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Wave energy conversion energizing offshore aquaculture: Prospects along the Portuguese coastline

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ABSTRACT

This paper seeks to identify promising sites and technologies, in Portugal, for co-located wave energy conversion and offshore aquaculture, whilst providing benchmark implementation references and guidelines to researchers. Accordingly, two case study sites are considered for deployment of five wave energy devices and up to six aquaculture species. A thorough analysis in terms of power ratios, efficiency, redundancy, species viability, device survivability and costs is performed, seeking to find viable co-located solutions. It is found that the Wave Dragon device yields the most promising energy demand coverage and energy output (5 226 to 6 817 MWh/year). Nevertheless, it may require rescaling towards optimal operation, while the OCECO 4 excels in terms of capacity factor (0.24–0.29) and default adaptation to the deployment sites. The WaveRoller® has the lowest single-unit cost (125 €/MWh) but requires up to nine units to cover all the energy demand targets. Larger wave farms are required for the BBDB and AquaBuOY, albeit with potentially greater economies of scale and single-unit redundancy. These sites also enable cultivation of most of the considered species, even under ideal conditions. Lastly, it is recommended that the devices enter survivability mode at a significant wave height threshold of 5.5 m.

1. Introduction

Managing the water-food-energy nexus [1] is a complex problem of upmost importance. It is expected that the world's population will surpass 9 billion by 2050, which will require an increase of up to 50% in terms of global food production [2]. On the water front, overfishing has significantly depleted marine species (over explored fish stocks at 34.2% in 2017) [3], resulting in a stabilization of total marine catches at less than 85 million tons/year since the mid-2000s [4]. On the energy front, it is estimated that, as early as 2040, the total global energy supply will surpass 200 000 TWh/year. By comparison, in 2019, the energy supply nearly surpassed 170 000 TWh/year, with fossil fuels representing about 81% [5]. Consequently, greater efforts are required to bolster the shares of renewable energy sources (RES), including marine ones (MRES).

MRES comprise numerous sources, from offshore wind to wave energy. The latter has an estimated theoretical resource of about 32 000 TWh/year [6], surpassing the global electricity consumption by nearly 30% in 2019 [5]. Wave energy is a predictable resource and has a density greater than solar and offshore wind: 0.17 kW/m^2, 0.50 kW/m^2 and 2.00–3.00 kW/m^2 for solar, wind and wave energy (operational conditions), respectively [7,8]. Furthermore, wave energy is more persistent and less susceptible to intermittency occurrences. In contrast, there is an absence of design convergence within the wave energy sector, despite the wide variety of concepts [9]. This results in a lower maturity of wave energy converters (WECs), further exacerbated by the challenges inherent to the ocean environment, such as severe wave climate/wave loads, accessibility and biofouling [10]. There is also an absence of early-stage co-design of functional requirements [11] and significant competition from more mature alternatives. An integrated approach is required, ranging from WEC development [11] to deployment towards supplying niche markets, where competition and requirements are less demanding. WEC demonstration at this level would signal a pivotal milestone towards viable commercialization [12], with aquaculture as one of the most promising markets.

The conjugation of strict fishing quotas, depleted species and an increasing consumption creates a deficit being currently suppressed by aquaculture, which has surpassed fish and crustacean species capture [13]: about 125 million tonnes in 2020, including algae aquaculture [14]. By 2030, about 62% of all consumed seafood should derive from aquaculture farms, with increasing standards on fish growth,

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sustainability and welfare [15]. These are assured by feeding, monitoring, hatching/nursing, cage maintenance, medication and distribution [16]. Marine aquaculture is, currently, concentrated nearshore, with fish species being generally placed inside moored floating gravity cages, although fixed, submersible and submerged variants exist [17]. Shellfish tends to be produced in bottom (oyster and mussels) or suspended cultures (mussels, 85% representation) [8]. Even so, nearshore aquaculture faces numerous challenges, including exposure to harsh sea conditions, spatial competitions with other coastal uses (*e.g.*, tourism and shipping) and environmental impact (*e.g.*, water contamination from xenobiotics and eutrophication) [16,18]. Therefore, there has been increasing pressure towards developing offshore aquaculture farms. Despite the advantages, including the available area for harvesting expansion, greater volume for contaminant dilution, job creation, production of low-impact protein, higher oxygen levels and offshore cage design developments [19–23], the harsher sea environment presents a sizeable challenge, to which adds specific environmental and property rights risks [24]. Moreover, the greater distance from shore stunts accessibility for maintenance, feeding replenishment and energy supply to sensors and feeding equipment (*e.g.*, aeration, filtration, temperature, sterilization, feed, *ph* and dissolved O_2 monitoring units) [18]. On the latter, standard solutions include batteries and solar panels, although co-design with wind farms has been studied [25,26]. An energy consumption and efficiency overview is provided in Ref. [27] for recirculating aquaculture systems.

Given the potential of wave energy, WECs may be a suitable solution to meet the energy demands of offshore aquaculture [23,28], Fig. 1, whilst providing a demonstration niche market. Existing offshore aquaculture projects can require hundreds to thousands of kWh/day, since the equipment can range from sensors, battery packs and lights of a few dozen to hundred watts (inside aquaculture buoys) to multi kW generators for supporting vessels, crew and management operations [23, 29–32]. WEC farms can also provide an artificial shelter to aquaculture systems by absorbing part of the incoming wave energy and transforming it into useable electricity for the aforementioned aquaculture operations [33]. Even so, further studies and, most importantly, practical demonstrations of the shielding effect from WECs are required, as existing literature/references are limited.

This paper seeks to: *i)* summarize key trends and the status of promising WEC technologies and offshore aquaculture projects, *ii)* identify the most favorable co-locations of these two technologies for two deployment sites on the Portuguese coastline, *iii)* compare the converted wave energy with the energy demands for different offshore aquaculture farming scenarios and *iv)* provide readers with recommendations for implementing WECs towards supporting offshore aquaculture. This paper is structured as follows:

- Section 2 describes the main methodologies and criteria towards selecting the case study sites, WEC technologies and offshore aquaculture species;
- Section 3 develops on Section 2's datasets to assess the energy supply-demand coverage, efficiency and redundancy alongside species viability, economic estimates and survivability remarks. A summary table is provided with the recommended combinations for co-located wave energy and offshore aquaculture;
- Section 4 highlights the main conclusions and provides further recommendations for follow-up studies.

2. Methodological approach

2.1. Case study characterization

The continental coastline of Portugal - reference study region - extends for approximately 900 km, with an exclusive economic zone of 1 727 408 km^2. It exhibits a sizeable wave energy resource - 20 kW/m, Spring and Summer, to 50 kW/m, Autumn and Winter. The resource is prevailing in the northwest, but drops considerably in the south. This distribution depends on *i)* the coastline facing the Atlantic Ocean, being subjected to a highly energetic wave climate; and *ii)* the North Atlantic Oscillation (NAO) that promotes strong seasonal variability, attributed to an atmospheric mass oscillation between the Azores High (anticyclone) and the Iceland Low pressure systems [34].

Portugal has a strong fishing and consumption tradition: over 50 kg/year/capita of aquatic food products are consumed [14]. In 2018, Portugal produced 200 000 tonnes of fish, molluscs and crustaceans (610 million euros), but only 14% derived from aquaculture. Furthermore, Portugal is a net importer of fish products (imports/exports ratio of about 1.5) with approximately 35 000 people employed in the seafood sector [35], which demonstrates the potential importance of aquaculture growth.

For the co-location with offshore aquaculture, it is required to have information on the available resource and the local metocean and water characteristics. This implies access to wave energy resource matrices alongside maps detailing local temperature, *ph*, salinity, O_2 and nutrient concentrations, among others. Bathymetric restrictions are considered with regards to the operational depth range of the selected WECs, as proposed in Ref. [36].

Based on existing data from literature, including resource potential,

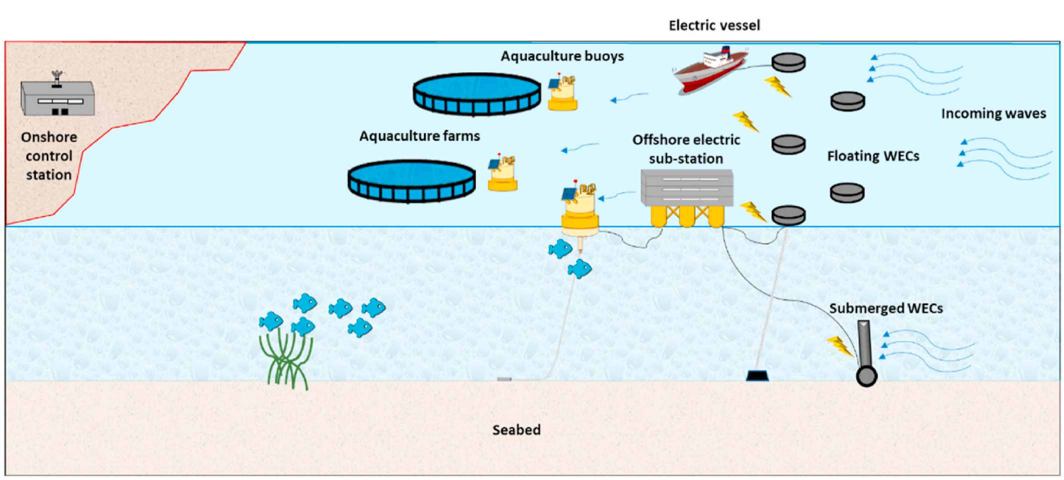

Fig. 1. Conceptualization of aquaculture facilities powered by WECs. The WECs attenuate the incoming waves whilst converting wave energy into electricity, which is sent directly to electric support vessels (supply station) or to an offshore sub-station and distributed to the aquaculture farms' equipment (*e.g.*, aquaculture buoys) via submerged cables.

two locations standout: Figueira da Foz and Sines, Fig. 2. The bathymetric profiles (50 m depth restriction applied) [36], omni-directional wave energy resource matrices (Figueira da Foz at 40.00° N, 9.32° W and Sines at 38.00° N, 9.30° W) [34] and physio-chemical conditions (Areas B and D) [37] were obtained from literature. The resource matrices derive, originally, from a hindcast model over an eleven year period (2005 through to 2015), which involved wave propagation modelling with SWAN [38]. The physio-chemical conditions originate from field surveys carried out in five sites along the Portuguese coastline, covering two different periods: 2018 and 2019. Mosqueira et al. [37] collected water samples along the water column (2–7 m depth), namely CTD (conductivity, temperature, depth) profiles, as well as information on nutrients, compost (*e.g.*, nitrates, ammonia and silicate) and chlorophyll *a* concentrations with the assistance of filters. Additional details are provided in Section 3.

2.2. Selection of wave energy devices

Considering the aforementioned bathymetric recommendations and available power matrices, the following WECs were considered in this study:

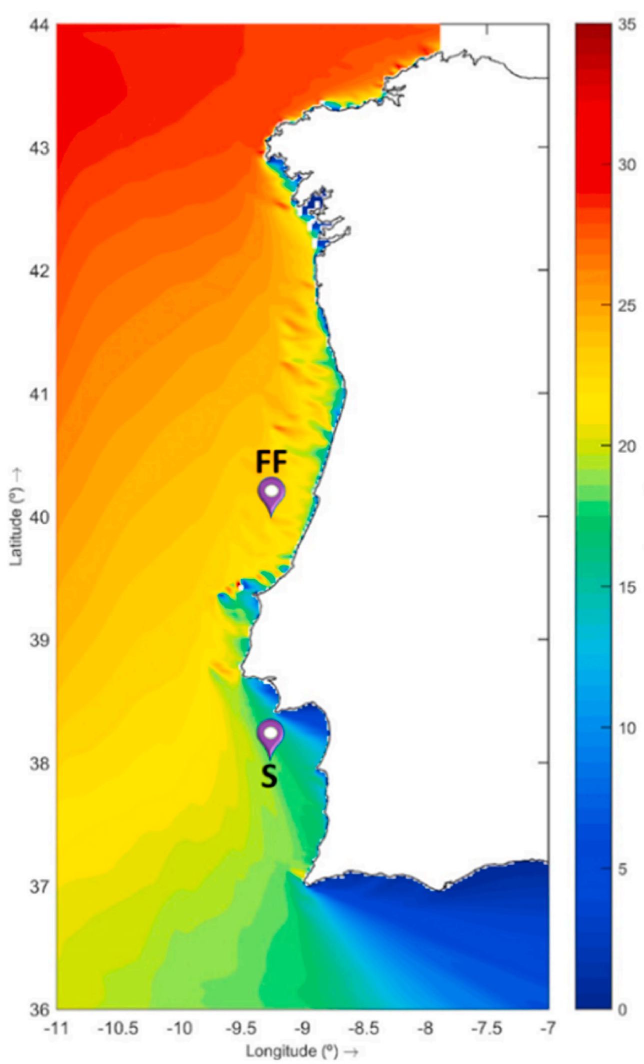

Fig. 2. Mean annual wave power distribution along the continental Portuguese coastline and location of the two case study sites: Figueira da Foz (FF) and Sines (S), adapted from Ref. [34]. Prevailing wave direction: NW.

- RM6 Backward Bent Duct Buoy (BBDB) [39]: oscillating water column principle (OWC) adapted to the offshore environment. It incorporates an L-shaped duct, an air chamber and auxiliary buoyancy modules. The Power Take-Off (PTO) unit is generally constituted of a generator and a low-pressure Wells air turbine. The BBDB operates by converting the air pressure differential, generated by the incoming waves within the air chamber, by means of airflow through the Wells turbine. As one of the most advanced types of WECs – OWCs [40] – and with its multi-frequency conversion efficiency, the BBDB presents itself as a suitable option. A 550 kW generator rating BBDB is considered in this study;
- OCECO [41]: the original CECO concept is a sloped motion WEC capable of converting the kinetic and potential energy of incoming waves into electricity via a rotary rack-pinion electric generator. Aside from a central supporting structure, there are two optimized lateral modules, which are coupled to a metal frame [42], that ensure buoyancy and enable translation along its inclined slope. An offshore version, the OCECO, has recently been proposed in Ref. [41], from which version 4 – tension leg platform with star-shape mooring system - yielded the best overall performance. This variant was considered in this study, assuming a 400 kW generator rating. The CECO and its offshore version have been developed based on the reference wave climates found along the Portuguese coastline [34];
- Wave Dragon (WD) [43]: the Wave Dragon consists of a doubly-curved ramp with a convergence point onto which waves run-up, making it a floating overtopping device. The water that overtops the ramp is accumulated within a rear reservoir, which is then allowed to drain back into the sea through a hydraulic circuit and low-head hydro turbines. As such, the Wave Dragon operates like a pseudo-floating hydroelectric dam, albeit its characteristic long reflector wings, which promote wave convergence and improve efficiency. Scalability, high rating (7 000 kW) and expected low operation and maintenance (O&M) costs further contribute to the Wave Dragon's selection [44];
- AquaBuOY (AB) [36]: this device was selected as a representative of point absorbers (PA), one of the most common types of WECs. It is constituted of a round buoy connected to a submerged shaft. The heave motions induced by the incoming waves rush the water upwards through the shaft and into an acceleration tube, which drives a piston to stretch a steel reinforced rubber hose. In turn, this pumps the water into a turbine and generator, which produce electricity. This is a modular and multipurpose device, as it can accommodate other systems (*e.g.*, small wind turbines and solar panels). It has been considered for one of the case study zones: Figueira da Foz. A 250 kW rating AquaBuOY device was selected for this study;
- WaveRoller® (WR) [45]: the WaveRoller® generally operates at relatively small depths, of similar order of magnitude as that considered in this study. Even so, it can be employed further away from the shoreline, albeit with lower accessibility and efficiency. This is attributed to the elliptic motion of water particles as they approach the shoreline (amplified horizontal amplitudes), since this is an oscillating wave surge converter. The main component - a partially/fully submerged panel, which spans the majority/entire water column – rotates back and forth in accordance to the elongated water particles' motion. The panel's motions drive a set of hydraulic pumps and pistons that generate electricity. Its hermetic design with a single moving part mitigates potential leaks and infiltrations, whilst incorporating a storage system to smoothen the power output. A 350 kW variant has already been successfully tested, at sea, near Peniche, Portugal [46], but a 1 000 kW version of the WaveRoller® is assumed in this study.

The respective power matrices can be found in the corresponding references listed above, alongside technical features, Fig. 3.

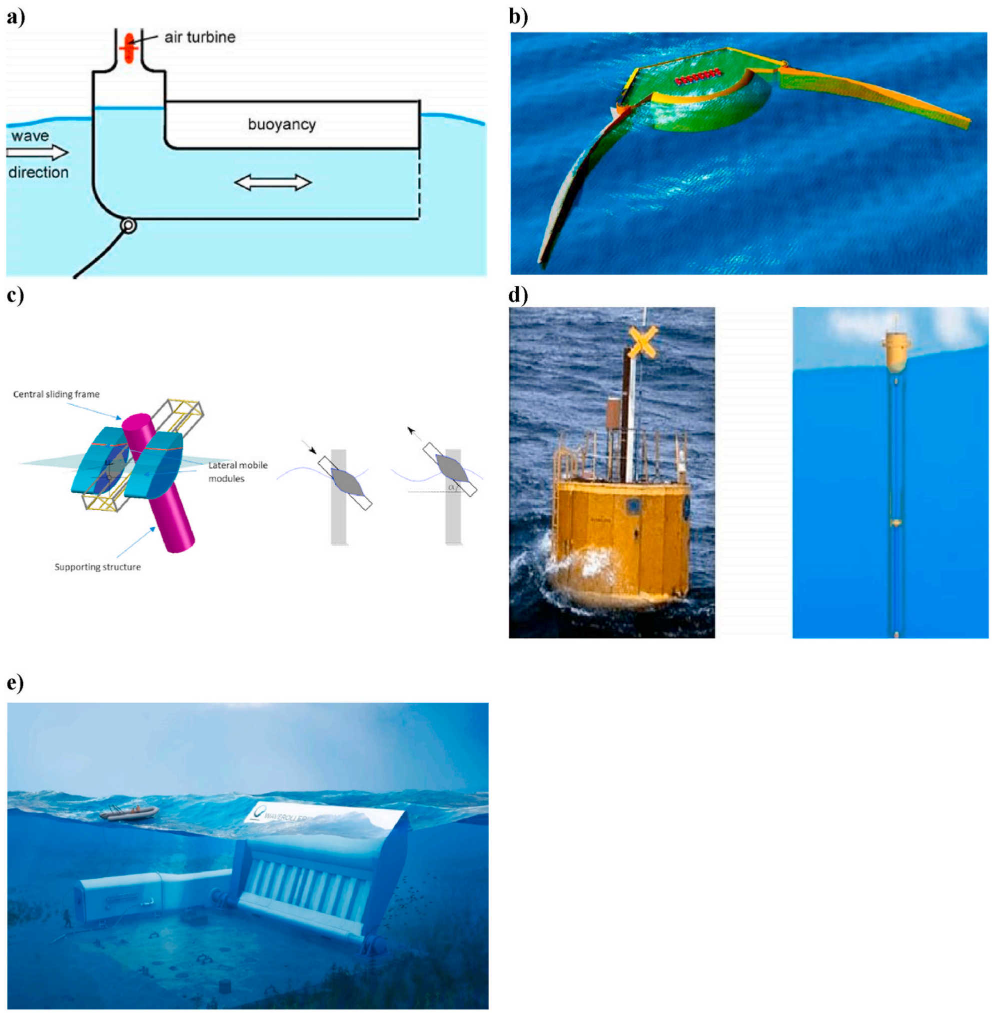

Fig. 3. Wave energy converter concepts: BBDB [9], Wave Dragon [36,47], OCECO [41], AquaBuOY [48] and WaveRoller® [49]. The respective reference widths are 27 m, 54 m, 22 m, 6 m and 18 m.

2.3. Offshore aquaculture: energy demand and species triage

A reliable selection of aquaculture species for offshore farming implies knowledge on numerous variables, as homeostasis/health, nutrition and safety of farmed species are pivotal for a viable exploration. To these adds energy demands of offshore aquaculture activities. A recent report [23] analyses the key findings from case studies around the world, including potential synergies with MRES. It is perceivable that the main explored species are finfish – salmon and seabass – and molluscs – oysters. Nevertheless, there are other noteworthy projects listed in that report, such as:

- Albatern and Marine Harvest Scotland: two WaveNET wave energy arrays (rated capacity of 7.5 kW–750 kW, total capacity above 10 MW) towards supporting offshore finfish aquaculture;
- MARIBE: deployment of the Wave Dragon (4 MW rating, 12 GWh/year) towards harnessing wave energy and creating a buffer/shielding zone, with attenuated waves, to provide suitable conditions for seaweed farming;
- SINN Power: deployment of SINN Power's PA (power capacity of 36 kW per 10 m^2 of installed area) towards supporting local prawn and shrimp farm operations;
- Carnegie Clean Energy: development and deployment of the MoorPower WEC (1.5 MW, inspired by the CETO 6), as an alternative to diesel engines in aquaculture feed barges;
- Penghu: Sharp Eagle WEC designed towards supplying electricity to offshore aquaculture, namely to the "Penghu" platform (60 kW wave energy plus 60 kW solar energy). Energy needs of 10 000–20 000 m^3 of offshore cages can be met by a 50–100 kW WEC device.

A summary of key case studies on the most explored species from which data on energy demand can be obtained is provided in Table 1.

In Portugal, aquaculture in transitional or marine waters is dominant, with a share of 94.7% and an estimated production of nearly 17

Table 1
Aquaculture farm sites and energy demand requirements around the globe [23]. The symbol (–) implies an absence of data.

Location (–)	Species (–)	Quantity/capacity (tonnes/yr)	Energy requirement		Installed power (kW)
			(kWh/day	kWh/tonne/yr)	
Australia	Finfish - Salmon	10 000	15 000	548	(–)
Chile		113 to 270	371	1198 to 502	100–250
Norway		3 120	700	82	(–)
Scotland		1 000	720	263	150
Singapore	Finfish - Seabass	166	9 416	20 704	(–)
USA	Molluscs - Oyster	(–)	1 019	(–)	(–)

000 tonnes (2020 values). Extensive farming accounts for 60.8% of transitional and marine waters aquaculture production. Floating systems only account for 1.9% of existing establishments, as nurseries hold an 89.0% share. Fish (mainly turbot, gilthead seabrim and seabass) represented 36.7% of the total aquaculture production, including interior waters, while molluscs (mostly oysters, clams and mussel) accounted for 58.0% [50]. Salmon is another relevant fish species, and was considered alongside seabass and oyster species (see Fig. 4), if feasible, for aquaculture farming.

The data summarized in this section will be processed and compared in Section 3, namely in terms of the energy supply-demand chain, efficiency, cost and redundancy. This will be complemented by a species analysis, based on the local ocean conditions and properties (particularly temperature) for the case study sites, alongside complementary remarks.

3. Results and discussion

The following results and discussion incorporate the input data from the previous section, in accordance to the methodology presented in Fig. 5. Several quantities are defined, namely the annual energy production (AEP), the capture width ratio (CWR), the capacity factor (CF) and the coverage ratio (CR). These will be defined and estimated in the next subsections.

3.1. Wave energy output and efficiency

Firstly, the AEP is computed based on the bivariate distribution - significant wave height, H_s, and peak (or energy) wave period, T_p (or T_e) - of the power and resource matrices. It is assumed that the local sea-states follow a JONSWAP spectrum profile with a peak enhancement factor of 3.3, resulting in the wave resource matrices found in Ref. [34]. Complementary, five condensed WEC power matrices are required to ensure a correspondence with the resource matrices (see Appendix A). This was achieved through an interpolation approach [40] between values of the original power matrices (except for the OCECO, whose matrix was already compatible) whilst considering the operational range for each WEC. The bathymetric restriction remained valid.

Aside from the average generated power values, $\overline{P}_i$, for each sea-state i and each device, the AEP also requires knowledge of the corresponding number of occurrence hours, h_i, assuming a total of SS sea-states [40]. For simplification, generator efficiency is not considered here, as it will be dependent on the selected generator and the wave-to-wire conversion chain. Therefore, the AEP can be obtained through:

$$AEP = \sum_{i=1}^{SS} h_i \overline{P}_i \qquad [1]$$

Considering the risks inherent to high energy wave climates, such as those found in the Portuguese coastline facing the Atlantic Ocean, it is prudent to assume unavailability scenarios. In other words, for sea-states with a H_s surpassing a given threshold, it is expected that the device enters survival mode and is not operating regularly (not producing energy). By considering the distributions found in the power and resource matrices and the definition of "storm" conditions for the Portuguese West coast (usually $H_s > 5$ m [51,52]), three scenarios are considered: *i)* $H_s = 5.5$ m, *ii)* $H_s = 6.5$ m and *iii)* $H_s = 7.5$ m, Table 2 and Table 3. This is adapted from the approach in Ref. [53] and concerns the "lightest storm" condition and the highest H_s for which there is a statistically significant hourly record in the resource matrix, with an intermediate scenario of evenly spaced H_s.

The AEP is virtually unaltered with the increasing H_s threshold. On the one hand, the high energy density inherent to the threshold sea-states is overruled by the very low frequency of occurrence, which is in agreement with the resource matrices' energy distribution. Furthermore, the AquaBuOY does not have power output data beyond 5.5 m, as does not the WaveRoller® for more than 6.0 m. Therefore, out of safety, it is recommendable that the WECs cease standard operation for the lowest H_s threshold of 5.5 m, given the negligible energy gain beyond it and, more importantly, the default operational ranges from the power matrices.

The energy generated in the FF location surpasses that of the S case, which is also in agreement with the resource matrix distribution. The theoretical wave energy resource greater for FF, particularly on the sea-states that overlap the highest corresponding values from the WECs' power matrices. The WD outperforms the other devices significantly in terms of single-device AEP, by more than one order of magnitude, while the AB yields the lowest AEP estimates, as a result of the corresponding power matrices' values for each sea-state. Even so, despite the importance of raw power output, efficiency should also be taken into account, as it can affect the long-term performance of a WEC. To that end, two metrics are computed: the capacity factor (CF) and the capture width ratio (CWR). By assuming a standard year of 8 760 h and the rated capacities (RC) of each device, as listed in Section 2, these metrics can be computed as:

$$CF = \frac{AEP}{8760RC} \qquad [2]$$

$$CWR_i = \frac{\overline{P}_i}{\overline{P}_{w,i}L}100 \qquad [3]$$

where $\overline{P}_w$ is the average wave power resource per metre of wave crest, inherent to a specific sea-state i, and L the characteristic width of each WEC, as specified in Fig. 3.

The CF is calculated from the entire matrices, Table 4, as it is dependent on the AEP, while the CWR is obtained for each sea-state, Fig. 6, for a better understanding of the individual conversion efficiency. This enables a more thorough assessment of each WEC's efficiency, from both a general and particular perspectives.

The efficiency follows a somewhat different trend than that observed for the AEP, namely with regards to the CF. Though the capacity factors are also slightly greater for FF, it is the OCECO that displays the highest CFs of 0.29 to 0.24. The other devices' CFs are equal to or below 0.11. This holds true even for the Wave Dragon, which hints at a potential oversizing of its rated capacity. In the long-term, this may be detrimental to its performance, as the corresponding generator units will likely operate far from their optimal points, in the respective efficiency curves, over long periods of time. Overall, adapted variants, from WEC scale and operational range to generator rating, may be recommendable for the

a) b) c)

Fig. 4. Atlantic salmon, European seabass and oyster specimens.

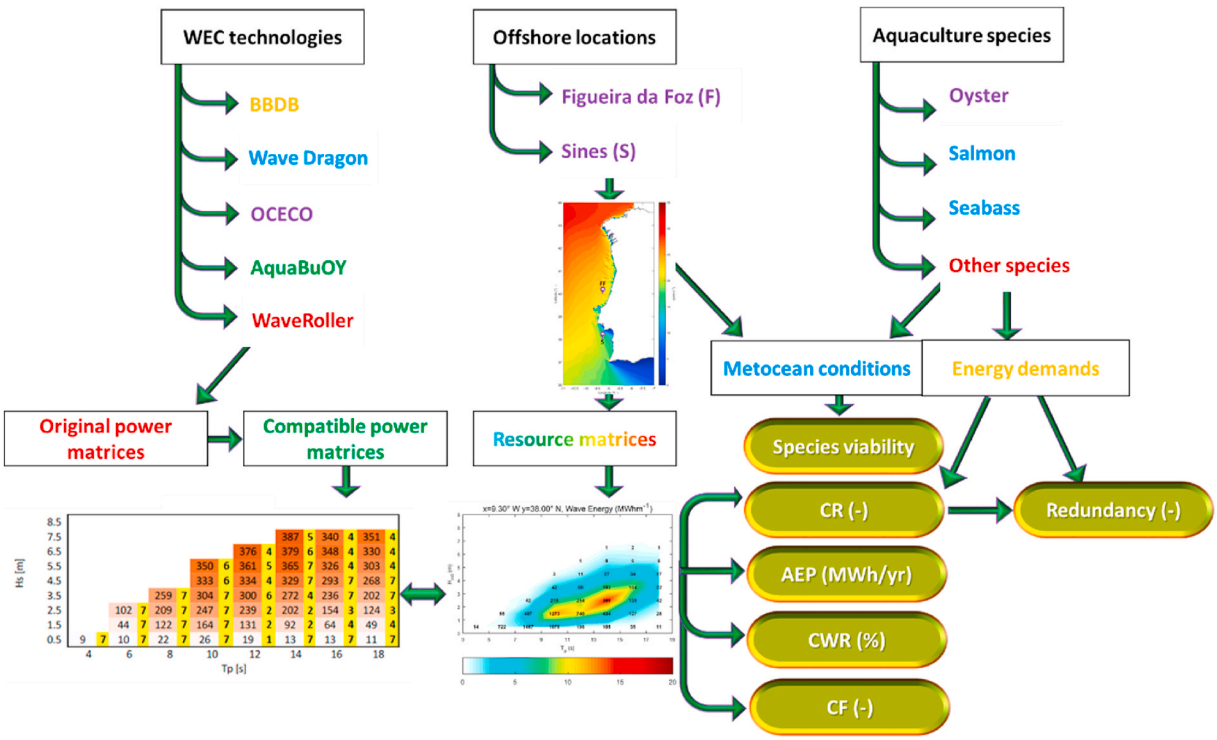

Fig. 5. Methodology schematic, with regards to the bi-variate wave energy resource and power matrices *versus* the offshore aquaculture energy demands. The "◀■▶" symbol represents different operations between the matrices, including multiplication.

Table 2
Estimated AEP for each WEC technology under different "storm" threshold scenarios: Figueira da Foz.

AEP (MWh/yr)	H_s threshold (m)		
WEC technology	*5.5*	*6.5*	*7.5*
OCECO	1 002	1 005	1 005
WD	6 817	6 866	6 866
AB	206	206	206
BBDB	323	325	326
WR	813	813	813

Table 3
Estimated AEP for each WEC technology under different "storm" threshold scenarios: Sines.

AEP (MWh/yr)	H_s threshold (m)		
WEC technology	*5.5*	*6.5*	*7.5*
OCECO	838	839	839
WD	5 226	5 245	5 245
AB	156	156	156
BBDB	256	257	257
WR	624	624	624

Table 4
Estimated CF for each device and for each case study location.

CF (–)	Case study location	
WEC technology	*FF*	*S*
OCECO	0.29	0.24
WD	0.11	0.09
AB	0.09	0.07
BBDB	0.07	0.05
WR	0.09	0.07

two sites, although a definitive technological solution requires information and a multi-criteria analysis beyond the scope of this paper.

With regards to the CWR values, the sea-states with higher $H_s - T_p$ exhibit lower ratios, given the increasing wave energy resource and the limits imposed by each device's rating. Although some values seem excessive, as they surpass 100%, such magnitudes have been reported in literature [40] under specific conditions, particularly for relatively low values of $H_s - T_p$. Furthermore, the definition of each device's characteristic length may be limiting. The Wave Dragon, for instance, has extensive concentric arms whose total size, alongside the central reservoirs area of the WD, exceeds the reference dimension – total width of 260 m [54] to 300 m [55], from literature. For the CWR, this would imply a reduction of the maximum values to a range between 31% and 27%, respectively. The mode of operation can also influence these results. For instance, the Wave Dragon operates via water accumulation and wave overtopping, while the OCECO can harness energy from sloped sliding motions. Resonance can also contribute to the higher CWRs. Returning to the individual analysis, it is perceivable, as well, that the OCECO is particularly suitable for relatively low-energy sea-states alongside the BBDB, while the WD and AB seem more adequate for intermediate sea-states. In fact, the OCECO has been developed specifically for the wave climate inherent to the Portuguese coastline. The WaveRoller®, being a submerged device, yields capture width ratios of similar magnitude over the different wave conditions, although some variation is perceivable.

3.2. Coverage and redundancy of offshore aquaculture energy demand

To assess each WEC's energy demand coverage, the scenarios from Table 1 are considered as a reference for potential deployment at the FF and S sites. To that end, a single WEC unit is considered, being its AEP matched against the energy demands of each aquaculture scenario for the two case study locations. It is assumed that the inherent reference demands are similar to those expected for these sites, although this must be corroborated in future studies. Should a single device be insufficient

OCECO

H_s (m)								
7.5	0	0	0	0	0	0	4	4
6.5	0	0	0	0	0	7	5	5
5.5	0	0	0	0	10	9	7	6
4.5	0	0	0	17	14	12	9	8
3.5	0	0	0	26	21	16	13	10
2.5	0	0	43	41	33	24	16	11
1.5	0	34	70	76	50	30	18	13
0.5	93	69	114	108	66	39	34	25
CWR (%)	4	6	8	10	12	14	16	18

T_p (s)

Wave Dragon

H_s (m)								
7.5	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	50	37	0
5.5	0	0	0	0	82	65	40	0
4.5	0	0	0	107	107	75	45	0
3.5	0	0	0	118	114	74	49	0
2.5	0	0	112	129	107	74	48	0
1.5	0	149	148	146	121	83	55	0
0.5	0	0	0	0	0	0	0	0
CWR (%)	4	6	8	10	12	14	16	18

T_p (s)

AquaBuOY

H_s (m)								
7.5	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0
5.5	0	0	0	0	26	15	14	0
4.5	0	0	0	45	27	15	14	0
3.5	0	0	0	45	27	16	14	0
2.5	0	0	53	44	27	16	14	0
1.5	0	37	53	44	27	15	13	0
0.5	0	0	0	0	0	0	0	0
CWR (%)	4	6	8	10	12	14	16	18

T_p (s)

BBDB

H_s (m)								
7.5	0	0	0	0	0	0	4	0
6.5	0	0	0	0	0	6	4	0
5.5	0	0	0	0	9	6	4	0
4.5	0	0	0	12	9	6	4	0
3.5	0	0	0	12	9	6	4	0
2.5	0	0	17	12	9	6	4	0
1.5	0	21	18	13	10	7	4	0
0.5	0	33	30	21	16	11	6	0
CWR (%)	4	6	8	10	12	14	16	18

T_p (s)

WaveRoller

H_s (m)								
7.5	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0
5.5	0	0	0	0	33	28	0	0
4.5	0	0	0	49	39	32	0	0
3.5	0	0	0	60	52	44	0	0
2.5	0	0	51	46	42	44	0	0
1.5	0	47	53	42	35	40	0	0
0.5	0	0	0	0	0	0	0	0
CWR (%)	4	6	8	10	12	14	16	18

T_p (s)

Fig. 6. CWRs per sea-state for each WEC device. The coloring grades are inherent to each matrix.

to meet the demand, the minimum number of units is displayed, in brackets, alongside a red coverage ratio between 0 and 1. If a single unit suffices, a green CR value above 1 is introduced. The CR is defined as the ratio between the case study annual energy demand (AED) and the AEP of a given WEC:

$$CR = \frac{AED}{AEP} \quad [4]$$

The results are summarized in Table 5.

While a single WD is capable of meeting all of the scenarios' demands (CR between 1.25 and 50.70), except for the Australia Salmon in Sines (CR of 0.96, given the lower wave energy density), both the OCECO and the WR need significantly more units for this scenario and that of the Singapore Seabass, in both FF and S (CRs between 0.11 and 0.29). The AB is only capable of fully meeting the Chile Salmon scenario with a single unit (CR between 1.15 and 1.52, above 1.00), while for other scenarios up thirty-six units are required (CR as low as 0.03). The RM6 BBDB can meet additional scenarios (CR very close to 1 in S for two case studies), but it also requires many units for a full coverage (up to 22 units, in Sines). As such, one to two Wave Dragon units are sufficient to meet the all the annual demands, while the OCECO 4 and the WaveRoller® require a small wave farm of less than ten units. Larger WEC farms are required for the BBDB and, even more so, the AquaBuOY.

A greater number of units enables higher system redundancy and economies of scale, but may imply excess energy generation for some technologies, and a greater initial investment. Considering the WD, one to two backup units would enable a 100% extra coverage in case of a multi-unit failure. Energy storage systems and/or downscaled WD units may prove more suitable to the FF and S locations, alternatively. For the OCECO and WR, a similar number of backup units may also be sufficient for most failure occurrences. Even without them, should only a small number of devices (or even single-unit failure) fail and assuming the minimum number of installed units, the OCECO farm would retain 85.7%–75.0% of its conversion capability, while the WaveRoller® farm would temporarily lose between 11.1% and 20.0% of its capacity. By contrast, a single-unit failure for the Wave Dragon could imply either a 50% drop in energy output or a full stop during maintenance/replacement operations. These outcomes are further exacerbated for the AquaBuOY and the RM6 BBDB, where a single-unit failure would have a somewhat negligible effect on larger wave farms (loss of less than 5% in Sines for the Australia Salmon case, for instance). In contrast, additional backup units (more than one or two) may be required to ensure a satisfactory degree of multi-unit failure redundancy for the AB and BBDB, particularly for the 10k ton/year Salmon and 0.17k ton/year Seabass scenarios.

The coverage assessment can be extended to the other projects from Ref. [23]. For instance, a comparison can be established between the rated capacities and the power requirements, whenever data on the yearly energy demand is absent. This is summarized in Table 6, from which one can see a similar pattern as that found in the previous case studies. The WD requires very few units to meet the installed power requirements (fixed for both sites), given its sizeable rating capacity. For the SINN Power project, one WD can cover nearly 2 000 m^2, while other WECs can support, at best, an area one order of magnitude smaller. The OCECO falls short with regards to the WR and the BBDB, since their respective ratings are higher. The only exception is the MARIBE project, where the yearly energy demand metric is more favorable to the OCECO: 12–15 units, in comparison to 15–20 and 37–47 of the WR and BBDB, respectively. Neither the power requirements or the energy demand are favorable to the AB, taking into account its power matrix and lower rated capacity. Overall, a few WD can meet all of the scenarios' requirements, albeit with the risk of lower long-term efficiency if the scale/rating is not adjusted. Small-to-medium size farms of WRs, OCECOs and BBDBs would also meet the installed power and energy demands whilst ensuring a significant conversion capability in case of single-unit failure, unlike the WD, and enabling economies of scale. This is exacerbated for the AB, as it requires a rather large farm by comparison, but it may imply significant initial costs and greater need of backup units in case of multi-unit failure.

Albatern and Penghu both focus on finfish production, yet one requires a significant installed capacity of 10 MW while the other specifies the rating of each WEC unit, which is met by all the considered devices in this study. The MARIBE case resorted to a Wave Dragon solution to both meet the energy requirements and shield a seaweed farm from wave action for depths above 30 m, as considered in this study. A small farm of OCECO or WaveRoller® units, however, can also satisfy the demand, and both have been studied within the Portuguese coastline context. There is also great interest in expanding the farmed species beyond the previous species of salmon, seabass and oyster. For instance, shrimp and prawn (SINN Power project) are considered delicacies in Portugal, capable of reaching high retail value. Some seaweed species (MARIBE project) can also be cultivated for consumption, cosmetics or towards bioremediation and medicine. They can also be grown, in a controlled manner, to promote water nitrogen removal, carbon capture/fixation and assist in combating anthropogenic climate change [56], as a

Table 5
Coverage ratios and minimum required units (in brackets) for each offshore aquaculture scenario: a) Figueira da Foz and b) Sines.

a)

	Case Studies	Salmon				Seabass	Oyster
	Power needs (GWh/yr)	10.00k ton/yr	0.27k ton/yr	3.12k ton/yr	1.00k ton/yr	0.17k ton/yr	0.17k ton/yr
		5.48	0.14	0.26	0.26	3.44	0.37
CR and minimum required units (brackets)	OCECO4	0.18 (6)	7.42	3.93	3.83	0.29 (4)	2.70
	Wave Dragon	1.25	50.70	26.87	26.13	2.00	18.47
	AquaBuOY	0.04 (27)	1.52	0.81 (2)	0.79 (2)	0.06 (17)	0.55 (2)
	BBDB	0.06 (17)	2.41	1.27	1.24	0.09 (11)	0.88 (2)
	WaveRoller®	0.15 (7)	6.00	3.18	3.09	0.24 (5)	2.19

b)

	Case Studies	Salmon				Seabass	Oyster
	Power needs (GWh/yr)	10.00k ton/yr	0.27k ton/yr	3.12k ton/yr	1.00k ton/yr	0.17k ton/yr	0.17k ton/yr
		5.48	0.14	0.26	0.26	3.44	0.37
CR and minimum required units (brackets)	OCECO4	0.15 (7)	6.20	3.28	3.19	0.24 (5)	2.26
	Wave Dragon	0.96 (2)	38.73	20.53	19.96	1.53	14.11
	AquaBuOY	0.03 (36)	1.15	0.61 (2)	0.59 (2)	0.05 (23)	0.42 (3)
	BBDB	0.05 (22)	1.90	1.01	0.98 (2)	0.07 (14)	0.69 (2)
	WaveRoller®	0.11 (9)	4.61	2.44	2.37	0.18 (6)	1.68

Table 6
Project coverage from each WEC wave farm. The minimum number of units and covered square metres per WEC unit (SINN Power project only) are split as: FF – S.

Project/WEC	OCECO	WD	AB	BBDB	WR
Albatern and Marine Harvest Scotland (10 MW)	25–25	2–2	40–40	19–19	10–10
MARIBE (12 GWh/yr)	12–15	2–3	59–77	37–47	15–20
SINN Power (3.6 kW/m^2)	111–111	1 944–1 944	69–69	153–153	278–278
Carnegie Clean Energy (1.5 MW)	4–4	1–1	6–6	3–3	2–2
Penghu (60 kW/unit)	1–1	1–1	1–1	1–1	1–1

nature-based solution. Furthermore, seaweeds are at a lower trophic level than oysters and, even more so, salmon and seabass. The latter two require noteworthy rations composed of other fish species, which implies less sustainable fishing and processing activities.

3.3. Species viability

Based on the field surveys and literature review found in Ref. [37], Table 7 summarizes the main metocean limits and compound concentration tolerances for the salmon, seabass and oyster species. For Areas B and D, corresponding to the Figueira da Foz and Sines sites, respectively, the local metocean conditions and nutrient concentrations are presented in Table 8. As a side note, parameters such as pH, dissolved O_2 and salinity concentration were found to be within the limits tolerated by these species. Furthermore, the average temperature T from Table 8 refers to the monthly average values of each year.

By comparing Tables 7 and 8, and in accordance to Ref. [37], one can conclude that:

- Atlantic Salmon: while the two nutrient concentrations are below the threshold tolerances of this species in both sites, the maximum average T values are surpassed in Sines (above 18 °C). In Figueira da Foz, and particularly in 2019, the temperature values are not only within the maximum and minimum tolerances, but also within the ideal T range, making it a suitable location for Salmon farming;
- European Seabass: once more, the nutrient concentrations are below the tolerated limits by the species in both sites and years. As such, the tie-breaker parameter is, again, the temperature. The seabass has a higher temperature range than the salmon, which enables its production in either FF or S. Given the ideal temperature range, Sines may present itself as a better alternative to FF;
- Oyster: alike the seabass, the higher temperature tolerances of this species enables its farming in both sites without reaching the lower or upper thresholds. Once again, Sines' higher average temperatures overlap the ideal T for oyster farming better than in Figueira da Foz. In terms of nutrient concentration, both ammonia and nitrites are below the specie's limits, while the chlorophyll *a* concentration is adequate for producing oysters in FF and S.

While in the aforementioned study there is no indication on shrimp and prawn production, some macroalgae (or seaweed) species can be recommended for the areas corresponding to the Figueira da Foz and Sines sites, Fig. 7. Currently, macroalgae production in Portugal is virtually non-existent [37]. From a species viability perspective, the main restricting factors are temperature, as well as nitrate and phosphate concentrations (beneficial in this case, as they promote faster growth), since other parameters are within the tolerated limits by the considered species. In accordance to Ref. [37], the recommendations are:

- Gracilaria (*Gracilaria gracilis*): this macroalgae is commonly found at a depth of 2–20 m, preferably on rocky steep slopes. It can withstand a wide range of salinities and is commonly cultivated to produce agar [57]. Although it can develop along most of the Portuguese coastline, this group of red algae would be particularly suitable for site S (18 °C to 23 °C, with tolerances between 10 °C and 28 °C). The nutrient concentrations of nitrate and phosphate are 0.55 ± 0.57 µmol/L (2018) to 0.75 ± 0.92 µmol/L (2019) and below 0.20 µmol/L (2018 and 2019), respectively and for Sines. As for Figueira da Foz, the NO_3 and PO_4 values are 0.53 ± 0.51 µmol/L (2018) to 0.77 ± 0.55 µmol/L (2019) and always 0.21 ± 0.14 µmol/L (2018) to less than 0.20 µmol/L (2019), correspondingly. This slightly favours the Sines location, overall;
- Atlantic Nori (*Porphyra umbilicalis*): this red macroalgae usually inhabits cold (3 °C to 20 °C) and shallow waters, but it can provide a very cost-effective solution given its significant growth rate [37]. With an ideal temperature range between 10 °C and 15 °C, site FF seems as a more reliable solution, although the nutrient concentrations should also be accounted for. Fast growth, for instance, is enabled for phosphate and nitrate concentrations of 19.5 µmol/L and 35.0 µmol/L, respectively;
- Wakame (*Undaria pinnatifida*): this group of seaweeds has the highest protein level – 24% - of brown macroalgae [58], making it an appealing source of aquatic protein for consumption. Their minimum-maximum temperature range is 5 °C to 25 °C, but the ideal T range is 12 °C to 15 °C, which encompasses better with the Figueira da Foz range, albeit both sites seem viable. Wakame can generally grow down to 20 m of water depth, so long as the surface is hard enough to attach, which is in agreement with the bathymetry considerations in this study (as are the other macroalgae).

Table 7
Metocean tolerances and optimal conditions for aquaculture species, adapted from Ref. [37].

Conditions *Species*	Temperature (°C) Min/Ideal/Max	Ammonia NH_3 (µmol/L)	Nitrite NO_2 (µmol/L)	Phytoplankton Concentration
Atlantic Salmon (*Salmo salar*)	0-7//22-28[1] 14/12–18/18 8//12[2]	Lc50-5.34[3] >2.06 (slow growth)	Smolt >74 (slow growth)	(–)
European Seabass (*Dicentrarchus labrax*)	2-5/20–25/28-32 11-15/20–22/26-32[4]	Lc50–99.8	Lc50-1035	(–)
Oyster (*Magallana gigas*)	8-10/18–20/32	(–)	(–)	25 cells/h/larvae (fast growth)
Notes:	Parr + smolt;[2] Post-smolt;[3] Lc50 – Lethal concentration that leads to a 50% mortality in test individuals;[4] Larvae			

Table 8
Local metocean conditions and compound concentrations from sites FF and S, adapted from Ref. [37]. Values obtained from field surveys during 2018 and 2019, at surface level (up to 1 m for T and 2–7 m water depth for the other parameters).

Conditions *Sites*	Average T (°C) Min - Max	Ammonia NH_3 (µmol/L)	Nitrite NO_2 (µmol/L)	Phytoplankton Chlorophyll *a* (µg/L)
Figueira da Foz (*Area B*)	~12.8–18.0 (2018) ~13.0–17.5 (2019)	<1.00	<0.10	0.94 ± 0.66 (2018) 1.26 ± 1.23 (2019)
Sines (*Area D*)	~13.7–18.5 (2018) ~13.8–18.6 (2019)	<1.00	<0.10	0.62 ± 0.49 (201) 1.35 ± 1.08 (2019)

3.4. Complementary remarks and recommendations

From an economic perspective, a standard metric is employed for comparing RES, including MRES: the Levelized Cost of Energy (LCoE), which takes into account the present value of capital (CAPEX) and operational (OPEX) expenditures, as well as that of the AEP. The present value is accounted for by introducing a discount rate, r, and assuming a WEC life-cycle of n years, starting at reference year t. The LCoE is calculated as:

Fig. 7. Gracilaria, Atlantic Nori and Wakame macroalgae specimens.

$$LCoE = \frac{CAPEX + \sum_{t=1}^{n} \frac{OPEX_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{AEP_t}{(1+r)^t}} \quad [5]$$

Estimates on the LCoE for each of the five WECs considered in this study required literature research and, when necessary, conversion of the original cost estimates to the two case studies of FF and S, Table 9. Even so, the following LCoE values are merely indicative, and should mainly be considered in terms of order of magnitude. This is justified, since the final costs will vary depending on several factors that cannot be fully accounted for, at this stage. For the Wave Dragon and the AquaBuOY, it was feasible to directly obtain the estimates, as the two sites are found within the study area from Ref. [36]. The corresponding magnitude values are 300 €/MWh and 3 000 €/MWh. As for the OCECO, the LCoE was obtained by assuming the same expenditures from Ref. [59], but updating the AEP (original 1.35 GWh/yr) with regards to the Figueira da Foz and Sines sites, resulting in an updated LCoE magnitude of 500 €/MWh (average between 450 €/MWh – FF - and 550 €/MWh – S). A similar approach was employed for the BBDB, based on the original LCoE (local site average resource of 276 MWh/yr) from Ref. [60], which resulted in an average LCoE magnitude of 625 €/MWh (550 €/MWh to 700 €/MWh, for the FF and S sites). Lastly, the WaveRoller®'s cost of energy estimate was indirectly taken from Ref. [61], based on direct feedback from the manufacturer – AW Energy Oy – and the wave energy resource from the original case study site at Peniche (local site average resource of 140 MWh/yr) [62]. As such, the WR's LCoE magnitude was estimated at 125 €/MWh (mean value between 100 €/MWh – FF - and 150 €/MWh – S).

From these results, the WR and WD seem to be the most economically interesting solutions, with a LCoE of 125 €/MWh to 350 €/MWh. The WR also surpasses the OCECO, which has a higher LCoE and potentially smaller economy of scale gains due to the slightly lower number of required units. The BBDB has an even higher LCoE but may benefit more from economies of scale. In fact, the aforementioned reference points to a cost reduction of nearly 66% going from an array composed of 1 unit–100 units. The WD, by contrast, requires so few units to meet the scenarios that potential cost reductions from a larger wave farm are very limited. The AquaBuOY exhibits very high maximum costs by comparison with all the other WECs and despite the greater number of required units.

To summarize all these results, a compilation and set of recommendations is provided in Table 10. It also features additional notes on

Table 9
LCoE magnitude summary for each device, per site, and references.

	LCoE Magnitude (€/MWh)	References
OCECO 4	500	[59]
Wave Dragon	350	[36]
AquaBuOY	3 000	[36]
BBDB	625	[60]
WaveRoller®	125	[61,62]

Table 10
Offshore aquaculture species and WEC selection recommendations for the FF and S sites.

	Sites	
	Figueira da Foz (FF)	Sines (S)
WEC (LCoE)	WR (1°) – WD (2°) – OCECO 4 (3°)	
WEC (AEP and CR)	WD (1°) – OCECO 4 (2°) – WR (3°)	
WEC (CF)	OCECO 4 (1°) – WD (2°) – WR and AB (3°)	
Offshore aquaculture species	Atlantic Salmon, European Seabass, Oyster, Gracilaria, Atlantic Nori (ideal) and Wakame (ideal)	European Seabass (ideal), Oyster (ideal), Gracilaria (ideal) and Wakame
Average annual wave energy	159 MWh/yr	118 MWh/yr,
Maximum currents	0.50 m/s (SSW direction)	0.36 m/s (NNW-SSE direction)
Survivability conditionings (H_s threshold)	5.5 m ("storm" from >5.0 m)	
Redundancy (single-unit failure)	AB (1°) – RM6 BBDB (2°) – WR (3°)	
Redundancy (multi-unit failure)	WD (1°) – OCECO 4 (2°) – WR (3°)	
Main benefits	Co-location and equipment sharing, renewable energy on site, aquaculture autonomy and shielding from waves through WECs	
Main challenges	Compatibility, survivability, energy cost competitiveness, technology maturity, real-time demand coverage, final location uncertainty	

survivability, since the FF site is prone to a more energetic sea-states (more severe wave climate) and stronger currents [37]. In general, both sites provide interesting opportunities for offshore aquaculture. FF provides greater wave energy resource, albeit with more challenging wave conditions and currents for survivability, and can accommodate a wider range of offshore aquaculture species. Sines has a lower annual wave energy resource, larger range of current direction and can accommodate less species, but provides improved conditions for three of them (up from two, in FF). Since little energy can be absorbed above 5.5 m of significant wave height, it would be beneficial for the selected WECs to cease operation upwards from this threshold, in order to minimize potential damage from extreme wave conditions. In terms of technology, both sites demonstrate similar outcomes. Overall, the Wave Dragon excels in terms of AEP and CR, while the OCECO 4 and the WaveRoller® are the most promising alternatives in terms of CF and LCoE, respectively. The AquaBuOY and the RM6 BBDB yield encouraging results when considering single-unit failure and economies of scale, as they always require a significant number of units in a wave farm to cover the aquaculture demands. However, the BBDB has a relatively lower LCoE. In other metrics, they tend to performer poorer than the WD, OCECO and WR, and may not be adequate solutions to consider. There is a clear interest in considering co-located wave energy conversion with offshore aquaculture, with benefits that range from equipment sharing and energy independency to protection of the aquaculture exploration from energetic sea-states [33]. Even so, several challenges must be overcome, ranging from uncertainty with regards to the final deployment sites' characteristics and relatively low maturity of both sectors to the difficulties of WECs meeting the real-time energy demands of an offshore aquaculture farm, albeit the expectedly lower requirements by comparison with supplying the mainland electrical grid. The devices will also need to be adapted in accordance to the final deployment sites, in order to optimize their operation and avoid potential undersizing/oversizing. This may require the introduction of storage units, for instance, which can increase the inherent costs. Furthermore, it will be important to assess the ocean area use compatibility, as other applications (*e.g.*, navigation and shipping routes or natural reserves) may imply unviable scenarios.

4. Conclusions

In this paper, offshore aquaculture co-located with wave energy is assessed on two sites along the Portuguese coastline, based on reference literature studies. The proposal encompasses local metocean conditions and water characteristics, WEC technologies and aquaculture species selection. The energy output and efficiency of each WEC are estimated and matched against demand targets from existing aquaculture projects. Demand coverage and redundancy are compared.

It was found that the Wave Dragon excels in terms of AEP, CR and multi-unit failure redundancy, followed by the WaveRoller™ (lowest LCoE) and the OCECO 4. The latter exhibits higher CF, but requires a larger wave farm than the WD to meet the target aquaculture energy demands, as does the WR. The RM6 BBDB yielded intermediate and good results on LCoE and single-unit redundancy, correspondingly, while the AquaBuOY faired poorer on all aspects apart from single-unit failure, as the required number of wave farm units is high. While additional units also enable greater economy of scale gains, they may introduce high initial investment costs, depending on the number of units and the LCoE (both of which are sizeable for the AB, for instance). As little energy is convertible upwards from H_s of 5.5 m, the operational range of the WECs is limited and there is risk of damage, the devices should enter survivability mode for local "storm" conditions.

For the FF site, all species are recommended for farming, although faster currents and a higher energy wave climate is expected. For the S site, only the European Seabass, Oyster, Gracilaria and Wakame are viable, but the growth conditions are ideal apart from the Wakame (FF site). There is less theoretical wave energy to be harnessed, and while the currents are slower their directionality is wider. When also considering the WECs' performance and operational range, viable co-location scenarios can be identified, such as farming the European Seabass or Oyster near Sines with a small array of WD, OCECO4 or WR units. Even so, it will be important to verify if the joint costs – WEC LCoE alongside aquaculture farming operations – can be surpassed by the joint savings and revenue – *in situ* renewable energy supply, equipment sharing and aquaculture production. For instance, co-located aquaculture and offshore wind can provide an alternative at a lower LCoE (as low as 61 €/MWh, according to Ref. [63]), but with its own challenges (*e.g.*, scouring and stability under wind/wave action) and absent the potential shielding effect provided by WECs.

Future studies should develop on these outcomes, namely with a more detailed site characterization and WEC/aquaculture species selection. An assessment of near-field and far-field effects inherent to the WEC farm should be performed, as well as a study on potential conflicts with other coastal uses, from navigation routes to natural reserves. Complementary to energy estimates, the hydrodynamic influence of different wave farm layouts and device quantity on the aquaculture systems should be further investigated. Lastly, the WECs may require some adaptation/scaling to the characteristics of the deployment sites (dimensions, rating and/or operational range). For reference, a methodology based on the Froude similarity criterion, as proposed by Ramos et al. [64] and Oliveira-Pinto et al. [65], provides scaled WEC power matrices adjusted to the local wave climate using a techno-economic model. Although other considerations should be accounted for (*e.g.*, generator efficiency curves), this approach enables a preliminary tuning of a WEC's characteristics to the most energetic sea-states of a potential deployment site.

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Declaration of competing interest

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Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.01.009.

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