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Statistical analysis of floating hybrid wind–wave energy systems

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HIGHLIGHTS

- Wave energy converters contribute 5 %–10 % of the wind turbine's power output.
- The semi-submersible platform with three heaving WECs is the most studied hybrid configuration.
- A single WEC in a hybrid wind-wave system is typically designed as a 100 kW unit.
- WECs generally amplify the platform's heave motion while reducing its pitch motion.
- Hybridisation of FOWTs with WECs increases the project cost.

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ABSTRACT

Recent advances in the development of floating offshore wind turbines have also generated great interest in hybrid wind–wave energy systems due to the resource and technological complementarity of both systems. Over the past decade, a large amount of research has been conducted to uncover the benefits of combining floating wind turbines with wave energy converters and to propose and evaluate new hybrid system designs. The aim of this study is to identify trends, patterns and insights of the hybrid wind–wave energy systems by collating, reviewing and analysing the data available in the literature. The statistical analysis is presented for the design aspects of the hybrid wind–wave system, power production of wave energy converters, methodologies used to investigate the hybrid system dynamics, and the reported findings. The analysis indicates that research on hybrid systems lags behind floating platform development by approximately five years, with a predominant focus on 5 MW wind turbines installed on semi-submersible platforms and coupled with heaving wave energy converters. However, hybridisation efforts must keep pace with advances in modern wind energy technologies. The share of wave energy in the total power production of a hybrid platform is less than 10 %, and the median rated power of a single WEC is close to 100 kW. Wave energy converters do not tend to change the wind turbine power production, while an increase in platform motions was observed, also negatively affecting loading on mooring lines. Therefore, new designs need to investigate motion suppression in order to explore additional benefits of the hybridisation, such as mooring and tower bending load reduction. Furthermore, integrating wave energy with a floating wind turbine increases the levelised cost of energy of the combined project, underlying the challenges in providing a techno-economically viable solution, which also should be considered in the design process.

1. Introduction

The idea of harvesting ocean wave energy has existed for at least two centuries, with the first mechanism proposed and patented in 1799 [1]. The development of wave energy converters (WECs) gained momentum following the oil crisis of the 1970s, driven by the search for alternative energy sources. Since then, progress has fluctuated, experiencing periods of rapid innovation and stagnation, largely influenced by the availability of funding from both private investors and government initiatives [2]. Fig. 1a presents a historical timeline of selected wave energy demonstration projects, illustrating that the rated capacity of WECs developed to

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Nomenclature

Acronyms

BEM	Blade element momentum theory
CFD	Computational fluid dynamics
DOF	Degree of freedom
FOWT	Floating offshore wind turbine
LCoE	Levelised cost of energy
OWC	Oscillating water column
OWSC	Oscillating wave surge converter
PTO	Power take-off
TRL	Technology readiness level
TLP	Tension leg platform
WEC	Wave energy converter

date has ranged from 20 kW to 1.25 MW. However, despite this broad range, the median power output has remained relatively stable over the past 25 years, consistently around 300 kW per unit.

Over the same period, the offshore wind industry has grown at a much faster pace, with offshore wind turbine capacity increasing from 2 MW in 2000 to 18 MW in 2024. The need for wind turbine installations in waters deeper than 60 m, where the wind energy resource is stronger and more consistent, has stimulated the development of floating wind solutions. Fig. 1b compares the growth in capacity of fixed-bottom and floating offshore wind turbines (FOWTs), distinguishing between reference designs and commercial or demonstration projects. Reference wind turbines, such as those released by the National Renewable Energy Laboratory and the Technical University of Denmark (DTU) [3–5], have typically been made available several years before the deployment of commercial prototypes. The rapid development of floating wind projects began with the construction of the first prototype in 2007. Since then, a time lag of approximately five years has persisted between the deployment of bottom-fixed wind turbines and their adaptation for installation on floating substructures.

Discussions on combining wave and wind energy began in the 1990s with projects like OSPREY (Ocean Swell Powered Renewable Energy), which featured a bottom-mounted oscillating water column integrated into the base of a fixed wind turbine [6,7]. Further expansion of research and development of hybrid wind–wave energy systems followed the rapid development of offshore wind turbines in the early 2010s [8–10]. The objective was to take advantage of the complementarity of wind and wave resources, with offshore wind offering high-capacity generation, while the wave energy provides a more consistent energy content. The potential to harness both wind and wave resources was seen as an opportunity to accelerate the development of both technologies by leveraging their numerous synergies [11,12]. Extensive research has been conducted on the design and analysis of hybrid wind–wave energy systems, though only a limited number of prototypes have undergone sea trials. Table 1 presents industry-driven hybrid system initiatives, including demonstration projects, prototypes, and conceptual designs. The most successful sea-tested hybrid platform to date is the P37 prototype developed by Floating Power Plant (FPP). Similar to FPP, companies such as Marine Power Systems (DualSub concept), Bombora Wave Power (InSPIRE project), and Pelagic Power (W2Power concept) were originally focused on wave energy development but later proposed hybridising their technologies with FOWTs.

Despite the limited number of hybrid demonstration projects, a substantial body of academic research explores new conceptual designs for hybrid platforms, evaluating their potential performance benefits and challenges. One of the earliest review papers on combined wave and offshore wind energy [19] was published in 2015, identifying synergies between the technologies and classifying wave–wind systems based on asset sharing and integration levels. Subsequent technology review papers (e.g., [20–25]) have typically examined advancements in offshore wind and wave energy devices, classified proposed combined wind–wave systems, and analysed their technical aspects. While these reviews provide valuable insights, no study has systematically summarised trends or analysed findings published by the research community. A statistical analysis of data collected from published papers could reveal key trends, patterns, and insights - an aspect currently missing in the literature.

This study aims to provide a big-picture overview of existing trends in combined wind–wave energy systems, focusing primarily on the hybridisation of floating offshore wind turbines with wave energy devices where they share a common platform. The statistical analysis is performed for the technology type, power performance, methodologies used, and reported findings. It should be acknowledged that all reviewed papers have a different focus, a different number of details included, and a different presentation of results. Therefore, in this work, it was necessary to make assumptions and approximations to reduce discrepancies in the collected information. However, uncertainties are still present due to differences in modelling fidelity.

The remainder of the paper is organised as follows. The methodology used to collect, review and analyse data is discussed in Section 2. The statistical analysis is presented for FOWTs and WECs separately

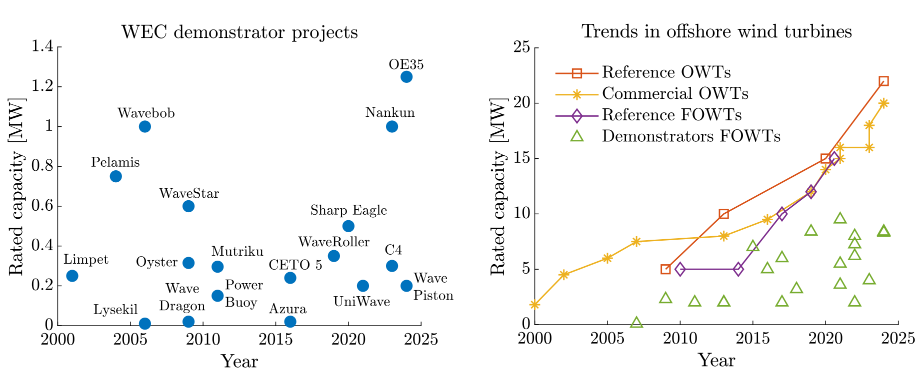
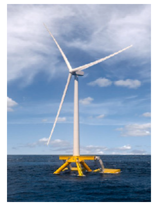


Fig. 1. Timeline of selected (a) wave energy and (b) offshore wind turbine commercial and demonstration projects between 2000 and 2025. Refer to Tables 2 and 3 for references and more details.

Table 1
Industry-driven demonstration projects of hybrid wind–wave platforms.

Poseidon P37 [13]	P80 [14]	DualSub [15]	InSPIRE [16]	W2Power [17]	NoviOcean [18]
					
Wind turbine power capacity [MW]					
3×0.011	4–10	2	8–12	2×3.6	3×0.05
Floating platform type					
Semi-sub	Semi-sub	Semi-sub	Semi-sub	Semi-sub	Barge
WEC power capacity [MW]					
10×0.003	2–3.6	0.5	4/6	18×0.1	0.65
WEC type					
Heaving	Heaving	Heaving	Pressure differential	Heaving	Heaving
Status					
Sea test in 2012–2013	1:30 scale tested in 2022	N/A	Scaled testing in 2022	1:3 scale tested in 2008	1:6 scale tested in 2024

in Sections 3 and 4, respectively. The review of research methods is summarised in Section 5, and the analysis of findings reported in the literature is shown in Section 6.

2. Methodology

The statistical analysis performed in the present work is based on data taken from references [26–107]. The information on design parameters, performance measures, and presented results varies significantly among the references. In preparing this paper, it was essential to develop a unified approach for collecting and analysing this information to ensure comparability among different hybrid wind–wave prototypes.

2.1. Discussion of sources

At the time of writing, a total of 110 references [26–135] were found that investigated the performance of floating hybrid wind–wave energy systems. A database was established using the information from these references. In cases where a particular hybrid system was used in multiple references with identical dimensions, inertia properties, number and locations of WECs, this prototype was included as one entry in the database for further analysis. For example, several studies have focused on the semi-submersible wind energy and flap-type wave energy converter called SFC concept [69,113–115], with the most representative study being [69]. This reference was selected and the information contained therein was used for the review and statistical analysis in the current work to avoid potential bias based on the activities of a particular research group. In cases where one reference investigated multiple hybrid configurations by varying the characteristic length and number of WECs, all these possible hybrid designs were included as separate case studies in the database, but only for the analysis related to the WECs. To summarise, out of 110 references reviewed, 82 references remained after screening, and 178 case studies were identified.

2.2. Classification of technologies

FOWTs are generally classified according to the approach used to provide static stability of the structure in rotational degrees of freedom [136]: ballast floating platforms (e.g., spar), tension leg platforms (TLP), and buoyancy floating platforms (e.g., barge or semi-submersible). In this study, barges and semi-submersible (or column-stabilised) platforms are included as separate categories, mainly because they offer different possibilities for coupling with wave energy converters (refer to Fig. 2). For example, barges are more suitable for coupling with

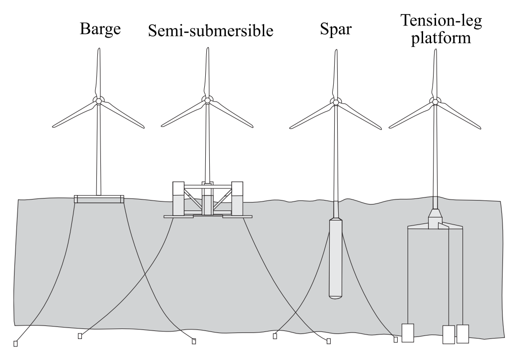


Fig. 2. Floating platform types for offshore wind turbines.

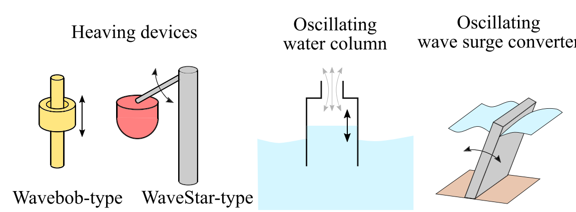


Fig. 3. Examples of WEC types proposed for coupling with FOWTs.

oscillating water columns (OWCs) due to the presence of moonpools in barge configurations that can be converted into an OWC chamber.

WECs in this work are classified according to the operating principle (following the approach proposed by Ref. [137]): heaving devices, oscillating water columns, and oscillating wave surge converters (refer to Fig. 3). It should be noted that none of the hybrid wind–wave systems found in the literature used overtopping devices, so this WEC category is excluded from the analysis. Fig. 3 shows schematics of two types of heaving devices, namely the Wavebob-type and the WaveStar-type, due to their popularity in hybrid wind–wave systems, as will be shown in Section 4. Wavebob is a two-body oscillating WEC where the torus-shaped floater slides along the spar to generate electricity [138]. WaveStar is a hemispherical floater connected to the rigid platform by an arm, and its heaving motion drives the hydraulic cylinder at the hinge. The Wavebob and WaveStar prototypes were extensively studied and tested at sea, but both projects were closed down.

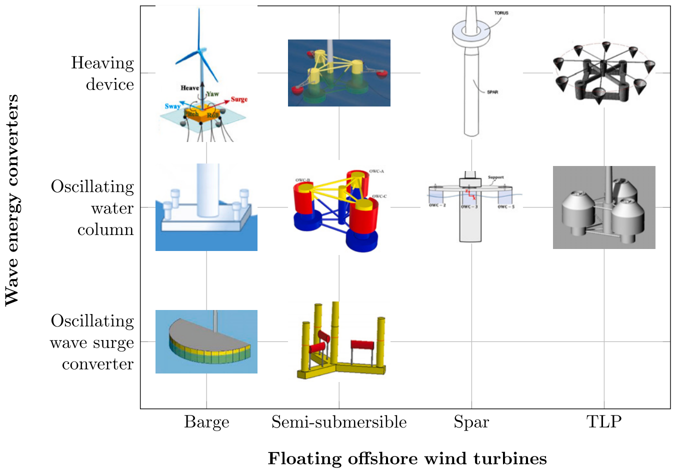


Fig. 4. Examples of floating hybrid wind-wave energy system designs across different FOWT topologies and WEC types.
Sources: Barge/Heaving device [86], Barge/OWC [84], Barge/OWSC [98], Semi-sub/Heaving device [28], Semi-sub/OWC [46], Semi-sub/OWSC [69], Spar/Heaving device [73], Spar/OWC [77], TLP/Heaving device [80], TLP/OWC [83].

Examples of hybrid wind–wave designs across different FOWT and WEC categories are shown in Fig. 4. All the designs reference the FOWT platform for WEC attachment, either by leveraging existing columns and structural elements or by incorporating additional support structures. Thus, heaving devices are typically mounted on the outer structure of the FOWT using a lever arm (e.g., the WaveStar WEC coupled with a barge [86]) or designed to slide along an existing column of a semi-submersible platform (e.g., [30]) or a spar (e.g., [73]). Oscillating water columns require a hollow structure for water to oscillate inside and compress air in the chamber for further power generation. Therefore, among the proposed designs, OWCs are created by modifying existing moonpools, enclosing them to trap air (e.g., barge [84]). Alternatively, the outer columns of semi-submersible platforms are adapted into OWC-type arrangements by opening the bottom of the column to allow water inflow (e.g., [47]). Another proposed OWC-FOWT coupling arrangement involves attaching additional cylindrical OWC chambers directly to the FOWT structure (e.g., spar [77]). Oscillating wave surge converters require a rigid structure with multiple attachment points for integration with an FOWT. Therefore, the design typically involves either positioning OWSCs on the wave-facing side of the platform, as proposed for a barge [98], or attaching flaps to a semi-submersible platform with pontoons (e.g., [69]).

2.3. Unification of power performance

A hybrid wind–wave energy unit usually consists of two power-generation systems: at least one or several wind turbines and wave energy converters. The horizontal-axis wind turbine is a mature technology that is typically characterised by a generator power rating of, for example, 5 or 10 MW. WEC power ratings are rarely mentioned in the references due to the immaturity of the technology, and it is more common to use linear dimensions (e.g., radius) to describe the WECs within the hybrid wind–wave system. Despite this, it was necessary to select a WEC power performance measure that could be compared with a wind turbine and between different wave energy technologies.

Wave energy developers tend to adopt different approaches to quote the power rating of their prototypes. Sometimes, they refer to the maximum *average* power that the WEC can generate over a period of time, while in other cases, the power rating of WECs is referred to as the *peak* output power at a time instant. This is mainly due to the WECs' much more variable power output compared to the wind turbines. A typical peak-to-average power ratio for a WEC exceeds 10, whereas for a wind turbine, this value is close to 1. For example, if a wind turbine has a rated capacity of 5 MW, it will produce an average of 5 MW at wind speeds above rated value. In the context of the WEC, to generate an average of 1 MW, the installed capacity of the generator should be 5–10 MW.

Each wind turbine is characterised by a rated wind speed at which the wind turbine generator produces maximum output power. The value of rated wind speed (typically 10–11 m/s) is relatively consistent among wind turbine developers [139]. Similarly, wave energy developers tend to limit the power generation of the WEC at certain wave heights, but the wave height threshold varies among developers. For example, WaveStar's average power generation is limited to 600 kW at wave heights above 3 m [140], Pelamis has a limit of average 750 kW power at wave heights above 5.5 m [141], and Wavebob's power output is limited to 1 MW at wave heights above 6 m [142]. For this work, to unify the WEC power analysis, it was decided to estimate the WEC power rating within the hybrid wind–wave system based on the *average* (not peak) power generated by the WEC, and to use a wave height of 6 m as a threshold value. Thus, the WEC power rating is estimated from the WEC power matrix, as shown in Fig. 5. It also should be noted that the mechanical (not electrical) power of the WEC is used in the analysis.

Unfortunately, none of the references presented data for the power rating of installed WECs, and the information about WEC power output varies greatly between references. Some references report WEC power or even relative capture width in regular waves, some references report WEC power output in limited design load cases (irregular waves), and only a few of the references present power matrices. To populate the WEC power matrix from the limited information provided, the methodology proposed in [137] is utilised in this work. In references, where only the regular wave power output is provided, firstly, the power absorption in irregular waves is estimated by integrating over frequency the product of the JONSWAP spectrum with the power absorption in regular waves. The entire power matrix can be populated following this approach across sea states with a peak wave period between 3 and 20 s and a significant wave height up to 6 m. The maximum power value from the power matrix is then used as an estimated power rating. In references, where the power production is provided for a limited number of sea states, the power matrix is populated by scaling power absorption with the square of significant wave height. Since most sources report the total power generation of all WECs, the individual power output

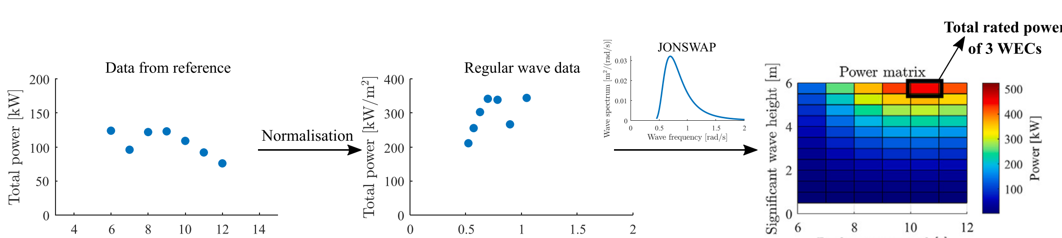


Fig. 5. Demonstration of the methodology used to unify the WEC power performance in this paper. The example data used from reference [26] (Fig. 17 for a 3WS case).

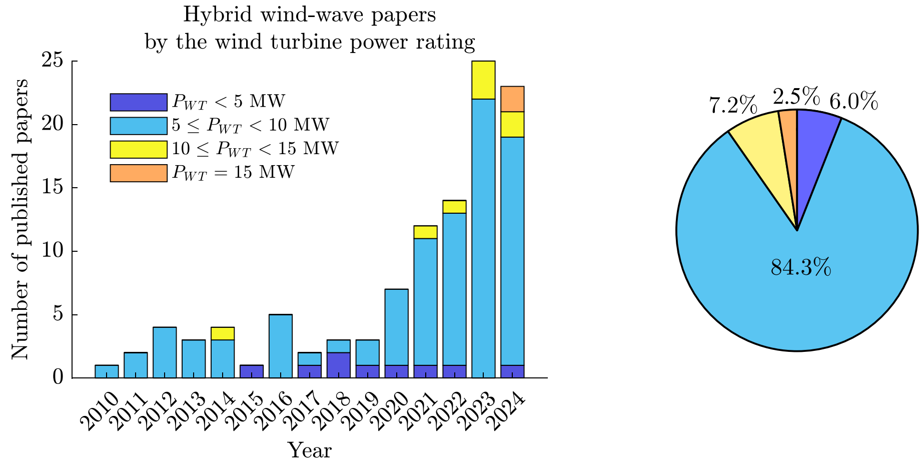


Fig. 6. Number of published papers on floating hybrid wind-wave units between 2010 and 2024, categorised by wind turbine power rating: by year (left) and total across all studies (right). References: $P_{WT} < 5$ MW [87,92,93,101,102], $5 \leq P_{WT} < 10$ MW [26–57,59–82,84–86,89,90,94,95,97–101,104,105], $10 \leq P_{WT} < 15$ MW [58,83,88,91,96,101], $P_{WT} = 15$ MW [106,107].

for each WEC is estimated as the total power divided by the number of WECs in the system. The procedure used for the unification of WEC power performance results is shown in Fig. 5. It is important to note that the power may scale differently depending on the level of nonlinearity and how the WECs interact with the platform. Thus, the results from the scale factor have an additional source of uncertainty, which is difficult to assess due to differences in the numerical modeling used in each reference.

Even with consistent methodologies for estimating energy delivery across various wave energy converters, the inherent analytical uncertainty remains around ±30 % as was found in [142]. Consequently, while acknowledging the significant uncertainty in statistical results for WEC power production, we believe this work offers value for preliminary high-level studies and early-stage model error detection.

3. Analysis of floating offshore wind turbines used in hybrid systems

A historical timeline of the development of hybrid wind–wave energy systems, categorised by the rated capacity of the wind turbine, is presented in Fig. 6. The data show that most published research continues to focus on wind turbines with a rated capacity of 5 MW, although there has been a gradual increase in studies investigating 10-MW and 15-MW wind turbines for hybridisation with WECs in recent years [58,83,88,91,96,101,106,107]. The first hybrid concept incorporating a 15-MW turbine was only published in 2024, while the reference platform for a 15-MW turbine [143] has been available since 2020, highlighting a lag in the theoretical development of hybrid systems.

This predominant focus on 5-MW turbines can be attributed to the availability of existing data and operational experience. These early platforms are often overdesigned, featuring heavier structures and enhanced stability, which reduces the necessity for integrating wave energy converters for motion suppression. However, as the offshore wind industry shifts toward larger turbines with rated capacities of 10 MW and beyond, new hybrid designs must be specifically tailored to address the challenges posed by these next-generation platforms. Higher-capacity turbines demand lighter and more optimised floating structures, which are inherently less stable and more sensitive to dynamic loading. In this context, the integration of WECs could have a more significant impact on platform dynamics, potentially enhancing overall system performance and stability. Therefore, hybridisation efforts must not only keep pace with advances in turbine technology but also actively exploit the synergistic benefits that WECs can offer in the design of future floating platforms.

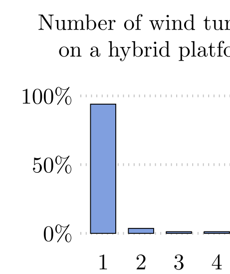


Fig. 7. Proportion of studies using different numbers of wind turbines in hybrid wind-wave energy systems. References: 1 [26–91,94–99,102–107], 2 [93,100,101], 3 [101], 4 [92].

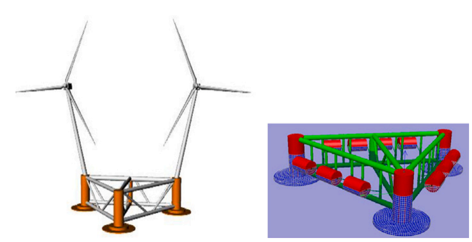


Fig. 8. Example of a hybrid wind-wave design based on multiple wind turbines [100]: the platform without buoys (left) and the same platform coupled with 10 heaving devices (right).

As shown in Fig. 7, only 6 % of all studies [92,93,100,101] have examined configurations involving multiple wind turbines on a single floating platform. This area warrants further investigation, particularly given that twin-rotor floating platforms have already been both studied [144] and deployed offshore [145]. An illustrative example is presented in Fig. 8, depicting a semi-submersible platform with two wind turbines and ten heaving WECs, based on the design proposed in [100].

Wind turbines can be designed with either vertical or horizontal axes, the latter being a more mature technology that has been deployed and tested offshore on floating platforms. Among the 110 papers reviewed, only two [74,93] proposed a hybrid wind–wave system design incorporating VAWTs (Fig. 9). [74] integrated a single VAWT on a spar platform with a Wavebob-type wave energy converter (WEC), while [93] installed two VAWTs on a barge-type floating offshore wind turbine (FOWT), incorporating four oscillating water columns (OWCs) for enhanced stability. Interestingly, among industry-driven hybrid projects (Table 1),

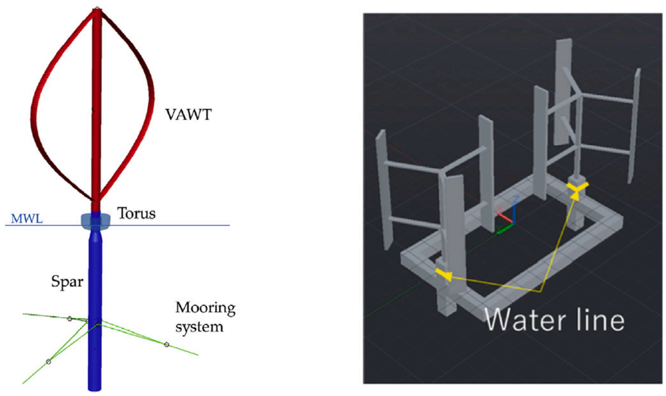


Fig. 9. Examples of hybrid wind-wave designs based on the vertical-axis wind turbines: [74] (left) and [93] (right).

NoviOcean [18] also used VAWTs in its design. The limited adoption of VAWTs in hybrid designs is likely due to their technical and commercial lag behind HAWTs, despite their widely recognised advantages [146].

Among the proposed platform topologies (Fig. 2), the semi-submersible FOWT appears to be the most attractive for hybridisation with wave energy devices, accounting for 74 % of all case studies (refer to Fig. 10a) [26–70,87–92,94–96,99–101,103,104,106,107]. The popularity of semi-submersible platforms can be explained by their higher Technology Readiness Level (TRL) compared to other topologies. In particular, over the past 15 years, at least 15 FOWT demonstration prototype projects and 4 floating wind farm projects have been implemented worldwide (see Table 3), and semi-submersible platforms have been used in half of these projects. Additionally, open-source tools such as OpenFAST and FOWT models developed by NREL have also contributed to the widespread use of semi-submersible topology. Among semi-submersible platforms, the OC4-DeepCWind [147] has the largest share of 38 %, while the novel designs, WindFloat [148], and CSC [113,149] platforms account for 26 %, 19 %, and 17 %, respectively, as shown in Fig. 10a.

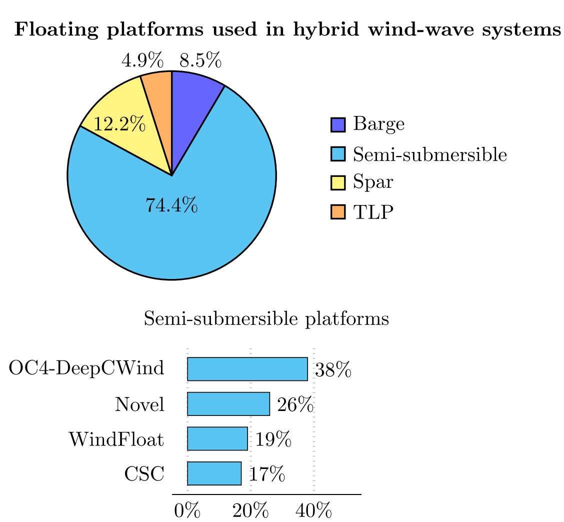
A less commonly used floating platform design for hybridisation is the spar (12.2 %) [71–79,97], although it is a widely used topology in demonstration and commercial FOWT projects. However, it provides fewer opportunities for mechanical coupling to the WEC due to installation constraints, and its stabilisation mechanism is less suitable for WEC integration (WECs increase the water surface area). The barge and tension leg platform (TLP) each account for 8.5 % [84–86,93,98,102,105] and 4.9 % [80–83] of the proposed hybrid systems, respectively. While this percentage is reasonable for TLPs due to their complexity, hybrid platforms using a barge may be explored in future work due to their simpler implementation.

As shown in Fig. 10a, most studied hybrid wind–wave solutions are based on standard FOWT designs (i.e., OC4-DeepCWind, WindFloat, CSC) by simply integrating them with WECs, illustrated in Fig. 10b. Due to the simplicity of the analysis, the properties of these standard FOWT platforms, such as inertia or mooring system design, usually remain unchanged even when the wave energy system is included. However, as mentioned in [25], future developments should explore a hybrid platform using an optimisation/framework where the conceptual design is considered from a global geometric perspective.

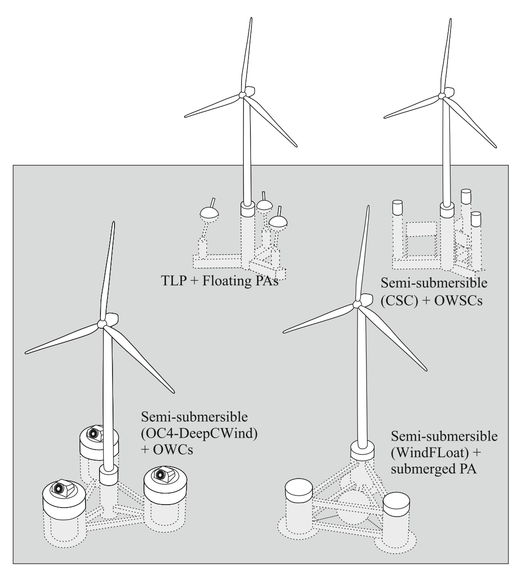
4. Analysis of wave energy converters used in hybrid systems

The correlation between the FOWT topology and the WEC type used to form the hybrid system is demonstrated in Fig. 11, where the circle size represents the number of hybrid systems within each category. In total, 10 different combinations out of 12 possible have been proposed. The barge is more commonly coupled with an OWC, as some designed barges already have moonpools (e.g., the Floatgen developed by BW Ideol [150]) that can be naturally converted to an OWC. In contrast, other FOWT topologies (spar, semi-submersible and TLP) are more frequently hybridised with heaving devices. This can be explained by the fact that the concept of heaving devices is the most favoured by wave energy developers [151]. OWSCs are only considered for coupling with barges and semi-submersible platforms, likely due to the attachment requirements for the reference substructure and the significant motions these WECs experience.

Fig. 12 demonstrates the proportion of WEC types used in hybrid systems regardless of the wind platform used. As already expected from



(a) Proportion of floating offshore wind platforms used in hybrid wind-wave energy systems.



(b) Examples of hybrid platforms.

Fig. 10. Distribution of floating offshore wind platforms used in hybrid wind-wave energy systems. References: barge [84–86,93,98,102,105], semi-submersible [26–70,87–92,94–96,99–101,103,104,106,107], spar [71–79,97], TLP [80–83], OC4-DeepCWind [26–48], WindFloat [49–60], CSC [61–70], Novel [87–92,94–96,99–101,103,104].

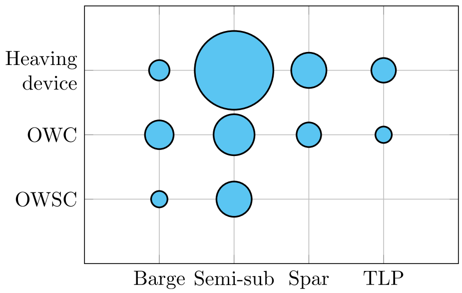


Fig. 11. Correlation between the floating wind platforms and WEC categories used for hybridisation. The circle size represents the number of hybrid systems within each category.

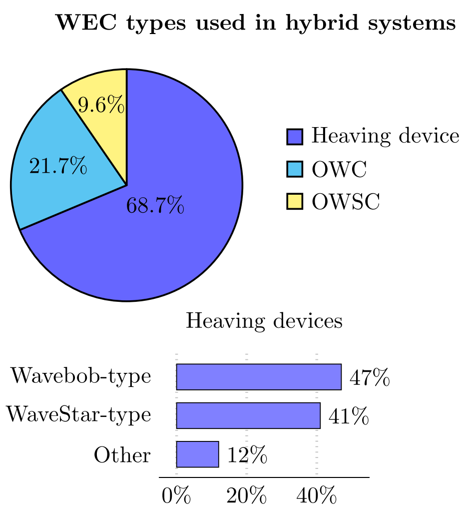


Fig. 12. Proportion of WEC types used in hybrid wind-wave energy systems. References: heaving device [26–44,48–56,60–66,71–76,79–82,86–92,100,101,103,105,106], OWC [45–47,57,58,77,78,83–85,93–97,102,104,107], OWSC [59,67–70,98,99,101].

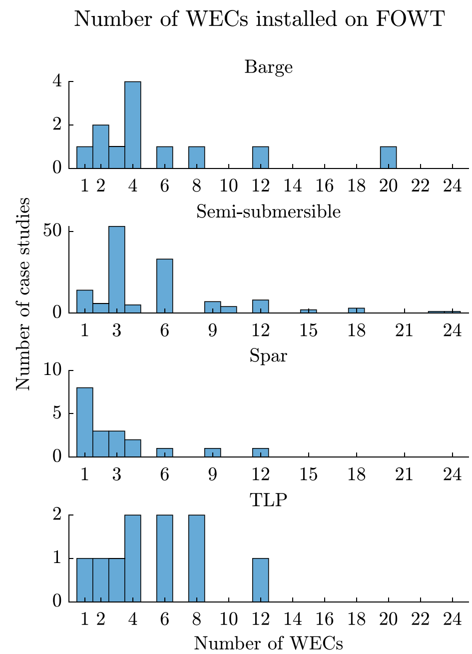


Fig. 13. Number of WECs integrated into the hybrid wind-wave energy system depending on the FOWT topology.

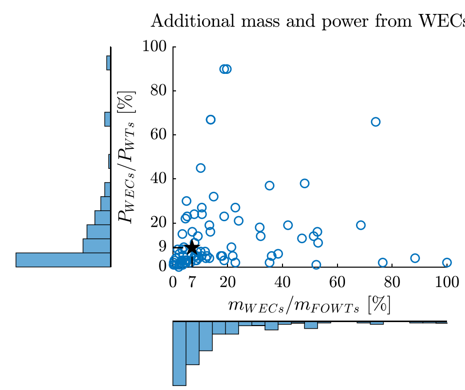


Fig. 14. Additional power capacity and mass associated with installing the wave energy system on a floating platform, given in %. The star indicates the median value of the dataset.

Fig. 11, WECs that extract power from the heaving motion are most often integrated with floating platforms, accounting for 68.7 % [26–44,48–56,60–66,71–76,79–82,86–92,100,101,103,105,106]. Less than a quarter (21.7 %) [45–47,57,58,77,78,83–85,93–97,102,104,107] of all hybrid designs use OWCs, and about one-tenth consider OWSCs [59,67–70,98,99,101]. Similar to the use of standard floating platforms, researchers tend to select well-studied types of heaving devices: Wavebob-type and WaveStar-type (illustrated in Fig. 3). The Wavebob is seen as a simple solution for coupling with platforms that have columns (i.e., CSC or spar), while the WaveStar is attractive due to its design, which includes both a floater and an arm that can be attached to any structure.

The number of wave energy devices installed on a floating platform highly depends on the platform topology as shown in Fig. 13, which varies between 1 and 24 [92] for the references investigated. A common trend for a semi-submersible platform observed is that the number of WECs is a multiple of the number of columns (usually three), which balances the loads across the structure, while for a barge and TLP the number of WECs is even. Moreover, it can be seen that three WECs integrated with a semi-submersible FOWT is the most widely studied combination, while spars are most often integrated with only one WEC. Due to the small number of cases involving barges and TLPs, it is difficult to identify any additional trends for these platforms.

One of the important considerations when designing a hybrid wind–wave system is the additional power capacity and mass associated with installing the wave energy system on a floating platform. Thus, the ratios of the mass and power of installed WECs to the mass and power of the FOWT are shown in Fig. 14. The analysis is done across all WEC types and FOWT topologies, and it demonstrates that wave energy system is usually designed to provide less than 10 % of the wind turbine power, which may be related to economic benefits and technology readiness. Similarly, the mass of installed WECs is close to 5 %–10 % of the total mass of the FOWT (platform, tower, rotor-nacelle assembly). However, it should be noted that there are designs [68,79,89] where WECs have comparable power production to wind turbines.

The analysis of the individual WEC characteristics is provided in Fig. 15. To ensure a fair comparison of WEC performance, we remind the reader that the rated power of each WEC in the hybrid system was estimated using the methodology detailed in Section 2.3. Despite the significant expected uncertainty associated with this power unification, we believe the outcomes of this analysis remain valid for most reviewed studies. The power rating of a single WEC varies between 5 kW [31] and 7 MW [89], while the median value is close to 127.5 kW across all WEC types (127 kW for a heaving device, 175 kW for an OWC, and 53 kW

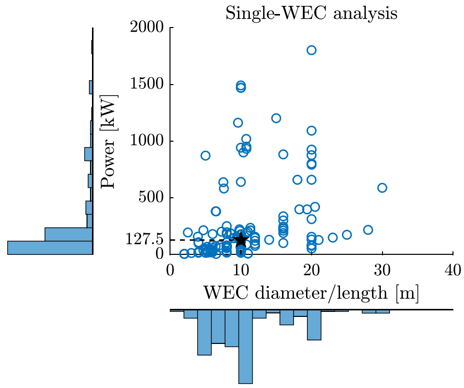


Fig. 15. Dimensions and power rating of individual WECs installed on a FOWT. The star shows the median value of the dataset.

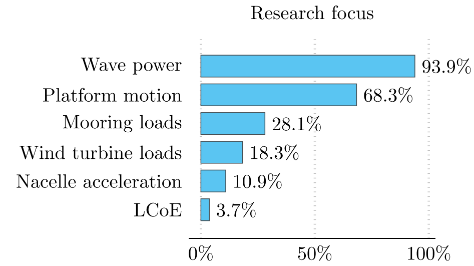


Fig. 16. Performance indicators of hybrid wind-wave systems and the proportion of studies devoted to their study. References: wave power [26–49,51–82,86–106], platform motion [28–34,36–38,40–43,45–49,55,56,58,60–79,81,84–88,90,91,93,94,96,104–106], mooring loads [28,29,32,33,43–46,53–55,60,62,63,69,70,73–75,81,90,105,106], wind turbine loads [37,41–43,46–48,60,65,68,69,74,81,86,106], nacelle acceleration [40,45,48,69,81,87,91,94,99], LCoE [55,91,101].

for an OWSC), and the majority of WECs are designed as 50–100 kW units. These trends do not align with the current progress in WEC development, shown in Fig. 1a, where the average rated power of WEC prototypes is approximately 300 kW.

The median value of the WEC characteristic length within the hybrid system is 10 m, while the maximum WEC diameter reported is 60 m (not shown in Fig. 15). Interestingly, there is a mismatch between the WEC size (10 m) and average power rating (127 kW) according to the classical wave power absorption theory [152,153]. According to Budal diagram [154], it is possible to evaluate the power absorption potential of a WEC depending on its volume and motion constraints. Thus, the heaving devices with a diameter of 10 m, similar to WaveStar, can potentially generate power above 1 MW in sea states with a significant wave height of 6 m, if advanced control is used [153]. However, as will be shown in Section 6.3, advanced WEC control is rarely used in hybrid wind–wave studies, while passive control is applied more frequently, significantly reducing WEC power production. Moreover, excessive power production and motion of WECs may adversely affect FOWT performance [155].

5. Analysis of research methods

The hybrid wind–wave energy system has complex dynamics that involve aerodynamic forces acting on the wind turbine rotor and tower, hydrodynamic and mechanical coupling forces acting on the floating platform and WECs, and loads from the mooring system. Before reviewing the methodologies applied to study hybrid system dynamics, it is important to understand the research focus and the performance characteristics of interest presented in research papers. Thus, Fig. 16 shows the characteristics of the hybrid wind–wave systems and the proportion of references used to investigate them. The results demonstrate that the wave power production and the motion response of an FOWT are the two main performance metrics that interest most researchers. It is interesting to note that mooring loads of the hybrid wind–wave system were reported in 28.1 % [28,29,32,33,43–46,53–55,60,62,63,69,70,73–75,81,90,105,106] of cases, while very few studies considered redesigning the mooring system of the FOWT after the integration with WECs. Only 10 %–15 % [37,40–43,45–48,60,65,68,69,74,81,86,87,91,94,99,106] of studies investigated the wind turbine loads and nacelle acceleration, and very little attention is given to the cost of energy of hybrid systems. Since the additional power provided by the WECs is between one or two orders of magnitude lower than that of the wind turbine, it is recommended that future analyses focus on motion suppression to reduce mooring, nacelle, and turbine loads, along with cost analysis, which is supported by the current literature [25,155].

The detailed analysis of the methodology used to investigate hybrid wind–wave systems is shown in Fig. 17, where the results are presented for different subsystems and associated loads. The results demonstrate that only 18 % [38,45,47,55,58,69,78,82,83,87,97,100,101] of the studied hybrid systems were tested experimentally in wave basins or tanks, while numerical simulations are a more common approach for investigating hybrid systems, likely due to their advanced maturity and accessibility.

5.1. Numerical modelling methodology

Aerodynamic loads on the wind turbine are not considered in 35 % [26,27,32,35,39,50–52,54,56,57,59,61,67,70,71,75–77,80,81,88,89,92,93] of the references that use numerical modelling, and a similar percentage of experimental studies were conducted without including forces acting on the wind turbine rotor. The outcomes of these studies are more relevant for the platform degrees of freedom (DOFs) where wind loads have a smaller effect, such as heave. However, care should be taken when evaluating performance in DOFs such as pitch or surge, due to the significant effect of the aerodynamic loads on them. In cases where the aerodynamic effects are considered, they are modelled either by using full Blade Element Momentum (BEM) Theory [156] in references [29,33,34,36,37,40–44,46,48,49,53,62–65,68,69,72,74,83,84,86,90,91,99,104–107] or using the steady state rotor thrust curve [31] in references [28,30,31,66–70,73,79,85,94–96,98,102,103] to identify the associated thrust forces acting on a rotor. The latter case is usually applied as an initial load assessment, while the full BEM is suitable for taking into account the control dynamics of the wind turbine. In cases where the platform motion is dominated by wave loads, simplification or absence of the aerodynamic effects can be used as an initial estimate.

In 99 % of reviewed papers, the hydrodynamic forces acting on a floating platform and WECs are modelled utilising linear potential wave theory, which assumes inviscid, irrotational and incompressible flow. Additional viscous losses are included only in 57 % [28,30–32,37,40,42,46,48,52–54,57,59,60,62–65,67–70,73,74,79,81,84–86,90,92,95,96,102,104–106] of all cases, which means that the WEC motions, and therefore the platform motion, as well as WEC power production, may be overestimated for the papers that have not included viscous losses. Due to the complexity of the interaction between the wave–wind devices, it is also interesting to note that only one study found [60] used Computational Fluid Dynamics (CFD), despite it being widely applied to investigate the WEC and FOWT dynamics separately.

The mooring forces acting on a hybrid wind–wave system are mainly modeled by quasi-static [29–31,36,37,40,73,79,94–96,98,99,107] or lumped-sum [28,33,34,41–44,46,48,49,53,60,62–66,68,69,72,74,84,86,90,91,105,106] methods. The quasi-static method assumes position-dependent restoring forces while neglecting inertia and hydrodynamic effects on the mooring lines, and the lumped-sum method models a mooring line as a series of nodes connected by springs and

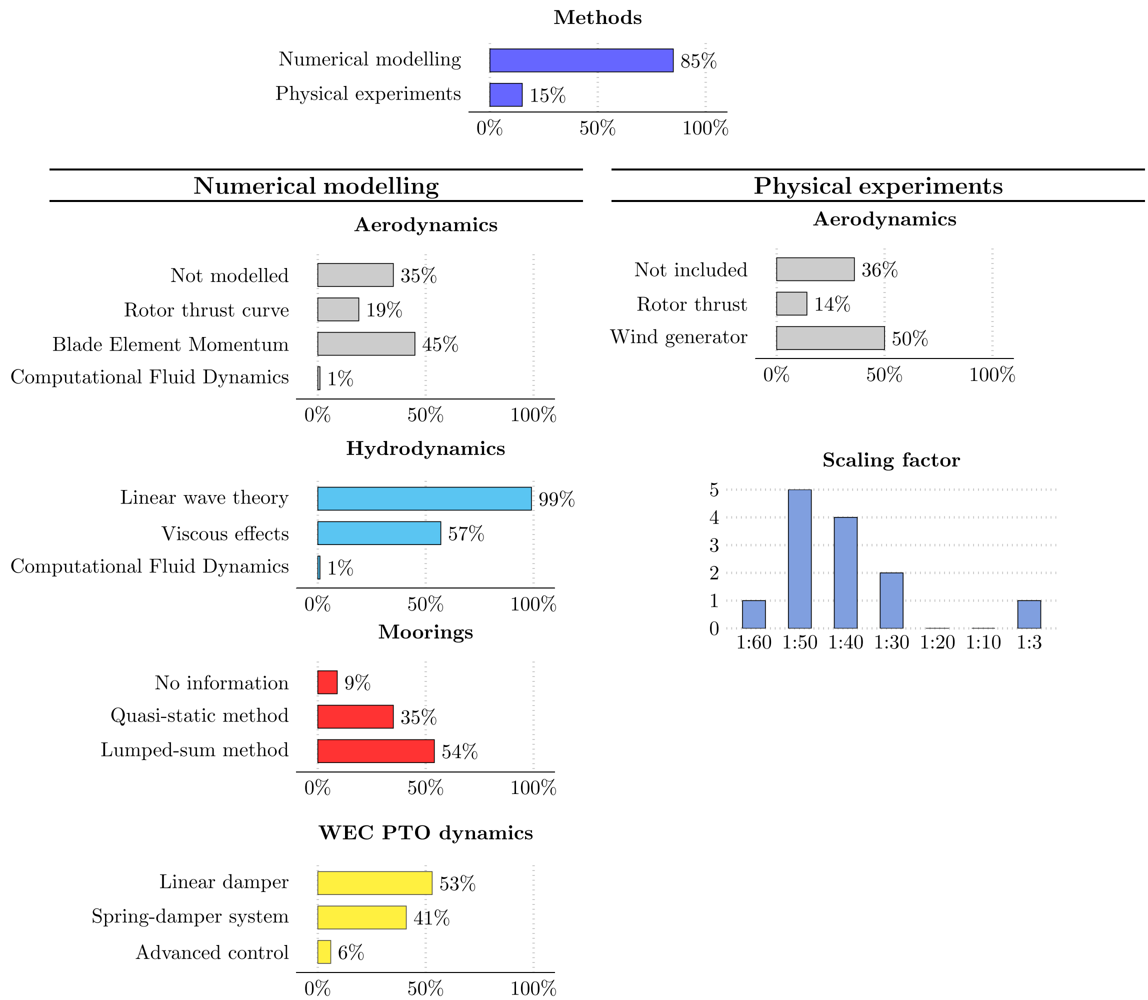


Fig. 17. Statistical analysis of methodologies applied to investigate the hybrid wind-wave system dynamics. References: numerical modelling [26–37,39–44,46,48–54,56,57,59–77,79–81,83–86,88–96,98,99,102–107], physical experiments [38,42,45,47,55,58,69,78,82,83,87,97,100,101]. The reader is referred to the main text for the references associated with each category.

dampers. Both modelling approaches are widely used in offshore engineering, and lumped-sum method was used slightly more frequently in the hybrid wind–wave system analysis. The mooring analysis is critical for such platforms and requires further investigation, as the loads can be intensified or reduced due to the coupling with WECs. However, as mentioned earlier, most designs have not adapted the mooring system for a hybrid platform.

The wave energy power take-off machinery is the system that usually couples the WEC dynamics to the dynamics of a floating platform, in addition to hydrodynamic coupling and kinematic constraints. Due to different TRL levels of the wind turbines and WECs, the type of PTO machinery (i.e., hydraulics, direct drive, etc.) is rarely mentioned in the reviewed references, and the PTO dynamics are usually simplified to the linear damper or spring-damper behaviour. The WEC power generation, assuming a linear passive system is used in half of the hybrid wind–wave studies [26–32,36,41,42,46–49,52–54,56,58,60,61,66–72,74,75,78,80,82,86,88,89,91,94,97], while a spring-damper is considered in 40 % of cases [28,33–35,39,40,43,51,57,59,62–65,73,79,84,85,87,90,92,93,95,96,98,99,102,104–106], and advanced control is rarely [28,50] used in this context. WECs with a passive PTO system act as tuned mass-dampers and their full potential is not utilised, while active WEC control can bring more benefits to the hybrid wind and wave energy system [157] if a proper control co-design methodology is followed.

5.2. Experimental methodology

Only 18 % of the reviewed references [38,42,45,47,55,58,69,78,82,83,87,97,100,101] tested their hybrid designs in wave basins using scaled prototypes or in the open sea. Approximately a third of the experimental studies [38,58,87,97,100] focus on hydrodynamic aspects of the system, not including the effects of the wind turbine. About 14 % of experiments [45,47,82,101] use a small fan or rotor on the platform that generates the required level of thrust force, presumably because this approach does not require any wind generation facility. Half of the experimental studies [42,45,47,55,69,78,82] generate wind speeds on top of the wave basins to test the dynamics of the hybrid wind and wave energy system under wind and wave environmental conditions. The challenge of this testing is that the wind turbine and floating platform should be scaled following different scaling laws (Froude number for hydrodynamics, and Reynolds number for aerodynamics) [158]. This explains why almost half of the experimental studies either do not include aerodynamic effects or use a relatively simple way to account for thrust forces. The majority of physical experiments of hybrid wind-wave energy systems are conducted at scales close to 1:50–1:40, which are generally used for TRL levels of 1–3 of these devices.

The limited availability of physical experiments poses a significant challenge for validating most modelling approaches used to assess hybrid wind-wave energy systems with complex coupled dynamics. Key knowledge gaps exist in the experimental testing of these systems under combined wind and wave loads, particularly regarding the accurate representation of mooring and WEC PTO dynamics. Furthermore, experimental studies on floating platforms [159,160] highlight the important role of nonlinear second-order effects in predicting platform pitch motion, a critical factor for studies aiming to utilise WECs for FOWT motion suppression. Finally, the response of hybrid wind-wave systems to extreme environmental conditions, a critical aspect of their performance, remains largely unexplored in both numerical and experimental investigations [161].

5.3. Environmental conditions

The hybrid wind-wave energy systems are designed to operate under both offshore wind and ocean wave conditions that are usually temporally uncorrelated. The economic attractiveness of the hybrid system is highly dependent on the potential deployment site, which should have sufficient wave and wind resources, as shown in [162].

The statistical analysis of environmental conditions used in all the reviewed papers is shown in Fig. 18. It is interesting to note that most references did not use any site-related information to assess the hybrid system performance (66 % are marked as 'No site' [26,27,29–31,33–35,38,40,44,50,51,53,55–61,67,69–71,76–79,82–85,88,89,92–94,96,97,100,102–104]), while the remaining references used either North Sea [28,37,43,45,46,48,63–66,68,73,74,90,106,107] or China Sea [32,39,41,42,47,49,52,54,95] conditions. It is important to highlight that, as shown in [163], optimisation algorithms applied to hybrid structures lead to different configurations depending on the chosen offshore site. Based on this, devices designed for the North or China Sea conditions may have different designs when optimised.

As explained in Section 5.1, about 40 % of the studies [26,27,32,35,39,50–52,54,56–59,61,67,70,71,75–77,80,81,87–89,92,93,97,100] focused only on the wave-driven response of the hybrid system, neglecting any loads caused by offshore wind environment. Almost a third of the studies used steady wind conditions [29–31,33,34,45,53,55,60,64,66,78,79,82–85,94–96,98,102,103,107], and the remaining 36 % [28,33,34,36,37,40–43,45–47,49,62–65,68,69,72–74,86,90,91,99,104,106] used more realistic environmental conditions with turbulent wind. Regarding the ocean wave modelling, regular wave analysis was used in 41 % of the studies [26,27,29,30,32,33,50,51,53,54,56,57,59–61,66,67,70,71,75,77,83–85,88,91,92,96,97,102,107], while 62 % [28,31,34–49,52,55,58,62–65,68,69,72–74,76,78–82,86,87,90,93–95,98–100,103–106] included irregular wave conditions. Undoubtedly, regular wave analysis is the quickest tool to investigate the response amplitude operators of the floating platform and WECs, identify their resonance periods and see the trends if the wave energy system is modified. However, similar to turbulent wind conditions, irregular waves represent a more realistic wave environment, and the number of studies that included both turbulent wind and irregular sea states is less than a third.

The importance of the chosen environmental conditions used for the hybrid system assessment cannot be overestimated. As was demonstrated in [40] a semi-submersible platform with three floating heaving WECs can effectively suppress the platform motion in pitch in short-period waves without reducing their power production, while in longer waves, the motion is amplified if WEC power output is not constrained. The comparison of wave conditions associated with two sites used for the hybrid wind-wave system assessment is shown in Fig. 19. The environmental conditions inspired by the North Sea wave climate have longer peak wave periods (10–14 s) as compared to the China Sea climate (5–10 s), where some hybrid wind-wave systems might be more effective.

Analysing the studies that used the design load cases from the North Sea [28,46,47,63–66,68,73,74,90], the majority of tested conditions fall within a wind turbine's control region 3, followed by region 2, with only several cases in region 4 (refer to Fig. 20). This indicates that the main

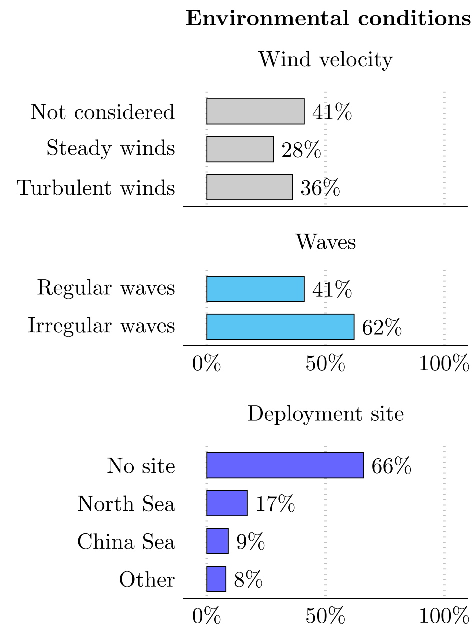


Fig. 18. Statistical analysis of environmental conditions used to assess the performance of hybrid wind-wave energy systems. The reader is referred to the main text for the references associated with each category.

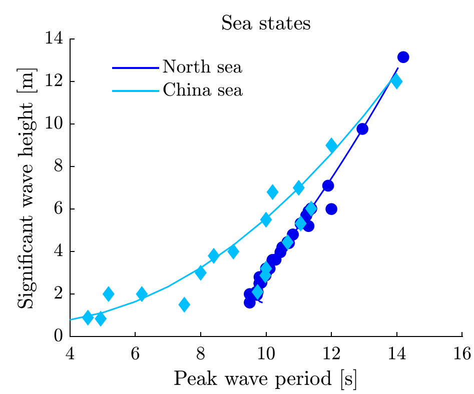


Fig. 19. Sea states used in the analysis of hybrid wind-wave energy systems depending on the deployment site location.

focus of hybrid wind-wave energy systems assessment is on operational conditions of the wind turbine and wave energy converters, with less emphasis on assessing survivability under extreme conditions.

6. Analysis of the reported findings

As shown in Fig. 16, the design and performance evaluation of a hybrid wind-wave system revolve around several key questions: How much additional power can the WECs generate alongside the wind turbine? To what extent do the WECs influence the dynamics and loading on the floating platform? And, are there economic advantages to constructing hybrid wind-wave systems? This section analyses the reported findings from all reviewed papers, considering the variations in methodology, focus, and conclusions across studies.

6.1. Mutual impact of WECs and OWTs on their power production

The information related to the power production of wind and wave power generation units within the hybrid system has been provided in Sections 3 and 4. Additionally, some studies have examined whether integrating WECs with a floating platform affects the wind turbine's power

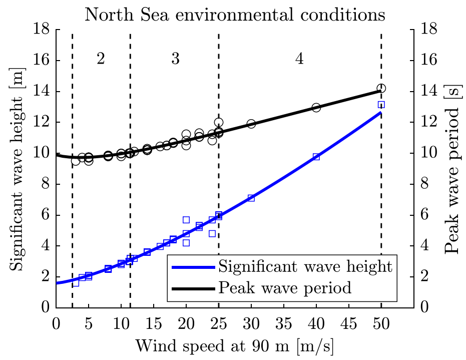


Fig. 20. Design load cases from the North Sea climate used to asses the performance of hybrid wind-wave energy systems.

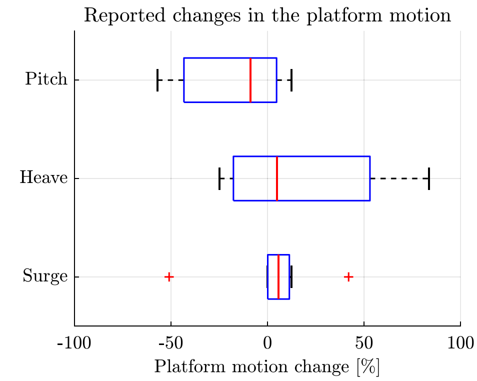


Fig. 21. Analysis of the reported changes in the standard deviation of the platform's response in surge, heave and pitch after integration with WECs based on 49 load cases from 10 hybrid wind-wave designs.

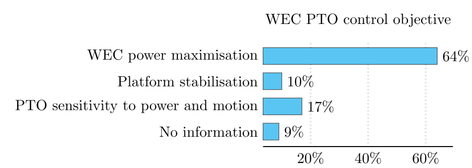


Fig. 22. Proportion of hybrid wind-wave energy studies categorised by the objective function of the WEC PTO control.

output or if the WECs' power generation is altered after being combined with FOWTs. Across all studies, there is a consensus that the presence of WECs has a negligible impact on wind turbine power output, with both the mean value and standard deviation varying by no more than 1 %. Few studies have examined the variations in WEC power production when compared to a standalone WEC system operating under identical environmental conditions, with findings differing based on the analysis approach. For instance, [34] investigated a modified DeepCWind semi-submersible platform integrated with a heaving device and a specific set of PTO coefficients. Their study reported enhanced WEC power output when attached to a floating platform, particularly when the incoming wave period aligned closely with the platform's natural heave period. Meanwhile, in [40], the analysis focused on the WEC efficiency across a range of PTO parameters, comparing a WEC mounted on a floating platform to a standalone WEC on a fixed foundation. The study found that, in general, efficiency decreased by approximately 10 % when the WEC was placed on a floating platform.

6.2. Effect of WECs on FOWT motion

One of the benefits of combining floating wind platforms with WECs is the potential reduction of platform motion. Therefore, most references report the resultant motion of the hybrid wind-wave system as compared to a standalone FOWT. However, the results vary significantly, showing either response amplitude operators, spectral densities at a given sea state, or motion statistics in terms of mean, standard deviation, and maximum/minimum values. For this work, the analysis of reported changes in the platform motion is performed only based on those studies that considered aerodynamic effects from wind and provided statistical data on the motion. Overall, results from only 10 [28,36,39,43,46,62,68,73,74,90] out of 82 references have been used for the motion analysis featuring the performance of hybrid wind-wave systems in 49 environmental conditions. Fig. 21 shows an analysis of the reported changes in the standard deviation of the platform's response in surge, heave and pitch after integration with WECs. Note that different combinations of WECs and platforms may lead to different responses due to their ability to alter platform dynamics, while these results are more general and based on available data.

On average, the integration of WECs with a floating platform does not significantly affect the platform's motion in surge, while [73] reported the surge motion reduction of up to 50 % and [90] reported amplification in the platform motion in surge of up to 42 %. The motion of the floating platform in surge is mainly driven by the mooring system restoring forces, and the majority of hybrid wind-wave system designs have kept the mooring line design similar to the standalone FOWT. In addition, second-order wave loads have an impact on the platform motion, which is still not commonly investigated in hybrid platforms.

There is considerable variation in the reported results for the platform's heave motion, though most studies indicate a significant increase in heave amplitude. This trend may be attributed to the prevalent use of heaving devices in hybrid wind-wave designs, which rely on large motion amplitudes to efficiently absorb wave energy, consequently amplifying the platform's heave motion. However, it is important to note that the wind turbine's performance and loading are not significantly impacted by the platform's heave motion and accelerations.

Adding WECs to a floating platform generally results in a reduction in pitch of up to 60 % with a median value close to -10 %, while some hybrid wind-wave system designs report a 12 % increase in pitch amplitude [28]. Out of the platform's three degrees of freedom, namely surge, heave and pitch, the latter is usually of the primary interest for the hybrid system designers. The inclination of the platform, tower and rotor from the designed vertical position negatively affects the wind turbine power output and induces undesired loads on the blades and tower.

6.3. Effect of WEC PTO control on FOWT dynamics

In hybrid systems, the WEC PTO plays an important role in both the power performance of the WEC and its impact on platform dynamics. As illustrated in Fig. 17, most studies assume that WECs are integrated with the FOWT platform using either a linear damping system or a linear spring-damper system, where the PTO stiffness is limited to positive values. The distribution of studies depending on the WEC PTO control objective is shown in Fig. 22.

The majority of studies optimise WEC PTO parameters to maximise WEC power production and then investigate how the integrated wind-wave system performs with these settings. For example, the impact of various control strategies on FOWT dynamics was investigated in [28], while still assuming WEC power-maximising control. The study considered approaches such as linear damping, spring-damping with positive stiffness, and reactive control equivalent to spring-damping with negative stiffness. The results indicated that reactive control could double the power production of WECs while also increasing platform heave and pitch oscillations by 15 %–30 %, depending on the specific load case.

In contrast, there are studies (e.g., [30,31,40,42,46,49,52,72,73,78,79,95,97,98]) that investigated how the changes in the PTO parameters

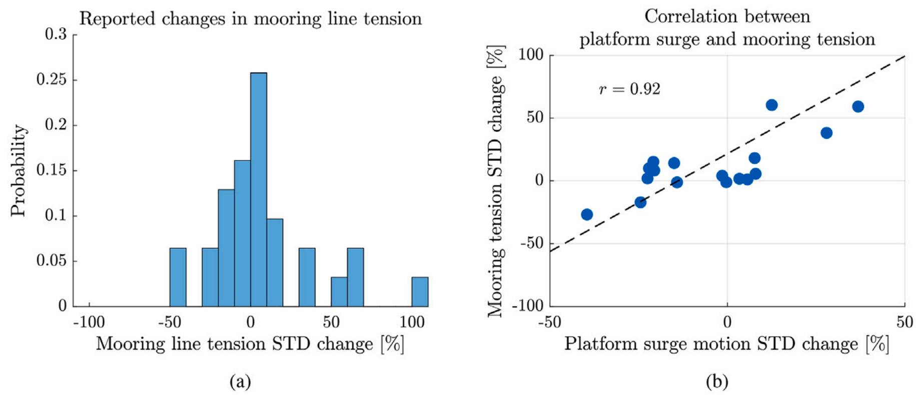


Fig. 23. Analysis of changes in the mooring line tension of the hybrid wind-wave systems compared to standalone FOWTs.

affect both WEC power output and platform motion. These studies report that maximising WEC power is often accompanied by an increase in platform motion, highlighting the need to find an optimal trade-off between power generation and stability.

Several studies have developed controllers specifically for stabilising FOWTs, mainly focusing on the platform's dynamics in pitch. For instance, [36] proposed a model predictive control strategy to minimise platform motion in roll and pitch, demonstrating that WECs can reduce the standard deviation of a semi-submersible platform's motion by a factor of two compared to a standalone case. Similarly, [164] developed a linear quadratic regulator with tunable coefficients that can be optimised either for WEC power maximisation or FOWT motion stabilisation, showing that a trade-off between these competing objectives is achievable.

Developing effective WEC control for FOWTs is challenging due to the complex system dynamics under combined aerodynamic and hydrodynamic loads. Current controller development studies for hybrid systems often oversimplify the problem, limiting their applicability to real-world scenarios. A promising solution is data-driven control, where the system model is derived from experimental data [165]. This approach highlights the need for experimental studies of hybrid systems discussed in Section 5.2.

6.4. Effect of WECs on the FOWT mooring loads

Among all the papers included in this study, only 19 [28,29,32,33,43–46,53–55,60,62,63,69,70,73–75,81,90,105,106] investigated changes in mooring line loads under various environmental conditions. Of these, 9 quantified the changes in terms of the standard deviation (STD) of mooring line tensions, while 4 reported only maximum load changes. The remaining 6 papers provided figures for the power spectral density (PSD) of mooring tension, which can be converted into STD of the tension. Overall, the majority of references reported an increase in the tension of each mooring line due to the presence of WECs, which can be because the WEC was not set to damp the platform, leading to higher offsets. In some concepts, the low-frequency motion in pitch, which is sensitive to damping levels, can be reduced by using WECs. This can lead to lower tensions in the mooring system. However, the WEC parameters need to be optimised to avoid increasing the motion at the wave-induced range, which is likely to increase the mooring loads [106].

The mooring line tension data were collected from the 9 references that quantified changes in load standard deviation (STD), covering a total of 31 environmental conditions, and are presented in Fig. 23a. The majority of studies reported a slight increase (up to 10 %) in tension STD due to the attachment of WECs to the floating platform. However, most of the proposed platforms did not design the mooring system. As shown in Fig. 23b, there is a strong correlation between changes in platform surge motion and mooring line tension, reinforcing the fact that the mooring design should be included and optimised in the analysis for a more realistic effect of the WEC on the mooring loads. The observed increase in mooring line tension aligns with the analysis in Section 6.2 regarding changes in platform motion.

6.5. Economic feasibility

Only a few studies in this review have explored the economic benefits of coupling FOWTs with WECs, reporting reductions in LCOE of 1.5 % [55] and 10 % [91] for hybrid systems compared to standalone FOWTs. However, a relatively recent study was conducted by Wave Energy Scotland [166] investigating opportunities and potential benefits for coupling wave and floating wind energy plants. The study examines 17 different scenarios or cost-sharing models for floating wind and wave energy, ranging from entirely separate projects for each technology to fully integrated hybrid platforms. Sharing opportunities in these scenarios include spatial co-location at the same deployment site, asset sharing of substations, transmission, and electrical systems, as well as synergies in project development, supply chain management, installation, operation and maintenance, and project ownership. The main findings of this study are summarised in Fig. 24, where the LCOE results from different combination scenarios are presented as a box and whisker plot. The base cases for individual wave energy and wind turbine projects are also included for comparison. The key finding is that the combined LCOE of wind and wave energy projects is always higher than that of standalone wind turbine projects. However, when considering wind and wave energy developers separately, all asset-sharing scenarios lead to overall cost reductions compared to the base case for each technology. Floating wind projects can achieve up to a 7 % reduction in LCOE through collaboration with the wave energy sector, while wave energy developers can benefit from a significantly greater cost reduction, reaching nearly 40 %. These findings align with those of Ref. [167], who conducted a similar study in 2017 comparing LCOE values for specific technologies, including a FOWT, a WEC, co-located wind-wave systems, and hybrid platforms such as W2Power and Poseidon P37. Among all configurations examined, the FOWT had the lowest cost of energy, followed by the co-located wind-wave system. Thus, it can be concluded that integrating WECs into a floating offshore wind platform consistently increases the overall project's LCOE while simultaneously lowering the LCOE for each individual technology.

The same study [166] evaluated the development prospects of hybrid wind-wave units and concluded that they may be unattractive in the near to medium term due to development risks. Key disadvantages identified include the potential for negative interactions between WECs, increased wave loads compromising FOWT stability, additional structural requirements for the FOWT platform, and increased complexity in platform development. Meanwhile, wind and wave energy developers can achieve economic benefits from combined wind-wave systems without the need to construct a fully integrated hybrid system.

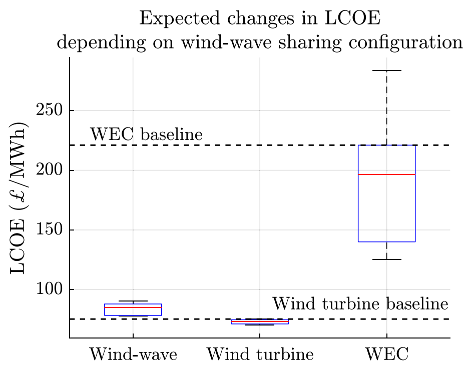


Fig. 24. Estimated LCOE values for coupled wind-wave systems and separately for floating wind and wave developers across different asset sharing configurations. The data is extracted and analysed from Figs. 4-4, 4-5, 4-6 in [166].

7. Discussion

This paper has already highlighted key gaps in hybrid wind-wave energy system research: (i) a noticeable time delay in exploring hybrid concepts compared to the established trends in offshore wind industry, (ii) limited experimental investigations that would significantly improve the accuracy of the numerical models used and enhance the development of WEC control systems, (iii) the absence of hybrid-specific mooring designs, (iv) inaccurate modeling of WEC PTOs and their electrical output, and (v) a lack of active WEC control development. Addressing these requires a multi-disciplinary design optimisation framework, similar to those developed for FOWTs [168]. While the 1–4 % LCoE reduction achieved through control co-design optimisation of the FOWT tower and platform might seem insignificant compared to the LCoE range of hybrid systems (Fig. 24), such frameworks are valuable for revealing the correlation and significance of design and control parameters for both FOWTs and WECs on hybrid system performance, thus informing future design strategies.

8. Conclusion

This paper reviews the literature on design solutions for floating hybrid wind-wave energy systems and attempts to identify trends that might interest the industry and research community. An extensive database was established containing information about the FOWT and WEC design parameters, methodologies used to study hybrid designs, environmental conditions used for performance assessment, and reported findings.

Analysis revealed that the majority of hybrid wind-wave designs are still based on a 5-MW wind turbine and this trend does not seem to change even despite the development of much larger wind turbines. However, based on recent advances in wind energy, larger turbines are recommended for future hybrid wind-wave projects.

The most widely used combination of a FOWT with WECs is the semi-submersible platform integrated with three heaving devices. The contribution of WECs to the power generation of a hybrid wind-wave system is 9 % on average. There is a lack of references presenting WEC power matrices, where future works could benefit the research community by providing such parameters for a better comparison between hybrid devices. The main focus of all the studies reviewed is on wave energy generation and platform motion, while very little attention is paid to techno-economic analysis and load suppression, which should be investigated in the future.

The performance assessment of the hybrid wind-wave system is mainly done using numerical modelling, where wind turbine dynamics is neglected in almost 40 % of the studies. Moreover, only a third of the studies consider the wind and wave climate of the potential deployment site, mainly focusing on operational (not survival) environmental conditions. The analysis of the reported results indicates that the integration of WECs with a floating platform generally amplifies motion in heave and suppresses pitch dynamics.

CRediT authorship contribution statement

Nataliia Y. Sergiienko: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lei Xue:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Leandro S.P. da Silva:** Writing – review & editing, Validation, Methodology, Formal analysis. **Boyin Ding:** Writing – review & editing, Supervision, Funding acquisition. **Benjamin S. Cazzolato:** Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Wave energy converter demonstrator projects

Table 2 provides data for the WEC demonstrator projects used to generate Fig. 1a.

Table 2
Selected WEC demonstrator projects.

Year	Project name	Power (MW)	References
2001	Limpet	0.25	[169]
2004	Pelamis	0.75	[170]
2006	Lysekil	0.01	[171]
2006	Wavebob	1	[172]
2009	WaveStar	0.6	[173]
2009	Wave Dragon	0.02	[174]
2009	Oyster	0.315	[175]
2011	Power Buoy 150	0.15	[176]
2011	Mutriku	0.296	[177]
2016	Azura	0.02	[178]
2016	CETO 5	0.24	[179]
2019	WaveRoller	0.35	[180]
2020	Sharp Eagle	0.5	[181]
2021	UniWave	0.2	[182]
2023	C4	0.6	[183]
2023	Nankun	1	[184]
2024	WavePiston	0.2	[185]
2024	OE35	1.25	[186]

Appendix B. FOWT projects

Table 3 summarises the FOWT demonstration projects and commercial projects globally.

Table 3
FOWT demonstration and commercial projects [187–190].

Project name	Year (on water)	Power [MW]	Platform type	Design company	Country
Demonstration projects					
Hywind	2009	2.3	Spar	Equinor	Norway
WindFloat	2011	2.0	Semi	Principle Power	Portugal
Goto	2013	2.0	Spar	TODA Corporation	Japan
Mirai	2013	2.0	Semi	Fukushima Forward	Japan
Shinpuu	2015	7.0	Semi	Fukushima Forward	Japan
Hamakaze	2016	5.0	Spar	Fukushima Forward	Japan
Floatgen	2017	2.0	Barge	Ideol	France
Hibiki	2018	3.2	Barge	Ideol	Japan
Sanxia Yinling Hao	2021	5.5	Semi	China Three Gorges Corp	China
TetraSpar	2021	3.6	Spar	Stiesdal	Denmark
Sath	2022	2.0	Barge	Saitec	Spain
FuYao	2022	6.2	Semi	China State Shipbuilding Corp	China
CNOOC Guanlan	2022	7.25	Semi	China National Offshore Oil Corp	China
Guoneng Sharing	2023	4.0	Semi	China Energy Investment Corp	China
OceanX	2024	16.6	Semi	Mingyang Group	China
Wind farms					
Hywind Scotland	2017	30.0	Spar	Equinor	UK
WindFloat Atlantic	2019	25.0	Semi	Principle Power	Portugal
Kincardine	2021	50.0	Semi	Principle Power	UK
Hywind Tampen	2022	88.0	Spar	Equinor	Norway
Provence Grand Large	2024	25.0	TLP	SBM Offshore	France

Data availability

Data will be made available upon request.

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