguz E, Clelland D, Day AH, Incecik A, López JA, Sánchez G, Almeria GG. Experimental and numerical analysis of a TLP floating offshore wind turbine. Ocean Eng 2018;147:591–605.

[95] AWC Technology. Cost-effective floating foundations. 2021, Accessed: 2022-06-23. https://awctechnology.com/.

[96] Armesto JA, Jurado A, Guanche R, Couñago B, Urbano J, Serna J. Telwind: Numerical analysis of a floating wind turbine supported by a two bodies platform. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2018.

[97] ESTEYCO. TELWIND project. 2018, Accessed: 2022-07-12. https://www.esteyco.com/projects/telwind/.

[98] Rodriguez-Lôpez E, Moreno-Narrillos C, Rueda-Guglieri F, Yáñez-González Á. Time domain hydrodynamics at panel level: an application to the structural analysis of telwind. In: Journal of physics: conference series. IOP Publishing; 2022.

[99] Yang Y, Bashir M, Wang J, Michailides C, Loughney S, Armin M, Hernández S, Urbano J, Li C. Wind-wave coupling effects on the fatigue damage of tendons for a 10 MW multi-body floating wind turbine. Ocean Eng 2020;217.

[100] Yang Y, Bashir M, Sakaris C, Loughney S, Wang J, Michailides C, Li C. Tuned mass damper effects on the tendon responses of a novel 10 MW multi-body floating offshore wind turbine platform. In: Developments in renewable energies offshore. CRC Press; 2020, p. 424–32.

[101] Solutions NF. We design offshore wind floating solutions. 2022, Accessed: 2022-06-30. https://www.nautilusfs.com/.

[102] Mahfouz M, Faerron-Guzmán R, Müller K, Lemmer F, Cheng P. Validation of drift motions for a semi-submersible floating wind turbine and associated challenges. In: Journal of physics: conference series. IOP Publishing; 2020.

[103] Jansson J, Nava V, Sanchez M, Aguirre G, De Abreu RV, Hoffman J, Villate JL, et al. Adaptive simulation of unsteady flow past the submerged part of a floating wind turbine platform. In: International conference on computational methods in marine engineering. 2015.

[104] Galvan J, Sánchez-Lara M, Mendikoa I, Pérez-Morán G, Nava V, Rodríguez-Arias R. NAUTILUS-DTU 10 MW floating offshore wind turbine at Gulf of Maine: Public numerical models of an actively ballasted semisubmersible. In: Journal of physics: conference series, Vol. 1102. IOP Publishing; 2018.

[105] Müller K, Guzman RF, Cheng PW, Galván J, Sánchez MJ, Rodríguez R, Manjock A. Load sensitivity analysis for a floating wind turbine on a steel semi-submersible substructure. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2018.

[106] Zhou S, Müller K, Li C, Xiao Y, Cheng PW. Global sensitivity study on the semisubmersible substructure of a floating wind turbine: Manufacturing cost, structural properties and hydrodynamics. Ocean Eng 2021;221.

[107] Ross AG, Dai BS. The drop keel concept: a semi-submersible-spar foundation adpated for ease of assembly for the floating offshore wind turbine market. In: 4th international conference on offshore renewable energy. 2019.

[108] Floating Energy Systems. Stinger keel. 2022, Accessed: 2022-07-20. https://floatingenergysystems.com/.

[109] Ghigo A, Cottura L, Caradonna R, Bracco G, Mattiazzo G. Platform optimization and cost analysis in a floating offshore wind farm. J Mar Sci Eng 2020;8.

[110] Ribot J. HEXAFLOAT: Innovative competitive offshore energy production. 2019, Accessed: 2022-06-22. https://mcedd.com/wp-content/uploads/2019/04/MCEDD-2019-Presentation-SAIPEM-18-March.pdf.

[111] Stiesdal. Tetra offshore foundations for any water depth. 2022, Accessed: 2022-06-29. https://www.stiesdal.com/offshore/tetra-offshore-foundations-for-any-water-depth/.

[112] Li C, Zhou S, Shan B, Hu G, Song X, Liu Y, Hu Y, Yiqing X. Dynamics of a Y-shaped semi-submersible floating wind turbine: a comparison of concrete and steel support structures. Ships Offshore Struct 2021;1–21.

[113] MonoBase Wind. Offshore wind foundations. 2022, Accessed: 2022-07-12. https://www.monobasewind.com/.

[114] Flowocean. Floating offshore wind. 2022, Accessed: 2022-07-28. https://www.hexicongroup.com/.

[115] Muliawan MJ, Karimirad M, Moan T, Gao Z. STC (Spar-Torus Combination): a combined spar-type floating wind turbine and large point absorber floating wave energy converter—promising and challenging. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2012, p. 667–76.

[116] Muliawan MJ, Karimirad M, Gao Z, Moan T. Extreme responses of a combined spar-type floating wind turbine and floating wave energy converter (STC) system with survival modes. Ocean Eng 2013;65:71–82.

[117] Wan L, Gao Z, Moan T. Model test of the STC concept in survival modes. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[118] Gao Z, Moan T, Wan L, Michailides C. Comparative numerical and experimental study of two combined wind and wave energy concepts. J Ocean Eng Sci 2016;1(1):36–51.

[119] Michailides C, Luan C, Gao Z, Moan T. Effect of flap type wave energy converters on the response of a semi-submersible wind turbine in operational conditions. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2014.

[120] Michailides C, Gao Z, Moan T. Experimental and numerical study of the response of the offshore combined wind/wave energy concept SFC in extreme environmental conditions. Mar Struct 2016;50:35–54.

[121] Wison Offshore & Marine Ltd. Offshore wind solution. 2019, Accessed: 2022-10-03. https://www.wison.com/en/offshore_marine_product?cid=86.

[122] Serret J, Tezdogan T, Stratford T, Thies PR, Venugopal V. Baseline design of the deep turbine installation-floating, a new floating wind concept. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2019.

[123] ECO TLP. ECO TLP: Patented deep water XXL offshore wind foundation. 2022, Accessed: 2022-07-22. https://ecotlp.com/.

[124] SENSEwind. SENSEwind: Engineering to reduce the cost of wind energy. 2021, Accessed: 2022-09-08. https://sensewind.com/.

[125] Silva de Souza CE, Berthelsen PA, Eliassen L, Bachynski EE, Engebretsen E, Haslum H. Definition of the INO WINDMOOR 12 MW base case floating wind turbine. Technical report, SINTEF Ocean; 2021.

[126] Equinor. Hywind tampen. 2022, Accessed: 2022-04-29. https://www.equinor.com/energy/hywind-tampen.

[127] Bassoe Technology. BT floater design. 2022, Accessed: 2022-07-20. https://www.basstech.se/17/11/renewables/.

[128] OffshoreEngineer. Technip Energies' floating offshore wind concept making progress. 2021, Accessed: 2022-07-26. https://www.oedigital.com/news/492713-technip-energies-floating-offshore-wind-concept-making-progress.

[129] Odfjell Oceanwind. Odfjell Oceanwind: We are shaping the future of floating offshore wind power. 2022, Accessed: 2023-02-23. https://odfjelloceanwind.com/.

[130] Bluenewables. Bluenewables: Innovating beyond shore. 2022, Accessed: 2023-02-23. https://bluenewables.com/.

[131] MAREAL. XCF. 2021, Accessed: 2022-07-28. https://www.mareal.eu/en/research-and-development/xcf.

[132] BW Ideol. Floating offshore wind. 2022, Accessed: 2022-05-12. https://www.bw-ideol.com/en.

[133] ABSG Consulting Inc. Floating offshore wind turbine development assessment: final report and technical summary. Technical report, ABS Group; 2021, Accessed: 2022-06-21.

[134] DORIS. Nerewind. 2019, Accessed: 2022-07-19. https://www.dorisgroup.com/nerewind/.

[135] Serret J, Kahn B, Cavanagh B, Lorente P, Pascal R, Girandier C, McEvoy P, Cortés C, Duran R, Romero A. FLOTANT concept: floater design, integrated modelling & global performance. In: Journal of physics: conference series. IOP Publishing; 2022.

[136] Frontier Technical. MARLIN modular floating platform for offshore wind. 2020, Accessed: 2023-03-02. https://www.frontier-technical.com/project/marlin-modular-floating-platform-for-offshore-wind/.

[137] Choi E, Wang B, Jung S, Han C, Park S. Optimal design of floating platform and substructure for a spar type wind turbine system. In: World congress on advances in civil, environmental, and materials research. 2012.

[138] Choi E, Cho J, Cho Y, Jeong W, Lee S, Hong S, Chun H. Numerical and experimental study on dynamic response of moored spar-type scale platform for floating offshore wind turbine. Struct. Eng. Mech. 2015;54(5):909–22.

[139] Wang B, Choi E, Jung S, Han C, Park S. Hydrodynamic response of alternative floating substructures for spar-type offshore wind turbines. In: World congress on advances in civil, environmental, and materials research. 2012.

[140] TetraFloat Ltd. Tetrafloat. 2020, Accessed: 2022-07-21. https://www.tetrafloat.com/.

[141] Garvey S, Pimm A, Wah Lieu K, Woolhead S, Buck J, Garvey A. Performance of a free-yawing tetrahedral floating platform for offshore wind turbines in wind and wave conditions. Technical report, MARINET; 2014.

[142] Luan C, Chabaud V, Bachynski EE, Gao Z, Moan T. Experimental validation of a time-domain approach for determining sectional loads in a floating wind turbine hull subjected to moderate waves. Energy Procedia 2017;137:366–81.

[143] Xu K, Gao Z, Moan T. Effect of hydrodynamic load modelling on the response of floating wind turbines and its mooring system in small water depths. In: Journal of physics: conference series. IOP Publishing; 2018.

[144] Luan C, Gao Z, Moan T. Design and analysis of a braceless steel 5MW semi-submersible wind turbine. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2016.

[145] Caillé F, Bozonnet P, Perdrizet T, Poirette Y, Melis C. Model test and simulation comparison for an inclined-leg TLP dedicated to floating wind. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2017.

[146] SBM Offshore. SBM offshore. 2022, Accessed: 2022-07-19. https://www.sbmoffshore.com/.

[147] Bredmose H, Lemmer F, Borg M, Pegalajar-Jurado A, Mikkelsen RF, Larsen TS, Fjelstrup T, Yu W, Lomholt AK, Boehm L, et al. The triple spar campaign: Model tests of a 10MW floating wind turbine with waves, wind and pitch control. Energy Procedia 2017;137:58–76.

[148] Serret J, Tezdogan T, Stratford T, Thies P, Venugopal V. Model test of the DTI-Floating wind concept. In: 3rd international conference on offshore renewable energy. 2018.

[149] Ikoma T, Nakamura M, Moritsu S, Aida Y, Masuda K, Eto H. Effects of four moon pools on a floating system installed with twin-VAWTs. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2019.

[150] Ma Z, Wang S, Wang Y, Ren N, Zhai G. Experimental and numerical study on the multi-body coupling dynamic response of a novel Serbuoys-TLP wind turbine. Ocean Eng 2019;192.

[151] Hallak TS, Guedes Soares C, Sainz O, Hernández S, Arévalo A. Hydrodynamic analysis of the WIND-Bos spar floating offshore wind turbine. J Mar Sci Eng 2022;10.

[152] Thys M, Souza C, Sauder T, Fonseca N, Berthelsen PA, Engebretsen E, Haslum H. Experimental investigation of the coupling between aero-and hydrodynamical loads on a 12 MW semi-submersible floating wind turbine. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2021.

[153] Somoano M, Battistella T, Fernández-Ruano S, Guanche R. Uncertainties assessment in real-time hybrid model for ocean basin testing of a floating offshore wind turbine. In: Journal of physics: conference series. IOP Publishing; 2021.

[154] Trivane. Trivane. 2022, Accessed: 2022-07-21. https://www.trivaneltd.com/.

[155] offshoreWINDbiz. Japanese consortium launches project to mass-produce floating wind foundations. 2022, Accessed: 2022-07-27. https://www.offshorewind.biz/2022/01/21/japanese-consortium-launches-project-to-mass-produce-floating-wind-foundations/.

[156] GAZELLE Wind Power. Gazelle wind power. 2022, Accessed: 2022-07-13. https://gazellewindpower.com/.

[157] Weinstein A, Ho K. WindWaveFloat (WWF): final scientific report. Technical report, Principle Power, Inc.; 2012.

[158] Ren N, Ma Z, Shan B, Ning D, Ou J. Experimental and numerical study of dynamic responses of a new combined TLP type floating wind turbine and a wave energy converter under operational conditions. Renew Energy 2020;151:966–74.

[159] Dolfines. Trussfloat floating technology. 2021, Accessed: 2022-07-28. https://www.dolfines.com/trussfloat-floating-technology/.

[160] Fred Olsen 1848. Dedicated to develop tomorrow's energy solutions. 2022, Accessed: 2022-07-26. https://www.fredolsen1848.com/.

[161] Marine Power Systems. Unlocking the power of oceans. 2022, Accessed: 2022-06-23. https://www.marinepowersystems.co.uk/.

[162] Hexicon. Floating offshore wind. 2022, Accessed: 2022-07-28. https://www.hexicongroup.com/.

[163] TechnipFMC, Bombora. InSPIRE: Integrated semi-submersible platform with innovative renewable energy. 2022, https://www.inspireoffshoreenergy.com/.

[164] Wayman EN, Sclavounos P, Butterfield S, Jonkman J, Musial W. Coupled dynamic modeling of floating wind turbine systems. Offshore Technol Conf 2006.

[165] Lee KH, Sclavounos P, Wayman E, et al. Floating wind turbines. In: Workshop on water waves and floating bodies. IWWWFB; 2005, p. 418.

[166] Hua J. A floating platform of concrete for offshore wind turbine. J Renew Sustain Energy 2011;3.

[167] Naval Group. Saipem and naval energies sign an agreement for the acquisition of naval energies' floating wind business. 2021, Accessed: 2022-06-21. https://www.naval-group.com/en/saipem-and-naval-energies-sign-agreement-acquisition-naval-energies-floating-wind-business.

[168] Dippel M. DNV GL certifies naval energies' floater design basis for floating wind farm and design methods. 2020, Accessed: 2022-06-21. https://www.dnv.com/news/dnv-gl-certifies-naval-energies-floater-design-basis-for-floating-wind-farm-and-design-methods-186387.

[169] 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.

[170] Housseine CO, Monroy C, de Hauteclocque G. Stochastic linearization of the Morison equation applied to an offshore wind turbine. In: Proceedings of the international conference on offshore mechanics and arctic engineering, St. John's, NL, Canada, Vol. 9. 2015.

[171] Bybee K. Use of a vertical wind turbine in an offshore floating wind farm. J Pet Technol 2011;63(07):105–7.

[172] Akimoto H, Tanaka K, Hara Y. Gyroscopic effects on the dynamics of floating axis wind turbine. In: Proc. grand renewable energy conference, (Tokyo, Japan). 2014.

[173] LLC MIC. Floating offshore wind foundations: Industry consortia and projects in the United States, europe and Japan. 2013.

[174] Collu M, Maggi A, Gualeni P, Rizzo CM, Brennan F. Stability requirements for floating offshore wind turbine (FOWT) during assembly and temporary phases: Overview and application. Ocean Eng 2014;84:164–75.

[175] Liu Z, Zhou Q, Tu Y, Wang W, Hua X. Proposal of a novel semi-submersible floating wind turbine platform composed of inclined columns and multi-segmented mooring lines. Energies 2019;12(9):1809.

[176] Pierella F, Avila OS, Sanz CG, Ashraf A, Aitor NA, Kim T. Numerical simulations of a 15MW wind turbine on a concrete TLP with rigid pipe tendons. In: Journal of physics: conference series. IOP Publishing; 2022.

[177] Nautica Windpower. Innovating to grow the floating offshore wind industry. 2022, Accessed: 2022-07-27. https://www.nauticawindpower.com/.

[178] Zhou Y, Ren Y, Shi W, Li X. Investigation on a large-scale braceless-TLP floating offshore wind turbine at intermediate water depth. J Mar Sci Eng 2022;10(2):302.

[179] Equinor. Floating wind. 2022, Accessed: 2022-05-10. https://www.equinor.com/energy/floating-wind.

[180] DNV. DNV provides concept certification of fred. Olsen 1848's floating wind turbine, BRUNEL. 2022, Accessed: 2022-07-26. https://www.dnv.com/news/dnv-provides-concept-certification-of-fred-olsen-1848-s-floating-wind-turbine-brunel-224828.

[181] OSIRenewables. Osirenewables offshore floating wind TLP. 2022, Accessed: 2023-02-23. https://www.osirenewables.com/wp-content/uploads/2022/05/Renewables-midwater-TLP-P.pdf.

[182] University of Maine Advanced Structures and Composites Center. NASA floater. 2022, Accessed: 2023-03-02. https://composites.umaine.edu/wp-content/uploads/sites/600/2022/06/TW_Focal.pdf.

[183] Wang Y, Shi W, Michailides C, Wan L, Kim H, Li X. WEC shape effect on the motion response and power performance of a combined wind-wave energy converter. Ocean Eng 2022;250.

[184] Flagship. Floating offshore wind optimization for commercialization. 2022, Accessed: 2022-06-21. https://www.flagshipproject.eu/.

[185] Henderson AR, Watson GM, Patel MH, Halliday JA. Floating offshore wind farms–an option? In: Proceedings of the offshore wind energy in mediterranean and other European seas, Siracusa, Sicilia, Italy. 2000.

[186] Henderson AR. Analysis tools for large floating offshore wind farms (Ph.D. thesis), University College London; 2000.

[187] Nilsson A, Englund K. Multiple use of a floating offshore windenergy platform: A case study on the Hexicon concept. 2015.

[188] Nakamura T, Mizumukai K, Akimoto H, Hara Y, Kawamura T. Floating axis wind and water turbine for high utilization of sea surface area: Design of sub-megawatt prototype turbine. In: International conference on offshore mechanics and arctic engineering. American Society of Mechanical Engineers; 2013.

[189] O'Sullivan KP. Feasibility of combined wind-wave energy platforms (Ph.D. thesis), University College Cork; 2014.

[190] Fenu B, Attanasio V, Casalone P, Novo R, Cervelli G, Bonfanti M, Sirigu SA, Bracco G, Mattiazzo G. Analysis of a gyroscopic-stabilized floating offshore hybrid wind-wave platform. J Mar Sci Eng 2020;8(6):439.

[191] Wang Y, Zhang L, Michailides C, Wan L, Shi W. Hydrodynamic response of a combined wind–wave marine energy structure. J Mar Sci Eng 2020;8(4):253.

[192] Floatgen. Floatgen wind power going further offshore. 2022, Accessed: 2022-05-13. https://live.floatgen.eu/en.

[193] Stiesdal. The TetraSpar full-scale demonstration project. 2022, Accessed: 2022-05-12. https://www.stiesdal.com/offshore-technologies/the-tetraspar-full-scale-demonstration-project/.

[194] Saitec. SATH technology. 2022, Accessed: 2022-06-21. https://saitec-offshore.com/sath/.

[195] 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.