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RESEARCH ARTICLE

Overview of the Recent Developments in Hybrid Floating Wind-Wave Platforms

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Abstract
This paper presents an overview of the recent developments in hybrid wind-wave energy. With the focus on floating concepts, the possible configurations introduced in the literature are categorized and depicted, and the main conclusions obtained from the references are summarized. Moreover, offshore wind and wave resources are discussed in terms of complementarity and supplementarity, offering a new perspective to developing hybrid wind-wave energy systems that look for synergies not limited to maximizing power output. Then, the feasibility of the concepts under development is discussed in detail, with focus on technical feasibility, dynamic feasibility and limitations of the methods employed. The hybrid configurations that surpassed the experimental validation phase are highlighted, and the experimental results are summarized. By compiling more than 40 floating wind turbine concepts, new relations are drawn between power, wind turbine dimensions, platforms' draft and displacement, which are further related to the payload allowance of the units to accommodate wave devices and onboard power take-off systems. Bearing in mind that it is a challenge to model the exact dynamics of hybrid floating wind-wave platforms, this paper elucidates the current research gaps, limitations and future trends in the field. Lastly, based on the overview and topics discussed, several major conclusions are drawn concerning hybrid synergies, dynamics and hydrodynamics of hybrid platforms, feasibility of concepts, among other regards.

Keywords Offshore renewable energy; Floating offshore wind turbine; Wave energy converter; Floating platform; Technology development

1 Introduction

As time passes, climate change mitigation becomes more urgent, for the observed trends of climate change persist and are alarming. Establishing international treaties in the past, such as the Kyoto Protocol (United Nations, 1997) and the Paris Agreement (United Nations, 2015), was vital to bringing the international community's attention towards the environment. First, industrialized economies and those in transition should be committed to limiting and reducing greenhouse gas emissions. Later, by establishing a physical target regarding global warming, namely, to hold the global average surface temperature below 2.0 °C above pre-industrial levels and to pursue efforts to limit the same increase to below 1.5 °C. After many years since the entry into force of these agreements, some return has been achieved: they have sparked low-carbon solutions, more countries and regions have established carbon neutrality targets, and zero-carbon solutions are becoming competitive across different sectors of the economy. Nowadays, the share of renewable energy to power homes, industries, and means of transportation is noteworthy.

The development of the wind energy sector was one of the key factors responsible for the increase in the share of renewable electricity. Thus, today, wind energy is competitive within the energy market. According to the International Renewable Energy Agency (2023), from 2010 to 2020, the Levelized Cost of Energy (LCoE) of onshore wind dropped from \$110/MWh to \$40/MWh. At the same period, the LCoE of offshore wind dropped from \$200/MWh to

Article Highlights
- All main hybrid floating wind-wave platforms are reviewed in detail.
- The hyrbid configurations are categorized and the categories are analyzed from the perspectives of dynamic and technical feasibility.
- Wind and wave energy resources offshore are analyzed from the perspective of technology development, thus, considering both complementarity and supplementarity of resources.
- All main floating offshore wind turbines are compiled and analyzed from the perspective of potential coupling with wave energy converters.
- The latest developments of floating wind-wave platforms, as well as the current and future trends of numerical and experimental methods, are discussed.

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$90/MWh, achieved from the successful commissioning of several bottom-fixed wind farms. The development of the offshore wind energy sector made it competitive against other sources of energy, such as coal and nuclear energy. According to the Global Wind Energy Council, offshore wind installations may add 150 GW to the grid during the 5 years 2024–2028, an increase of about 180% compared to the 5 years 2019–2023 (GWEC, 2024).

Floating Offshore Wind Turbines (FOWT) (Uzunoglu et al. 2016) are more expensive than onshore or bottom-fixed offshore wind turbines(Castro-Santos et al., 2016, 2017). Nevertheless, commercial wind turbines based on FOWTs started operation in 2017 after the successful commissioning of the Hywind Scotland wind farm, with 30 MW of power generation, which was later succeeded by WindFloat Atlantic in Portugal, with 25 MW. These full-scale projects were commissioned after successful prototype projects, namely, the 2.3 MW Hywind Demo (Skaare, 2017) and the 2 MW WindFloat prototype (Roddier et al., 2017). These two references also give valuable analysis for FOWTs in general and go beyond dynamic assessment: During the Hywind Demo project, there has been development in control functionalities based on measured floater motions, including an active damping control system for pitch stabilisation as well as yaw motion control system based on blade pitch control (Skaare, 2017). For the WindFloat prototype project, marine operations have been detailed, including the amount of capital expenditures (CAPEX), Operation & Maintenance (O & M) expenditures, and CAPEX breakdown (Roddier et al., 2017). Nevertheless, other FOWTs made through prototype-scale projects, which have been recently reviewed by Edwards et al. (2024).

For some years, wind farms have been heading towards floating solutions and farther from the shore, as well as wind farms with a larger number of turbines and bigger turbines (Bagbanci et al., 2012; Díaz & Guedes Soares, 2020). European countries by the Atlantic and China are the fastest developing regions of FOWT. In Norway, Hywind Tampen project installed almost 100 MW using concrete spars, making it the world's largest floating wind farm (GWEC, 2024). Notwithstanding, it can be pointed out that large-scale floating wind farms still might be hindered by excessive costs and due to the natural intermittency of wind resources, mainly because more powerful wind turbines require higher cut-in speeds. For instance, wind speeds greater than 5 m/s have only 30%–40% availability (Arinaga & Cheung, 2012; Stansby & Li, 2024).

Because FOWTs are mainly designed for deep waters (> 50 m), they may benefit from the wave energy potential in the surroundings with the use of Wave Energy Converters (WECs) (Guedes Soares et al., 2012). Thus, many scientists and research groups have been devoted to investigating hybrid wind-wave energy systems. The technologies under development have been constantly reviewed: first by Pérez-Collazo et al. (2015) and Karmakar & Guedes Soares (2015), later updated by McTiernan & Sharman (2020) and Dong et al. (2022), yet several novel configurations appeared in the years of 2022 and 2023, and many others may appear in the near future. More recent review papers tend to focus on particular aspects of hybrid wind-wave energy systems, e. g., Saeidtehrani et al. (2022) and Cao et al. (2023a) reviewed the numerical methods initially applied to simulate the coupling between wind and wave devices, concluding that most nonlinear effects are still not being encompassed by multi-body simulation tools; Ayub et al. (2023) reviewed the co-generation technologies for hybrid wind-wave power supply; and Zhang et al. (2023b) reviewed the different hybrid wind-wave technologies with particular focus on commercial projects and the pursuit of economic feasibility.

In the case of floating hybrid energy systems, floating wind-wave platforms have the potential to significantly reduce overall CAPEX as well as operational expenditures (OPEX). While OPEX is decreased mainly due to joint O & M operations, CAPEX may be more significantly reduced because both the platform and mooring system are shared and because costs associated with licensing and grid connection are reduced as well. Also, hybrid energy systems, in general, make better use of ocean space. For instance, while wind turbines need large spacings to take advantage of the wind field, WECs can be more densely arranged. Moreover, recent research proved the new advantages of hybrid wind-wave energy systems, which are useful for fixed and floating solutions. First, by investigating two different locations, namely, an offshore site near Sydney, Australia, and another in the North Sea, Europe, Gao et al. (2024) showed that hybrid wind-wave energy systems may be solutions to the intermittency problem of wind energy resources. The findings point to a reduction in energy storage capacity by up to 35% in hybrid wind-wave farms when compared to stand-alone wind farms. Second, Teixeira-Duarte et al. (2024) demonstrated that WEC arrays may significantly increase the weather window to assess wind turbines due to WECs' shield protection, representing almost 2 000 hours/year added to the weather window for O & M operations at the farm.

On the other hand, the commercial operation of large-scale hybrid wind-wave energy systems is hindered by two main factors: First, it is still unknown how these systems behave offshore, for there is barely no empirical data regarding these systems operating at sea, and, especially for floating solutions, their dynamics are highly nonlinear in nature and possess many degrees of freedom (DOF), which is hard to model, and demanding to simulate numerically. Second, given that these energy systems cost millions of dollars, e.g., the WindFloat prototype cost $25 M CAPEX – 2011 conversion rate (Roddier et al., 2017), reliability is a key factor, thus hybrid wind-wave technologies still require

Research and Development (R & D) to become economically feasible.

Though no floating wind-wave platform is qualified for commercial operation, hybrid prototypes have been demonstrated in offshore environments. Therefore, the Technology Readiness Level (TRL) of hybrid floating wind-wave platforms is at a maximum 7. This landmark was first achieved by the project Poseidon 2, by Floating Power Plant (Yde et al., 2014), which demonstrated a hybrid platform with 3×11 kW wind turbines and 10×3 kW oscillating water columns in offshore Denmark. Though the hybrid platform was demonstrated offshore (typically TRL 7), the energy systems were relatively small in scale, so it can be argued that the TRL is still lower than 7. Another pioneering project was the W2Power platform by Pelagic Power of Norway, where a hybrid FOWT technology was investigated in-depth. The system was originally designed to accommodate 2×3.6 MW wind turbines and several PA-WECs for an extra nominal 2–3 MW power. Though it is hard to find information about the validation of the hybrid W2Power platform in the relevant space environment, proof of concept was achieved in 2012, and by 2014, the hybrid platform was already validated in wave basin in a condition with several WECs (Legaz et al., 2018). McTiernan & Sharman (2020) reviewed and summarised these two pioneering projects.

The wave energy industry, clearly in a less mature stage of technology development compared to the wind energy industry (Guedes Soares et al., 2014), is relatively advanced in Portugal: In the 1990s, the country hosted the first wave energy plant designed to supply electricity to the grid permanently – a 400 kW Oscillating Water Column (OWC) in Ilha do Pico, Azores (Falcão et al., 2020), followed by other prototype-scale projects such as the Pelamis project, in Aguçadoura (Frandsen et al., 2012). Today, the country hosts the WaveRoller surge flaps in Peniche (Lucas et al., 2012), and the CorPower Ocean C4 Point Absorber (PA), also in Aguçadoura (Santiago et al., 2023). The CorPower C4 device is taking the lead in wave energy technology – it made a breakthrough in November 2023 when it survived waves up to 18.5 meters in height during a heavy storm, setting a new record in the wave energy industry (CorPower Ocean, 2023). Moreover, in Portugal, there is a high interest in investment and high expectations for the offshore wind energy industry (Maritime Journal, 2024).

Though some review papers have been written on the scope of hybrid wind-wave energy systems, new hybrid configurations, methodologies, and perspectives have been recently introduced in the literature. Moreover, some limitations and research gaps have never been systematically detailed. Thus, this paper extends and updates the review analysis provided by the literature, offering an overview of the latest developments in floating wind-wave platforms. It is organised as follows: Section 2 discusses the availability of wind and wave energy resources offshore within a new perspective; Section 3 compiles, categorises and details the hybrid wind-wave platforms so far investigated; Section 4 brings detailed analyses and discussions regarding feasibility of the concepts under development, limitations of the methods, research gaps and future trends of floating wind-wave platforms. Finally, Section 5 draws concluding remarks within the research topic, summarising the findings of this paper.

2 Wind and wave resources: complementarity vs. supplementarity

According to the present theory, the exact behaviour of any sufficiently large portion of the fluid in motion is chaotic and unpredictable. That is particularly true for ocean waves and troposphere winds. Therefore, sea elevation and wind speed at a particular location are non-deterministic and should be ultimately treated as stochastic variables. Consequently, the prediction of waves and winds can only be accurate for the short-term near future. Nevertheless, it is possible to assess reliable estimates of many statistical parameters of ocean waves and offshore winds by in-situ measurements and satellite data.

Extensive research on offshore wind and wave resources is found in the literature. Lately, in the scope of hybrid Offshore Renewable Energy (ORE), offshore sites have been investigated given the wind-wave resource complementarity, sometimes including tidal and solar energy resources. However, it is very important to remark that the term complementarity in those studies normally stands for regional, occasionally seasonal, complementarity, i. e., in opposition to global complementarity, which can only be assessed from an international perspective. That said, wind and wave resources have proven complementarity along the Portuguese coast (Silva et al., 2018; Salvação et al., 2022; Onea & Rusu, 2022). In contrast, other territories have specific sites with proven ORE complementarity, e.g., in Greece (Kardakaris et al., 2021), Ireland (Said et al., 2023), South China Sea (Zuo et al., 2023) and Spain (Vázquez et al., 2024).

To better compare the potential of combining wind and wave energy devices, a discussion within a global perspective of wind and wave resources is followed, which investigates the prospective areas around the globe for hybrid wind-wave energy systems. It considers two different points of view: i) wind-wave complementarity – the more wind and wave energy resources, the better; and ii) waves supplement wind – the more wind resources, the better, and the area is not listed as in complementarity.

The first point of view is extensively considered in the literature to justify hybrid wind-wave energy systems in the pursuit of maximising energy output. In contrast, the second point of view is usually disregarded. However, it is undeniable that WECs provide much less energy than wind turbines. Given that wind turbines are moving towards rated power values above 10 MW while single WECs provide at maximum some hundreds of kilowatts. Thus, the WECs in hybrid configuration hardly account for 10% of the total power generation, a value that does not increase significantly when considering multi-WEC configurations. For instance, in the W2Power concept, with 10 WECs, wave power still accounts for 20% of the total power generation (Legaz et al., 2018). In consequence, several authors are nowadays looking into the prospects of coupling WECs on FOWTs not for maximising energy output but seeking to provide power to on-board systems or to improve power stability as well as platform stability, which, again, has been proven recently to increase the weather windows for O & M operation and avoid intermittency issues. Following this new perspective on hybrid wind-wave technology, the idea that total wave energy can supplement wind energy must also be considered a prospective starting point for hybrid wind-wave platform development.

Figures 1 and 2 present the global distributions of average wind speed and annual wave power. The wind speed values stand for 100 m height estimations, which are more useful for wind turbines. These figures serve as a basis for the identification of prospective locations for the installation of hybrid wind-wave energy systems around the world. However, it must be noted that ocean space is not always available, for many sites are already in use for other purposes: fishing, aquaculture, military areas, port entrances and other navigation areas, among others. Furthermore, resources more than 200 km from the coastline usually do not belong to any territory and thus may not be exploitable.

A closer look into Figures 1 and 2 gives the most prospective areas for hybrid wind-wave energy systems around the globe. Following the first point of view (complementarity), the most promising locations are those at medium latitudes and usually near the west coastlines: North Atlantic European countries such as Portugal, North of Spain, France, Ireland, UK, Iceland and Norway, as well as Chile, South Africa, Western Australia, New Zealand, USA and Canada (both west and east coastlines in the latter two countries), and Japan's east coastline. Following the second point of view (wave energy supplements wind energy), other locations are promising: West Africa, Argentina, Peru, Northeastern Brazil, Somalia, Vietnam, South China Sea, East China Sea, Caribbean Sea, Sea of Okhotsk, Baltic Sea, and the Mediterranean Sea.

Though all locations mentioned are prospective, future medium-to long-term projects shall depend on the particular technologic aspect, namely, whether hybrid wind-wave energy systems will be demonstrated in harsh wave environments. That is because, as already discussed, structural integrity and reliability are key factors for high-CAPEX energy systems.

Last but not least, if hybrid energy technology development goes through all TRLs in sequence, it means that concepts must be proven in the relevant environment before going to the operational environment. In that sense, it must be noted that concepts based on supplementarity may be proven before and serve as starting points for those based on complementarity.

3 Floating wind-wave platform types

This section categorizes the hybrid floating wind-wave platforms found in the literature. Extensive research was done seeking to encompass all floating configurations that went through R & D. Though some authors have been devoted to bottom-fixed hybrid systems, e.g., Pérez-Collazo et al. (2018), most of the R & D on hybrid wind-wave energy is devoted to floating concepts, the subject of this paper.

A few acronyms have been introduced in the literature to encompass all floating wind-wave types. The one getting more well-known is FWWP, that stands for Floating Wind-Wave Platform, which will be adopted from now on in this paper.

The various FWWP types are reviewed and divided into categories based on FOWT geometry and WEC-type. Figures 3–6 present 14 of the main possible configurations. It is clear that semi-submersible and spar platforms are the preferred ones to consider in FWWP development; after all, commercial FOWT technologies have been proven to be suitable for these types.

3.1 Semi-submersible FOWT with PA-WECs

The most studied FWWP type is the coupling between a semi-submersible FOWT and PA-WECs. The pioneering W2Power platform was the first concept of this type.

Several configurations that belong to this type are based on the OC4 DeepCWind platform (Robertson et al., 2014a), for the data of this FOWT is available in open-access, and the stability and hydrodynamic performance of the platform was validated in a very consistent benchmark study (Robertson et al., 2014b, 2017; Uzunoglu and Guedes Soares, 2018). Three main configurations have been tried: first, with heaving buoys below the bracings of the platform (Chen et al., 2022b; Zhu et al., 2023), where the buoys are constrained by mechanical rods that connect the lower and the upper bracings; second, by connecting the buoys with the outer columns of the platform employing articulated-arms (Hallak et al., 2021; Si et al., 2021; Zhu, 2022; Jin et al., 2023) – shown in Figure 3(a); and third, by connecting the buoys with the upper bracings by means of articulated-arms (Ghafari et al., 2021, 2022; da Silva et al., 2022).

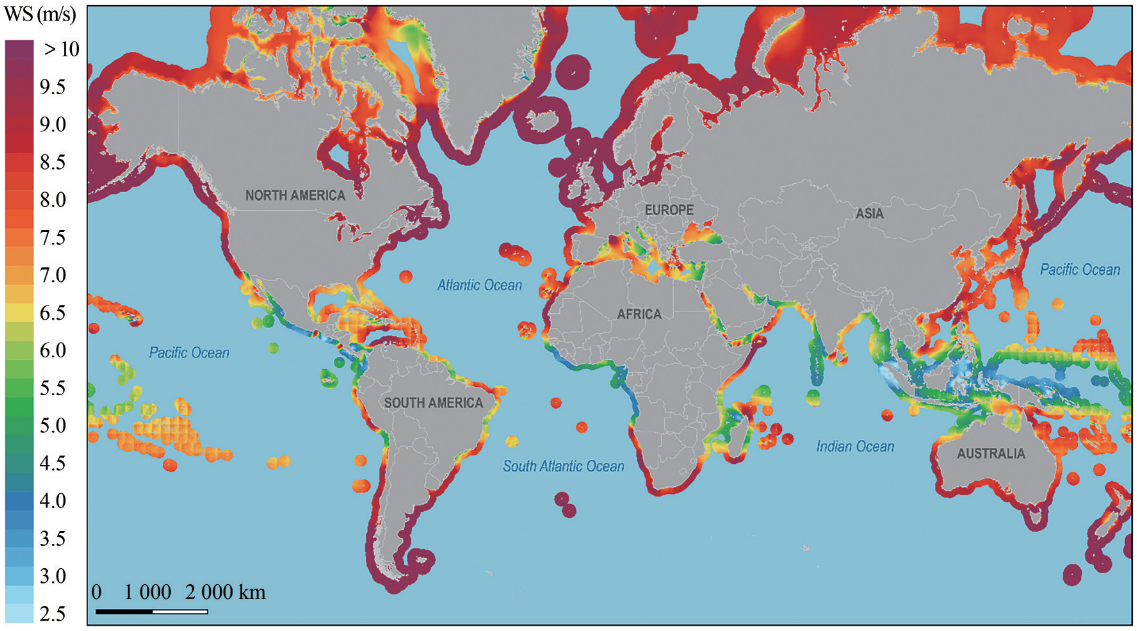

Figure 1 Global distribution of average wind speed at 100 m height and up to 200 km from the coastline (Davis et al., 2023; ESMAP, 2023)

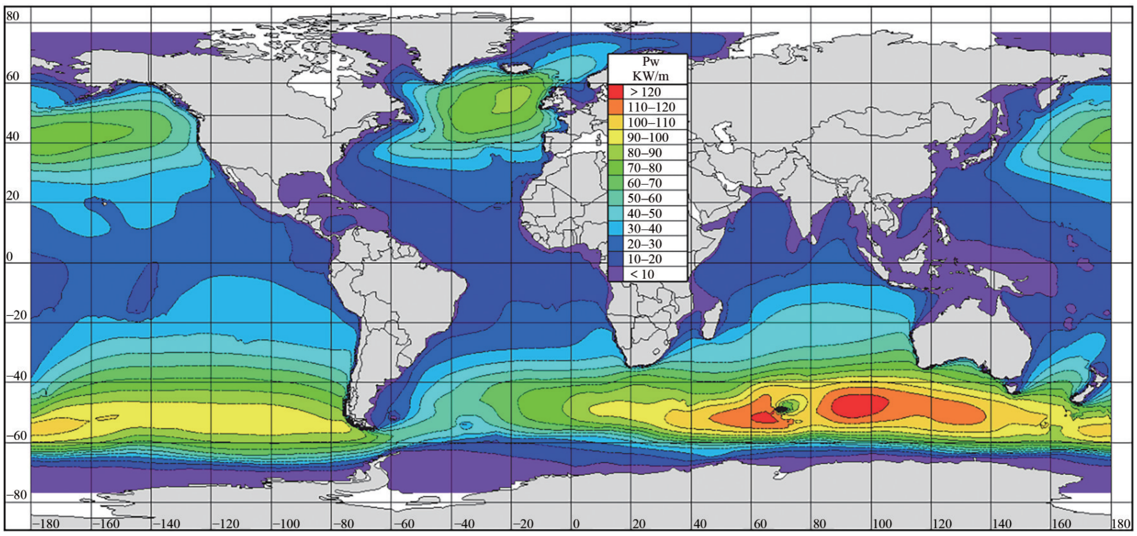

Figure 2 Global distribution of annual mean wave power (Cornett, 2008)

Other concepts are based on coupling PAs and the WindFloat semi-submersible platform. Different configurations have been tried: with heaving WECs below the bracings of the platform (Hu et al., 2020; Zhou et al., 2023a) or WECs connected with the bracings by means of articulated arms (Wang et al., 2022). Another configuration is achieved by employing the WECs near the middle of the platform, which is accomplished by adapting the FOWT's substructure with new bracings that connect the columns to a central hull that accommodates the power take-off (PTO) system (Chen et al., 2020, 2022a, 2024; Zhang et al., 2022b).

General findings for DeepCWind-and WindFloat-based hybrid platforms are: i) Significant reduction of overall heave motion may be accomplished with optimal PTO, i.e., mainly absorbing energy from the relative heave motion between FOWT and WECs; ii) Pitch motion usually is increased near the resonance frequency, mainly due mechanical coupling and phase effects, because an optimal FOWT design has mitigated wave excitation force in the resonance but that is usually lost after the coupling with the WECs; and iii) Multi-body configuration affects the hydrodynamic coefficients of the WEC, whereas the dynamic behaviour and power absorption of WECs depend upon not only on the dimensions but also on the arrangement of devices. The hydrodynamic coefficients of the FOWT are much less affected, though, as discussed in the previous point, special attention is required near the pitch resonance frequency.

A relatively new concept, and with somewhat different geometry in comparison to the previous two, is the SPIC semi-submersible FOWT, developed to host a 10 MW wind turbine (Cao et al., 2020, 2021). It has been studied numerically and experimentally in hybrid configuration by employing Wavestar PAs in the surroundings of the novel platform (Zhang et al., 2023c, 2023d, 2024; Wu et al., 2024). The findings show that the SPIC platform has a higher allowance to employ several WECs without affecting the pitch motion of the platform significantly. This platform's critical motion response appears in the low-frequency surge response, which increases abruptly when too many (in fact, up to 18) WECs are employed.

In addition, some non-trivial semi-submersible designs have been tried, e.g., the semi-submersible platform similar to the WindFloat concept though with conical columns (Deng et al., 2023), another one similar to the WindFloat though with square columns and fewer bracings (Cao et al., 2023b), and the semi-submersible with six outer columns and controllable ballast that has been investigated numerically by Hallak et al. (2018) and Gaspar et al. (2019, 2021) and went through a couple of test campaigns in wave basin (Kamarlouei et al., 2019, 2020a, 2020b, 2022a, 2022b) with different numbers and configurations of WECs, as well as different PTO stiffness and damping parameters. It is found that second-order effects play an essential role in the pitch motion of the system. In contrast, the experiments validated the feasibility of controlling the pitch motions employing a rational hybrid design because of geometry and PTO.

3.2 Semi-submersible FOWT with Torus-WECs

The coupling between torus-WECs and floating platforms is relatively simplified, for the WECs are located around the platform's columns and move along the columns' axes. Because semi-submersibles possess many columns, several configurations may be tried. First, the 4-column 10 MW Nautilus concept (Galván et al., 2018) was investigated with four torus WECs – one around each column. To accommodate the WECs, the Nautilus dimensions had to be modified accordingly: both the column diameter and total displacement were reduced. The major findings in the study point to hybrid wind-wave energy farms with more stable platforms and about 10% lower LCoE in comparison to stand-alone FOWT wind farms (Petracca et al., 2022).

Other configurations may be achieved by combining torus-WECs with the braceless semi-submersible (Bachynski et al., 2016). For instance, it is possible to couple one WEC with the central column, while other configurations possess multiple torus, e.g., three WECs around the outer columns or four WECs around all columns, as shown in Figure 3(b). These configurations have been investigated and compared (Shi et al., 2022; Homayoun et al., 2022; Tian et al., 2023). The findings point to suitable configurations with a central torus-WEC where the dynamics of the FOWT are not significantly affected, whereas the WEC may account for about 100 kW in that configuration. In the configuration with 3 or 4 WECs, i.e., employing torus-WECs around the platform's outer columns, though their ability to generate power is higher due to FOWT's pitch-to-WECs' heave coupling, in fact, almost twice, the pitch motion of the FOWT is considerably increased and may not be suitable to the proper operation of the wind turbine.

3.3 Semi-submersible FOWT with Flaps

The configurations including submerged flaps benefit from the fact that submerged flaps may receive reduced impact, whilst the wave-absorbed power is around the same as in floating WECs.

Some configurations have been tried. First, by coupling three submerged flaps with the braceless semi-submersible FOWT (Michailides et al., 2014), as shown in Figure 3(c), which was later investigated experimentally (Michailides et al., 2016). It was named SFC, that stands for semi-submersible flap combination. Second, an adaptation of the previous configuration where the WECs may yaw in relation to the platform and more WECs may be employed. It was named SYFC, that stands for semi-submersible yaw-drive flap combination (Neisi et al., 2023). Third, by coupling a single flap above a modified lower pontoon structure, e.g., in a 4-column semi-submersible (Lin & Pei, 2022) or in a 3-column semi-submersible (Celesti et al., 2023). In the latter reference, a simplified 2-DOF model was considered, where only the pitch of the platform and the relative pitch between platform and flap are accounted.

The work of Michailides et al. (2014, 2016) provides a multi-DOF numerical model of the SFC concept that has been consistently validated against empirical data. Then, Neisi et al. (2023) showed that yaw-drive flaps may significantly increase the wave power absorption, achieved by adjusting the heading of the WECs with the wave incidence angle. By compiling the findings of all references belonging to this configuration, it is noted that the configuration also presents slightly improved stability, achieved from the increase in GM value that leads to smaller heeling angles and increases pitch natural periods when no PTO stiffness is accounted. After including PTO stiffness, pitch motion response and natural frequency may vary considerably depending on the stiffness value.

3.4 Semi-submersible FOWT with OWCs

The configuration that couples the INO WINDMOOR 12 MW semi-submersible platform (Silva de Sousa et al., 2021) with OWCs within its three columns has been investigated in-depth by Aboutalebi et al. (2023, 2024). Because the principle of stabilisation of semi-submersibles is based

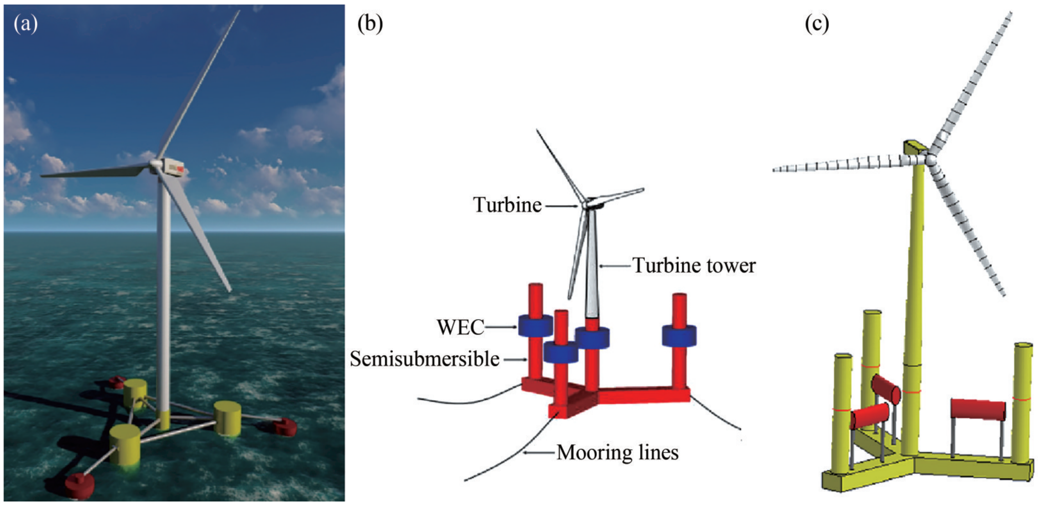

Figure 3 FWWP configurations, Pt.I (a) DeepCWind semi-submersible FOWT with 9.8 m diameter WECs (Jin et al., 2023); (b) Braceless semi-submersible FOWT with four tori-WECs (Tian et al., 2023); (c) Braceless semi-submersible FOWT with flap combination (Neisi et al., 2023)

on the great inertia of the hull's waterplane area, the relations between the OWC chambers and the stability of the platform is one of the major foci in those papers – see Figure 4(a). Also, the OC4 DeepCWind semi-submersible with three OWCs in the outer columns has been investigated experimentally (Zhang et al., 2022a) and recently investigated by Sebastian et al. (2024). Experimental results point to a wave power production between 10 and 50 kW for this combination and possible mitigation of pitch motion depending upon control strategy.

In comparison to the other semi-submersible-based hybrid configurations using similar platform geometry, Aboutalebi et al. (2023, 2024) showed that the hybrid platform using OWCs presents improved motion response: While heave response is mitigated around the resonance frequency, pitch response is practically the same within the wave period band 10–25 s, and pitch natural period is increased by around 5 seconds. However, the OWC power generation capacity has only been detailed by Sebastian et al. (2024), where it is possible to check that the wave power absorption is somewhat similar to the PA-WECs configurations, namely, around 100 kW per WEC.

3.5 Barge FOWT with OWCs

Based on the ITI Energy barge (Jonkman, 2007), the combination of a barge FOWT and an OWC was apparently the first hybrid FWWP concept investigated in the literature (Jonkman & Buhl, 2007). The concept was later updated by a different research team to include more OWC chambers, as shown in Figure 4(b). It became the object of several studies(Aboutalebi et al., 2021a, 2021b, 2022; M'zoughi et al., 2021, 2023).

Because the barge is highly stable, the coupling with OWCs can be very advantageous. Thus, the coupling problem has been investigated with a focus on different control strategies, e.g., by switching the control strategy (Aboutalebi et al., 2021b), or by using fuzzy airflow-based active control (M'zoughi et al., 2023), whereas the pitch-control of the ITI Energy barge-based FOWT had been previously investigated by Olondriz et al. (2018). Usually, the trade-offs arising from highly stable barge-based FOWTs are the accelerations at the nacelle and structural integrity of the wind turbine because barges the high restoring forces lead to high accelerations overall. The investigations above do not focus on that issue, though coupling barges with OWCs, at first sight, may be advantageous to the acceleration issues of barge FOWTs.

3.6 Spar FOWT with PA-WECs

Karimirad & Koushan (2016) investigated the coupling between the Hywind spar and the Wavestar concept. The hybrid platform was named WindWEC, and it was initially designed to accommodate a 5 MW wind turbine and a single WEC at the rear of the platform. The research presents numerical analyses that account for many dynamical effects, such as viscous damping, slow drift, and sensitivity to PTO damping parameters are considered. However, the hydrodynamic multi-body interaction was disregarded entirely.

Later, Skene et al. (2021) evaluated the prospects of this hybrid type in detail. By considering generic PTO parameters as well as variable WEC's dimensions and variable spacing between the floating bodies, the research pointed to an ideal geometry where the PA-WEC is massive (around the same mass of the FOWT), in a way that the mechanical coupling makes it possible to tune the dynamic response of the FOWT to be out-of-phase with the waves, though it is somewhat unclear if this design is feasible in terms of PTO coupling.

The spar-PA configuration is illustrated in Figure 4(c).

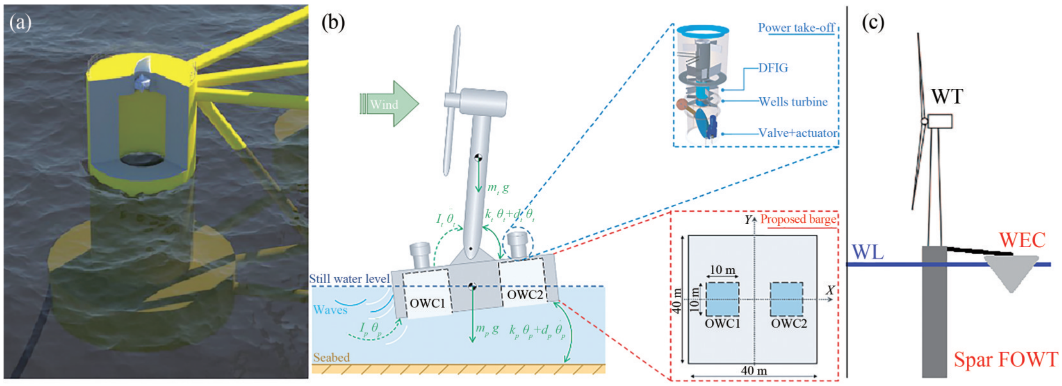

Figure 4 FWWP configurations, Pt. II (a) OWC within a column of the DeepCWind semi-submersible FOWT (Zhang et al., 2022a); (b) Barge FOWT with two OWCs (M'zoughi et al., 2021); (c) Spar FOWT and a PA-WEC at the rear

3.7 Spar FOWT with Torus-WEC

The spar-torus combination (STC) is deeply investigated in the literature. Because it represents a reduced complexity in terms of dynamic behaviour, the numerical models are relatively more straightforward to formulate and validate. Only one WEC is employed around the free surface, as shown in Figure 5(a), which adds only one extra DOF into the dynamical system, namely, a relative heaving mode.

Two research groups must be noted. First, the consistent numerical work done by Muliawan et al. (2011, 2012, 2013a, 2013b), that introduced the STC concept and performed several dynamic analyses. The investigation was later updated by Ren et al. (2015), and followed by an in-depth experimental investigation (Wan et al., 2015, 2016a, 2016b). More recently, other research groups have been involved in both numerical and experimental analysis of the STC concept, including as well a combination with tidal turbine (Li et al., 2018; Zhao et al., 2021; Zhou et al., 2023b; Li et al., 2023).

In general, the results presented in the different references show that the heave motion of the platform is drastically increased after coupling the platform with the torus-WEC. Consequently, the survivability of the hybrid concept is constantly a matter of concern in the above-referenced research. Nevertheless, out of the configurations with only one WEC employed, the STC is one of the most powerful concepts, for the torus-WEC may absorb up to 500 kW in this configuration.

3.8 TLP FOWT with PA-WECs

The coupling between a Tension-Leg Platform (TLP) and 3 PA-WECs was investigated in detail by Bachynski & Moan (2013), using a 5 MW wind turbine and achieving 900 kW total wave-rated power. Two PA designs were considered, namely, WECs constrained to pure heave motion and WECs constrained by a hinge at 10 m depth (located on the pontoon of the TLP), as depicted in Figure 5(b). The WECs are spheroids of the same dimension and have limited excursion due to the application of the end-stop mechanism. The system was simulated in the time domain, considering different wind and wave conditions and structural dynamics. The study is very insightful for TLP-based hybrid systems. It is concluded that, though the hybrid system presented favourable dynamic interactions in benign environments, there are huge tendon tension variations compared to the stand-alone TLP in extreme conditions, mainly due to impacts with the end stop mechanism. Thus, a more suitable and complex locking mechanism should be developed to ensure the feasibility of TLP-PA configurations.

Wright et al. (2017) also studied a TLP-PA hybrid configuration, where the PAs are similar to tori, in a configuration with 4 WECs and a total wave-rated power of 1 MW for a 5 MW wind turbine. Whereas the investigation is somewhat limited in coupled dynamic behaviour, it demonstrates a novel possibility of survival mode in hybrid wind-wave systems, where initially floating WECs get submerged in the survival mode. It has been shown that such a strategy mitigates fatigue and is favourable for reducing tendon tension variations in TLPs.

3.9 TLP FOWT with Torus-WEC

The coupling between a TLP and a torus-WEC located in the free surface and around the hull of the FOWT is shown in Figure 5(c). It was investigated by Chaitanya Sai et al. (2019) in a comparison study that also comprised the STC combination and the DeepCWind platform coupled with three PA-WECs. The three hybrid platforms are designed to accommodate a 5 MW wind turbine. Thus, the systematic comparison is valuable, for rather few FWWP types can be easily compared as in this study, which was later updated by Rony et al. (2023).

A similar TLP-torus concept was investigated experimentally (Zhang et al., 2023a), whereas the torus-WEC can be split into three modules to constitute a split PA. The hybrid platform presented promising dynamic behaviour

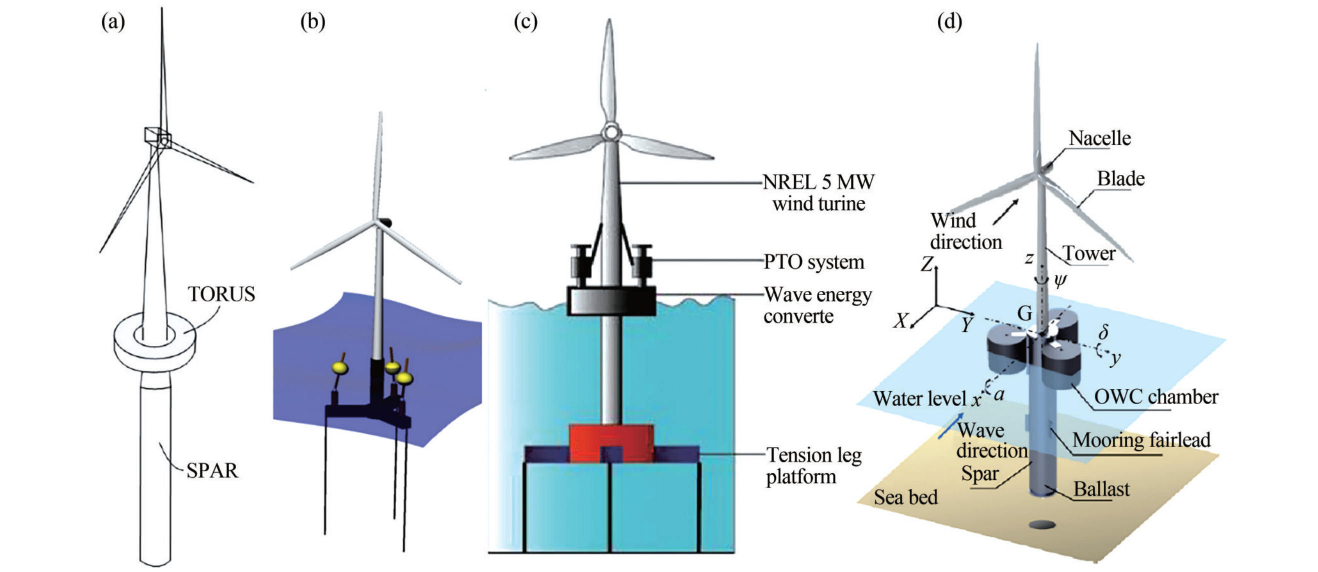

Figure 5 FWWP configurations, Pt. III (a) The spar-torus combination (STC) (Muliawan et al., 2013b); (b) TLP FOWT with three PA-WECs (Bachynski & Moan, 2013)–shared with permission from ASME; (c) The TLP-torus concept (Chaitanya Sai et al., 2019); (d) The spar with three OWC chambers (Fenu et al., 2023)

and showed that the split-absorber has improved power efficiency more than the torus-WEC, for it may absorb high-frequency energy components in irregular sea states when the waves are in many directions. The reference also demonstrated that the relative heave motion between WEC and spar FOWT has two separated peaks: while one represents WEC's natural frequency, the second arises from out-of-phase excitation components.

3.10 Other Hybrid FWWP-types

Other hybrid configurations of interest are the ones that follow. First, the coupling between a spar FOWT and three OWCs around the spar is shown in Figure 5(d). This configuration was investigated experimentally by Fenu et al. (2023), whereas the spar has been optimized for a location in the Mediterranean Sea in a study conducted by Ghigo et al. (2020). Fenu et al. (2020) also studied a gyroscopic-stabilized FOWT, where the gyroscope may absorb wave energy at a rated power of 50 kW. This study has been conducted after the conduction of the wave energy project ISWEC in Pantelleria, Italy (Bracco, 2010; Mattiazzo, 2019). Though the gyroscope conversion is not powerful, the results are very promising, for the gyroscopic unit helps in the stabilization of the platform and reduces the accelerations at the wind turbine (around-10% at the nacelle) for a broad set of environmental conditions.

The braceless semi-submersible, previously investigated with different tori configurations and flap combinations, was once more an object of study in a novel configuration that couples it with Multi-Salter's duck configurations. Salter's duck WECs are similar to flaps, though they have a particular geometry such that they absorb wave energy following a different physical principle compared to flaps. Configurations with 12, 15 and 18 WECs have been tried (Yazdi et al., 2023).

Soulard and Babarit (2012) investigated several hybrid configurations mainly using multi-flaps arrangement. That preliminary study led to the concepts of T-Hyp (Soulard et al., 2013a) and C-Hyp (Soulard et al., 2013b), shown in Figure 6(a) and 6(b), respectively, where it is possible to see that dozens of WECs are considered in the models: concept T-HyP uses 12 pitching-WECs while C-Hyp uses a total of 20 flaps. Though these concepts present relatively high wave power absorption, the investigation is rather focused on structural aspects of the platform, whereas it is unclear how the coupled hydrodynamic and mechanical interactions could sustain the wind turbine with rather too many onboard systems.

Last, two very recent and innovative concepts have been introduced in the literature. First, the spar-inerter configuration (Asai et al., 2023), whereas the inerter works in the coupling between the upper and lower parts of the spar hull, as shown in Figure 6(c). This novel configuration was proven to be promising in terms of dynamical behaviour, whereas the natural modes of the system are easily obtained, and, therefore, the dynamic response of the FWWP may be optimised in a very straightforward way. Because an inerter is considered within a heavy structure, structural reliability is a key factor for this configuration. Second, the semi-submersible platform with hinged floats for omnidirectional waves (Stansby & Li, 2024) is depicted in Figure 6(d). It is concluded that the semi-submersible with hinged floats may absorb energy from swell waves coming from different directions, whereas those waves are present even when there is not enough wind to generate wind power; thus, it is a solution to the intermittency of ORE power devices.

These two concepts are the only ones that use the main floaters of the hybrid platform as active displacement hulls for wave power absorption, which can ultimately lead to higher-rated power but require structural strength and a very calibrated hydrodynamic model.

The realisation that the configurations referenced in this sub-section (and many others within this section) were investigated recently supports the idea that novel FWWP concepts will appear in the near future.

4 Analysis and discussion

4.1 Dimensions and capacity

By compiling the data published in the literature (work referenced so far, plus Tong, 1998; Henderson et al., 2003; Viselli et al, 2016; Dankelmann et al., 2016; Le et al., 2019; Silva, 2019; Uzunoglu & Guedes Soares, 2020; Gaertner et al., 2020; Ren et al., 2022; Mei & Xiong, 2021; Yang et al., 2022; Hsu et al., 2022; Hmedi et al., 2022; Hallak et al., 2022a, 2022b; Sergiienko et al., 2022; Wiley et al., 2023), Table 1 is constructed. It includes 42 prototype-and full-scale Horizontal Axis Wind Turbines (HAWTs) FOWT designs. Numbers in italic stand for values calculated based on platforms' geometry and dimensions, i.e., not initially presented in the references and might be approximated.

In designing a floating wind-wave platform, there is particular interest in the draft and volume displacement. In light of this, Figure 7 was drawn and plots the displacement of the different FOWTs against the nominal wind power. Then, Figure 8 plots the draft against the displacement.

With 16 semi-submersible and 14 spars, it was possible to perform square-polynomial regressions. Even by setting the intercept at 0, the R-squared values demonstrate that some correlation exists between variables; thus, first estimates for draft and volume displacement can be obtained based on the regressions for future FOWT designs. For instance, the regressions point to around 40 000 m^3 displacement for a future generation 15 MW conventional spar (namely, only the Hexafloat concepts are not conventional spars and are disregarded in the regression) and around 45 000 – 50 000 m^3 displacement for a future generation 20 MW semi-submersible. The regressions also point to the following future generation 20 MW offshore wind turbine dimensions: 175.0 m hub height and 290.0 m rotor diameter.

Regarding TLPs and barges, relatively few FOWTs have been found per type to obtain reliable estimates based on regressions. Figure 7 shows that TLPs of various dimensions were thought for the 5 MW reference wind turbine and, in Figure 8, TLPs are the only ones to have a more evident relation between draft and displacement: most of the designs present around 3–4 meters draft per 1 000 m^3 displacement, whereas the TWindWave and Iberdrola are outliers, with about 10 meters draft per 1 000 m^3.

For semi-submersibles, spars and barges, Figure 8 shows that draft and displacement are not mathematically related, though a relation exists between FOWT-type and drafts because the platform type is usually a design choice that relates to the water depth among other environmental aspects of the operation site, which may relate to draft. Suppose the spar outliers are disregarded (namely, the advanced spar concept Fukushima Hamakazee and the relatively small 1.4 MW FLOAT). In that case, spars shall have between 60 and 120 meters draft, whereas semi-submersibles between 12 and 30 meters draft (except for the 120 kW Volturn US prototype), and barges between 4 and 10 meters draft.

It is also worth mentioning the outliers of Figure 7: The Damping Pool is an over-weighted platform for a mere 2 MW wind turbine, which can lead to a great disadvantage in CAPEX, especially high steel cost and installation cost. On the other hand, the lightest platforms are mainly TLPs, such as the 10 MW CENTEC-TLP and the 5 MW TWindWave and Iberdrola platforms. The Hexafloat unconventional spar is also relatively light, for this concept employs a deep magnetite ballast to stabilise the plat-

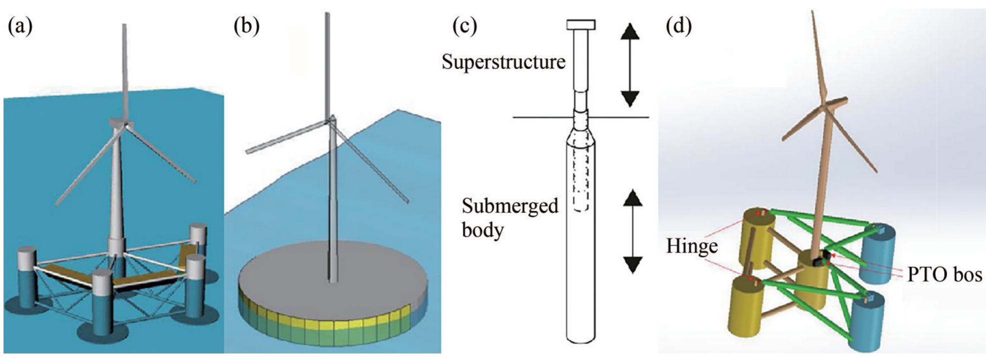

Figure 6 FWWP configurations, Pt. IV (a) T-Hyp: Semi-submersible FOWT with pitching WECs (Soulard et al., 2013a); (b) C-Hyp: Barge FOWT with multiple flaps. Source: Soulard et al. (2013b) – shared with permission from ASME; (c) The spar-inerter configuration. Source: Asai et al. (2023); (d) Semi-submersible FOWT with hinged-floats. Source: Stansby & Li (2024) – shared under Creative Commons License 4.0: https://creativecommons.org/licenses/by/4.0/

Table 1 Prototype- and full-scale FOWT data compiled from the literature

Concept	WT Power (MW)	Displacement (m^3)	Draft (m)	Hub height (m)	Rotor diameter (m)	Type
ITI Energy Barge	5	6 000	4.0	86.0	126.0	Barge
MIT/NREL Barge	5	5 100	5.0	84.5	126.0	Barge
DemoSATH	2	3 500	8.0	72.0	96.0	Barge
Damping Pool	2	32 000	10.0	90.0	122.0	Barge
WindFloat Prototype	2	2 750	13.7	70.0	80.0	Semisub.
WindFloat Atlantic	8.4	15 500	30.0	100.0	160.0	Semisub.
Shinpuu	7	10 000	17.0	105.0	167.0	Semisub.
OC4 DeepCWind	5	13 900	20.0	87.6	126.0	Semisub.
Braceless Semisub.	5	10 500	30.0	90.0	126.0	Semisub.
GustoMSC	5	3 627	13.2	90.0	126.0	Semisub.
OO-Star	10	23 509	22.0	118.4	178.3	Semisub.
SPIC	10	16 400	30.0	119.0	178.3	Semisub.
ActiveFloat	15	36 400	15.0	150.0	240.0	Semisub.
Kincardine	9.5	18 500	30.0	105.0	164.0	Semisub.
Nautilus	10	16 330	21.0	119.0	178.3	Semisub.
INO WINDMOOR	12	16 900	21.4	131.7	216.9	Semisub.
Fu Yao	6.2	15 600	18.0	96.0	152.0	Semisub.
VolturnUS 1:8	0.012	16.5	2.9	12.2	9.6	Semisub.
VolturnUS	6	8 500	23.2	97.6	152.0	Semisub.
Fincantieri Sea Flower	5	15 000	12.0	90.0	126.0	Semisub.
Toda	2	3 400	100.0	72.0	80.0	Spar
Hamakazee	5	8 000	33.0	86.4	126.0	Spar
Hywind Scotland	6	11 400	78.0	98.0	154.0	Spar
Hywind Tampen	8	22 000	78.0	95.0	167.0	Spar
OC3 Hywind	5	8 030	120.0	90.0	126.0	Spar
Hywind Demo	2.3	5 300	100.0	65.0	85.0	Spar
Hywind 5 MW	5	13 500	82.9	90.0	126.0	Spar
Hywind 10 MW	10	20 000	106.1	119.0	178.3	Spar
TetraSpar	3.6	6 100	70.0	88.3	129.0	Spar
WIND-Bos	10	27 750	81.0	112.0	164.0	Spar
FLOAT	1.4	3 570	27.0	45.0	60.0	Spar
Hexafloat 5 MW	5	4 200	99.5	90.0	126.0	Spar
Hexafloat 10 MW	10	9 400	100.0	119.0	178.3	Spar
TELWIND	5	12 000	60.0	86.3	132.0	Spar
GICON	5	9 970	30.7	90.0	126.0	TLP
Tension-Leg Floater	5	8 500	25	80.0	115.0	TLP
Iberdrola	5	4 334	39.8	90.0	126.0	TLP
TWindWave	5	3 200	32.0	90.0	126.0	TLP
MIT/NREL TLP	5	12 180	47.9	90.0	126.0	TLP
SFOWT	5	6 116	20.0	90.0	126.0	TLP
Multi-column TLP	5	4 900	16.5	90.0	126.0	TLP
CENTEC-TLP	10	7 786	20.0	119.0	178.3	TLP

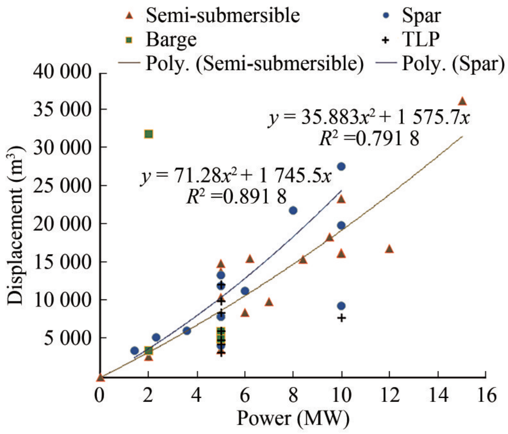

Figure 7 FOWT displacement against nominal wind power

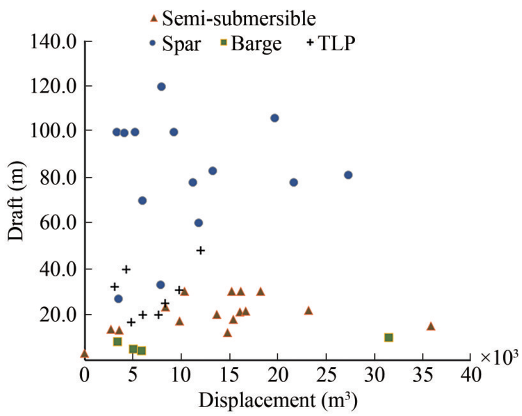

Figure 8 FOWT draft against displacement

form. It was investigated to accommodate 5 and 10 MW wind turbines (Ghigo et al., 2020), presenting half the conventional spars' displacement for equivalent wind turbines.

The displacement of FOWT units is known to be much less than the total weight of the wind turbines they carry. Indeed, large-volume displacement structures are required mainly to counteract the high overturning moments acting on the floating wind turbine, i.e., to provide stability. While the WECs provide their buoyancy, PTOs are on-board systems whose weight must be supported by the FOWTs. For instance, the Wavestar test unit's total weight at Roshage is around 1000 tonnes for two PAs only (Marquis et al., 2010). Thus, on the one hand, it is clear that FOWTs must possess a minimum payload allowance to support on-board PTOs, which might hinder very light structures, e.g., up to a few thousand m^3 volume displacement. On the other hand, most structures designed for 5 MW wind turbines or more are relatively heavy. For these structures, if the PTO topology further decreases the centre of gravity or the WEC-PTO systems help in stability, it would be possible to save some amount of structural weight whilst still accommodating on-board systems and maintaining the stability performance of the platform.

4.2 Technical feasibility and limitations of the methods

Because the hybrid platforms are in an early stage of development, it is ultimately important to discuss the feasibility of the concepts. Two main requirements must be checked: mechanical feasibility and dynamic feasibility.

Regarding mechanical feasibility, because the WECs are connected to the FOWTs, robust mechanical connections are required, whereas the salinity in offshore locations may undermine many articulated solutions. In general, the hybrid FWWPs that include flaps do not consider the mechanical connection of existing flaps and PTOs, e.g., as detailed by Calvário et al. (2020). In those references, single-point PTO models are employed, and it is entirely unclear how the real WEC-PTO connection will be performed on the substructures. Moreover, optimal PTO parameters may be considered without looking into actual PTOs, for example, Homayoun et al. (2022) conducted a systematic study between different PTO parameters with damping up to 12 000 kNs/m, but the maximum feasible PTO damping was actually 750 kNs/m that same year (da Silva et al., 2022). This particular aspect may be overcome in the future, achieved by further development of PTOs.

Once more, it is worth of note that the total weight of the Wavestar test unit at Roshage is around 1 000 tonnes for two PAs only, and thus, the minimum payload allowance of FWWPs can be significant. That is, unfortunately, constantly neglected in the literature. For example, the TWindWave TLP has less than 4 000 ton displacement, and it is coupled with 4 WECs of 250 kW rated power each – it is a configuration that may be unfeasible with current PTO topologies used in tori and PA-WECs.

Regarding dynamic feasibility, it is worth referencing the benchmark study conducted by Babarit et al. (2012), who investigated eight types of WECs (no hybrid FWWP was considered). By comparing dynamic results, the investigation makes it clear that, independently of the WEC-type, the PTO forces easily reach the order of 10^4 kN, that is, near the order of magnitude of the hydrodynamic forces acting on both the WECs and the FOWT., with the exception of FOWTs' roll/pitch motions, that present even higher forces. Not considered in the benchmark study, the PTO forces in hybrid floating systems may further increase due to relative motions. Therefore, besides the fact that PTO and constraint forces relate directly to the structural reliability of the mechanical parts, which is vital for FWWPs, it is very important to note this proves that the dynamic simulations of FWWP must include a robust mathematical-numerical model for the simulation of the exact mechanical coupling between WECs, PTO and FOWT. In the case of PA-WECs, all references consider single-point PTOs, which is unrealistic regarding force constraint and may lead to severe underestimation of fatigue and unrealistic constrained motion dynamics. To overcome this issue, a new formulation has been developed recently (Hallak et al., 2023), that computes, accurately, the hydrodynamic and mechanical interactions of articulated multi-body systems using realistic hydraulic-PTO models.

While the configurations including torus-WECs and the spar-inerter configuration, indeed, represent reduced complexity in terms of dynamic behaviour, most configurations actually present complex mechanical interactions. Some references miss this point entirely. For example, the studies conducted by Chaitanya Sai (2019), Rony et al. (2023), and Deng et al. (2023) present numerical results with unphysical dynamic behaviour, where the WECs may heave up to 18 m for 1 m of the wave height, or the FOWT may pitch more than 20 degrees for 1 meter of the wave. Most importantly, it means that the numerical results obtained from simulations are undermined when the limitations of the mathematical-numerical methods applied are exceeded.

4.3 Experimental validation of concepts

The technical feasibility of some FWWP configurations has been proven in the laboratory conditions.

In a technical report published by Principle Power, Inc. in partnership with NREL, the WindFloat semi-submersible scaled for a 5 MW wind turbine was investigated experimentally with three different WECs, namely OWCs (2 chambers in the front columns of the unit), a PA-WEC in the middle of the platform, and flap-type WECs mounted below the bracings of the platform (Weinstein et al., 2012). This study provides the most consistent experimental comparison between different WEC types arranged on a validated FOWT. The major conclusions of the investigation are that the tested WECs do not considerably affect the dynamics of the platform and that there is no significant reduction in the final LCoE. The results of wave power absorption show that, for 2 meters height waves, PA-WEC absorbs only 50 kW near the optimal wave period of around 3 seconds; the OWCs absorb 139 kW near the optimal wave period of around 5 seconds; whereas the flap WECs present the best performance, with 150 kW at wave periods around 5 – 6 seconds. The response of the WindFloat unit in combination with flaps is not modified for both heave and pitch motions. In contrast, surge response is increased after the coupling with the flap-WECs, especially around and below the natural period of the flap.

The work of Kamarlouei et al. (2019, 2020a, 2020b, 2022a, 2022b, 2023) validated the concept of coupling PA-WECs on a semi-submersible platform. However, the power of the wind turbine was significantly reduced in that project. The concept is shown in Figure 9(a) in a configuration with 3 WECs. The platform was tested using different numbers and configurations of WECs and different PTO stiffness and damping parameters. The experiments validated the feasibility of controlling the pitch motions FOWT by a means of rational hybrid design, that has been previously suggested by Zhu & Hu (2016). The latter authors studied the lower dimension problem to achieve preliminary estimates of PTO-controlled hybrid platforms.

Experimental investigation of the SFC concept has been conducted by Michailides et al. (2016), where valuable results are drawn for a range of operational conditions with and without wind. Though that article is focused on the SFC concept, further comparison with the stand-alone braceless semi-submersible can be performed by considering the numerical work of Luan et al. (2016). It is found that wind effects (for a wind speed somewhat below the rated value) do not modify the motion responses of both the platform and WECs; also, the inclusion of the flaps on the platform does not affect the natural periods of the platform and have a small influence on platform's surge and heave motion. However, some pitch amplification is observed in the whole frequency range, amounting to 25% increase in the resonance frequency. That does not affect the operation of the wind turbine, for the accelerations at the nacelle stay in a rather small level.

Lin & Pei (2022) conducted an experimental study on the hydrodynamic response of a flap-type WEC mounted on a modified sub-structure of a 4-column semi-submersible platform. However, the platform geometry is rather generic and not necessarily a FOWT. If the empirical results are observed with care, they can still be insightful for the development of hybrid FWWP systems of the kind. That said, the experimental results were obtained for different platform sizes and mooring stiffness in a scenario where the WEC to platform mass ratio is considerably higher than the work of Michailides, thus pointing to a strong coupling between flaps and floating platforms. Moreover, since the flap-type WEC has a significant size compared to the platform and is not far below the waterline, it is concluded that the flap does not behave as a damping plate – it is very excited by wave action. Moreover, pitch response is strongly affected by the coupling and mooring stiffness, which may, in a rationale design, counteract the flap's effects on the platform's pitch motion.

The STC concept has been consistently validated in laboratory (Wan et al., 2015, 2016a, 2016b), as shown in Figure 9(b). The three references focus on different aspects of the system: wind effects to mooring effects, survivability, and validation of numerical models. The findings from the experimental campaign include the verification that the platform's surge and pitch motion, as well as mooring forces, are not significantly affected by changes in PTO damping, and the validation of the survival mode of the platform, in which the WEC goes submerged and effectively reduces the environmental loads acting on the system.

The semi-submersible-OWC combination has also been consistently validated in a laboratory (Zhang et al., 2022a).

The reference conducted a numerical-experimental comparison showing that the simulation of such configuration can be performed by adding free surface models to the coupled aero-hydro-elastic-servo-mooring framework to account for the OWCs dynamics. Whereas most results nearly match, the numerical simulations slightly overestimate the wave-absorbed power. The investigation also compared different control strategies, showing that PTO influences the dynamics of the platform in such configuration: Whereas traditional PTO control may lead to an increase in the platform's pitch motions, Continuous Gain-scheduling Damping (CGD) control leads to 6% mitigation on tower base fatigue loads and Two-state Gain-scheduling Damping (TGD) control leads to a 15% reduction on platform's pitch motions.

Finally, a wave basin has also validated the coupling between a torus-WEC and a TLP (Zhang et al., 2023a). In this study, the sensitivity of the motion response regarding the PTO damping parameter and the mooring forces is investigated in detail, which is ultimately important in a TLP design. The experimental results presented evidence of the multi-DOF nature of hybrid systems, whereas two peaks are found in the heave RAO of the system that are associated with two natural frequencies and relate to the FOWT-WEC coupling. In Figure 9(c), the TLP platform coupled with torus-WEC is depicted in the wave basin.

4.4 Research gaps and future perspectives

The review analysis makes it clear that most of the research done so far in the field of FWWPs has two main focuses: First, on the conceptual design of hybrid platforms and, second, on the preliminary investigation of platforms' dynamic behaviour, with primary attention to motion response and power absorption, followed by structural response, survivability and control strategies under operational conditions. However, the huge majority of investigation is based on simulations that still lie within linear first-order frameworks. Some investigations perform coupled analysis using commercial software, emphasising Ansys AQWA®, mainly because it allows the definition of multi-body coupling into time domain simulations (Ansys, 2020). With a recently developed framework (Yang et al., 2020), it is also possible to couple AQWA with FAST, which enables fully-coupled simulations of hybrid FWWPs. The new framework goes beyond usual FOWT simulation tools, e. g., the aero-hydro-servo-elastic tool OpenFAST (Jonkman & Buhl, 2004) and the aero-elastic-hydro-mooring-wake model by Yu et al. (2023). Thus, the conduction of coupled time domain simulations of FWWPs is expected to be one of the research foci in the near future.

The review analysis also put it clear that most configurations are thought of as WEC designs employed on FOWT structures. A design process starting from scratch, or optimization of a hybrid geometry from early development stages, is not seen. At most, some papers optimize the WECs and/or PTOs for a given geometry, e. g., Zhang et al. (2022b). Thus, a framework where the hybrid system is optimized from a global geometric point of view or even developed from scratch is missing, that is pointed as a missing research gap.

Another research gap to be identified is the lack of knowledge on the nonlinear and second-order effects FWWPs are subject to. For instance, experimental investigations of stand-alone FOWTs have already pointed out that difference-of-frequency wave excitation must be accounted within accurate predictions of pitch motions in irregular waves because the second-order components tend to excite the platform aroud the resonance frequency. That has been observed in the basin for different FOWT geometries, e. g., Karimirad et al., 2017; Simos et al., 2018; Hallak et al.,

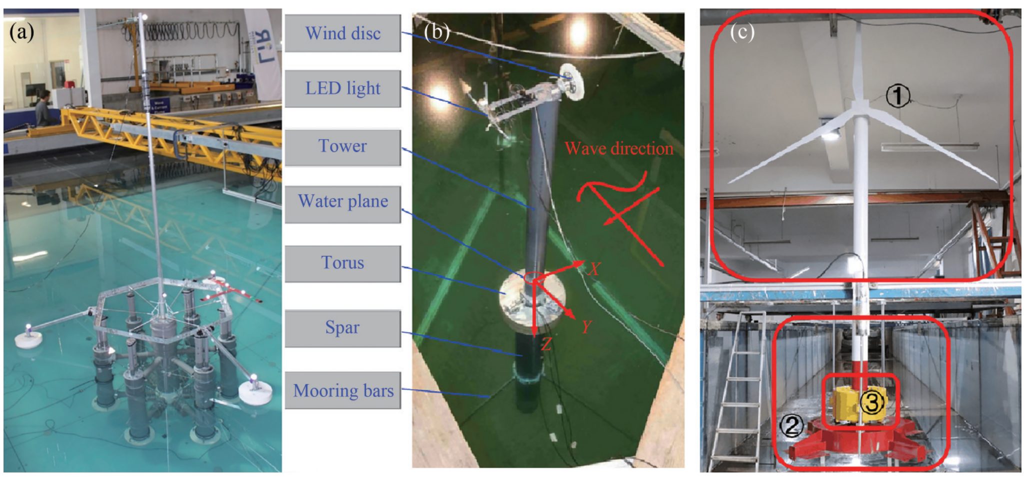

Figure 9 Experimental validation of FWWPs (a) Semi-submersible FOWT with three PA-WECs in the ocean basin of Lir – National Ocean Test Facility (NOTF), Ireland (Kamarlouei et al., 2022b); (b) The STC in the wave basin of the Italian National Institute for Naval Architecture Studies and Testing (INSEAN) (Wan et al., 2016b); (c) The TLP with a torus/split absorber at the Shandong Provincial Key Laboratory of Ocean Engineering, China. 1. Wind turbine; 2. FOWT; 3. WEC (Zhang et al., 2023a) – reproduced with the permission of AIP publishing

2018. Moreover, sum-of-frequency wave excitation components may excite the structural response of the wind turbine because the tower has a relatively high natural frequency, as investigated by Bachynski & Moan (2014). With an increase in the number of underwater bodies/modules, second-order force components may also increase due to wave-to-wave interactions. Today, it is rather unclear how second-order force components affect FWWPs' dynamic behaviour.

Chen et al. (2022a) and Shi et al. (2022) studied the nonlinear effects of damping lid on the wave elevation within the hybrid platform's surroundings and WEC's heave motion for, respectively, a PA-WEC and torus-WEC both in the middle of a semi-submersible platform. Based on their findings, in the case of torus-WEC with an inner radius bigger than the platform's central column radius, the free surface between the modules must be simulated with a damping lid to avoid spurious frequencies with unrealistic WEC heave motion, which is not required for hybrid platforms with modules far apart. Moreover, though it can be argued that, when the FOWT and WECs are far apart, the nonlinear multi-scattering effects are negligible, that definitely poses a question to configurations using torus-WECs, as well as configurations using bigger WECs and/or multi-WECs configurations: How can the wave field be simulated accurately and how can the WECs benefit from variations in the wave field? That is a highly nonlinear problem, ruled by, besides first-order diffraction and radiation, sum-of-frequency components, multi-scattering effects and surface damping, the latter two being nonlinear in nature, and both sum-of-frequency and multi-scattering effects are related to near-trapping of waves that, in turn, may strongly relate to rather unknown peaks of wave power absorption. It is also worth of note the work of Newman (2001), who reviewed the hydrodynamics of multi-body geometries at the time, with emphasis on near-trapping modes within WEC arrays, among other effects. It is discussed that multi-scattering techniques have been verified and validated mainly for multi-column structures and WEC arrays with identic or axi-symmetric bodies. In contrast, the same methods applied to somewhat different floating bodies are rare and may lack validation (Mavrakos, 1991; Mavrakos & McIver, 1997; Mavrakos & Kalofonos, 1997; Chakrabarti, 1999, 2000; Kim & Cao, 2008). Thus, the research on hybrid FWWP presents gaps in those complex nonlinear phenomena.

The last research gap to be noted regards experimental investigation. There is a lack of empirical data and experimental analysis for the majority of the possible configurations and, especially for the vast majority of concepts under development. Indeed, few FWWP models have been validated (see Section 4.3). The absence of empirical data makes validating coupled numerical techniques difficult. Nevertheless, some research institutes are currently involved in projects with future test campaigns, e.g., Gaspar & Guedes Soares (2020) and Nepomuceno (2024); thus, it can be pointed out that the pursuit of experimental tests is a future trend in the development of hybrid FWWPs.

5 Conclusions

In this paper, the FWWPs considered in the literature to extract wind and wave energy in the offshore have been reviewed and classified by type.

The concepts of wind-wave complementarity and supplementarity have been defined, whereas the prospects of wave energy as a supplement to FOWTs have been detailed – this idea offers a new perspective for future hybrid ORE development.

Then, by compiling data from more than 40 FOWTs, trends relating to the platform's draft, displacement, wind power and wind turbine dimensions have been obtained, ultimately relating these parameters with the wave energy conversion systems, also due to the maximum payload allowance of FOWT platforms.

The extensive review analysis led to the final sub-sections, which discuss in detail the technological feasibility of concepts, current limitations of the methods, research gaps and future trends in FWWP development.

The major conclusions drawn from the overview are summarized below.

• The review analysis of FWWPs shows that the generated power of a single WEC is one to two orders of magnitude below that of a stand-alone wind turbine. Thus, the major advantage of hybrid FWWPs is not the increase in nominal power. The significant advantage concerning the energy output of a hybrid wind-wave system is the reduction of intermittency and smoother power output. Other benefits are: increased weather windows for O & M operations, better use of ocean space, and overall cost reduction. There is still a potential increase in the wind turbine's efficiency, though that depends on rationale design;

• The differentiation between complementarity and supplementarity offers a new perspective for future hybrid FWWP development. Following the new standpoint of supplementarity, several offshore locations that are generally disregarded for the commissioning of FWWPs due to benign waves can be prospective areas for the commissioning of hybrid platforms, bearing in mind the actual major advantages of FWWPs as stated in the previous point, as well as the possibility of proving FWWPs in a relevant environment before moving to harsher offshore locations;

• The overview presented in this paper supports the idea that WECs may be accurately controlled to suppress system loads and, therefore, reduce the accelerations and fatigue loads on FOWTs, thus increasing the life cycle of the wind turbines. However, this depends on very rationale designs considering optimized PTOs–that are, again, not necessarily optimized to maximize wave power output, as well as a global geometric optimization of the whole hybrid geometry, namely, floating platform, WECs and WEC arrangement;

• By comparing the many configurations, it can be stated that a hybrid FWWP with single-WEC will present very similar dynamic behaviour with the stand-alone FOWT and a relatively small increase in power absorption, which does not lead to potential advantages. Thus, the most promising configurations are the ones employing multi-WEC arrangements, as well as the concepts where wave energy is absorbed from the relative motion between massive displacement hulls, namely, the spar-inerter configuration and the semi-submersible with hinged-floaters;

• Whereas most of the FWWP configurations investigated so far have been analyzed from a simplified numerical perspective, mechanical issues may often undermine their feasibility, as well as unrealistic PTO models and/or extreme dynamic behaviour;

• The major research gaps today are: First, the lack of knowledge in nonlinear and second-order effects acting on the coupled multi-body motion of FWWPs, also including lack of knowledge on how the WECs can benefit from the disturbed wave field. Second, there is a lack of a framework where FWWPs can be designed from earlydesign stages or optimized from a global geometric perspective. Third, the a lack of empirical data and experimental analysis. The latter can only be obtained from tests in wave basin or sea trials, and the first may only be consistently validated with the latter. Nevertheless, overcoming these gaps is the near-future trend in FWWP development, whereas the second gap appears as a missing point.

Hybrid wind-wave energy is a relatively new branch of offshore renewable energy facing rapid development. It is expected that novel configurations, methods and experiments will be published in the years that follow.

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