

Review

Enhancing Wave Energy Competitiveness through Co-Located Wind and Wave Energy Farms. A Review on the Shadow Effect

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Abstract: Wave energy is one of the most promising alternatives to fossil fuels due to the enormous available resource; however, its development may be slowed as it is often regarded as uneconomical. The largest cost reductions are expected to be obtained through economies of scale and technological progress. In this sense, the incorporation of wave energy systems into offshore wind energy farms is an opportunity to foster the development of wave energy. The synergies between both renewables can be realised through these co-located energy farms and, thus, some challenges of offshore wind energy can be met. Among them, this paper focuses on the longer non-operational periods of offshore wind turbines—relative to their onshore counterparts—typically caused by delays in maintenance due to the harsh marine conditions. Co-located wave energy converters would act as a barrier extracting energy from the waves and resulting in a shielding effect over the wind farm. On this basis, the aim of this paper is to analyse wave energy economics in a holistic way, as well as the synergies between wave and offshore wind energy, focusing on the shadow effect and the associated increase in the accessibility to the wind turbines.

Keywords: wave energy; offshore wind energy; co-located wind-wave farm; synergies; cost reductions; weather windows for O & M

1. Introduction

Ocean energy has emerged with force in the search for alternatives to conventional energy resources. Nevertheless, there are some barriers that may hinder the development of marine energies, such as the early stage of development of the technologies [1–11], high costs involved [12–16] or uncertainties regarding the environmental impacts [17–27]. Among the different alternatives of ocean energy, this work focuses on two of them: Offshore wind and wave energy. As for the former, investment in offshore wind systems has been growing rapidly throughout Europe in order to achieve EU targets for renewable energy in 2020 [28], due to the powerful available resource [29–32] and its similarities to its onshore counterpart. However, there exist some limitations that could hinder its introduction into the energy mix, such as the higher investment implied, more demanding maintenance tasks or power variability. For its part, wave energy presents extensive possibilities for the future thanks to its enormous potential for electricity production [12,15,33–39]. In fact, the global wave energy potential resource has been estimated at 10 TW [22], and depending on what is considered to be exploitable, this covers from 15% to 66% of the total world energy consumption [40,41]. Its technology is in its infancy, despite recent research on Wave Energy Converters (WECs) [42–45] and its structural response [46–48], and it presents higher levelised costs than any non-renewable energy and also than most renewables [49]. Therefore, at present, wave energy is only economically viable if subsidized. However, over time important cost reductions can be expected to occur through economies of scale and technological effects, such as technological advances and improvements by practice.

In this sense, combining wave energy systems with offshore wind farms has been regarded as a good solution to promote and accelerate the development of wave energy technology [50–52]; at the same time a better use of the marine resource would be achieved [53] and the installation and operation costs would be reduced by sharing common installations [53]. Besides, other synergies arise when this combination is considered, such as a better predictability of the energetic resource [49], smoothed power output [54] or enlarged weather windows for operation and maintenance tasks [55]. The latter is of special interest for this paper: The energy extraction of an array of WECs creates a wake that modifies the local wave climate by reducing the mean wave height, which is known as the *shadow effect* [56].

On this basis, the first aim of this study is to offer a review of wave energy economics, comparing this renewable with other conventional energy sources and assessing the influence on the conclusions about wave energy profitability of including other factors like the learning curve or externalities. Second, combined wave and wind systems are proposed as a way to reduce costs and boost the joint development of both renewables taking advantage of the mutual benefits of their combination. In this line, the existing synergies between wave and offshore wind energy systems are analysed in this paper, paying special attention to the shielding effect of co-located WECs, which leads to enlarged weather windows for Operation and Maintenance (O & M) tasks, thereby reducing the non-operational periods of wind turbines due to delays in maintenance tasks—one of the challenges of this renewable, not least when it is compared with onshore wind. The analysis of the so-called shadow effect is based on the results of previous studies, which allow the assessment of the influence of the wind farm characteristics and the co-located WECs layout on the benefit achieved—which are translated into monetary terms.

2. Economics of Wave Energy

Among the different options of wave energy farms (onshore, nearshore and offshore), this paper focuses on offshore wave energy farms since this is closer than any other to commercial development [40,57]. The main costs in a wave energy plant are the following: (i) pre-operating cost; (ii) capital expenditure (CAPEX); (iii) operational expenditure (OPEX); and (iv) decommissioning costs. As Figure 1 shows, the pre-operating and decommissioning costs are insignificant in the total, whereas O & M (plus the replacement) represents 64.99% of the total, and the initial investment 34.68% [58].

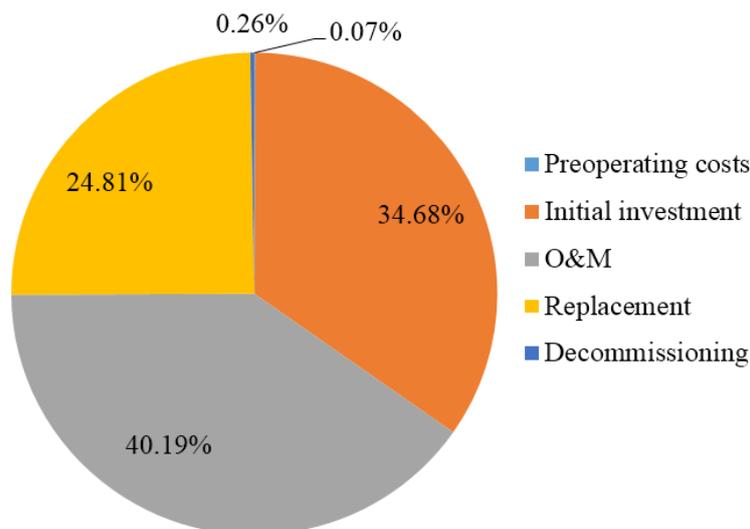


Figure 1. Percentage of each individual cost in the levelised cost.

As for the former, the pre-operating cost involves all the expenses incurred on preliminary studies, projects, environmental impact assessment, consenting procedures, *etc.*, as well as direction and coordination. It will depend on a number of factors, such as the location, as policies vary from one country to other, or the size of the installation. Because of that, there is a wide range of values for this cost reported in the bibliography, and it is usually expressed as a percentage of the capital costs (Table 1).

Table 1. Pre-operating and licenses costs.

Category	Cost	Source
Pre-operating cost	10% CAPEX (€)	[14,59]
	500,000–2,000,000 €	[60]
Licenses and permissions	$0.037 \times \text{Installed Power in W (\$)}$	[61]
	2% WECs cost (€)	[14,59]

For its part, the capital expenditure (CAPEX) includes the costs of the WECs and other elements of the wave energy plant, as well as their installation (Table 2). There is little available information about the cost of wave energy technology due to its initial stage of development. Table 3 shows the cost of three WECs that are close to a commercial stage. If the installation is included, the total cost rises to 2.5–6.0 M€ per installed MW [62–64].

Table 2. Summary of initial costs.

Element	Cost	Source
WEC and installation	2.5–6.0 M€/MW	[62–64]
Mooring system	10% WECs cost 0.265 €/N	[12,59,65,66]
Mooring Installation	50,000 €/day	[67]
Underwater cable	10% CAPEX	[14,68]
Cable installation	2.07 €/m	[69]
Electrical substation	≈1.2 M€	[70]

Table 3. Rated power and estimated cost of WaveDragon, Pelamis and AquabuOY (sources: [71–74]).

Technology	WaveDragon	Pelamis	AquabuOY
Rated power (kW)	7000	750	250
Cost (\$/unit)	16,800,000	25,000,000	200,000

Both with the initial investment, the operation and maintenance cost (OPEX) has an important weight in the total cost of the installation throughout its lifetime. Since there is not enough experience in wave energy installations, a preliminary estimation of this expenditure can be made on the basis of the experience in the oil and gas and offshore wind energy sectors (Table 4). Moreover, the whole plant is supposed to be dismantled after 20 years and the decommissioning cost is estimated to be 0.5%–1% of the initial investment [60].

Table 4. Annual costs of operation and maintenance (source: [49]).

Cost	€/MWh	% CAPEX	%OPEX
O & M tasks	20–35	1.5%–5%	57%
Revision and time off		10	
Spares		90	
Public services	3.5		
Renting		2.5	
Insurance cost	15	0.8%–2%	13%–14%

All in all, the levelised cost of wave energy—which is the ratio of total lifetime expenses vs. total expected outputs expressed in terms of the present value [12]—ranges between 180 €/MWh and 490 €/MWh [49]. These values are quite higher than those of other traditional non-renewable electricity generation methods like pulverized fuel or even more recent methods like combined cycle gas turbine with carbon capture and storage, whose costs are respectively 32.57 €/MWh and 59.78 €/MWh [49]. Moreover, wave energy is also more expensive than consolidated renewables like onshore wind energy (67.68 €/MWh) and even than other emerging renewables like offshore wind energy (101.43 €/MWh). Therefore, wave energy seems not to be economically competitive in the present days. However, cost reductions are expected to be increased through economies of scale and technological effects, such as technological advances and improvements by practice, which are reflected by the learning curve (Equation (1)). In this line, there are not many studies examining the impact of learning curves on the profitability of wave energy plants. Despite that, most of them agree on a

learning rate of 85%–90% within the next 10 years [14,75–78]. If this is considered, even in a pessimistic scenario characterised by slow development of wave technology, low installed capacity and, consequently, small learning factor, a reduction in the levelised cost of wave energy around 22% may be obtained [58].

$$\frac{C_x}{C_0} = \left(\frac{P_x}{P_0} \right)^{\left(\frac{\log f}{\log 2} \right)} \quad (1)$$

where C_x is the costs at time x , C_0 is the costs at time 0, P_x is the cumulated capacity at time x , P_0 is the cumulated capacity at time 0 and f is the learning factor. Furthermore, decisions about energetic planning are usually based on the generation cost of each source of energy, forgetting the other stages in energy production. Nevertheless, as with all human activities, energy production has impacts (positive and negative), which must be considered in the total energy cost. This is known as externalities. A new tendency has emerged to assess the energy cost which consists on internalizing these externalities [58]. For that purpose, the first step is to determine the impacts (positive and negative) which have to be considered in the energy production process taking into account entire the life cycle. One of the procedures followed to evaluate physical impacts is the Impact Pathway Approach of ExternE [79,80], which identifies: (i) emission sources; (ii) dispersion (increase in ambient concentration); (iii) impacts; and (iv) associated cost. For example, it is estimated that carbon emissions in wave energy are 6 gCO₂/kWh [81], whereas the average value for conventional energy sources is around 250 gCO₂/kWh [82]. Therefore, a reduction of 244 gCO₂/kWh would be achieved by wave energy production, and this should be included in the energy price. Additionally, the environmental externalities there are others that should be considered, such as the creation of new jobs or the increase of the supply security, reducing the risk of supply cuts of conventional fuels, and therefore avoiding important economic losses; e.g., a cut of one day in the gas supply in Spain would produce a loss of 0.03% of the GDP [83]. All in all, oil and coal technologies for electricity production have associated high external costs (60 and 58 €/MWh, respectively) in comparison with other non-renewables like natural gas (15 €/MWh), and the difference is still greater in the case of wind energy, with an external cost of a mere 1.75 €/MWh [84–86]. In fact, a study [58] concluded that if the externalities were included in the economic studies analysing which technology is most viable, the conclusions would change substantially (Figure 2).

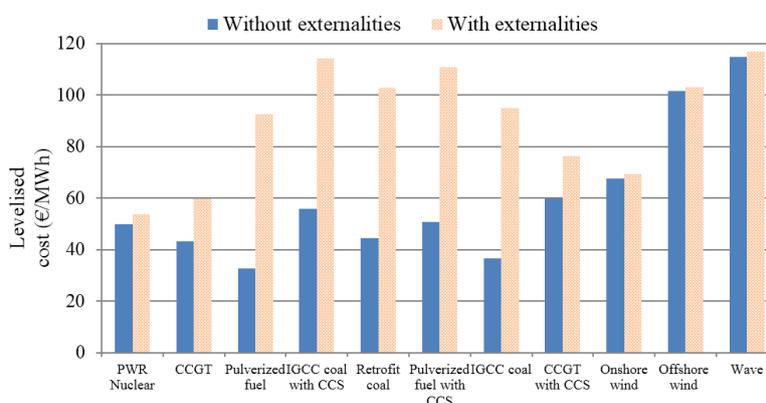


Figure 2. Levelised cost (€/MWh) of different technologies including external costs. (Reprinted with permission from [58]. Copyright 2015 Taylor & Francis)

3. Co-Located Wind and Wave Energy Farms

Taking advantage of various renewable resources simultaneity is being regarded as an opportunity to turn renewables into a more cost-competitive option. In the case of wave energy, the combination with offshore wind energy is emerging with force due to the existing synergies between both renewables. According to the global distribution of the wind and wave energy resources (Figure 3), it is apparent that there are some areas with large possibilities to these combined options.

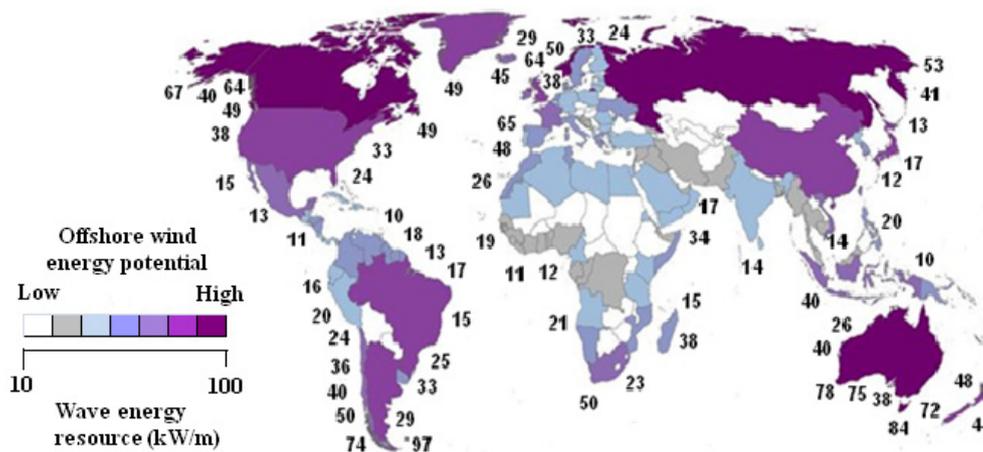


Figure 3. Global distribution of offshore wind and wave energy resources. The former is reflected through the colour scale and the latter by means of the energy density (kWm^{-1}): 10 kWm^{-1} is the minimum needed for a commercial scale wave energy project.

There are different possibilities for a combined wave and wind array [53]: (i) co-located wind-wave energy; (ii) hybrid converters; and (iii) energy islands (Figure 4). This work focuses on the former, co-located systems [87,88], since they are the simplest option at the present stage of development of wave and offshore wind technologies [30,89,90]. These systems combine an offshore wind farm with a WEC array with independent foundation systems but sharing: The same marine area, grid connection, O & M equipment and personnel, port structures, *etc.* [51].

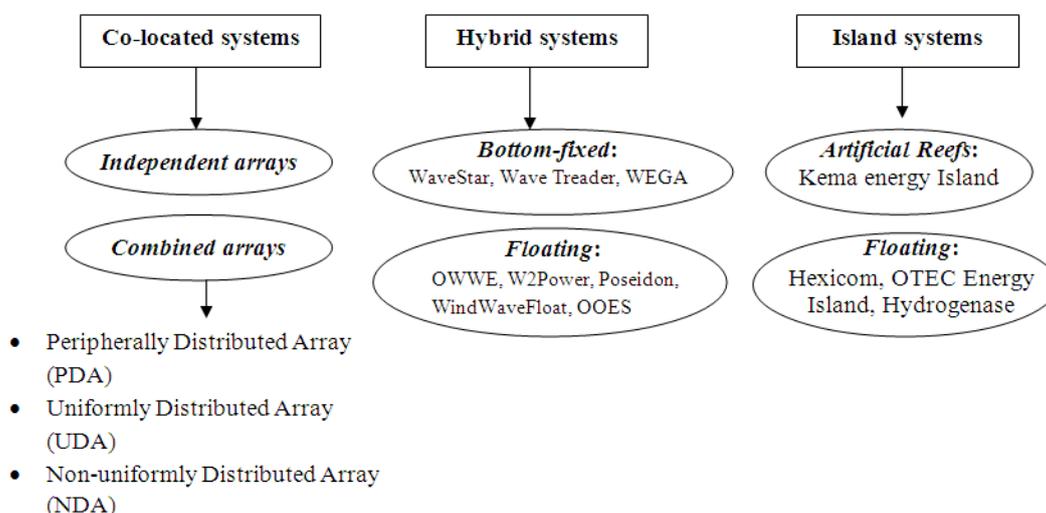


Figure 4. Classification of combined wave-wind technologies.

There are many synergies that could be exploitable to overcome some of the barriers that marine energies could present to entry into the market. First of all, important cost savings could be achieved during the setup of the energy farms because of common elements and coordinated strategies [54,91–93]. The largest savings would be achieved in the electrical connection, since the offshore station and the export cable can be the same for both installations. When hybrid technology was developed, important cost reductions in the substructure foundation system would be achieved as hybrid wave converter systems share the same substructure or foundation with the offshore wind turbine [89,91]. Moreover, the cost of O & M tasks can be reduced in co-located farms since the scheduled maintenance of wave and wind energy can be organised to be done at the same time or in continuous length of time [53]. A recent study [94] achieved cost savings around 25% in the capital costs and up to 14% in the maintenance costs of combined wave and wind energy farms. Moreover, offshore developers pay for leases according to the area occupied, so covering the same area with two sources of electricity generation reduces these costs.

Besides, the combination of two different technologies harnessing different sources of energy at a single array site will increase the global energy yield per array unit and thereby contribute to a more sustainable use of the natural resources [53]. In this sense, combined energy farms would reduce the feasible environmental impact of these offshore energy installations since the affected area will be smaller than in the case of wave and wind farms as separate installations. Furthermore, recent studies have concluded that introducing WECs in offshore wind energy parks compensates the power variability and, thus, smoothes the power output [87,95–97]. This way, balancing cost could be reduced up to 35% [98]. Moreover, a recent work [99] found that waves and the power output of WECs are 23% and 35%, respectively, more predictable than winds and the wind turbine power output. Finally, wave energy developers can eliminate part of the financial risk in this unproven technology by coordinating with wind projects. As a consequence, the learning curve effect would lead to faster reductions in the cost of wave energy, enhancing its competitiveness.

Enlarged Weather Windows

In addition to the above benefits, other technological synergies would be realised through combined wave and wind energy farms, such as the so-called *shadow effect*. The operational limit of workboats for O & M tasks—the most cost-effective access system—is a significant wave height of 1.5 m [100,101]. When this threshold is exceeded delays in maintenance and repairs ensue, and the resulting downtime causes earnings to be missed. Co-located WECs deployed at the periphery of the wind farm could produce a shielding effect over the offshore wind farm that enlarges the weather windows for O & M. This increase in the accessibility to the wind turbines brings in reduced downtime and, thus, in considerable cost savings—around 25% of the O & M costs that would lead to an reduction in the overall project cost of energy of 2.3 percent [102]. The analysis of the shadow effect provided by co-located WECs at the periphery of a wind farm was investigated in previous studies [55,103,104] through four real wind farms currently in operation, whose locations and characteristics are presented in Figure 5 and Table 5, respectively. Comparing this information, it can be stated that these four wind farms encompass a wide variety of characteristics on which to establish a comparative analysis. The third-generation numerical wave model SWAN (Simulating WAVes

Nearshore) was used to simulate wave propagation. In all simulations, high-resolution results were obtained as the model was implemented by grids with resolution higher than 40 m. Both WECs and wind turbines were represented in the model by a transmission coefficient, whose value can vary from 0% (*i.e.*, 100% of incident wave energy absorbed) to 100% [17,18,20,27,30,105–108].



Figure 5. Location of the four wind farms: Alpha Ventus, Bard 1, Horns Rev 1 and Lincs. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Table 5. Characteristics of the offshore wind farms. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Wind Farm	Depth (m)	Distance from Shore (km)	Installed Capacity (MW)	Number Turbines	Area (km ²)
Alpha Ventus	33–45	56	60	12	4
Bard 1	39–41	90–101	400	80	59
Horns Rev 1	6–14	14–20	160	80	21
Lincs	8–16	8	270	75	41

With regard to the wind farm layout (Figure 6), the Alpha Ventus wind farm is composed by 12 turbines: six AREVA turbines with a tripod substructure and six Repower 5 M turbines with a jacket-frame substructure [109]. For their part, Bard 1 has 80 wind turbines of 5 MW (Bard 5.0) and a tripod substructure [110–112], Horns Rev 1 has 80 turbines (Vestas V80-2MW) with a monopile substructure erected on a grid of 10 rows [113] and Lincs is composed of 75 wind turbines Siemens 3.6 MW with monopile substructure [114,115]. At Alpha Ventus and Horns Rev 1 the wind turbines are ordered on a Cartesian grid, whereas in Bard 1 and Lincs they are not organised in clearly defined rows, and the distance between turbines varies in each case.

The wind farms selected as baseline scenarios presented levels of accessibility to the wind turbines—percentage of time when the significant wave height within the wind farm is under the workboat limit, 1.5 m—between 57% and 74% during the study period (Table 6), whereas a level of accessibility around 82% is required to ensure an availability—the percentage of time that the farm is able to produce electricity—of 90% [116]. This is in well concordance with the general panorama,

since while modern onshore wind turbines show availability levels of 98% [117], this level is significantly reduced in offshore installations [117–120].

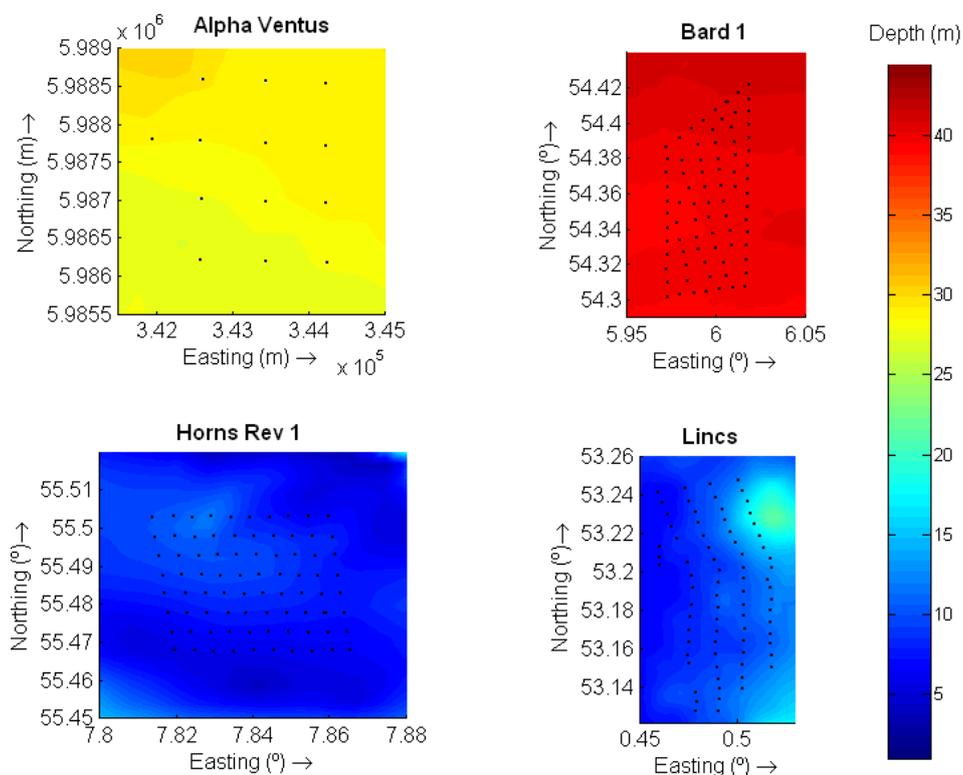


Figure 6. Layout and bathymetry of Alpha Ventus, Bard 1, Horns Rev 1 and Lincs (water depths in m). (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Table 6. Accessibility to the wind turbines in the baseline scenario for the annual period analysed. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Wind Farm	Accessibility (%)
Alpha Ventus	67.53
Bard 1	56.99
Horns Rev 1	59.86
Lincs	74.11

In the light of this situation, a wide variety of co-located wave farm layouts were analysed in Alpha Ventus (Table 7, Figure 7) in order to identify the configurations that maximise the wave height reduction. They are characterised by different spacing between WECs, disposition and number of devices, with the aim of providing shelter not only from NW waves (the prevailing wave direction) but also from W and SW waves, which are relatively frequent in the area. In all cases, WaveCat, a floating offshore WEC, whose principle of operation is wave overtopping with a hull length of 90 m [121], was the WEC employed. The simulations were carried out considering the predominant sea state in the Alpha Ventus site: $H_s = 1.5$ m, $T_p = 6.5$ m and $\theta = 330^\circ$.

Table 7. Characteristics of the WEC layouts, with n_{WECs} the total number of WECs. (Reprinted with permission from [55]. Copyright 2015 Elsevier Science Ltd.)

No.	Spacing (m)	Configuration	n_{WECs}	Short Description
1		A _i	9	2 rows to the NW.
2	750	A _{ii}	12	2 rows to the NW and 2 more rows to the W, at an angle of 45°.
3		A _{iii}	12	Arch to the NW.
4		B _i	12	2 rows to the NW.
5	450	B _{ii}	17	2 rows to the NW and 2 more rows to the W, at an angle of 45°.
6		B _{iii}	17	Arch to the NW.
7		C _i	22	2 rows to the NW
8	198	C _{ii}	30	2 rows to the NW and 2 more rows to the W.
9		C _{iii}	28	Arch to the NW.
10		C _{ib}	27	2 rows to the NW and 1 row to the SW of the farm constituted by 5 additional WECs.
11		C _{ic}	31	2 rows to the NW and 2 more rows to the SW of the farm constituted by 9 additional WECs.
12	198	C _{iib}	32	2 rows to the NW and 2 more rows to the W, at an angle of 45°. (2 additional WECs)
13		C _{iic}	34	2 rows to the NW and 2 more rows to the W, at an angle of 45°. (4 additional WECs)
14		C _{iiib}	30	Arch to the NW with 2 additional WECs.
15		C _{iiic}	32	Arch to the NW with 4 additional WECs.

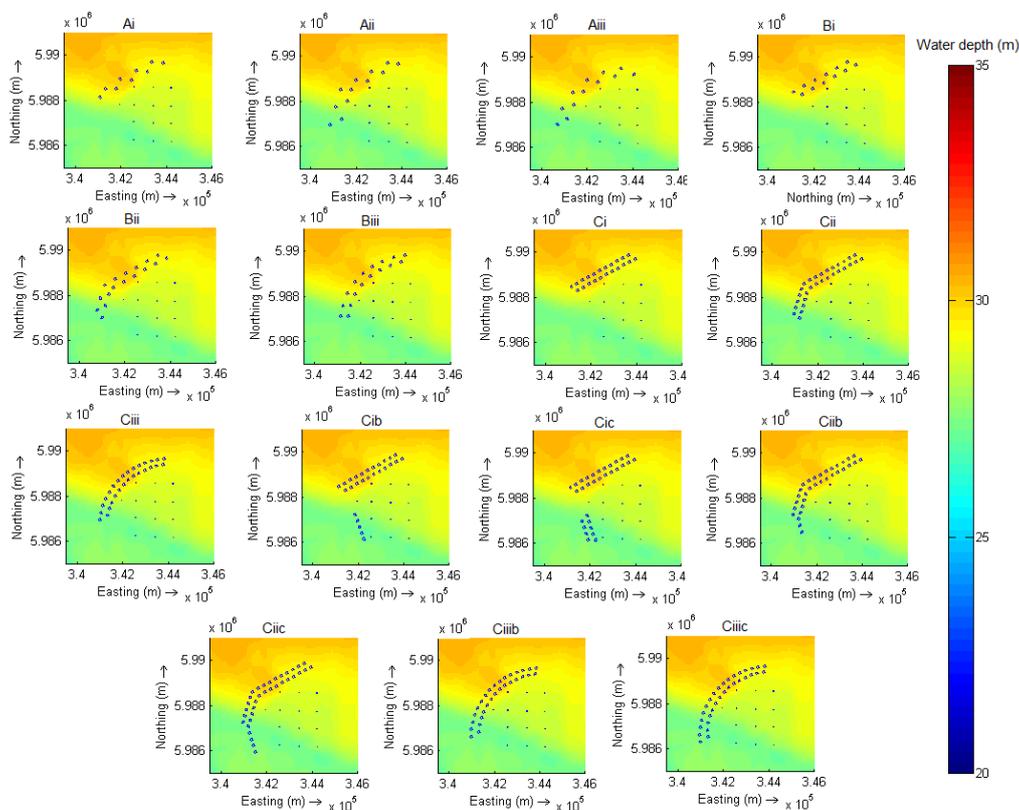


Figure 7. Co-located wave-wind farm layouts (configurations A_i to C_{iiic}). (Reprinted with permission from [55]. Copyright 2015 Elsevier Science Ltd.)

In view of the results, the highest wave height reductions were obtained in the configurations with low spacing between devices, not only due to the larger number of WECs but also by the aggregation of the shadow effect provided by each device, reaching average wave height reductions up to 24.91% in the whole farm. Among these layouts, C_i , C_{ib} and C_{ic} should be rejected since they leave part of the wind farm unprotected (Figure 8). Therefore, the best WECs layouts were C_{iic} and C_{iiic} which corresponds with: Two main rows of WECs with a spacing of 198 m orientated towards the prevailing wave direction and other two rows of devices to face secondary waves deployed in an angular configuration in the first case and forming an arch in the latter.

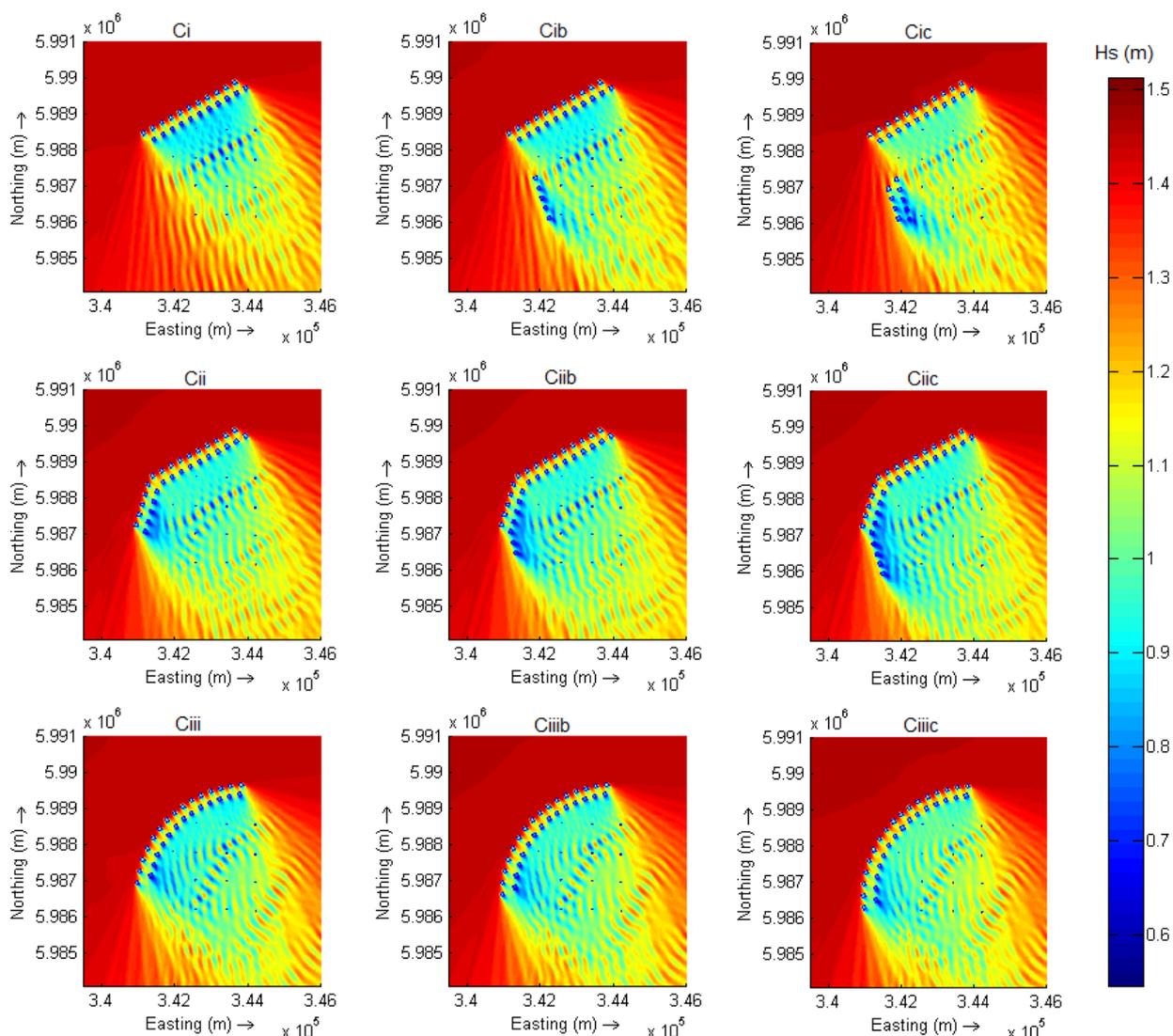


Figure 8. Wave height reduction within the Alpha Ventus wind farm for the predominant sea state in this site: $H_s = 1.5$ m, $T_p = 6.5$ m and $\theta = 330^\circ$ and configurations C_i to C_{iiic} . (Reprinted with permission from [55]. Copyright 2015 Elsevier Science Ltd.)

On this basis, these both configurations (Figures 9 and 10) were analysed in depth in the four wind farms—Alpha Ventus, Bard 1, Horns Rev 1 and Lincs—by considering annual measured wave data during 2012 and 2013 by buoys located in the vicinities of the wind farms [103]. The number of WECs and the rate with the number of wind turbines is shown in Table 8.

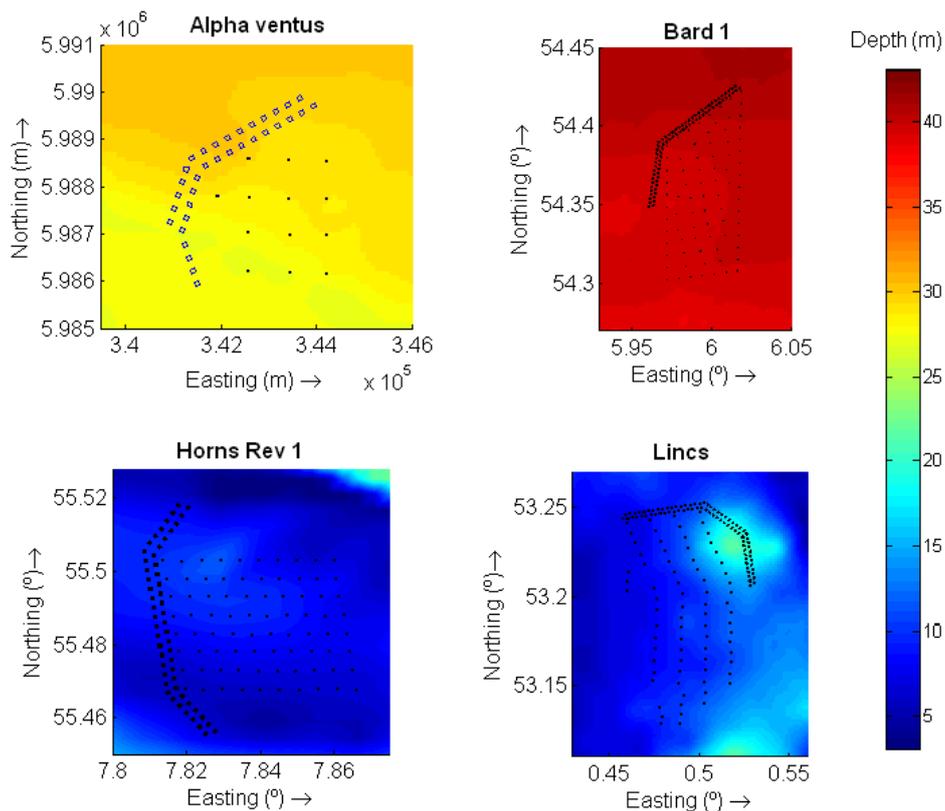


Figure 9. Co-located wind farm layouts with WECs at an angle. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

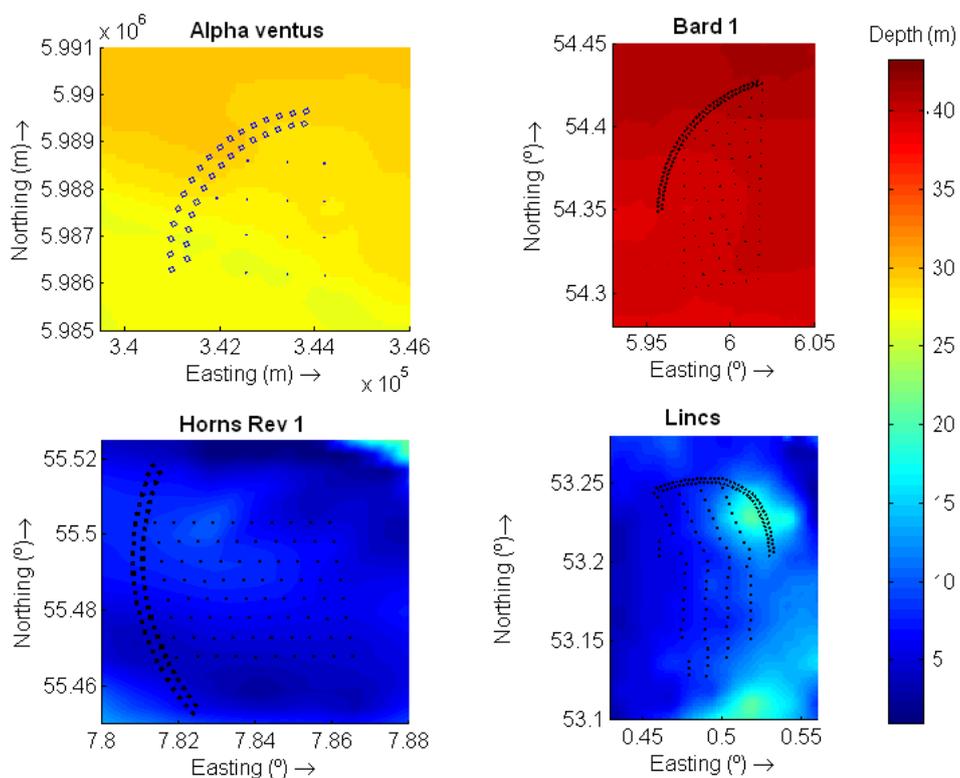


Figure 10. Co-located wind farms with an arched WEC layout. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Table 8. Total number of co-located WECs, number of devices in each i -th Vertical Row (VR_i) of co-located WECs and rate between the total number of WECs and wind turbines (r).

Wind Farm	Layout in Angle				Layout in Arch			
	$VR1$	$VR2$	Total	r	$VR1$	$VR2$	Total	r
Alpha Ventus	19	15	34	2.83	17	15	32	2.67
Bard 1	40	39	79	0.99	40	39	79	0.99
Horns Rev 1	28	27	55	0.69	27	26	53	0.66
Lincs	41	40	81	1.01	40	40	80	1

In all cases, important wave height reductions were obtained, especially in Bard 1 with an average wave reduction between 17% and 19%, thanks to the good interception of the incoming waves (Figure 11). These results were followed very closely by those obtained in Alpha Ventus (around 17%) and Horns Rev 1 (between 15% and 17%), whereas the wave height reduction achieved at Lincs was smaller (around 13%) since part of the farm remained unprotected against incoming waves from secondary directions due to its elongated shape (Figure 12). This fact was supported when the spatial variation in the wave height reduction was analysed, since in the case of Lincs the wave height reduction decreased from 40% in the wind turbines just behind the co-located WECs to 5% in the further turbines [103]. In fact, the most homogeneous reduction throughout the wind farm was achieved in the case of wind farms with geometry similar to a square and smaller spacing between wind turbines, such as Horns Rev 1. Moreover, this kind of farms would require fewer WECs to protect the whole farm from incoming waves. Another important factor in the results is the distance from the coast: Being closer to land is not a positive factor to implement co-located WECs, since it normally implies lower water depths and a milder sea climate, and consequently there is less available wave energy to be extracted by the WECs [103].

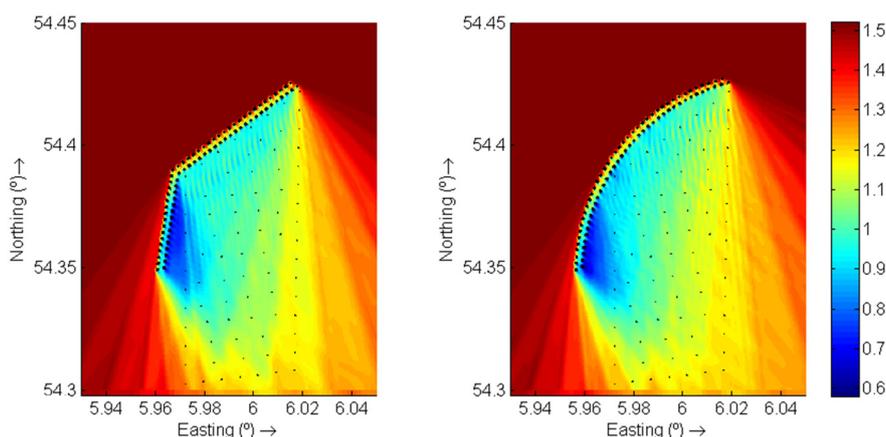


Figure 11. Wave height reduction due to co-located WECs at Bard 1 under a sea state with: $H_s = 1.71$ m, $T_p = 6.09$ s and $\theta: 229.6^\circ$. The colour scale represents the significant wave weight, H_s (m).

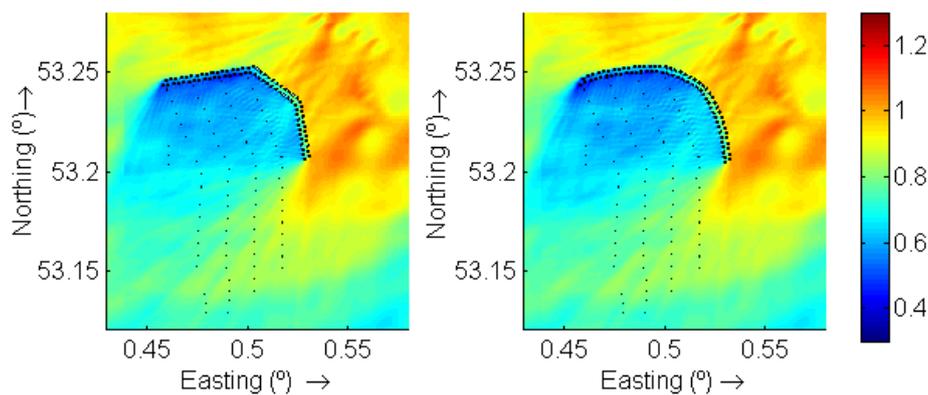


Figure 12. Wave height reduction obtained with co-located WECs at Lincs under a sea state with: $H_s = 1.18$ m, $T_p = 6.03$ s and $\theta = 60.16^\circ$. The colour scale represents the significant wave weight, H_s (m).

Although the combination of wave and wind energy farms presents better results in some cases than in others, the wave height reductions achieved bring in important improvements of the accessibility to the wind turbines for all the cases analysed (Table 9). In fact, the accessibility raised over 82% for two of the farms, which is the reference value to maintain a farm availability of above 90% [116]. In order to translate this increase of time accessibility into monetary terms, it could be considered an estimated cost (or lost earnings) of delayed repairs about 300 €/h [122,123].

Table 9. Accessibility of the co-located farms and the increase (Δ) in comparison with the baseline scenarios. (Reprinted with permission from [103]. Copyright 2015 Elsevier Science Ltd.)

Wind Farm	Layout	Accessibility (%)	Δ (%)
Alpha Ventus	in angle	82.33	17.97
	in arch	82.19	17.83
Bard 1	in angle	69.66	18.19
	in arch	69.04	17.46
Horns Rev 1	in angle	70.89	15.56
	in arch	69.52	13.89
Lincs	in angle	81.30	8.85
	in arch	81.10	8.61

Further, given that the wave height reduction within the wind farm decreases with the distance from the WECs barrier towards the periphery, it is interesting to analyse the accessibility to each individual wind turbine apart from the accessibility in the entire farm. The most remarkable thing is that a quite homogeneous level of accessibility is achieved within the entire farm, since around 50% of the wind turbines experienced an increase in the accessible timeframe of 20%, and the remaining part an increase of at least 10%, with the exception of Lincs where waves recover more quickly throughout the farm due to the soft climate and enlarged shape of the farm, and only the turbines of the first half of the farm experienced an increase in the accessibility over 10% [103]. Indeed, in the case of Alpha Ventus, Bard and Horns Rev the ratio between the wave reduction in the most distant area and the average within the farm is over 60%, whereas it is around 38% in Lincs.

In order to translate the increase of time accessibility into monetary terms, it could be considered an estimated cost (or lost earnings) of delayed repairs about 300 €/h [122,123]. The aggregate failure rate per wind turbines is approximately five failures per year [124], and they occur particularly in the winter months due to the storm periods [125]. Therefore, it is likely that when these failures occur do sea conditions overtake the operational workboats limit, having to wait until the end of the storm—winter storm periods have an average duration between three and four days in the North Sea [126]. Thus, avoiding one of this downtime periods would involve cost savings around 25,000 € per turbine.

4. Conclusions

The first aim of this paper was to present a general view of the economics of wave energy, a renewable which is still in its infancy but presents a large available resource. It was concluded that its offshore character—in most cases—along with the initial stage of development of the technology reduce the economic viability of wave energy, which may curb the development of this promising renewable technology. However, in a second part of the analysis, in which the learning curve factor was included in conjunction with the externalities, the levelised cost of wave energy was found to be closer to that of conventional energy resources. In fact, this assessment of the energy cost is a fairer analysis since includes all the factors involved throughout the life cycle of the energy installations.

The second purpose of this paper was to demonstrate that co-located wave and wind energy results in more convenient options than individual systems. In this sense, the paper gave a glimpse into the different synergies that can be realised by these combined systems, such as the reduced investment costs or smoothed power output, translating these benefits into monetary terms. Among the different synergies, this study focused on the reduction of operation and maintenance costs in a wind farm by increasing the accessibility to the wind turbines and, thus, reducing downtime periods. It was concluded that implementing co-located WECs in wind farms could raise significantly the accessibility to the wind turbines. In fact, increases by up to 18% were found, reaching high levels of availability even over 90%. However, the shielding effect of the co-located WECs depends on the farm layout and characteristics of the wind farm. The best results were found for farm layouts with the minimum spacing between WECs, and protecting the wind farms not only from the predominant waves but also secondary directions. Wind farms with a disposition similar to a square required fewer co-located WECs than enlarged farms, and wind farms located in areas with less energetic wave climates benefited the least by the co-location of WECs.

Therefore, both offshore wind and wave energy would achieve mutual benefit throughout co-located farms. First, offshore wind farms would obtain enlarged weather windows for O & M tasks, avoiding non-operational periods and the associated costs, while producing a smoother power output. Second, the inclusion of co-located WECs into wind farms could accelerate the development of wave energy technology, which may be expected to lead to reductions in the cost of wave energy based on the learning curve.

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Author Contributions

Sharay Astariz implemented the main research, checked results, wrote the paper, and discussed the results. Gregorio Iglesias provided guidance and supervision and reviewed the paper. All authors read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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