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Nonlinear dynamic assessment tools

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Review article

Review on floating wave-wind energy converter plants: Nonlinear dynamic assessment tools

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ABSTRACT

Hybrid wave-wind energy converters are considered an innovative solution to decrease costs in the various phases of installation and operation and lead to a lower Levelized Cost of Energy. Currently, there are different concepts in various Technology Readiness Levels. This paper provides a comprehensive review of existing wave-wind energy converters and the possible nonlinear dynamic assessment tools along with a discussion on their advantages and limitations. This paper broadly reviews and highlights the current level of understanding and knowledge of the relevant phenomena and their effects on the dynamic response of the existing concepts. The synergies between wind and wave energy -converters are discussed and key points for their future research and development are provided. It is shown that more than 60 % of studies are linear based which cannot reflect the highly nonlinear dynamic interaction between multi-bodies. It is demonstrated that the current lack of accurate simulation tools can be compensated by the proposed multilevel micro–macro modelling. This novel approach will allow representing the involved physical phenomena in the simulation of hybrid concepts taking into account the known limitations and lessons learned from the development of single or hybrid concepts and the simulation tools.

Introduction

The vast wind and wave energy resources around the World along with the global urgency to counteract climate change absorbed great interest in the last decades and attracted investment to the marine renewable energy industry. According to [1], the global primary energy demand is expected to grow by over 25 % until 2040, reaching circa 206,000 TWh/yr. In this context of energy demand, the theoretical potential of marine renewable energy (*i.e.* wave, tidal, etc) of about 151,300 TWh/yr is considered to be one of the most promising ways to meet future energy demands. Moreover, this estimate does not consider other energy sources such as marine biomass, or offshore solar and offshore wind, which contribute to an even more appealing scenario. For instance, offshore wind has a globally estimated potential of about 192,800 TWh/yr [1].

The rapid growth in the size and number of energy converters in offshore farms, and the tendency of deploying different concepts in deeper waters imposed increasing demands and challenges to the industry [2–4]. The interest in developing cost-effective harvesting technologies also encouraged the industry to find innovative solutions to make steady and under-control power production [5], which not only increases the power production in an optimized ocean space but also decreases the relevant costs of installation, operation, and maintenance.

Hybrid concepts combining Wave Energy Converters (WECs), with a predictable and high-density energy resource [6], along with Offshore Wind Turbines (OWTs), a further mature marine energy harvesting technology [7], are considered as a promising solution for the ever-increasing energy demands and transition to more sustainable energy systems. Hybrid concepts have the advantage of allowing an optimization of the use of the ocean space [8], sharing the support structures and infrastructures [5,9], as well as the grid connections, which is still one of the most important challenges and constraints in the marine renewable energy industry [10].

The high energy density of these two renewable resources (between 2 and 3 kW/m^2 for wave energy and 0.4–0.6 kW/m^2 for offshore wind

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Nomenclature

HAWT	Horizontal Axis Wind Turbines
TLP	Tension leg platform
HWNC	Hywind-Wavebob-NACA Combination
TRL	Technology readiness levels
LCOE	Levelized cost of energy
VAWT	Vertical Axis Wind Turbines
OWSC	Oscillating wave surge converter
WEC	Wave Energy Converter
OWT	Offshore Wind Turbine Units
PTO	Power Take-off
kW/m^2	Kilo Watt Per Square Metre (units for energy measurement)
SFC	Semi-submersible flap concept
TWh/yr	Terawatt-hours per year (units for energy measurement)
STC	Spar-Torus Combination

[10]) combined with their usually different timing, also promoted the development of several innovative hybrid concepts in recent years. In terms of availability, on average, the wave resource is accessible circa 90 % of the time, which can be considered a significant value in comparison to a maximum of 20–30 % of the time for wind energy [10].

It is worth mentioning that sharing logistics and reducing environmental impacts can also be considered as a big advantage of hybrid energy converters [11]. Therefore, there are considerable efforts to study the available resources for efficiently harnessing wave-wind energy [5]. More recently, consistent efforts have emerged to identify hotspots for co-locating wave and wind energy converters or using combined concepts to harness these resources [12]. The presence of different sites and hot spots that can provide a considerable source of energy for both wave and wind energy converters also motivates the progress in this industry.

Although, the look to the future is the effective usage of energy converters in a harsh high-power environment with fewer risks associated, yet both WECs and OWTs industry are struggling with the uncertainties in the reliability and performance of each device [1], which is the main challenge in the development and commercialization of hybrid concepts. Variation of concepts gives rise to the development of simulation tools for their operational condition and specific parameters related to the device peculiarity [13,14], to provide enough information for the assessment and viability of each concept.

This paper aims to provide a review of the various floating wave-wind energy converter concepts and also the state-of-the-art of technology's assessment tools. It also specifies and outlines the barriers or gaps at different technology readiness levels (TRL). Recent development in the offshore wind and wave industry have highlighted the need for a practical while accurate methodology for the simulation of the devices. This paper presents the following contributions:

- A novel multi-level micro-and macro-modelling methodology;
- A novel methodology based on the lessons learned and the gaps found in the current works;
- A systematic review on the simulation of hybrid systems for wave and wind energy conversion;
- A discussion of synergies between wave and wind energy structures.

The organization of the paper is as follows: The typically recognized concepts and TRLs are discussed in Section 2. Section 3 covers diverse experimental and numerical simulations performed by academia or industry stakeholders to get a clear picture of the expected behaviour of hybrid wave-wind energy converters. Section 4 provides the conclusions and final remarks.

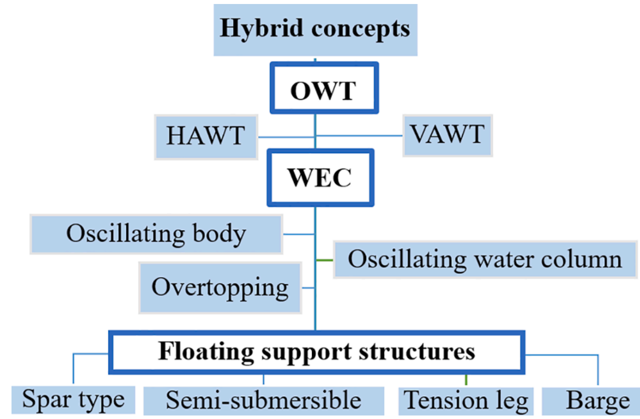


Fig. 1. Generic concept categorization of the floating hybrid devices.

Review on hybrid concepts

Different concepts were already developed to harness wave and wind energy simultaneously. Choosing the most suitable device for a specific environment is an important aspect for the development of any type of hybrid concept and strongly depends on the local environmental conditions and the parameters affecting the functionality and performance of the device. The device structures and geometry of potential floating support structures, OWT and WEC devices for hybrid concepts are further explained in Section 5.

A generic concept categorization and review of the possible floating hybrid concepts is provided in Fig. 1. As will be shown in the following sections, the most known devices combine HAWT with oscillating body WEC devices. While WTs should be sufficiently stable, usually oscillating body WECs require large oscillations to harvest wave energy. The hybrid concepts use an opportunity-focused approach on the functionality and the requisites of the two technologies to make this combination a successful set.

Apart from the development of the hybrid concept and the required technical and economic feasibility studies [15] for its implementation in a specific site, some of the most innovative hybrid concepts combining OWT and WEC devices are summarized in this chapter. The last part of Section 2 is dedicated to the tabularised overview of each concept, the main characteristics, advantages versus limitations, and challenges along with a schematic view of the device (see Table 1).

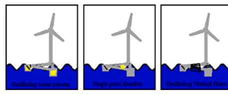
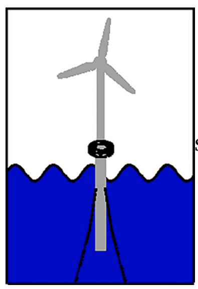
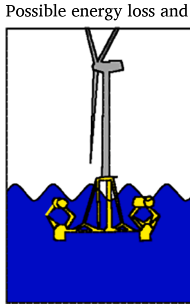
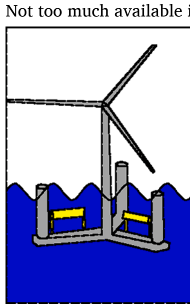
Wind-Wave float

The wind-wave float concept combines oscillating water columns or oscillating wave energy converter (point absorber or flap type) with the wind float, a semi-submersible support structure for a wind turbine. This new concept was developed under the Department of Energy (DOE) [16] grant and by a contract between Principle Power Inc. [17] and National Renewable Energy Lab (NREL) [18]. The goal was to carry out the technical feasibility study of the proposed concept [19]. The granted project studied several combinations of Wind float with various types of WECs.

The new concept was claimed to overcome several barriers priorly recognised for the WEC development, such as implementing the devices in deep water or the environmental footprints. Besides, the combination of wind and wave, this project paved the path for decreasing the installation and operation costs for harvesting a continuous source of energy [20].

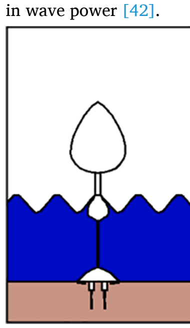
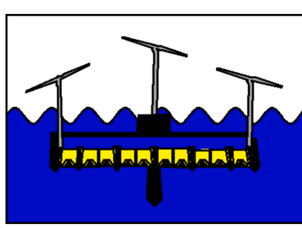
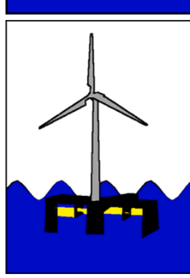
The platform provides the opportunity to mix different concepts of oscillating WECs with OWT. This could be a useful feature to utilize the most suitable WEC concept according to the environmental and site

Table 1
Exemplary floating wave-wind energy converter prototypes, important features, and challenges.

Prototype Support structure OWT WEC Water depth TRL	Important features and challenges
1) Wind Wave float [20] Semi-submersible, HAWT, Oscillating body and water column >45 m [19] 8–9 for Windfloat[34,40]	 Important features Possibility to use activated body or water column WEC Single 5-MW wind turbine [19] Deck space for additional equipment [19] Wind turbine is located on the side column Integrating WEC to previous OWT platform Challenges Increasing unwanted motions and forces on the main elements, especially for oscillatory flaps Maximum wave energy is around 250 kW per PTO [19] No reduction in levlized cost of energy (LCOE) was reported [19]
1) Spar-Torus Combination (STC) [21] Spar type HAWT Oscillating body Intermediate and deep water [21], Draft: 30 m [41] 2–3[33]	Important features  Single 5-MW wind turbine [42] Active water ballast for wave energy optimization and submerging the device in survival mode [42] Integrating WEC to previous OWT platform Challenges The synergy increase the wind and wave power production around 6 and 5–8 %, respectively [42] To decrease the motions of STC, Torus should be fully submerged [42] which could make difference in energy absorption. Possible energy loss and required maintenance in connections to prevent other motions than a relative heave
1) Dualsub [22,23] Tension leg HAWT 3) Oscillating body 4) - 5) 7–9 [43]	 Important features Integrating wind turbine to the previous wave energy platform (Wavesub) Each WEC float can capture > 1.5 MW Wavesub has an adaptive survival configuration Challenges Not too much available information to conclude on possible challenges
1) Semi-submersible flap concept (SFC) [7] Semi-submersible HAWT Oscillating body Draft: 30 m [7] 4–5[33]	 Important features Single 5-MW wind turbine [44] Wind turbine is located on the central column[44] Fully submerged elliptical cylinders as rotating flap [7] Integrating WEC to previous OWT platform Challenges

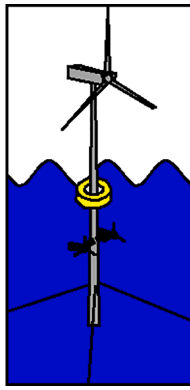
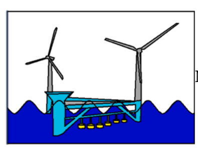
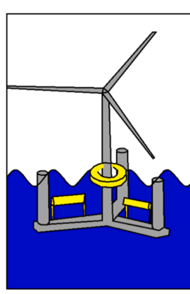
(continued on next page)

Table 1 (*continued*)

Prototype Support structure OWT WEC Water depth TRL	Important features and challenges
	The effects of rotary flaps on the dynamic and stability of the system Design of supporting arms and the joints connecting the flaps to the supporting arms [44] The geometry optimization is mainly for bottom supported flap [45], the question arises if it can also be effectively implied for the integrated wave-wind device.It is reported that the combination of wave and wind for SFC has a negligible change in wind power production and a 3–5 % increase in wave power [42].
1) Blackbird [26] Tension leg platform, VAWT, Oscillating body - 1–2 [33]	Important features Single VAWT Tension leg reduces vertical motions Challenges Performance and reliability of VAWT WEC connection to the main body Phase control to reduce motions of the device due to the WEC effects
1) P37 (Poseidon's hybrid energy) [46] semi-submersible, HAWT, oscillating body and water column Ideally 40–100 m [47] 4–5 [33]	Important features First hybrid device with 3 × 11 kW wind turbines and10 × 3 kW WECs connected to the grid [29] Integrating wind turbine to the previous wave energy platform Challenges Not too much available information to conclude on possible challenges
1) P80 (Floating Power Plant - Floating Power Plant [32]2) semi-submersible, HAWT, 4) > 45 m [28] 5) 4–5 [33]	Important featuresSingle wind turbine (from 2.3 to 5 MW) and WEC (2.6 MW) [29], the new FPP platform includes a single wind turbine (from 4 to 15 MW) and WEC (2–4 MW) [28] The WEC dimensions are tuned based on wave characteristics [48] Vane 360 degrees to incoming waves and could absorb around 50–70 % of the wave energy [32]. Challenges Not too much available information to conclude on possible challenges

(*continued on next page*)

Table 1 (*continued*)

Prototype Support structure OWT WEC Water depth TRL	Important features and challenges
1) Hywind-Wavebob-NACA Combination (HWNC) [49] Spar type, HAWT, Oscillating body 320 m [35] 8–9 for Hywind [34,40]	 Important features Reduced surge and pitch motions due to the presence of two tidal turbines [35] Challenges Increased heave motion [35] Increased tension in mooring lines because of WEC and tidal turbines [35]
1) W2power [37] semi-submersible, HAWT, Oscillating body > 40 m [37] 4 [60], wind platform, 6 [38]	Important features Two wind turbines (2 × 3.6 MW) and WEC (2 to 3 MW), > 10 MW in total with strong waves [50] Inclination of OWTs outward by 15 degrees[38] Challenges  Not too much available information to conclude on possible challenges
1) STFC [51] semi-submersible, HAWT, Oscillating body ~ 200 *m* 0–1	Important features Three Flap types WEC  A Torus WEC 5 MW braceless semi-submersible Challenges The nonlinear dynamic of the system would need further verification in terms of the effect sof PTO and interdependency of heave motion of torus and mooring lines.

*Note: Images are drawn by the author and inspired from the reference number provided in front of each prototype name.

conditions. As can be expected by using different WEC concepts, there would be various challenges that should be addressed. For oscillating water columns and vertical plates, the main challenge is the significant wave load; whereas for the single point absorber, the floater may be stranded in the windfloat [20].

Spar-Torus combination (STC)

This hybrid system combines two advanced concepts of point absorber WEC (torus, donut-shaped) and spar type floating platform OWT. The main bottleneck in the development procedure is the lack of proper assessment tools for the various phases of the analysis and design procedure [9].

STC has some interesting features to provide the required stability for the tower and also increase the power extraction. The spar buoy is equipped with ballast to maintain the centre of gravity below the centre of buoyancy to provide enough stability for the device. A ballast in the Torus is used as a tuning mass to increase power production [21].

One of the STC design difficulties is the connection between the bodies. Although the heave motion of torus and spar buoy should be independent to extract wave energy, they should be connected in the surge, sway, roll, and pitch degrees of freedom by a bearing system. The remaining degree of freedom, yaw, is also restricted by two end stops. End stops restrict the Power Take-off (PTO) forces during extreme

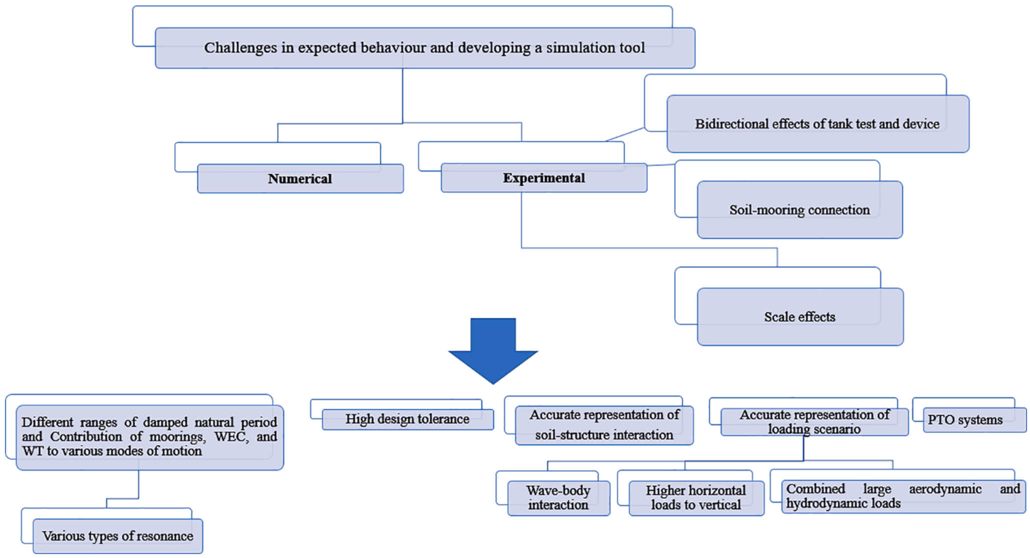


Fig. 2. Main challenges in developing simulation tools for hybrid energy converters.

environmental conditions [21].

It seems that by providing some kind of phase delay in the response of torus and spar buoy, the relative motion between these two elements, and consequently the extracted power, can be increased. This could also be in the direction of decreasing unwanted motions during the storm conditions.

The proposed installation process is fully integrating in the yard and then towing the whole system offshore. However, the presence of the Torus could cause some extra wave forces during the transportation process. Another way could be assembling the pieces in an offshore environment [21].

DualSub

Following the successful development of Wavesub technology, Marine Power Systems (MPS) announced the combination of wind and wave energy converters [22]. In this system, the main structure, mooring, and grid connection are allocated for both wave and wind energy converters. It is expected that the first hybrid system presents a rated power higher than 20 MW [23]. Stability assessment of the prototype with 1:4 scale model of DualSub has already been conducted [22] and it is expected to run sea testing in early 2022 [24].

Although as presented on the website [23], the proposed configuration uses a single WEC concept, it seems that the WT platform allows other concepts of activated bodies to be installed. Such as other combinations of WEC and OWT, it can be expected that there would be a need for phase control to reduce the unwanted motions in a harsh environment; especially due to the presence and interaction of various floaters e.g. [25].

Semi-submersible flap concept (SFC)

The semi-submersible flap-type concept combines a floating offshore wind turbine (5 MW) with flap wave energy converters. The semi-submersible support structure is composed of four columns, being the wind turbine tower standing on the central one [7]. The side columns are connected to the central one by three sets of pontoons on which floating flaps are mounted. Floating flaps are fully submerged and their upper and lower parts are 2 m below the still water level and 15 m higher than the pontoons. Three mooring lines are used for the stability of the proposed concept.

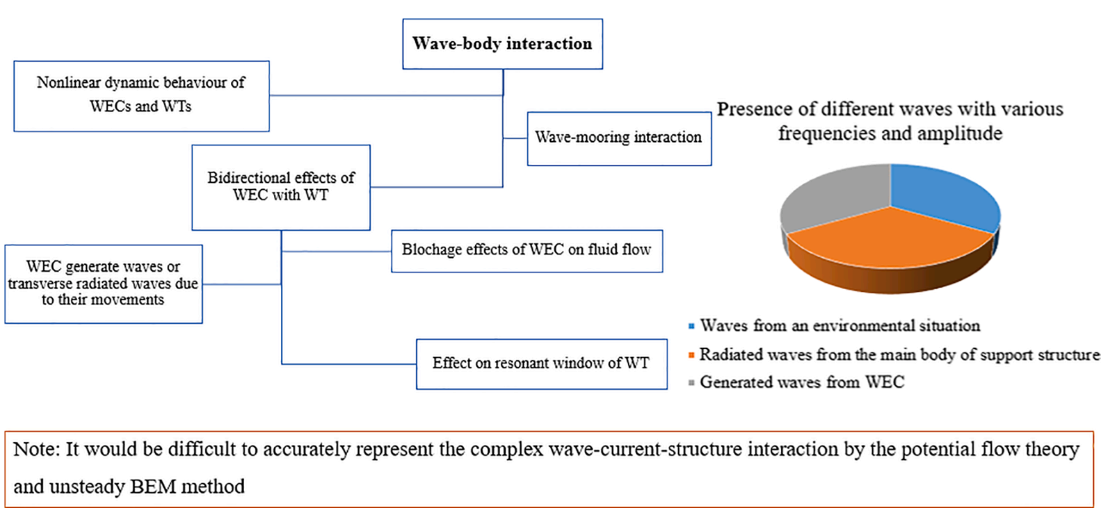


Fig. 3. Challenges in simulating wave-body interaction and the formation of waves with various frequencies and amplitudes.

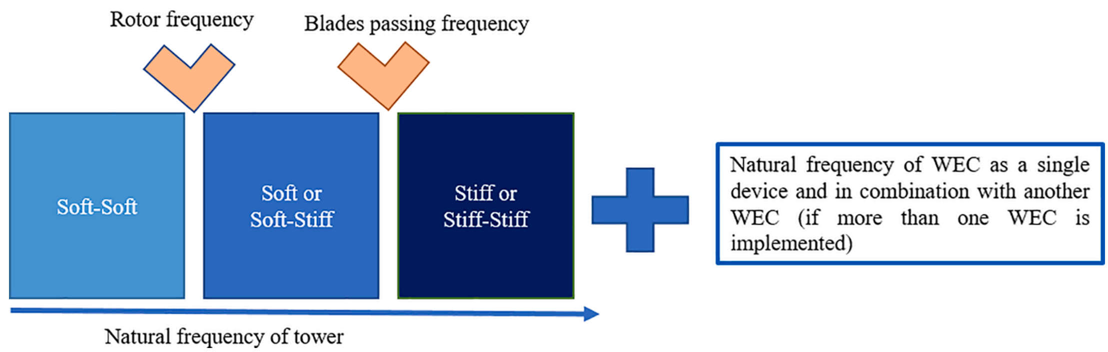


Fig. 4. Possible design windows for hybrid concepts base on the relative natural frequencies for wind turbine inspired by [77].

Blackbird system

The Blackbird concept is still conceptual and was first presented by [26]. It is comprised of a VAWT and a "winged" hollow cylinder heave plate working as a WEC device [26]. This device is composed of a combination of concepts and designs at various TRLs [26] and is supported by a submerged composite floating and anchored with a single linear axis tension leg. The WEC is a part of a buoyancy submerged unit that supports the floating wind above the water level [27]. The presence of heave plate wings and the restriction on the movement resembles the relatively simple version of turret weather-vaning bearing systems [26].

Poseidon's hybrid technology (P37)

The Poseidon's hybrid technology (P37) is a floating platform [28] essentially composed of a wave energy plant that also functions as an offshore wind platform. The conceptual and testing of this idea have been started in 1998 and went under several tests on different scaled models. A ¼ scaled test plant composed of three 11 kW wind turbines and 30 kW WECs [29] was launched in 2008 and as a first hybrid concept integrated to the grid was connected to the existent wind farm in Denmark [28]. The basic design and detailed design were started in 2012. In 2014, the first commercial floating power plant was launched [30]. A megawatt-scale of (P37) is a floating power plant (P80).

Floating power plant (P80)

The Floating Power Plant (FPP) is a semi-submersible floater comprising a single 5–8 MW wind turbine and a 2–3.6 MW wave energy converter [31,32], hence it can be considered as an advanced version of P37 [33]. A commercial-scale (FPP), or as is called P80 (since it is 80-meter-wide), will be deployed at the Plocan test site off Spain's Canary Islands [31]. The disconnectable turret mooring can ease the life cycle procedures from installation to operation and maintenance.

Hywind-Wavebob-NACA combination (HWNC)

The Hywind-Wavebob-NACA Combination (HWNC) is comprised of floating WTs, a heave WEC directly connected to the spar buoy and two tidal turbines. Although Hywind can be removed from the anchors and towed to shore if required, its large draft can limit its inshore maintenance and construction [34].

The WEC is only allowed to move in relative heave to the platform. The operation depth is considered 320 m, in which three mooring lines at 60, 180, 300 degrees about the vertical axis are oriented from fairleads at depth 70 m below the still water level [35]. The wind turbine power production can be unstable in severe sea conditions; however, the wind turbine energy production will be more stable due to the presence of WEC and tidal turbine and their consequent effects on the surge and pitch motions.

One of the main drawbacks could be the large tension in the mooring lines, which makes it impossible to use the same mooring design for the integrated device like the ones used for the single wind turbines [35]. It is also shown that the presence of other devices could mitigate the side effects of shutdown in amplified responses during the transient part of the dynamic response [35].

W2power

W2power is a hybrid wind-wave energy converter plant that includes two WT installed on two columns of a semi-submersible platform. The third column is used for the PTO of the WEC system [36,37]. The symmetrical array of WECs is integrated into the platform [38].

The W2power integrates a hydraulic PTO system; however, it has the ability to use other types of PTOs. The turret-type mooring system and the symmetrical WEC array shape provide a weather vanning for the system [39].

Summary of the main characteristics of existing hybrid concepts

A summary of the floating wave-wind energy converter prototypes and the type of support structure, WEC, and WT along with its main features and challenges are presented in Table 1. It should be emphasized that the tabulated information is mainly based on discussions provided on various literature and the conclusions obtained from the results of studies or reports. The main challenge in all concepts is the integrated nonlinear behavior for two devices, which can bidirectionally affect each other.

Hybrid concepts: Challenges in expected behaviour and developing a simulation tool

Developing high-fidelity simulation tools is mandatory for any step of the development and commercialization stages of each concept. Considering the large number and interdependent failure modes, the real behaviour of any marine structure can only be fully understood with a complete examination of the whole phenomena involved. This holistic approach is aligned with a concept of rationally-based design which literally means accurate analysis of all effective factors in safety and operation [52].

The way for developing an accurate assessment tool looks challenging and full of unsolved questions (see Fig. 2). Several studies have been conducted to improve the understanding of the different involved physical phenomena for isolated wave or wind energy converters [53,54] and simulation of hybrid devices by means of experimental and numerical tools [55], with some simplifications in considering the comprehensive nonlinear aero-hydro-servo-elastic-geo interaction. These simplifications could limit the simulations to specific circumstances, and any simplification in developing simulation tools should be conducted by awareness of the special features and load-response

Table 2
Numerical simulation tools developed for aero-hydro-servo-elastic-geo interaction.

Applied to:	Aero	Hydro	Control system	Mechanic/elastic	Support structure
Semisubmersible FOWT and a heave-type WEC [41]	Simplified mean constant thrust load	Potential Flow Theory For large-diameter elements, Morison Equation (Cylinders of the Semisubmersible Platform), Heave mode viscous load effects on the WEC	Spring-damper model	Rigid bodies	Linear springs for mooring lines
Semi-submersible wind platform and an array of point absorbers [89]	–	Using hydroD [90], and Morison for representing non-linear drag forces. *Wave energy converters are not modelled.	–	–	–
SFC[44]	The blade element momentum theory or the generalized dynamic-wake theory	Morrison Equations and linear potential hydrodynamic loads	PTO Linear rotational damping	Beam elements and rigid bodies * Interrelation between the flap WECs is not considered	Beam elements
HWNC [35,49,91]	Modified blade element momentum (BEM) method to simulate the unsteady wind turbine thrust force (Wind-SKLOE [92])	Linear potential flow and Morison equation (WEC-Sim [93])	Spring-damper model	Multi-body dynamics	Lumped mass mooring lines
NREL 5 MW wind turbine [94]	Coupled Blade Element Method with a wake inflow model	Linear frequency-domain potential for simulating hydrodynamics with the ability to simulate the free surface deformation effects and an approximation of viscous loads	Blade pitch and generator torque	Rigid elements for blade and towers and spring and dampers for hinges	Lumped mass mooring lines simulated by Multibody tool MoorDyn [95]
Point absorber WEC [96]	–	Morrison Equations (Equations are solved by using Comsol Multiphysics [97])	–	–	Dynamic equations describing the mooring movement
Spar-Torus Combination [8] A coupled simulation tool called SIMO-RIFLEX-AERODYN [98–100] was used.	Time-dependent aerodynamic	Linear wave theory and Morison forces on tower elements (hybrid frequency- and time-domain analysis)	PTO damping force	FEM *Damping and stiffness forces caused by the mechanical interfaces between WEC and OWT are considered.	Nonlinear restoring force
Semi-submersible wind turbine [101]	–	- CFD simulation and potential flow theory (using OpenFOAM)- Potential flow with Morison drag (using SIMA [102])	–	–	–
Wavesub[103] (using Nemoh [104] and WEC-Sim [93])	–	Potential flow theory considering drag coefficient	Spring-damping behaviour of PTO		Linear spring mooring
Array of WECs [105,106]	–	Hybrid experimental and numerical CFD model	Spring-damping behaviour of PTO	dynamic equation of motion	Hinge connection
Floating offshore wind turbine and point absorber WEC [107]	Standard blade element momentum method	Frequency-dependent wave forces by using Nemoh [104]	Generic spring and damper system	Frequency-dependent dynamic equation of motion	stiffness and damping
Oscillating wave energy converter [108]	–	Time domain CFD simulation considering the nonlinear drag coefficients	Spring-damping behaviour of PTO	dynamic equation of motion	Hinge connection
Wind Turbine with combined flap type and torus wec [51]		SIMO [109] and RIFLEX. SIMO [99]	Spring-damping behaviour of PTO	Rigid bodies	

characteristics[56], consequences, and the possible weaknesses in predicting real behaviour.

Experimental tests can be a viable and practical way to get a deeper knowledge of a device and hence increase its power extraction performance and reliability. However, the experimental facilities, namely the wave tank dimensions, can inevitably affect the results [57]. Therefore, it demands careful attention and a good understanding of the physical problems involved and their effects on the nonlinear dynamic response of the system [58,59]. Some of these effects, such as the period-dependent phenomena and the correlation between tank dimensions and floating objects, were studied during some experimental simulations [57,60]. However, many concerns related to the uncertainties in the reliability of the tests and the results remained to be addressed.

Actually, physical modeling could be sensitive in various ways, such as providing enough depth or accurate reprodution of connections and soil-mooring interactions. Another important limitation is linked to the scale effects (Fig. 2).

Some physical attributes of the mooring lines are related to the scale and would be difficult to be captured during experimental tests [61]. In the case of hydrodynamic analyses for floating WECs, the scale effects can be important and significantly affect their response. Scale effects are also considered important for the VAWT.

PTO systems are another challenging part of the procedure. Different PTO families are under development for various WEC concepts. Due to the diverse dynamic loading patterns and the variability of the renewable energy resources in time, the design of cost-effective PTOs is hard and sometimes a utopian task. The faithful and accurate reproduction of PTOs in experimental studies is also a complex task due to the variety of

Table 3
Aim, Methodology, and the results of the studies on combined or isolated wind and wave energy converters.

Applied to:	Aim	Methodology	Main findings and Results
Semisubmersible FOWT and a heave-type WEC [41]	• Introducing a combined floating offshore wind-wave structure Analyzing the effect of geometry and other influential parameters such as PTO damping and stiffness on the dynamic response	Development of the numerical model for Performance modeling Survivability under extreme wave conditions	The trend of the dynamic response characteristics under regular and irregular waves
Semi-submersible wind platform and an array of point absorbers [89]	• Presenting a combined floating offshore wind-wave structure Numerical study of the hull in absence of WECs	Development and validation of the numerical model for the stability and seakeeping performances	A calibrated numerical model for future studies of the combined structure
SFC[44]	• Presenting a combined semisubmersible wind-wave structure Study the PTO and mass of the WECs on power generation	Development of the numerical model for addressing the effects of the PTO and mass of the WECs	Discussing the relation between generated power with mass, wave period, and damping coefficients
HWNC [35]	• Improving the power production Decreasing the device motions	Numerical modeling to study the platform motions and power production	The synergy of converters can increase power and decrease the surge and pitch motions
HWNC [49]	Evaluating extreme responses and fatigue	• S—N method for cumulative fatigue damage Numerical modelling of the device	Increasement of tension and higher fatigue damage in moorings for combined win-wave-and tidal converter
HWNC [91]	Long-term extreme response with a modified environmental contour	Proposing a modified environmental contour method	The proposed method is more appropriate for combined devices.
NREL 5 MW wind turbine [94]	Study the stability and the response to the regular and irregular waves	A fully coupled model for aero-hydro-servo modelling is used.	An effective controller is proposed for various ranges of loads.
Point absorber WEC [96]	To develop a validated numerical model for catenary moorings	The results of the numerical model were compared with several tests to regular waves.	It is shown that the validity of the model is related to the drag coefficients used in the model.
Spar-Torus Combination [8]	Comparison between response, and power of three concepts of hybrid wind and wave for various depths and environmental conditions	the concepts include similar WECs with different support structures. The numerical model for each concept has been developed and the results were investigated.	As can be expected, dynamic response of concepts is considerably influenced by various support structures and water depths.
Semi-submersible wind turbine [101]	Investigation of nonlinear wave load on semi-submersible wind turbine	CFD and potential-based theory models have been used and validated by experimental results.	It was found that the CFD model can better estimate the response to various wave loads; while differences in potential flow theory were significant for higher order wave loads.
Wavesub[103]	Optimization of a multi-float layout based on spacing and numbers	Numerical modelling is used for the WEC simulation, and a genetic algorithm is utilized to find the minimum LCOE as an objective function.	Consideration had been given to the effects of drag and nonlinear forces on the estimated response and performance. These nonlinear forces are mainly due to PTO and mooring lines.
Floating offshore wind turbine and point absorber WEC [107]	Investigation of power production and motion of the device	Development of a numerical model for investigation of the effects of wave parameters, PTO effects, WEC size	• Smaller WEC sizes can less disturb the floating movements and would be more optimized. The range of effective power production based on wave parameters is also presented.
Combination of wind Turbine with combined flap type and torus WEC [51]	Proposing and feasibility study of a new concept	A fully coupled model used for decay tests, and response to regular and irregular waves	• Higher power of the combined system in comparison to single WT The results need further investigation by using optimized PTO for each type of WEC

unscaled friction effects e.g. [62] and the downscaling of electrical systems and components. Some other experimental test challenges are related to the uncertainties from the test setup to power estimation [63].

Since the same scaling rules are not applied for dimensions and non-inertia parameters, the scaling of friction or other similar parameters and their representation in experimental tests would be difficult [58,64,65]. Furthermore, some sources of damping, such as mechanical-, viscous damping and vortex shedding in sharp edges, cannot be scaled correctly with Froude similitude [66].

It can be concluded that most of the experimental tests have some limitations in representing the whole aero-hydro-servo-elastic-geo behaviour. Therefore, it is essential that experimental tests will be compared with field data [67], and the discrepancies will be studied and identified in order to decrease the uncertainties of experimental tests.

The Dualsub is presented as the first example of a hybrid device with mooring systems. MPS considers the efficient usage of both wave and wind energy and an optimized array of single or hybrid concepts together [24]. This subject is another possible challenge in developing the farm of hybrid concepts. For layout optimization, several factors should be considered which are mainly defined based on the operation and maintenance requirements. From the simulation of physical phenomena, the wake model can be considered as one of the important parameters in defining the optimized distance in offshore wind farms [68]. Indeed, OWTs are spaced in order to minimize the wake effects and inter-turbine wake losses [69]. The optimization goal can be achieved following two different paths: minimizing the cost or maximizing the total energy [70]. As was discussed, the DualSub is a combination of WT with WaveSub concept. Therefore, to maximize energy production, layout optimization should be carried out considering the productivity of the whole system.

Another example of a physical modelling application is the experimental demonstration of the Semi-submersible flap concept (SFC) at the Hydrodynamic and Ocean Engineering Tank in Ecole Centrale Nantes, France. The device was placed at the centre and the wind was simulated by using eight centrifugal fans on one corner of the basin [71]. The natural frequency of the platform and WECs were measured and compared with the corresponding numerical simulation results, and small differences were reported. It was mentioned that the agreement of numerical and physical behaviour was mostly seen under wave loads without the presence of wind.

The full understanding of the hybrid concept behavior needs to consider the complexity in both geometries and physics, which can be achieved by a combination of different numerical methods and experimental tests – composite modelling. Although several numerical studies have been conducted to consider the different involved physical phenomena, many questions arise on the sensitivity of the solver, accuracy

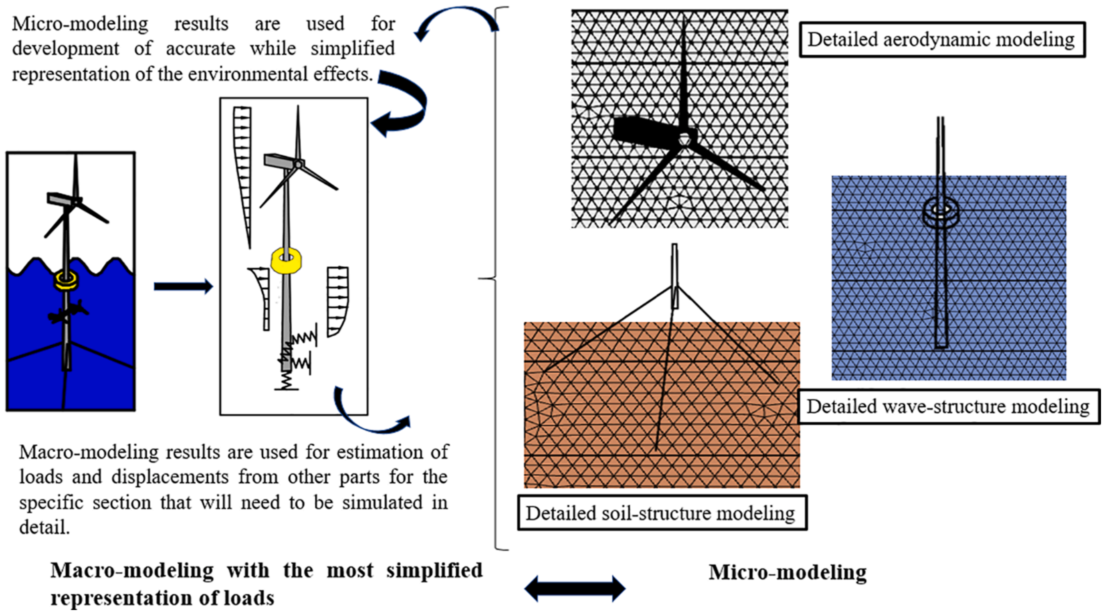


Fig. 5. Exemplary sketch of multi-level micro-and macro-modelling.

of the modeling, the simplifications made to simulate interactions between phenomena, and still there exist discrepancies in guidelines for analysis and design procedure of OWTs and WECs. Accurate representation of wave-body interaction can be considered one of the main challenges in developing simulation tools (Fig. 2 and Fig. 3).

The wave-structure interaction for oscillating WECs and floating wind turbines, especially under moderate to harsh environmental conditions, is highly nonlinear [59,72] and, therefore, the development of a fairly accurate simulation tool while decreasing the computational/time efforts [73] is still ongoing [53,74]. It is mandatory to get a thorough understanding of the formation of waves from different sources (Fig. 3). Then, it would be possible to use the combined system to increase the resultant energy by wise usage of the control systems e.g. [59].

Typically, the support structures are designed to decrease the blockage effect and facilitate the passage of waves e.g. [33]. Appending WECs could block the fluid passage and increase the wave impact on the wind turbine support structures. On the other hand, the bigger scale wave field should be considered in the simulation to fully represent the fluid-body interactions of the whole system which is mainly due to the mooring configuration which occupied more space in comparison to monopile foundations [75].

Fundamental issues in wave-structure interaction are the limitations of the old theories which are now used for a new generation of marine structures, the multidisciplinary nature of the project, its limitations, and the challenges ahead to develop a fairly accurate simulation tool. Moreover, it should be highlighted that using computationally demanding tools cannot be always a good solution for the industry. Especially during the operation procedure, it is critical to develop a solution algorithm that can be solved in a fraction of time and process the information for possible fault or malfunction.

Another consideration that should be taken into account is the design tolerances of OWTs that are much stricter than in the oil and gas industry, which means that the critical impacts can be caused by even little variances due to soil strength or fabrication [76]. On the other hand, there are a large number of complexities in loading scenarios with a higher horizontal load to vertical, resonance effects at different windows of period ranges [76] to name but a few.

It must be underlined that the damped natural period of offshore structures is nonlinear and dynamic. This fact becomes more crucial for hybrid concepts. It is vital to investigate the vulnerability of the whole structure to different environmental conditions by considering the possible range of natural periods of the whole system including the turbine components (such as blade and rotor periods), WEC device, and the possible bidirectional effects.

For offshore wind turbines, three possible modes of design include Soft-Soft, Soft-Stiff, Stiff-Stiff (see Fig. 4) that are defined based on the relative natural frequencies of tower, rotor, and blades [77]. The concept of categorizing from a flexible structure to a very stiff system and possible design windows is to consciously avoid period-dependent phenomena such as resonant [78,79].

Although this approach is useful, it needs to be carefully applied for a successful hybrid concept. Vibration control is one of the most sophisticated topics in OWT mainly because of the complex dynamic behaviour of OWTs [80]. Flexibility could increase loads and implementing the WEC device would change the natural period of the whole system (Fig. 8). Previous studies were mainly focused on the range of interdependency of the tower's natural period with rotor and blades. However, more recent studies consider the soil-structure interaction effects on the natural period into account [81]. In the case of floating OWT combined with WEC, the other periods that exist in the system should also be considered.

The station keeping system for floating bodies is another major topic in the development of simulation tools and design of floating hybrid concepts. The station keeping system can be a passive, active, or combined passive-active system based on the principle of providing the restoring force [82]. Typical foundation and mooring response assessment include several steps and the response analysis procedures, which can vary from static to dynamic, are the topic of several guidelines [83] and studies [84].

The design of foundation for OWT is a complex process in comparison to the oil and gas industry, due to the significant forcing loads induced by inevitable large aerodynamic loads combined with the hydrodynamic forces [85]. While for OWTs, it is advisable to provide a safe platform, for WECs it is expected that its motion is not restricted by the presence of mooring lines [86]. On the contrary, in some concepts, the mooring lines are used and tuned to increase the performance [87]. It should be noted that the presence of WEC can increase the loads on mooring lines and consequently increase the chance of fatigue-related damages [49].

The complicated behaviour of soil-mooring line interaction cannot accurately be represented in experimental tests or by some simplified numerical simulations. There are several details that should be considered for the mathematical description of the mooring lines such as their significant contribution to various modes of motion. To capture phenomena related to low and high frequency, long simulation time with short time steps would be necessary [88]. The summary of numerical simulation tools developed for different hybrid or floating wind turbine concepts are summarized in Table 2.

As can be seen in Table 2, there is not a unique model and the simulation tool could be tailored based on the analysis requirement. For example, for preliminary analyses, simplified models could be acceptable, though a more demanding tool would be necessary during fatigue simulation [88]. Table 3 shows the aim, methodology, and results of the corresponding studies.

As summarized in Table 2, almost 60 % of studies are based on linear theories for wave-structure interaction. It will be further explained that due to the nonlinearities involved in the expected dynamic response of wave energy converters and combined systems, these models cannot capture the rapid change in the response. Lower than 30 % of the reviewed works combine the model with a higher source of nonlinear damping. This leads to the importance of the development of more accurate modeling techniques for constantly growing offshore hybrid concepts.

The solution for the issues presented previously could be developing multi-level micro-and macro-modelling. In macro-modeling, representative models replace the detailed model. This simplification reduces the unknowns, the interpretation of the results will be easier and can be made with less computational and time efforts. Although it cannot precisely represent the local behaviour, it can be used for global analyses or in combination with micro-modeling. On the contrary, in micro-modelling simulation would consider all possible details to accurately represent the physical phenomena.

The general sketch and the correlation between macro- and micro-modelling are shown in Fig. 5. It should be emphasized that according to the importance or complex behavior of each part of the aero-hydro-servo-elastic-geo interaction model, further detailed simulations are conducted. For this example, only schematic CFD aerodynamic simulation of blades and detailed wave-structure and soil-structure simulation are shown. By comparing the results from micro-modeling with the simplified models, a better approximation can be developed and used in the macro-modeling.

To the best of the authors' knowledge, in experimental and numerical modelling studies, the geotechnical aspect is not fully and accurately investigated and, in most cases, it is ignored. To emphasize its importance, even the anchor type of moorings is dependent on the soil type and characteristics [110]. In other studies, it was shown that for various soil types the assumptions for simulating the interaction between the soil and the length of the mooring would be different. For example, for sandy sea bed, it is possible to assume a mooring line above the sea bottom. However, this assumption may not be true for silt and clay soils with significant penetration of the mooring lines [111].

Due to the vulnerability of floating WTs in comparison to the classic oil and gas platforms, even a small variance in the soil strength can make a significant change in the response of the system. Therefore, the best solution could be developing an accurate and more sophisticated micro-modeling of soil-structure interaction solver. In this model, the reactions and movements of top-side structures should also be modeled. These reactions and movements can be obtained from the macro-modeling of the whole top-side.

Conclusion and final remarks

Developing cost-effective hybrid wind-wave harvesting technologies needs the development of creative approaches for the efficient harnessing of both wind and wave energy resources and sound knowledge of the challenges ahead. The presence of WEC and its contribution in providing stability/sheltering or suppressing unwanted motions of OWT are not fully understood neither accurately could be predicted. This interaction could even affect the foundation protection as was discussed in [112]. The randomness of the sea and the multi-directionality of waves can effectively change the dynamic response of each component which in turn could affect the efficiency of the hybrid device.

The development of a simulation tool and a successful set of wave-wind energy converters go hand-to-hand. Simulation tools should be comprehensively verified to be sure about their accuracy and practicability. It should be stressed that even a model that could well predict the behaviour of a particular concept may not necessarily be successful for other prototypes. Moreover, there are ever-increasing advanced concepts that may not share the same demands, functionality, or expected behaviour.

Although there is significant progress in developing experimental and numerical tools representing multibody dynamics, there is still a lack of fairly accurate simulation tools able to represent all the involved physical phenomena. Therefore, the dynamic characteristics of the device and tuning the design properties to harness the maximum power are subject to some kind of uncertainty.

The present review concluded that a reasonable approach for future studies and development could be developing multi-level micro-and macro-modelling which combines the required detailed simulation of each part of the aero-hydro-servo-elastic-geo interaction with a model reproducing the general behavior.

This methodology would be iterative to find the most convergence between the micro-and macro modeling. Since the analysis and design procedure need different levels of accuracy, the micro–macro model should also be multilevel and composed of refined, simplified, and complex methods for preliminary and detailed design and reliability assessment and tailored for the specific needs of the site. It is possible to find the approximate linear level and study if under the extreme environmental conditions on the specific site, the behavior of each part can be simulated by simple models which are completely or partly linear.

The accurate procedure would need different levels of interdependency analysis considering aero-hydro-servo-elastic-geo interaction which should be compared with experimental results. The discrepancies between the measured and the numerical results should be studied, and the source of errors due to modeling or measurements should be categorized. Although experimental studies can be used as a great tool to achieve deeper insight into the expected response of structure; it needs a solid interpretation of the results and acquaintance with the flume/wave tank effects on the dynamic response. Moreover, due to the limitations of the experimental tests to completely reflect the real environmental situation, it is crucial to use the in-situ measurements to modify the possible misunderstanding in the experimental prediction and make the numerical model more reliable representative of the structural response.

Appendix A. Structure and geometry of hybrid concepts

This section provides information on the evolution of OWTs and WEC and their supporting structures. The evolution of OWTs started from monopiles (up to 30 m of water depth) and continued to floating devices for depths above 100 m [7]. Among the various floating support structures, some are considered more suitable for implementing WEC devices [9]. For studying different floating wave-wind energy converter plants, it is necessary to have a review on the main floating support structures, wind turbine concepts, and the practical types of WEC devices, which can be combined to make a hybrid energy converter.

Floating support structures

Floating support structures facilitate the deployment of the energy converters in deep waters, where bottom-fixed structures cannot be easily employed or are less cost-effective [113]. Additionally, floating concepts often present a compliant behaviour, which to a certain degree may enable a higher energy conversion efficiency. Since bottom-fixed structures have restrictive criteria when it comes to the dynamic behaviour and natural frequency, which should be within acceptable ranges.

However, floating support structures are also recognized as those presenting the main challenges in design and analysis procedures [114]. The different concepts developed for floating support structures for OWTs can generally be categorized into four main concepts: semi-submersible, spar buoy, tension leg platforms, and barge (see Fig. 6).

The primary concepts of floating support structures along with their main features and some dynamic considerations are also summarized in Table 4.

The TRL of these support structures along with a breakdown of TRLs are summarized and depicted in Fig. 7 by inspiration from [118–120].

Offshore wind turbines

OWTs can generally be categorized into two main groups according to the rotation axis of the turbine: horizontal and vertical axis (see Fig. 8) turbines [80]. Although the Vertical Axis Wind Turbines (VAWT) did not get much attention, as the fixed offshore structures, it is predicted that they can get their place in the future of floating structures. Several reasons justify this prediction. Firstly, most of the pieces of equipment of Horizontal Axis Wind Turbines (HAWT) are located high above the water, which could be a negative point in operation and maintenance, while for VAWT, the presence of heavy components could help the stabilizing of the turbine and lowering the centre of gravity [121].

The performance and efficiency of VAWT in cramp space are predicted to be higher while for HAWT, longer distances are required to compensate for the wake effects, which means long-distance cabling between each HAWT.

Applicable wave energy converters for hybrid concepts

In comparison to WTs, the number of WECs technologies developed so far is much higher and there is also more variability in the underlying concepts, which cover plenty of ideas developed both for nearshore and offshore applications. In 1991, >1000 proposals for WECs were presented [122], which could be classified based on location, working principle, and size [123]. Based on working principles, the WECs can be categorized as oscillating water columns, overtopping devices, and wave-activated bodies [124] in which the latter has mostly appeared in hybrid floating concepts (see Fig. 9).

Wave-activated bodies move and oscillate around a reference point and the energy is extracted from the relative motion of the moving body to the reference body [124]. These converters can be subcategorized as devices with translation or rotation movement [125]. Maximum hydrodynamic efficiency is reported to vary between 17 and 68 %, depending on the testing scale, for oscillating body-heave, and fixed oscillating wave surge converter (OWSC), respectively [126].

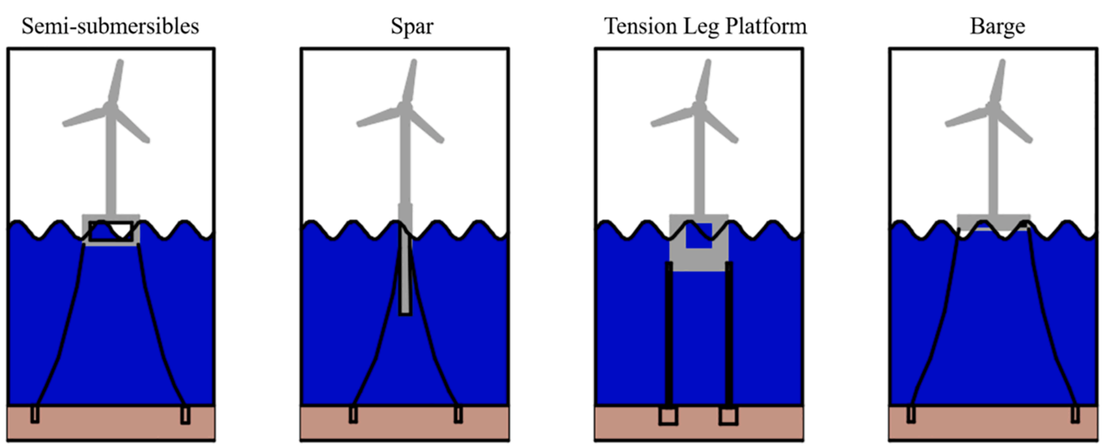


Fig. 6. Main types of floating support structures for offshore wind turbines.

Table 4
Main types of floating support structures and their characteristics.

Primary Concept [115]	Stabilizing mechanism [113,115]	Important features	Dynamic considerations
Tension leg platform (TLP)	Mooring stabilized	Heave, roll, and pitch restriction [116]	Possibility of high-frequency dynamic effects [117]
Spar-based	Ballast stabilized	Large draughts [115]	Vortex induced motions [115]
Semi-submersible	Column-stabilized (water plane based)	Small water plane [115]	High heave natural period [115]
Barge	Water plane based	Large water plane and small draughts [115]	Significant accelerations in roll [115]

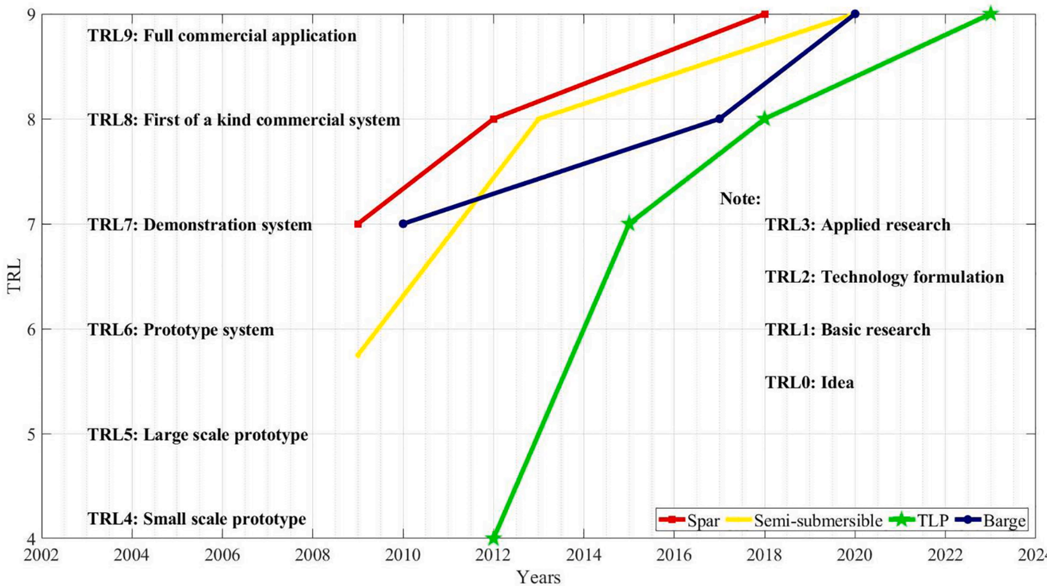


Fig. 7. Breakdown and definition of TRLs inspired by [118–120].

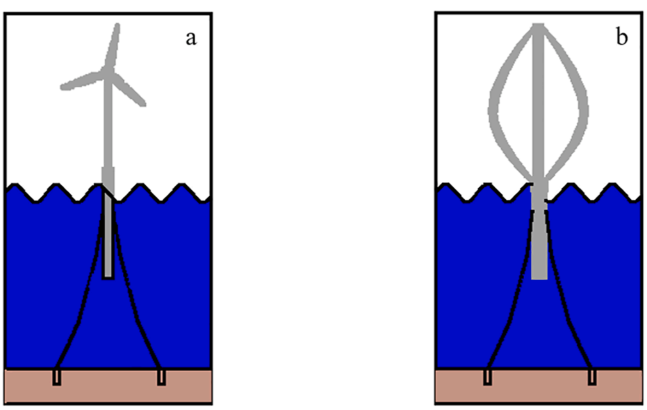


Fig. 8. Horizontal (a) versus vertical axis (b) wind turbine.

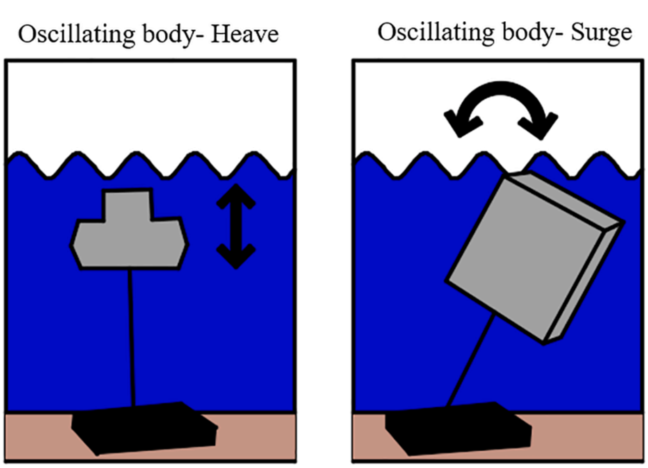


Fig. 9. Wave-activated bodies applicable to hybrid concepts.

CRediT authorship contribution statement

Saghy Saeidtehrani: Conceptualization, Investigation, Methodology, Data curation, Visualization, Writing - original draft, Writing - review & editing. **Tiago Fazeres-Ferradosa:** Writing - Review & editing. **Paulo Rosa-Santos:** Writing- Review & editing. **Francisco Taveira-Pinto:** Writing - Review & editing

Declaration of Competing Interest

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

Data availability

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

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