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# Monopile-mounted Wave Energy Converter for a Hybrid Wind-Wave System

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## Abstract:

Multipurpose platforms are innovative solutions to combine the sustainable exploitation of multiple marine resources. Among them, hybrid wind-wave systems stand out due to the multiple synergies between these two forms of marine renewable energy. The objective of this work is to develop a hybrid system for monopile substructures, which are currently the prevailing type of substructure for offshore wind turbines, and more specifically to focus on the wave energy converter sub-system, which consists in an oscillating water column. For this purpose, an in-depth experimental campaign was carried out using a 1:40 scale model of the wave energy converter sub-system and the monopile substructure, considering regular and irregular waves. Based on the experimental results the performance of the device and its interaction with the wave field were characterised – a fundamental step to fully understand the benefits and limitations of this hybrid wind-wave system, which sets the basis for its future development. Regarding the performance, the best efficiency was obtained with the turbine damping corresponding to a 0.5% orifice size, and two resonance peaks were identified ( $T = 9$  and 6 s). As for the interaction of the hybrid system with the wave field, between 5% and 66% of the incident wave power is reflected and between 3% and 45%, transmitted. The wave period was found to be the parameter that most influenced wave run-up on the substructure. This characterisation of the behaviour of the hybrid system shows that it is indeed a promising option for further development.

**Keywords:** Hybrid wind-wave; Wave energy, Offshore Wind; OWC; Physical modelling

31    **Highlights:**

- 32        •    A hybrid wind-wave energy converter for monopile substructures is developed
- 33        •    A thorough experimental campaign is carried out using a 1:40 model
- 34        •    The interaction of the hybrid energy converter with the wave field is characterised
- 35        •    The influence of turbine damping and wave conditions on performance is assessed

36

37

## 38 1. Introduction

39 In the current scenario of climate change[1], with the marine environment under threat [2], a rapid  
40 transition towards a sustainable and environmentally-friendly economy is a pressing challenge that our  
41 society cannot afford to postpone [3], . In this transition offshore renewable energy (ORE) technologies  
42 are poised to play a leading role. With 18.8 GW of installed capacity worldwide at the end of 2017 [4],  
43 of which 15.8 GW in Europe [5], the European offshore wind sector is clearly leading the transition  
44 towards a sustainable energy system. This exceptional development has raised great expectations and  
45 pushed the industry to set the target of installing 460 GW of offshore wind energy, in European waters,  
46 by 2050 [6]. To realise this target and to make the offshore wind industry become the large-scale clean  
47 energy provider that it is expected to, the present momentum in the sector must be strengthened.

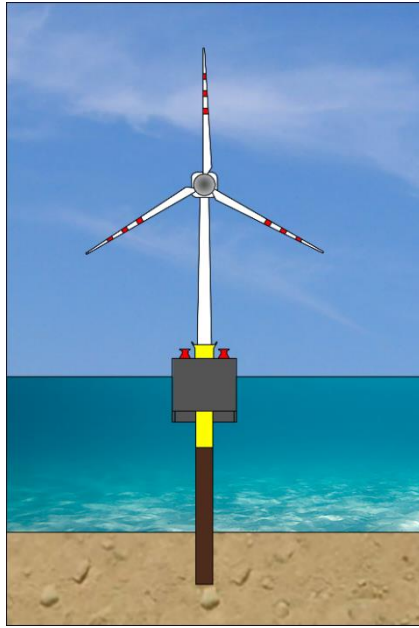
48 To increase the sustainability of offshore wind installations, at a time when they are becoming  
49 more and more popular in many regions worldwide, multipurpose platforms arise as an alternative to  
50 conventional offshore wind systems [7], which enables other resources in the same marine space to be  
51 exploited in addition to wind energy itself [8] – wave energy [9], maritime leisure [10], aquaculture  
52 and seaweed farming [11], fisheries, logistic nodes. In this manner, the use of marine space is  
53 optimised. Hybrid wind-wave energy systems are a particular type of multipurpose platforms that is  
54 predicated on the multiple synergies between offshore wind and wave energy installations, as  
55 described in [12], previously outlined in [13] and [14], and further investigated by [15].

56 Research on hybrid wind-wave systems has been driven primarily by a number of European  
57 research projects aimed at developing the concept of hybrid and multiplatform systems, and at setting  
58 the basis for a future involvement of European industry (e.g., Marina Platform[16], ORECCA [17],  
59 TROPOS [18], H2OCEAN [19] and MERMAID [20]). These projects set the basis with a series of  
60 incipient concepts, such as: Floating Power Plant [21], NEMOS [22], Wave Star [23] and W2Power  
61 [24]. However, the number of works addressing the development of hybrid wind-wave systems is  
62 rather limited. Zanuttigh et al. [25] present a methodology a multi-criteria design of multi-use offshore

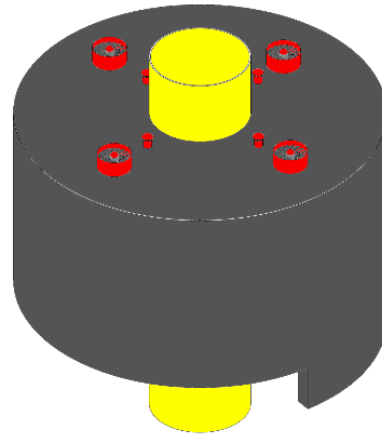
platforms, O’Sullivan’s PhD [26] addresses the feasibility of different combined wind-wave platforms in the framework of the MARINA Platform project, further investigated in [27] and [28]. The development of hybrid solutions for floating wind is further investigated in several works, e.g., [29]. The characterisation of the joint wind-wave resource has been investigated by [30] for islands and [31] at a global level. The variability and predictability of the combined wind-wave resource has been investigated by [32]. The potential co-location of both technologies was addressed in [33]. Other publications have addressed the manner in which the temporal correlation of wind and wave resources influences the combined power output (e.g., [34]) and its interaction with the electric grid (e.g., [35]), as well as the potential of combined wind-wave systems to smooth the power output and reduce downtime [36]. Finally, the interesting concept of the ‘shadow-effect’ [37], i.e., how wave energy converters (WECs) deployed around the periphery of a wind farm can result in a milder wave climate within the farm and thus reduce its operational costs was studied by [38].

This paper deals with the development through laboratory tests of the University of Plymouth’s hybrid wind-wave energy converter presented in [39] and further investigated for jacket-frame substructures in [40], which integrates an oscillating water column (OWC) with an offshore wind substructure of the monopile type (Figure 1). For this research, a 1:40 scale model, of an upgraded version of the hybrid system considered in [41], was manufactured and tested. The wave climate of an offshore wind farm off the west coast of Denmark was taken as a reference. Based on the experimental results, the interaction of the hybrid system with the wave field was established.

This article is structured as follows. Section 2 describes the materials and methods used during the experimental campaign. Results from the experimental campaign are presented in Section 3, and discussed in Section 4. Finally, conclusions are drawn in Section 5.



(a)



(b)

**Figure 1:** University of Plymouth's hybrid wind-wave energy converter: (a) conceptual representation of the hybrid system for monopile offshore wind substructures; and (b) perspective view of the WEC sub-system; (partially reproduced from [40])

## 2. Materials and methods

The materials and methods considered for the physical modelling campaign of the hybrid wind-wave energy converter can be structured into three different sections: (i) the definition of the physical model itself, (ii) the description of the experimental facility, set-up and test programme, and finally, (iii) the data analysis techniques followed to process the data obtained in the experimental campaign.

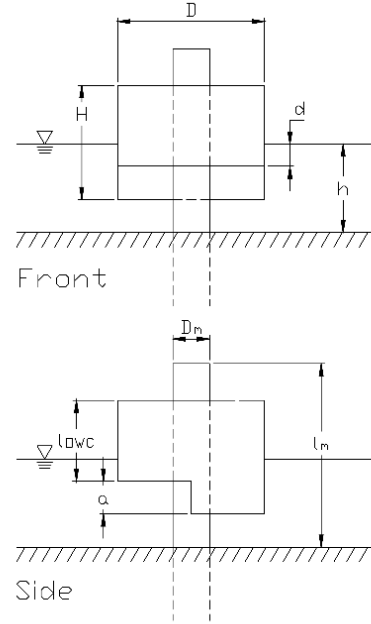
### 2.1. The hybrid model

A 1:40 scale model (Figure 2) was built based on the proposed hybrid device. The design of the model was carried out considering multiple factors, such as: experience from previous models, available 'out-of-the-shelf' materials for model manufacturing and the capabilities of the experimental facility, and the reference text [43]. Table 1 defines the most relevant dimensions of the model. The Froude similarity criterion was applied. The scale model was designed in accordance with: (i) the most common diameters of monopile substructures being installed in offshore windfarms; (ii) the dimensions of the wave basing where the tests are to be conducted; (iii) the sensitivity and working

102 ranges of the sensors; (iv) the water depth and wave conditions tested, and if these are within the  
 103 working limits of the wave maker. Only the WEC sub-system was considered for this experimental  
 104 campaign, as the wind turbine sub-system does not influence significantly its hydrodynamic response.



(a)



(b)

**Figure 2:** 1:40 scale model of the hybrid device: (a) being tested at the University of Plymouth's COAST Laboratory and (b) a sketch showing front and side views of the model

**Table 1:** Model characteristics and dimensions

Parameter	Symbol	Dimension
Chamber draught	$d$	0.100 m
Chamber external diameter	$D$	0.500 m
Chamber height	$l_{owc}$	0.275 m
Chamber wall-thickness	$e_c$	$4.0 \times 10^{-3}$ m
Inner chamber water plane area	$A_{owc}$	0.174 m <sup>2</sup>
Monopile external diameter	$D_m$	5.563" (0.141 m)
Monopile length	$l_m$	0.750 m
Monopile wall-thickness	$e_m$	0.258" ( $6.6 \times 10^{-3}$ m)
Skirt length	$a$	$7.5 \times 10^{-2}$ m
Skirt angle	$\alpha$	180 deg
Water depth	$h$	0.500 m

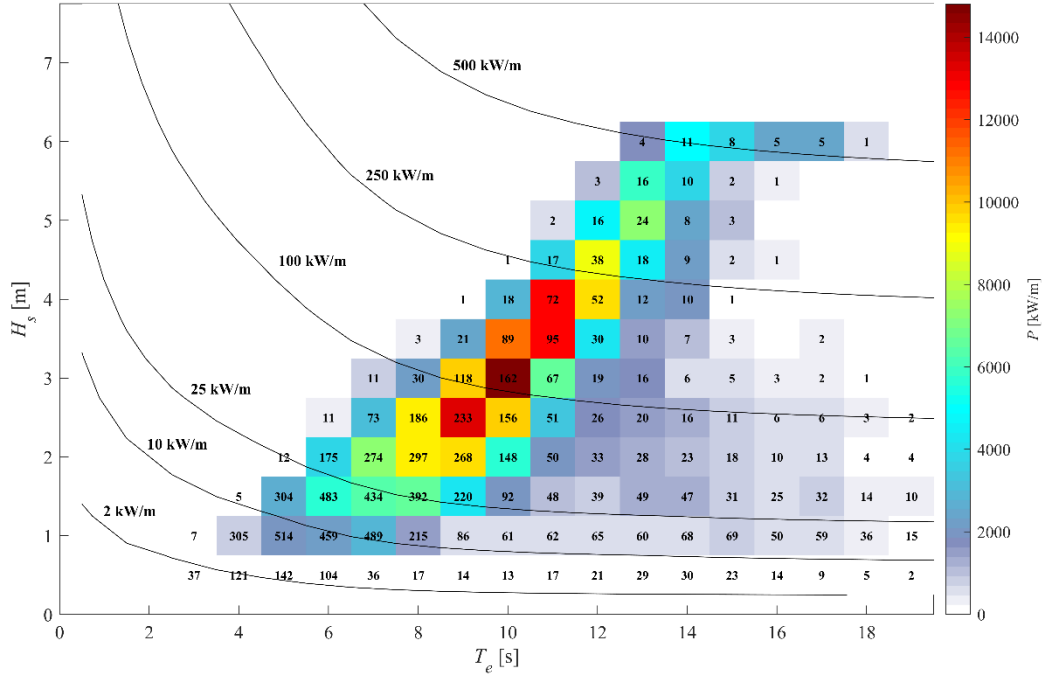
110 The model of the hybrid device was built considering materials, such as: PVC, methacrylate, stainless  
111 steel and mild steel. A 500 mm external diameter PVC pipe with a wall thickness of 4 mm was used  
112 to build the OWC chamber. The skirt section was built out of an angular section of the same PVC pipe  
113 as the OWC chamber. Two internal radial reinforcement beams were laser cut out of a 10 mm thickness  
114 PVC sheet. The OWC chamber's lid was built out of a 10 mm thickness methacrylate sheet. A 5"  
115 internal diameter stainless steel pipe (manufacturing schedule 40) was used to build the offshore wind  
116 turbine monopile. Two annular rings, built out of a 6 mm thickness stainless steel plate, were welded  
117 to the monopile as attachment points for the OWC chamber. A 6 mm thickness stainless steel disk was  
118 welded at the bottom part of the monopile to solidary link the model to a square, 6 mm thickness, mild-  
119 steel plate, as the main support of the model, which was screwed to the bottom of the basin. The  
120 damping induced by the full-scale power take-off (PTO) on the WEC sub-system – i.e., an impulse  
121 turbine – was modelled by means of a number of exchangeable perforated plates with different orifice  
122 diameters, a common technique followed by numerous authors (e.g., [44]). The values of the orifice  
123 diameter selected (34 mm, 42 mm, 48 mm and 60 mm) corresponded to the following values of the  
124 area coefficient [45]: 0.5%, 0.75%, 1% and 1.5%, respectively.

## 125 2.2. *Experimental set-up and test programme*

126 The University of Plymouth's COAST Laboratory, and in particular its coastal basin, was the facility  
127 used for the experimental campaign. This is a 15 m long and 10 m wide wave basin, with a variable  
128 water depth of up to 500 mm. For this work the water depth was set at 500 mm to match the 20 m  
129 water depth of the Horns Rev 3 offshore wind farm, off NW Denmark. In particular, the MetOcean  
130 study for this offshore wind farm [46] was used as a reference for selecting a realistic set of wave  
131 conditions for a monopile based offshore wind farm (Figure 3). A wave-maker, from Edinburgh  
132 designs ltd (EDL), is used to generate the waves. In relation to the tide, the power extraction of a fixed  
133 OWC has been proved to be affected by the variation of the tidal level for fixed OWC systems (e.g.,



[47]). This has not been considered in this work, for the hybrid system considered here has the capability to adapt to the tidal level by raising or lowering the OWC, as described in the patent [48].

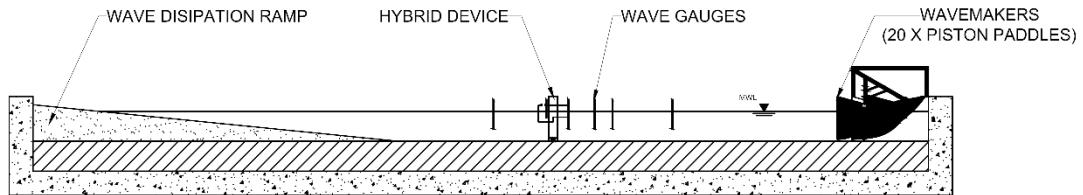


**Figure 3:** Horns Rev 3 significant wave height – energy period scatter diagram. The curves represent wave power isolines, and the numbers, hours in an average year of the corresponding *energy bin*

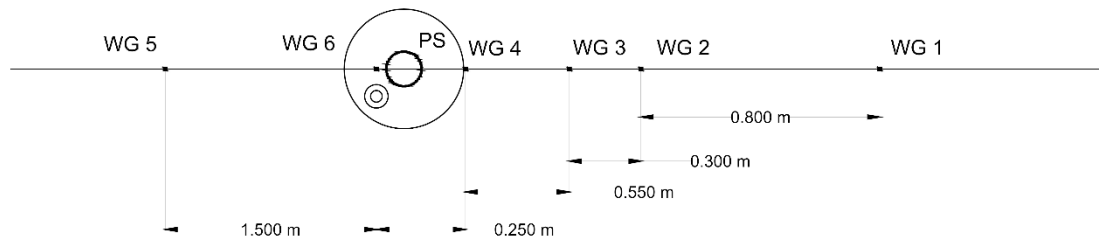
For the experimental set-up (Figure 4), six conductive wave gauges were positioned along the basin to record free surface elevation. The first three wave gauges (WG1, WG2 and WG3), in front of the model, were used to record the input signals for incident and reflected wave analysis (IRWA), following the Mansard and Funke [49] wave reflection analysis method as modified by Baquerizo et al. [50]. Another wave gauge (WG4) was used to record the wave run-up at the front of the model and positioned at the front of the model – in contact with the OWC chamber external surface. WG6 was installed in the OWC chamber to record free surface motion. Finally, WG5 was installed in the lee of the model to record the transmitted wave. Furthermore, an Omega differential pressure transducer (PT), PX2650-10BD5V, was set up to measure the pressure inside the OWC chamber with reference to the outer (atmospheric) pressure. Table 2 defines the position, along the centreline of the basin, of

150 the different elements of the experimental set-up – the coordinate system for the experiments follows  
 151 the convention defined in [41].

## EXPERIMENTAL SET-UP



## WAVE GAUGE LAYOUT



**Figure 4:** Lateral view of the flume and schematic of the wave gauge layout

**Table 2:** Position of wave gauges and model

Element	X [m]
WG1	2.475
WG2	3.275
WG3	3.575
WG4	4.125
Hybrid device model	4.375
Pressure transducer (PT)	4.375
WG5	5.875
WG6 (OWC)	4.375

156

157 Regular and irregular waves, together with four different orifice sizes, were considered to define the  
 158 experimental programme –the 48 mm orifice size (1%) alone was used in the tests with irregular waves.  
 159 The experimental campaign was structured into four different experimental series, following [43].  
 160 Series A defines the regular waves tests, while Series B and C does it for the irregular waves tests.

Finally, Series R covers the repeatability tests for both regular and irregular waves. Table 3 defines the wave conditions matrix for Series A, where the duration for each one of the regular waves tests was set to 100 times the wave period. Furthermore, Table 4, shows the irregular sea states – considering a JONSWAP spectrum [47] – for Series B and C, where the duration of the tests was set at a minimum of 569 s – i.e., 60 min at prototype scale.

**Table 3:** Wave conditions for Series A, regular waves (data in prototype values)

Series A	T [s]									
	4	5	6	7	8	9	10	11	12	13
1.5	A01	A02	A04	A06	A09	A13	A18	A23	A28	A33
2.5		A03	A05	A07	A10	A14	A19	A24	A29	A34
3.5				A08	A11	A15	A20	A25	A30	A35
4.5					A12	A16	A21	A26	A31	A36
5.5						A17	A22	A27	A32	A37

**Table 4:** Wave conditions for Series B and C, irregular waves (data in prototype values)

Test Series	Test number	H <sub>s</sub>	T <sub>E</sub>	T <sub>Z</sub>	T <sub>P</sub>
Series B	B01	1.5 m	5.13 s	4.28 s	5.50 s
	B02	1.5 m	6.07 s	5.06 s	6.50 s
	B03	2.5 m	7.00 s	5.83 s	7.50 s
	B04	2.5 m	7.93 s	6.61 s	8.50 s
	B05	3.5 m	8.86 s	7.39 s	9.50 s
	B06	3.5 m	9.80 s	8.16 s	10.50 s
	B07	4.5 m	9.80 s	8.16 s	10.50 s
	B08	4.5 m	10.73 s	8.94 s	11.50 s
Series C	C01		4.20 s	3.50 s	4.50 s
	C02		5.13 s	4.28 s	5.50 s
	C03		6.07 s	5.06 s	6.50 s
	C04		7.00 s	5.83 s	7.50 s
	C05	1.5 m	7.93 s	6.61 s	8.50 s
	C06		8.86 s	7.39 s	9.50 s
	C07		9.80 s	8.16 s	10.50 s
	C08		10.73 s	8.94 s	11.50 s
	C09		11.66 s	9.72 s	12.50 s
	C10		12.60 s	10.50 s	13.50 s

The accuracy of the experimental set-up was evaluated through the repeatability tests (Series R), which was divided into two subseries: Series RA for regular waves, and RB for random waves. For regular waves four different wave conditions were selected (A06, A08, A18, and A20 from Table 3), while,

for irregular waves two were the sea states selected (B04 and B05, from Table 4). Four consecutive tests were run for each one of the wave conditions defined for each subseries. Based on the recorded data, the repeatability of the experimental campaign was assured, as may be observed from the values of the statistical indicators in Table 5 – the correlation coefficient ( $R^2$ ) and the normalised root mean square error ( $NRMSE$ ) (Appendix A).

**Table 5:** Average values of  $R^2$  (correlation coeff.) and  $NRMSE$  (normalised root-mean-square error) for the repeatability tests series

		WG1	WG2	WG3	WG4	WG5	WG6	PT
Series RA	$R^2$	0.991	0.983	0.987	0.984	0.977	0.978	0.992
	$NRMSE$	5.66%	7.06%	6.34%	6.99%	8.59%	8.48%	4.76%
Series RB	$R^2$	0.970	0.958	0.958	0.934	0.951	0.951	0.992
	$NRMSE$	4.15%	5.31%	4.80%	4.95%	5.67%	6.11%	1.90%

### 2.3. Data analysis

The interaction of the hybrid wind-wave energy converter with the wave field may be characterised based on the reflection ( $K_R$ ) and transmission ( $K_T$ ) coefficients. For its part, the performance of the system may be assessed using the response amplitude operators for the following: (i) free surface oscillation within the OWC chamber ( $RAO_C$ ); (ii) relative pressure in the chamber ( $RAO_P$ ); (iii) run-up coefficient, in different versions for regular ( $C_R$ ) and random ( $C_S$  and  $C_{max}$ ) waves; and (iv) the capture-width ratio ( $C_{WR}$ ). In the case of regular waves:

$$K_R = \frac{H_R}{H_I}, \quad (1)$$

$$K_T = \frac{H_T}{H_I}, \quad (2)$$

$$C_{WR} = \frac{P_m}{P b}. \quad (3)$$

$$RAO_C = \frac{H_C}{H_I}, \quad (4)$$

$$RAO_P = \frac{1}{\rho_w g} \frac{H_P}{H_I}, \quad (5)$$

$$C_R = \frac{R}{H_I}, \quad (6)$$

189 In the foregoing equations  $P$  denotes wave power per metre of wave front;  $P_m$  represents the average  
 190 pneumatic power captured by the system,  $b$  represents the width of the OWC device – in this case, the  
 191 external diameter of the OWC chamber ( $D$ );  $H_C$  is defined as the range of the free surface oscillation,  
 192 and  $H_P$  as the range of the pneumatic pressure, within the same oscillation cycle;  $R$  stands for wave  
 193 run-up in front of the model;  $H_I$ ,  $H_R$  and  $H_T$  stand for the incident, reflected and transmitted wave  
 194 height, respectively;  $g$  stands for the acceleration of gravity;  $\rho_w$  represents the density of water.

$$P = \frac{\rho_w g H_I^2 c_g}{8}, \quad (7)$$

$$P = \rho_w g \sum_{i=1}^N S_i (c_g)_i \Delta f \quad (8)$$

195 where  $N$  is the number of frequency components or bands (for each  $\Delta f$ ), and  $S_i$  and  $(c_g)_i$  are the spectral  
 196 density and the group velocity for the  $i$ -th band, respectively.

197 Alternatively, for irregular waves:

$$K_R = \sqrt{\frac{m_{0R}}{m_{0I}}}, \quad (9)$$

$$K_T = \sqrt{\frac{m_{0T}}{m_{0I}}}, \quad (10)$$

$$C_S = \frac{R_S}{H_{SI}}, \quad (11)$$

$$C_{max} = \frac{R_{max}}{H_{SI}}, \quad (12)$$

198 where  $m_{0I}$ ,  $m_{0R}$  and  $m_{0T}$  are the zero-th order moment of the incident, reflected and transmitted waves,  
 199 respectively.  $R_S$  and  $R_{max}$  are the significant and maximum wave run-up respectively, with  $H_{SI}$  the  
 200 incident significant wave height. Note that the capture-width ratio ( $C_{WR}$ ), defined from Equation 3, is  
 201 valid for both, regular and irregular waves. Further details about this method and the definition of some  
 202 of the parameters can be found in [40].

203 The behaviour of an OWC does not depend solely on the sea state, but also on the damping exerted by  
 204 the air turbine – represented in the model by the orifice – on the system [51]. In order to account for  
 205 this effect when characterising the hydrodynamic response, a non-dimensional damping coefficient  
 206 can be defined, following [47]:

$$B^* = \frac{\Delta p^{1/2} A_{OWC}}{q \rho_a}, \quad (12)$$

207 where  $\Delta p$  is the relative pneumatic pressure,  $q$  represents air flowrate,  $\rho_a$  stands for air density and  
 208  $A_{OWC}$  is the horizontal surface area of the inner OWC chamber. Therefore, the values of the damping  
 209 coefficients obtained for diameters of the orifice of  $d_o = 35, 42, 48$  and  $60$  mm are  $B^* = 68.85, 50.50,$   
 210  $46.04$  and  $45.81$ , respectively.

### 211 3. Results

212 This section presents the results acquired during the experimental campaign and processed following  
 213 the data analysis methods defined in Section 2.

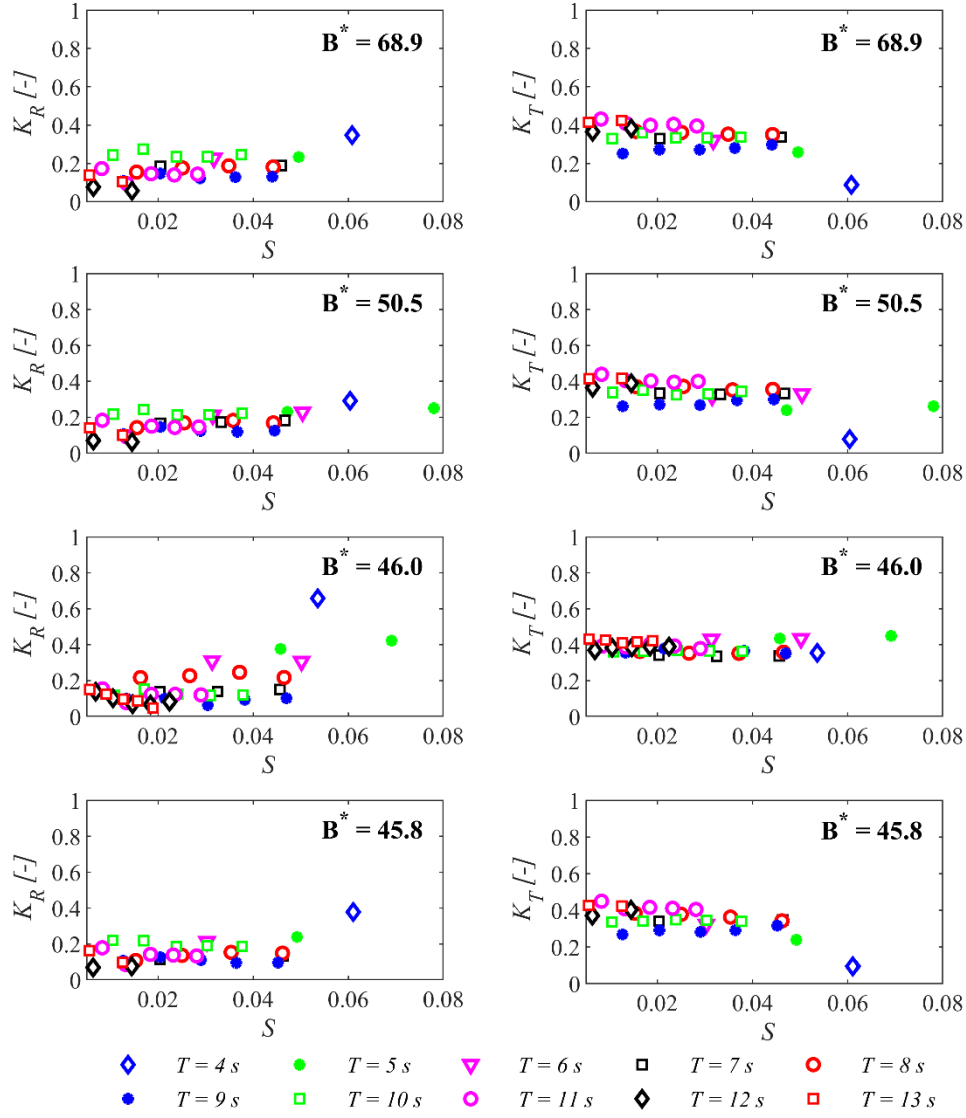
#### 214 3.1. Interaction with the wave field

215 The interaction between the wave field and the hybrid device is quantified using the reflection and  
 216 transmission coefficients ( $K_R$  and  $K_T$ ), obtained from the IRWA. Results for regular waves and for the  
 217 four damping coefficients are represented versus the non-dimensional wave number ( $kh$ ) in Figure 5.  
 218 For random waves, results for the value of the damping coefficient corresponding to the orifice with  
 219 area coefficient of 1% ( $B^* = 46.0$ ) are plotted in Figure 6. In general, both ( $K_R$  and  $K_T$ ) present a strong  
 220 dependence on the wave period, and a weaker relationship with the damping exerted by the turbine.

221 For a certain wave height (Series C), the tendency of the  $K_R$  graph is clear: wave reflection decreases  
 222 as the wave period increases (Figure 6).  $K_R$  increases, in general, with the non-dimensional wave  
 223 number ( $kh$ ). On the contrary, the transmission coefficient ( $K_T$ ) increases with the wave period. In  
 224 general,  $K_T$  values are around 0.32 for regular waves and 0.18 for random waves – with the exception

225 of the three smaller wave periods ( $T = 4, 5$  and  $6$  s), where a decrease in wave transmission can be  
 226 clearly observed when  $kh$  increases. In addition, an influence of the damping coefficient may be  
 227 observed in both reflection and transmission, with the damping coefficient corresponding to the 1%  
 228 orifice ( $B^* = 46.0$ ) showing the largest effect – in particular for larger values of  $kh$ .

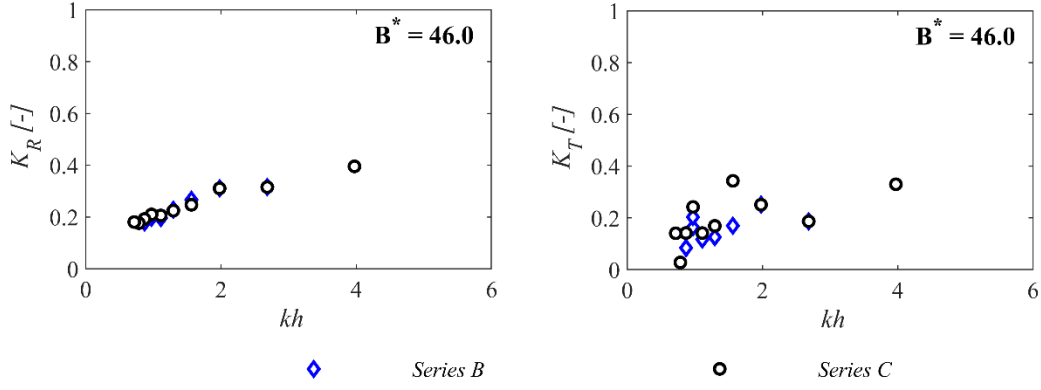
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231 **Figure 5:** Values of  $K_R$  and  $K_T$  for different damping coefficients ( $B^*$ ) and wave periods ( $T$ ), regular waves (Series A); (data in  
 232 prototype values)

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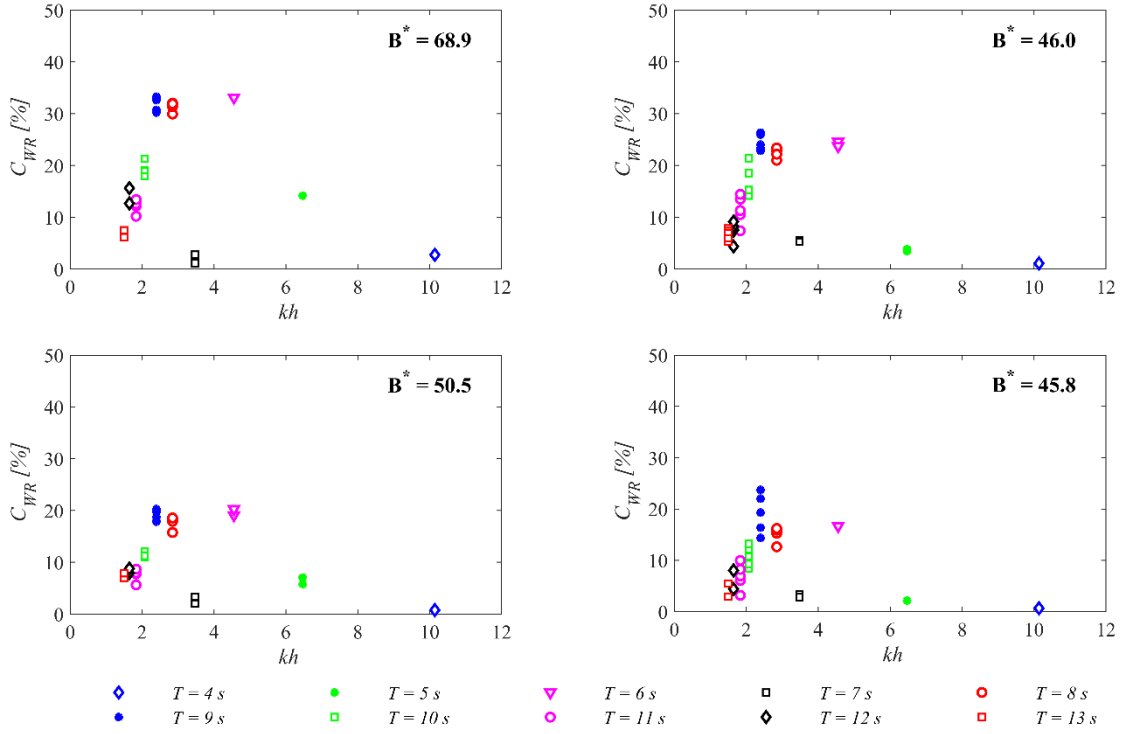


**Figure 6:** Values of  $K_R$  and  $K_T$  under random waves (Series B and C); (data in prototype values)

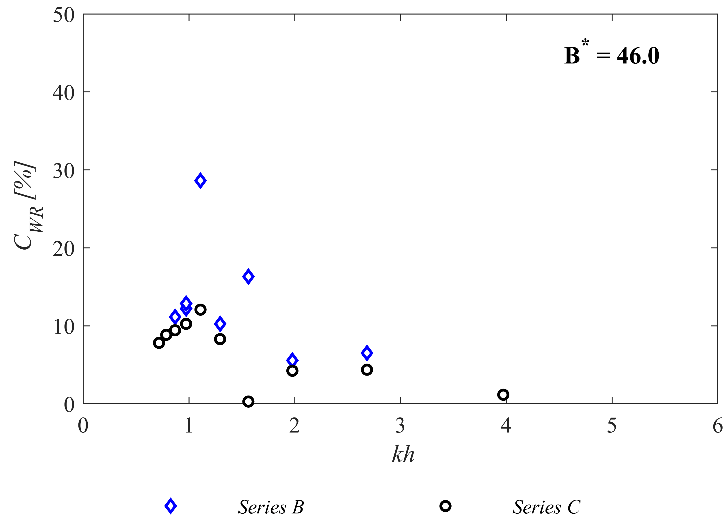
### 3.2. Device performance

The capture-width ratio ( $C_{WR}$ ) was the tool for evaluating the performance of the WEC sub-system (Equation 3). Figure 7 represents the  $C_{WR}$  versus the non-dimensional wave number ( $kh$ ) for the four damping coefficients tested and regular waves. The plot for random waves, Figure 8, considers the damping coefficient value corresponding to the 1% orifice ( $B^* = 46.0$ ). Furthermore, Figures 9 and 10 represent the capture-width ratio and power matrices respectively. Two peaks of maximum efficiency can be clearly identified at different values of the wave period ( $T = 6$  s and  $T = 9$  s) – note that for the peak occurring at the shortest wave period ( $T = 6$  s), a significant amount of sloshing was observed at the inner OWC chamber, during the experiments. It is clear that the main parameters influencing the  $C_{WR}$  are the turbine damping and the wave period, followed by the non-dimensional wave number ( $kh$ ).





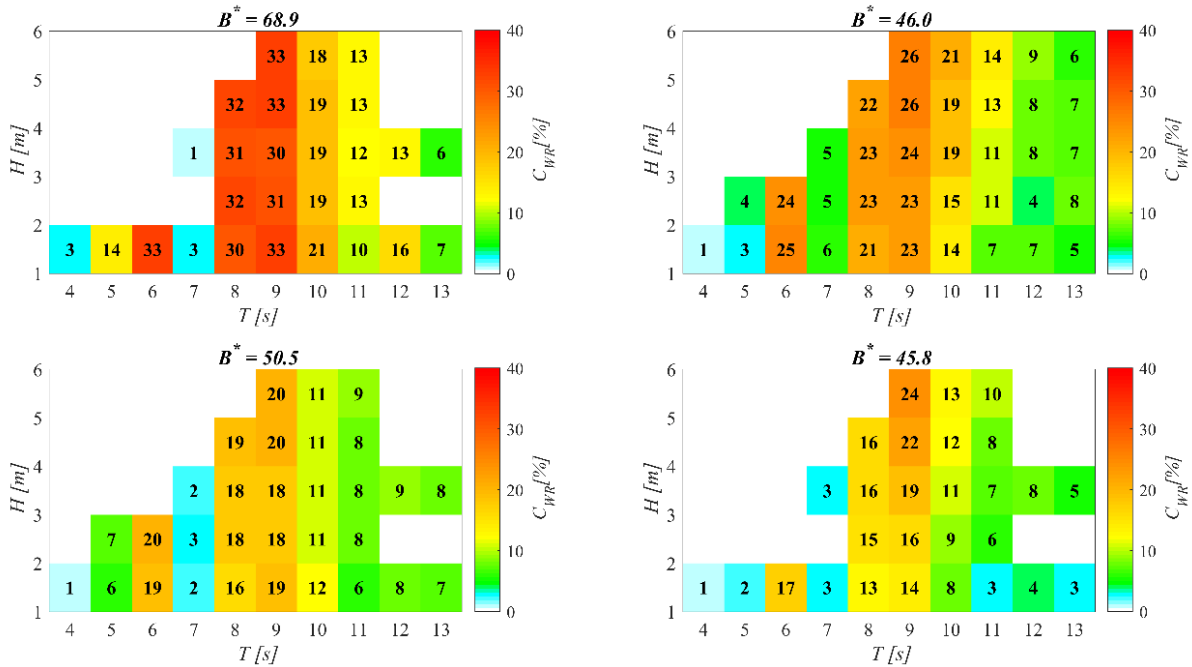
**Figure 7:** Capture width ratio ( $C_{WR}$ ) for different damping coefficient ( $B^*$ ) and wave period ( $T$ ) values, and regular waves (Series A); (data in prototype values)



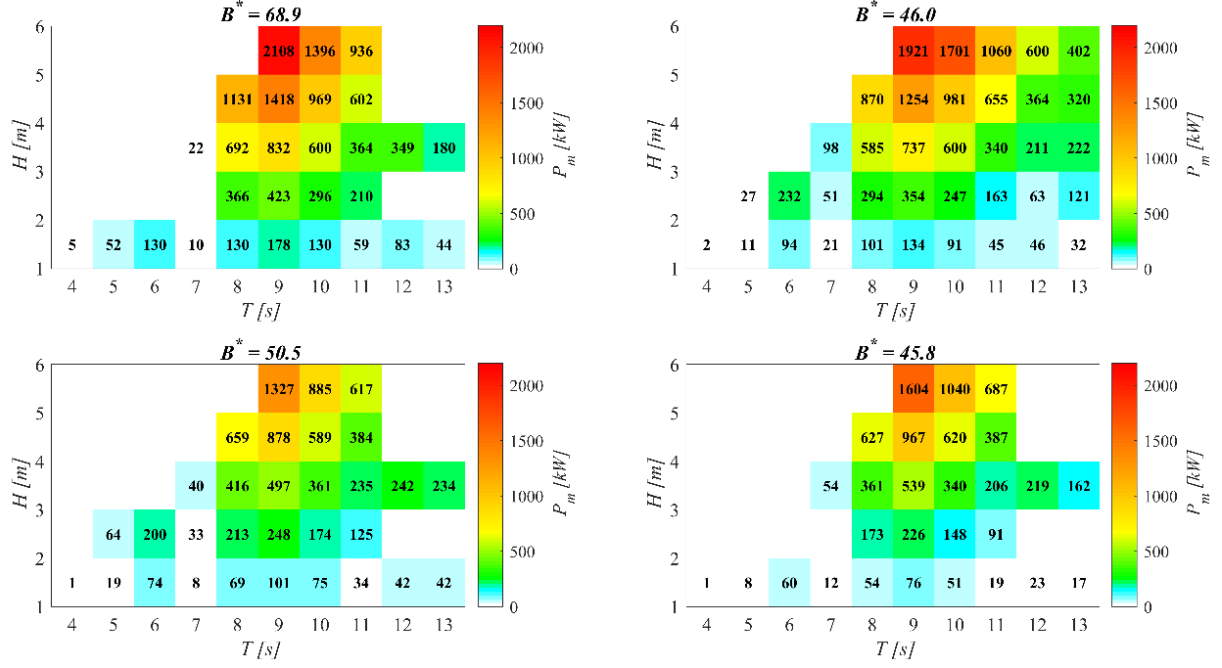
**Figure 8:** Capture width ratio ( $C_{WR}$ ) and irregular waves (Series B and C); (data in prototype values)

Figures 7 and 8 show strong influence of the damping exerted by the turbine on the capture width ratio ( $C_{WR}$ ) – with average values of the  $C_{WR}$  19%, 11%, 14% and 10% for turbine damping values of  $B^* = 68.9, 50.5, 46.0$  and  $45.8$  respectively, for regular waves and 9% for irregular waves and  $B^* = 46.0$ .

256 The best performance is found for the 0.5% orifice sizes ( $B^* = 68.9$ ) followed closely by the 1.0%  
 257 ( $B^* = 46.0$ ), while the worst performance can be seen at the 0.75% orifice ( $B^* = 50.5$ ). The four orifices  
 258 present maximum values of  $C_{WR}$  at ( $T = 6$  s and  $T = 9$  s) and minimum values of  $C_{WR}$  at ( $T = 7$  s and  
 259  $T = 4$  s). In addition, the  $C_{WR}$ , is strongly affected by the wave period, increasing this, in general, when  
 260 the wave period decreases until it reaches its maximum value at  $T = 9$  s, and then decreases to almost  
 261 null values before finally increasing again for a second peak at  $T = 6$  s. A similar behaviour can be also  
 262 identified for irregular waves (Figure 8), in particular when fixing the significant wave height and  
 263 varying the peak wave period (Series C).



265 **Figure 9:** Matrices of the capture width ratio ( $C_{WR}$ ) for different values of the damping coefficient ( $B^*$ ) and regular waves (Series A),  
 266 showing its variability in terms of the wave height ( $H$ ) and wave period ( $T$ ), (data in prototype values)



**Figure 10:** Matrices of the mean pneumatic power ( $P_m$ ) for different values of the damping coefficient ( $B^*$ ) and regular waves (Series A), showing its variability in terms of the wave height ( $H$ ) and wave period ( $T$ ), (data in prototype values)

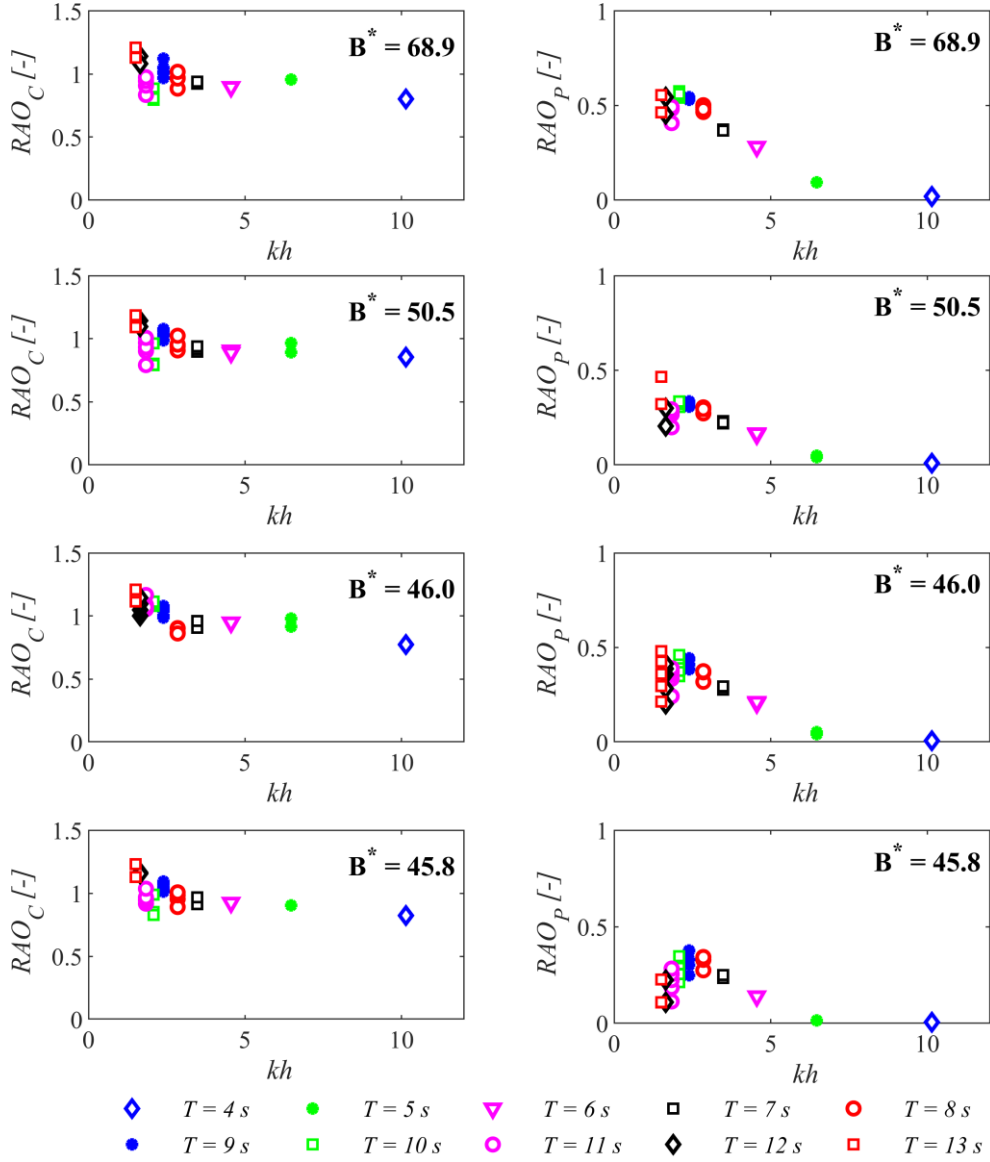
To clarify the role of the different parameters influencing the performance of the converter, the matrices of capture-width ratio ( $C_{WR}$ ) and average pneumatic power ( $P_m$ ) are represented in terms of the wave height ( $H$ ) and the wave period ( $T$ ) and the four values of damping ( $B^*$ ) for regular waves (Figures 9 and 10, respectively). Two regions of best performance appear in the capture-width ratio matrix (Figure 9), for the four damping values. The first corresponds to wave periods between  $T = 8$  s and  $T = 11$  s, with a primary peak at  $T = 9$  s – note that for the 0.5% and 1.0% orifice sizes ( $B^* = 68.9$  and  $B^* = 46.0$ ) the extent of this area of best performance increases in comparison with the other two orifices, showing its maximum extent for the smallest orifice size ( $B^* = 68.9$ ). The second is a narrow band concentrated at  $T = 6$  s., which represents the secondary efficiency peak – note that for the smallest orifice size ( $B^* = 68.9$ ) the width of this region extends to also  $T = 5$  s. Furthermore, when analysing together the capture width and mean pneumatic matrices (Figures 9 and 10, respectively), the role of wave height on performance is apparent. Although this influence is less significant than that

284 exerted by wave period ( $T$ ) or damping ( $B^*$ ), it does have an effect, increasing the efficiency when  
285 wave height increases.

### 286 3.3. *Device response*

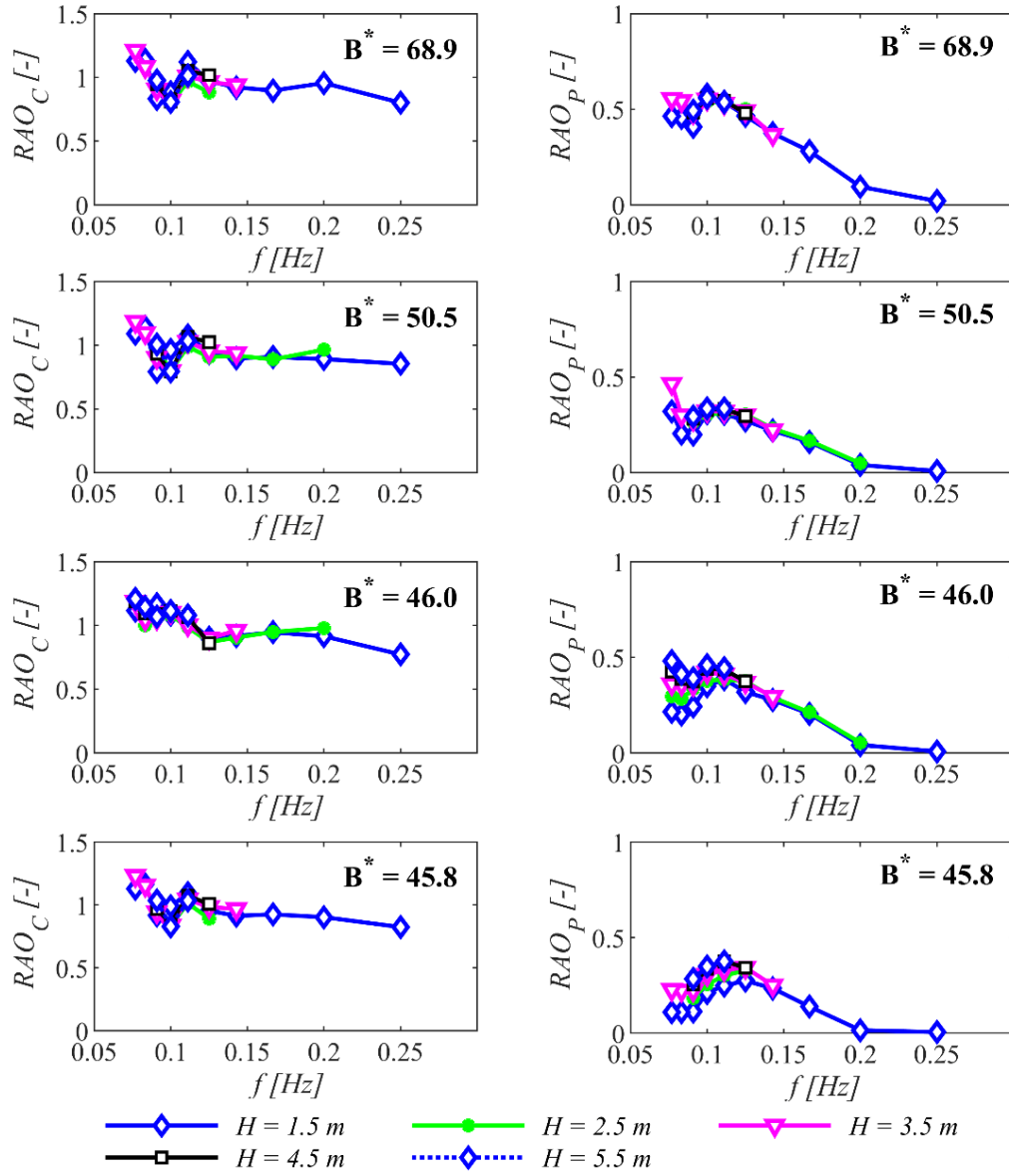
287 The hybrid device response to the incident waves was analysed by means of the response amplitude  
288 operator (RAO), which was used to characterise the response of the free surface in the chamber ( $RAO_C$ )  
289 and the relative pressure ( $RAO_P$ ). Figure 11 presents the results for regular waves and the values of the  
290 damping coefficient versus the non-dimensional wave number ( $kh$ ) and in Figure 12 versus the wave  
291 frequency. It is clear that the main parameter influencing both RAOs is the turbine damping ( $B^*$ ),  
292 followed by the wave period ( $T$ ), as seen in previous sections (Figure 11). In particular,  $RAO_P$  values  
293 show a clear peak of maximum relative pneumatic pressure, around the area of best performance of  
294 the hybrid device.

295 It is clear from Figure 11 that the damping coefficient ( $B^*$ ) and the non-dimensional wave number ( $kh$ )  
296 are the two parameters influencing the most the behaviour of both RAOs, showing  $RAO_C$  and  $RAO_P$   
297 opposite behaviours – i.e., when  $RAO_C$  increases  $RAO_P$  decreases and vice versa. Maximum values of  
298 both RAOs are found for 0.5% and 1.0% orifice sizes ( $B^* = 68.9$  and  $B^* = 46.0$ ) – which is coherent  
299 with the best performance data from previous section. Essentially,  $RAO_C$  tends to decrease when the  
300 non-dimensional wave number ( $kh$ ) increases along with the damping coefficient ( $B^*$ ).



**Figure 11:** RAO<sub>C</sub> and RAO<sub>P</sub> versus non-dimensional wave number for various damping coefficients ( $B^*$ ) and wave periods ( $T$ ) (Series A) (data in prototype values)

The conventional representation of the RAOs versus the wave frequency ( $f$ ) is presented in Figure 12. It may be seen that the influence of the wave frequency on the values of  $RAO_C$  is accentuated for  $f < 0.15$  Hz. For higher frequencies,  $RAO_C$  tends to unity. The influence of the wave height on  $RAO_C$  is rather weak, and hardly noticeable for the lower wave frequencies. Furthermore, the turbine damping is the factor that primarily influences  $RAO_P$ , followed by wave frequency and, to a minor extent, wave height – whose relevance increases when the turbine damping decreases.

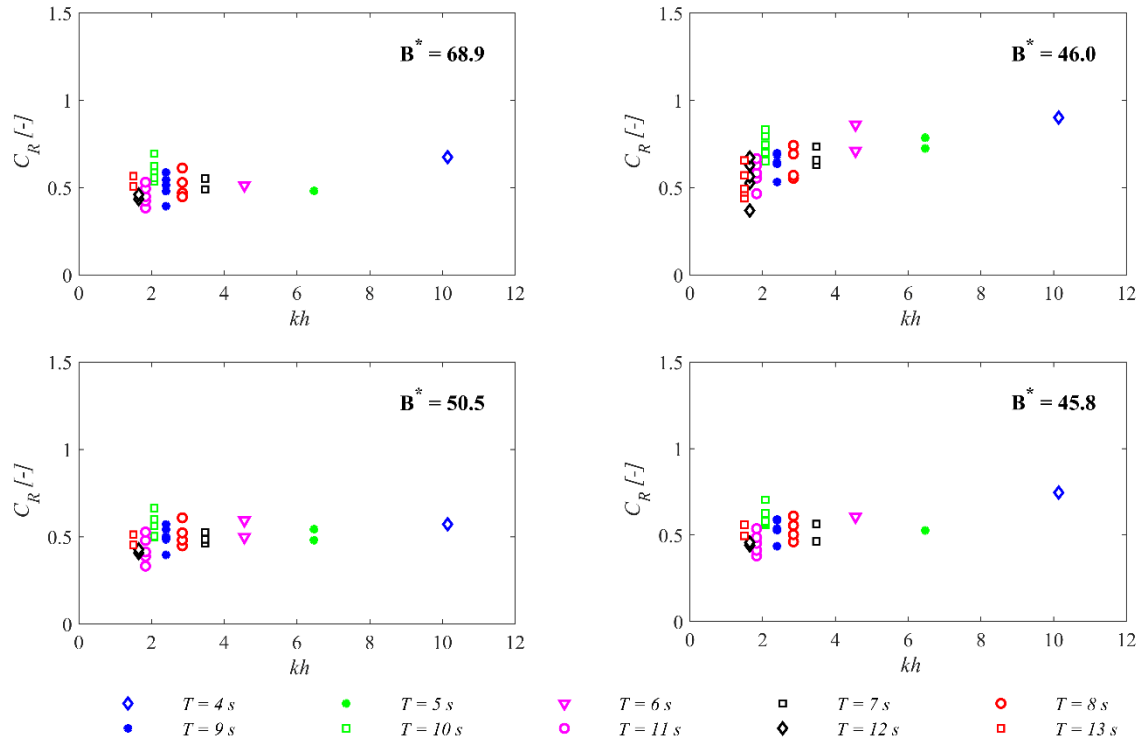


**Figure 12:**  $RAO_C$  and  $RAO_P$  versus wave frequency for various damping coefficients ( $B^*$ ) and wave height ( $H$ ) (Series A) (data in prototype values)

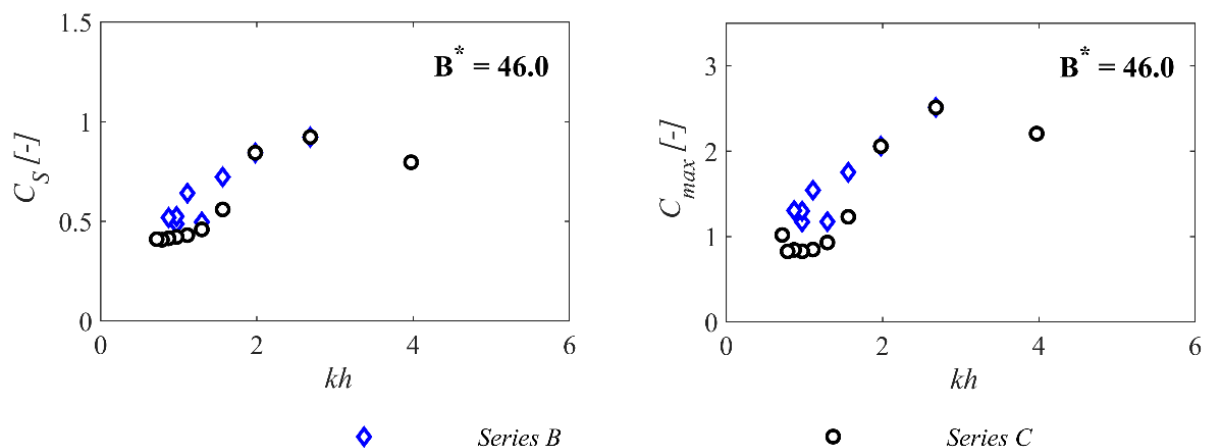
#### 3.4. Run-up

The study of the wave run-up at the front of the hybrid device, gives a valuable information for future design and structural integration of the WEC sub-system into a monopile offshore wind substructure. For this research the run-up was characterised by means of the run-up coefficient ( $C_R$ ), for regular waves, and the significant and maximum run-up coefficients ( $C_S$  and  $C_{max}$ , respectively) for irregular waves. Figure 13 represents the  $C_R$  for regular waves and the four damping coefficients tested versus

321 the non-dimensional wave number ( $kh$ ). Furthermore,  $C_S$  and  $C_{max}$  are represented for irregular waves  
 322 in Figure 14 for the damping coefficient corresponding to the 1% orifice ( $B^* = 46.0$ ) versus the non-  
 323 dimensional wave number ( $kh$ ). In general, the wave run-up is clearly controlled by the wave period,  
 324 being the influence of the turbine damping less accentuated.



**Figure 13:** Run-up coefficient ( $C_R$ ) for various damping coefficients ( $B^*$ ) and wave periods ( $T$ ) (Series A) (data in prototype values)



**Figure 14:** Significant and maximum run-up coefficients ( $C_s$  and  $C_{max}$ ) under random waves (Series B and C) (data in prototype values)

For regular waves (Figure 13), the run-up coefficient ( $C_R$ ) shows, in general, values around 0.5. In general, the wave run-up tends to increase when the wave period decreases, and shows two maxima, for  $T = 10$  s and  $T = 4$  s. It is clear that the turbine damping value corresponding to the 1.0% orifice size ( $B^* = 46.0$ ) has the greatest influence on the run-up, leading, in general, to larger values. In contrast, when looking at the run-up of irregular waves (Figure 14), the effect of the non-dimensional wave number shows a clear influence on the wave run-up. This is testament of the strong influence of the wave period, as may be observed from Series C data (where the significant wave height is kept constant for a range of peak wave periods). Both significant and maximum run-up coefficients ( $C_s$  and  $C_{max}$ , respectively), in most cases, increase considerably when the non-dimensional wave number increases – when the peak wave period decreases.  $C_s$  ranges from about 0.5 to about 1, while  $C_{max}$  varies from about 1 to over 2, with a maximum of  $C_{max} = 2.51$  – i.e., a run-up that is two and a half times larger than the incident wave.



#### 4. Discussion

This work develops the University of Plymouth's hybrid wind-wave energy converter for installation on monopile offshore wind substructures. A comprehensive set of physical modelling tests were carried out to understand better its behaviour and further advance in the prototype development. A simplified model version of the hybrid device was defined and tested at 1:40 scale. Based on the results from these tests, the performance of the device and how this interacts with its surrounding wave field was studied to characterise its hydrodynamic response.

The wave height and period together with the damping exerted by the turbine were the parameters considered to investigate the hybrid device. A number of interchangeable orifice plates, with orifice sizes of different diameters, were used to model the turbine damping. A total of 184 tests, structured into four tests series, were performed considering regular and irregular waves. The hydrodynamic response of the hybrid device was fully characterised.

Concerning the interaction of the system with the wave field, the wave period was identified as the main parameter influencing the reflection and transmission coefficients – much more relevant than the turbine damping or wave height.  $K_R$  decreases when the wave period increases, a behaviour that is accentuated for irregular waves – note that this behaviour is coherent with that observed for previous versions of the hybrid device, as observed in [41], and other WECs (e.g., [52]). For regular waves,  $K_T$ , in general, increases with the wave period, while for irregular waves a more random behaviour is observed, and further investigation is needed to determine a clear pattern; however, most  $K_T$  values for irregular waves are grouped around 0.18. A reflection of between 5% and 66% of the incident wave power and a transmission of between 3% and 45% was observed. These values help understand the implications that the 'shadow effect' may have at a larger scale – at the wind farm scale or on the leeward coasts.

369 When looking at the device performance, the damping exerted by the turbine and the wave period  
370 stand out as the main factors determining the capture-width ratio. The influence on the selection a  
371 turbine that exerts the optimum damping OWC chamber highlights the importance of an optimum  
372 coupling between turbine and chamber during the design phase, as previously identified by several  
373 authors (e.g., [53]). Moreover, the wave period plays a significant role in the device performance; two  
374 resonant peaks were identified  $T = 9$  s and  $T = 6$  s). The first peak is linked to the resonance of the free  
375 surface motion in heave and the chamber itself, as is well known, in the literature (e.g., [54]). By  
376 contrast, the peak observed at the shorter wave period ( $T = 6$  s) is linked to a resonance effect induced  
377 by the sloshing of the inner free surface, and this sloshing was observed visually through the clear  
378 acrylic lid of the model at this frequency. Further research is needed to fully understand this effect;  
379 however, the authors believe that it may well be induced by the interaction between the diffracted  
380 waves from the inner monopile and the OWC chamber. For the wave conditions and damping values  
381 considered in this research, the highest damping coefficient ( $B^* = 68.9$ ) – i.e., the smallest orifice  
382 diameter size – generally, results in the highest values of the capture-width ratio. The capture-width  
383 ratio matrix shows two areas of maximum efficiency, which match the two resonant peaks across most  
384 of the wave heights.

385 From the analysis of the response of the free surface oscillation inside the chamber ( $RAO_C$ ) and the  
386 relative pneumatic pressure in the chamber ( $RAO_P$ ) – i.e., the two fundamental elements affecting the  
387 power output of an OWC – it is clear that both RAOs are mostly influenced by the turbine damping  
388 and wave period, not least  $RAO_P$  – when the damping coefficient increases,  $RAO_C$  decreases and  $RAO_P$   
389 increases. The maximum values of both RAOs are achieved simultaneously by turbine damping values  
390 corresponding to orifice apertures of 0.5% and 1.0% ( $B^* = 68.9$  and 46.0, respectively), which explains  
391 the better performance shown by these turbine damping values. In general,  $RAO_C$  increases when the  
392 wave period increases, while  $RAO_P$  shows a maximum for wave periods between  $T = 8$  s and  $T = 10$  s

and decreases for the remaining periods. It should be noted that this region of increased pressure matches the area of best performance of the hybrid device observed in the  $C_{WR}$  matrix (Figure 9).

Finally, the study of the run-up at the front of the model, by means of the run-up coefficient, shows a strong influence of the wave period on the wave run-up, which increases as the wave period decreases. An influence of the turbine damping over the run-up can also be observed, with the turbine damping corresponding to the 1.0% orifice size ( $B^* = 46.0$ ) leading to the largest run-up values. Furthermore, for regular waves the run-up ranges between 33% and 90% of the incident wave height. For irregular waves, while the significant run-up ranges between 41% and 92% of the incident wave height, similar values to those observed for regular waves the maximum run-up ranges between 83% and 251% of the incident wave height.

## 5. Conclusions

In this work, the University of Plymouth's hybrid wind-wave energy converter was further developed for installation in monopile substructures and thoroughly investigated through physical modelling. On the basis of the results from the experimental campaign, two main outcomes were obtained. First, the proposed hybrid system was successfully proved as valid concept to be considered for monopile substructures – the most common type of substructures for offshore wind turbines. Then, the hydrodynamic response of the WEC sub-system (OWC) was fully characterised, This lead to a better understanding not only in the relationship between OWC performance, the incident wave field and the turbine damping, but also in the interaction between device and the wave field itself.

Based on the analysis of the hydrodynamic response of the hybrid device, the following main conclusions may be drawn:

- The hybrid device interacts with the near wave field by reflecting between 5% and 66% of the incident wave power and transmitting between 3% and 45%.

- The best performance occurs with the turbine damping corresponding to the 0.5% orifice, followed closely by the 1.0% orifice.
- Two resonant peaks of best performance are found at  $T = 9$  s and  $T = 6$  s.
- A wider area of best performance is found between  $T = 8$  s and  $T = 11$  s.
- The RAO was used to understand the effect of the incident wave field on the two main parameters influencing the device power output – the relative pneumatic pressure between the chamber and the atmosphere, and the free surface oscillation inside the chamber.
- The RAO of free surface oscillation in the OWC chamber increases when the wave period increases.
- The relative pneumatic pressure between inside the OWC chamber and the atmosphere shows a peak of maximum  $RAO_P$  for wave periods between  $T = 8$  s and  $T = 10$  s, matching the area of best performance observed in the capture with matrix.
- The wave run-up is strongly influenced by the wave period; furthermore, the run-up of irregular waves being between 1 and 2 times larger than that of regular waves.

In sum, the wind-wave energy converter developed in this work represents a viable hybrid solution for integration with existing offshore wind turbines with a monopile substructure. This work contributes to understanding the interaction between the hybrid device and the near wave field, which is relevant in assessing the impact of this type of devices on the marine environment. Further work is required to develop this hybrid system, notably to ascertain the structural implications of the WEC sub-system on the substructure.

## Supplementary Materials

The research materials supporting this publication may be accessed at [\[link to the enclosed dataset will be added here in the final version of the manuscript after acceptance by the editorial team\]](#). If

439 you have any question regarding these research materials, please contact the corresponding author of  
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#### 447 **Author Contributions:**

448 All the authors conceived and designed the physical modelling; Carlos Perez-Collazo conducted the  
449 experimental campaign, analysed the data and wrote the paper; Richard Pemberton, Deborah Greaves  
450 and Gregorio Iglesias gave helpful comments and revised the paper; and all the authors have reviewed  
451 and approved this manuscript.

#### 452 **Appendix A**

453 Two statistical operators, the correlation coefficient ( $R^2$ ) and the normalised root mean square error  
454 ( $NRMSE$ ), are defined to evaluate results from the repeatability test Series RA and RB.

$$R^2 = \frac{(\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y}))^2}{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}, \quad (20)$$

455 where  $x_i$  and  $y_i$  are the equivalent data points from the two different data sets, of length  $N$ ; and  $\bar{x}$  and  
456  $\bar{y}$  are their respective arithmetic averages. This coefficient evaluates the relationship between two  
457 variables, giving an idea on how similar are the time series compared, being 1 when both series are  
458 identical.

$$NRMSE = \frac{1}{x_{max} - x_{min}} \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - y_i)^2}, \quad (21)$$

459 where  $x_{max}$  and  $x_{min}$  are the maximum and the minimum values of the data set used as reference.

460 **Figure captions**

461 **Figure 1:** University of Plymouth's hybrid wind-wave energy converter: (a) conceptual  
462 representation of the hybrid system for monopile offshore wind substructures; and (b) perspective  
463 view of the WEC sub-system; (partially reproduced from [47]).

464 **Figure 2:** 1:40 scale model of the hybrid device: (a) being tested at the University of Plymouth's  
465 COAST Laboratory and (b) a sketch showing front and side views of the model.

466 **Figure 3:** Horns Rev 3 significant wave height – energy period scatter diagram. The curves represent  
467 wave power isolines, and the numbers, hours in an average year of the corresponding energy bin.

468 **Figure 4:** Lateral view of the flume and schematic of the wave gauge layout.

469 **Figure 5:** Values of  $K_R$  and  $K_T$  for different damping coefficients ( $B^*$ ) and wave periods ( $T$ ), regular  
470 waves (Series A); (data in prototype values).

471 **Figure 6:** Values of  $K_R$  and  $K_T$  under random waves (Series B and C); (data in prototype values).

472 **Figure 7:** Capture width ratio ( $C_{WR}$ ) for different damping coefficient ( $B^*$ ) and wave period ( $T$ )  
473 values, and regular waves (Series A); (data in prototype values).

474 **Figure 8:** Capture width ratio ( $C_{WR}$ ) and irregular waves (Series B and C); (data in prototype values).

475 **Figure 9:** Matrices of the capture width ratio ( $C_{WR}$ ) for different values of the damping coefficient  
476 ( $B^*$ ) and regular waves (Series A), showing its variability in terms of the wave height ( $H$ ) and wave  
477 period ( $T$ ), (data in prototype values).

478 **Figure 10:** Matrices of the mean pneumatic power ( $P_m$ ) for different values of the damping  
479 coefficient ( $B^*$ ) and regular waves (Series A), showing its variability in terms of the wave height ( $H$ )  
480 and wave period ( $T$ ), (data in prototype values).

481 **Figure 11:**  $RAO_C$  and  $RAO_P$  versus non-dimensional wave number for various damping coefficients  
482 ( $B^*$ ) and wave periods ( $T$ ) (Series A) (data in prototype values).

483 **Figure 12:**  $RAO_C$  and  $RAO_P$  versus wave frequency for various damping coefficients ( $B^*$ ) and wave  
484 height ( $H$ ) (Series A) (data in prototype values).

485 **Figure 13:** Run-up coefficient ( $C_R$ ) for various damping coefficients ( $B^*$ ) and wave periods ( $T$ )

486 (Series A) (data in prototype values).

487 **Figure 13:** Significant and maximum run-up coefficients ( $C_S$  and  $C_{max}$ ) under random waves (Series

488 B and C) (data in prototype values).

489

490 **Table captions**

491 **Table 1:** Model characteristics and dimensions.

492 **Table 2:** Position of wave gauges and model.

493 **Table 3:** Wave conditions for Series A, regular waves (data in prototype values)

494 **Table 4:** Wave conditions for Series B and C, irregular waves (data in prototype values)

495 **Table 5:** Average values of  $R^2$  (correlation coeff.) and  $NRMSE$  (normalised root-mean-square error)

496 for the repeatability tests series

497

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