SYNERGIES FOR A WAVE-WIND ENERGY CONCEPT

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Abstract

In recent years, with more and more offshore wind farms being constructed, the question arises as to the possibility of integrating other marine renewables together with offshore wind. This integration presents a number of advantages, including a better utilisation of the marine space and lower installation costs relative to separate installations. Therefore, new hybrid or multiplatform solutions are being developed.

This work is focused on the integration of Wave Energy Converters (WECs) into offshore wind farms. Furthermore, the sustainable development of both offshore wind and wave industries requires a reasonable and responsible use of the natural resources, optimizing their exploitation where present. And it is in relation to this and on the shared challenge for both in reducing cost that the option to integrate these energies arises.

I. Introduction

Wave and offshore wind energy are part of the marine renewables energy family, which is called to become an important part of the EU electricity mix, prospectively satisfying 15% of the European electricity demand and, in some countries, up to 20% of the national demand by 2050 [1]. Sharing the same hostile sea environment, some of the challenges that wave and offshore wind energy confront are similar. However, wind and wave energy converters are not at the same level of technological maturity. In Europe, bottom-fixed offshore wind is a proven technology with 3.8 GW of installed capacity in Europe and employing 35,000 people directly at the end of 2011 [2]. However wave energy – as well as floating offshore wind energy – is still at an early stage of development.

A shared objective between these industries is to reduce cost, prompting the option of integrated technology solutions, taking advantage of the fact that there are a number of technical and economic advantages when combining different energy converters. This paper tackles the issue of integrating wave energy into offshore wind, and in particular considers the characteristics of current technologies in order to propose three initial hybrid prototypes.

Firstly the positive synergies when offshore wind and wave energy technologies share the same marine space are considered. These positives include: shared cost, a smoother and highly available power output compared to individual productions, improved forecasting of the power output, and shielding effects of WECs over the offshore wind farm, which contribute to increase the weather windows for operation and maintenance.

Secondly, this work outlines the risks and challenges that arise when combining these energies. To some extent WECs increase the uncertainty of the project, leading to higher project cost and an increase in the associated financial risk.

Finally three case studies are proposed to illustrate different possibilities of a combined wave and wind array. Different types of WECs are considered together with various array configurations, such as: (i) co-located wave and offshore wind turbines, i.e. the WECs are located at the outer rim of the wind farm; (ii) hybrid energy converters, i.e. both technologies share the same structure; and (iii) a combination of the two previous cases.

II. Synergies and challenges

This section focuses on the positive synergies of combining Wave Energy Converter (WEC) and offshore wind turbines occupying the same marine area. The second part of the section defines the predicted risks and challenges associated with combined wind-wave arrays.

1. Synergies

A large number of combined wave and offshore wind arrays utilising a single array site have been proposed over the last 20 years [3-6]. These combined concepts are supported by a number of positive impacts, synergies, such as increased energy yield and a reduction on the Operation & Maintenance (O&M) costs. By conducting a literature review of [7-9], the wave and offshore wind synergies can be defined as follows:

- **An increased energy yield.** 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;

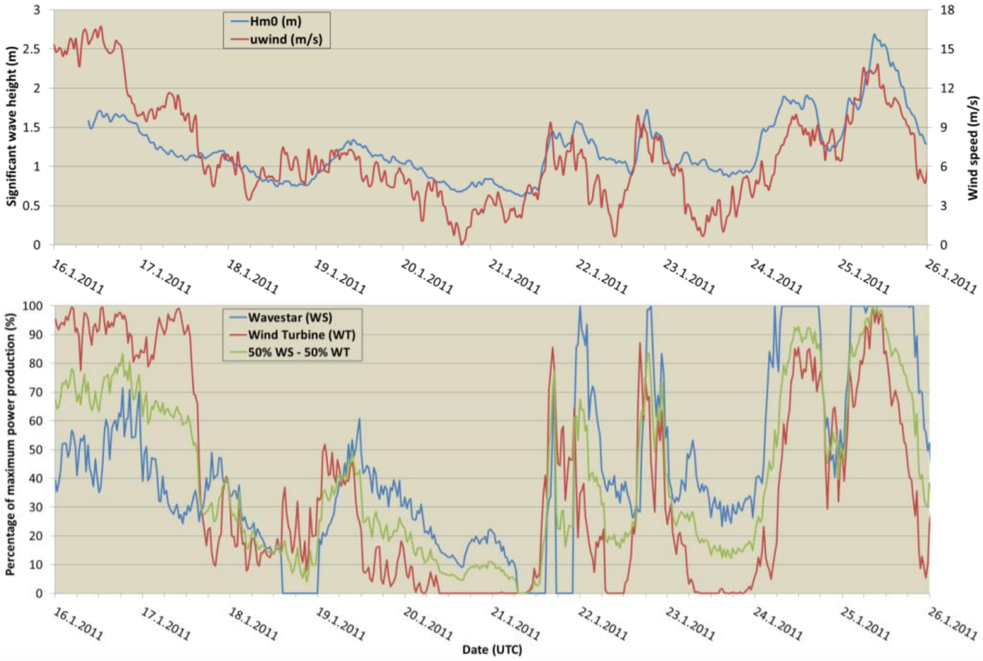

Figure 1: Significant wave height (blue), wind speed (red), and real power productions of Wavestar wave energy converter (blue), of a closely located wind turbine (red) and a combination of both (green), expressed as a percentage of maximum power output, during 10 days of January 2011 in Hanstholm, Denmark, in the Danish North Sea. Source [10].

- **An increased predictability.** Waves are more predictable than winds [10]. Results of a recent study [11] and [9] suggest that for day-ahead forecasts, waves are 23% more predictable than winds, the power output of WECs is 35% more predictable than for wind turbines, and the inclusion of wave energy in a wind-only system reduces balancing costs up to 35%. For the Danish electricity system this would imply annual savings of 13 MEUR.

- **A smooth and highly available power output.** As well as being more predictable than winds, wave climates are less variable and peak wave potential lags some hours behind peak wind potential, for the same weather system. [9]. Therefore a combined harness of the wind and wave resources at the same array location allows for combined power output to avoid rapid reduction in supply to the electric grid due to unpredictable wind resource variation. Furthermore, a combined use of the resources allows to design a grid connection able to absorb the maximum combined energy production with lower capacity than the combined power rated, as the wave and wind energy productions peaks are delayed in time (as seen in Figure 1);
- **A shared common grid infrastructure.** To connect an offshore wind or wave park to the electric grid (usually onshore) represents one of the most significant costs for marine energy arrays. Therefore, a combined production of electricity using a shared electric connection would become an important factor for cost reduction;
- **A shared substructure foundation system.** One alternative to combine wave and offshore wind within a single array is a hybrid design. Hybrid wave converter systems share the same substructure or foundation with the offshore wind turbine. This shared cost will lead to an important cost reduction, as the substructure represents one of the most important cost of an offshore project;
- **Other shared costs.** By combining wave and wind converter arrays, specialisation on site equipment and personnel can be shared: (e.g. the specialised logistic infrastructure or vessels, O&M equipment and personnel);
- **A reduced environmental impact.** The environmental impact of a combined production of wave and wind energy is expected to be smaller than the separate alternative, as the affected area will be smaller. This will signify: a better utilization of the natural resources, a reduced area of impact, and the advantage of the knowledge transfer from one sector to the other;

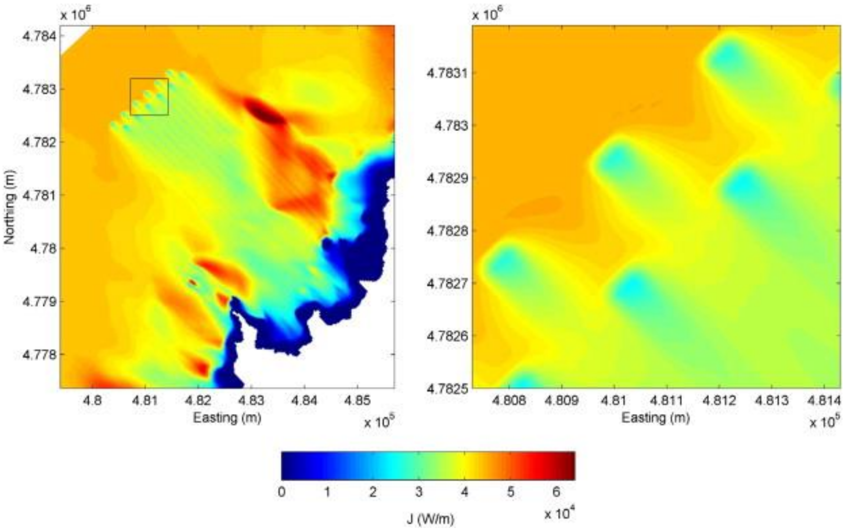

Figure 2: Array of Wave Energy Converters with their respective wakes. Source [12].

- **The shadow effects.** Finally, it should be taken in consideration the shadow effects of the WECs. The energy extraction produced for an array of WECs modifies the local wave climate reducing the mean wave height, creating the shadow effect or wake (as seen in Figure 2). Combining WECs and offshore wind farms at the same location, in an array where the WECs are located on the perimeter, will result in a milder wave climate at the inner part of the wind farm. This creates more frequent and longer Access weather Windows and consequently reduced O&M cost.

2. Risks and challenges

Even though new wave-wind combined concepts have been proposed in previous years, none of them has reached the commercial stage. The main reason being the nascent stage of the wave energy industry compared to the wind energy industry, where many manufacture and installation costs are already minimised. Considering the different development stages of these two renewable industries, this work outlines the main practical risks and challenges.

- **Technology readiness of wave energy.** The wave energy industry has not reached the necessary level of technology readiness to attract main investors yet [13]. However, during the last couple of years, some of the most advanced wave energy concepts (e.g. Pelamis, Oyster, Wavestar and Wave Dragon) have drastically reduced this gap, reaching technology readiness levels suitable for a synergy industrial development;
- **Uncertainty of mooring lines.** Current mooring lines used in the offshore industry are mostly designed for traditional offshore applications, such as oil and gas, and their response under the dynamic loading of a WEC has not been refined;
- **Failure due to lack of experience.** The lack of full scale experience, for both arrays of WECs and full scale prototypes of combined systems, represents a strong barrier. This is due to the lack of real data supporting the reliability of WECs and combined solutions, greatly the failure risk;
- **Impact risk.** Deploying floating WECs at the same array location as an offshore wind farm represents a high risk of impact between the WECs and the wind turbines or substructures. This is due to the lack of experience limited or no contingency plan for a mooring failure or collision event; and
- **Project insurance.** Another major consequence from a lack of practical experience when dealing with combined technologies, there is an additional economic risk associated to combined projects.

These facts outline the weaknesses of a combined concept. However, these must be used to set new challenges for the sector, challenges which are aimed to lead new research and development. On one hand, further research and development is necessary on key technology components such as: new materials for mooring lines; new concepts of mooring systems, which include anti failure safety systems; anti-collision systems, to avoid damage of the wind turbines in the event of mooring failure and minimise the collision risks. However on the other hand, there is the need of develop full scale concept of combined technologies to prove the validity of the synergies and their economic impact on a real project, and to understand the interaction between wave and offshore wind technologies.

III. Combining the concepts

To illustrate the different possibilities of a combined wave and wind farms, a qualitative analysis has been followed, and three different case studies are proposed as an analysis of the possibilities and challenges that the combined parks can offer. Four analytical steps have been considered:

1. The problem definition

Firstly, the base problem and conditions are defined as a starting point to reference back to in further analysis. For the purpose of this work, a generic offshore wind farm, monopile driven turbine type, has been chosen. The perimeter dimensions are set to 10km by 5km. An average water depth of 20m is assumed and the distance to shore is between 20 and 30 km. The power capacity is considered to be 200 MW. For comparative purposes, a wave energy array of similar dimensions is considered at the same site. Both, the wind and the wave farms have a predominant wave direction from the NW.

2. A cost overview

The second factor to consider is the distribution of costs for a typical offshore wind farm. These costs have also been extrapolated to evaluate similar figures for a wave energy farm. This is determined by evaluation of a study from NREL comparing different offshore wind farm costs

[14], Figure 3 shows the distribution of cost from this study. It is shown that most relevant capital costs for an offshore project are: the wind turbine, the Operation and Maintenance (O&M), the support structure or substructure, and the electrical connection. This suggests that, cost reductions in these areas will significantly contribute to general cost reduction of the project and impact the development of the synergy sector.

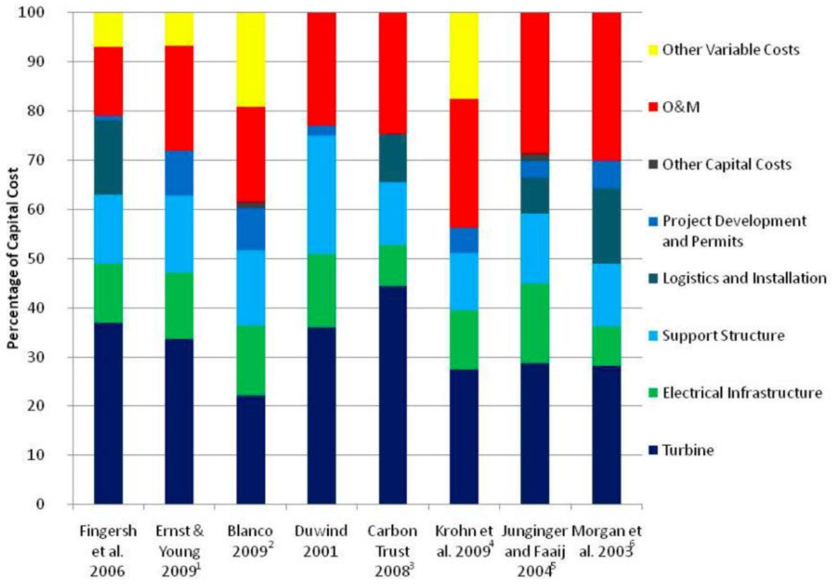

Figure 3: Share of different costs for an offshore wind project by different sources. Source [14].

3. WECs alternatives

A literature review of the wave energy sector shows that there are more than 100 different WECs under development at the moment. However all these different technologies can be grouped into three main categories, based on the fundamental working principle: (i) Oscillating Water Columns (OWC) devices; (ii) oscillating devices; and (iii) overtopping devices. A complete review of these Categories and their fundamental energy extraction principles can be found in [15].

The interaction between the WECs and the offshore wind farm is crucial, and must be considered carefully, as performance is greatly dependent on the WEC technology type. Furthermore, the characteristics, dimensions and foundation systems of each one of these technologies varies affecting the costs and suitability for technical integration.

For the purpose of this work, three WECs have been considered, shown in Figure 4:

- **Wavestar** is based on a combination of multiple point absorbers on different rows. The main advantage of this technology is that it has purposely been conceived to be integrated to an offshore wind turbine as a hybrid device, sharing its substructure costs with the wind turbine;
- **Wave Dragon** is a large floating terminator device, which bases its working principle on the overtopping of waves through a ramp up to an elevated water reservoir. Wave Dragon covers a large marine area, creating a large area of calm water in the device wake. Wave Dragon has also being conceived to accommodate two wind turbines over it; and
- **Wavebob** is a single body point absorber, based on an oscillating buoy. These kind of devices are small in comparison with the two previous ones and requires smaller areas. A point absorber can be deployed inside the offshore wind farm without presenting a big disturbance to the operability of the wind farm or to other marine users.

Figure 4: The WECs considered for this work: Wavestar, up; Wave Dragon, down left; and Wavebob, down right. Sources [16] and [17] and [18].

Table 1 shows the main parameters that have been defined to apply the analytical analysis for each one of the three WECs considered. These parameters can be defined as follows:

- **WEC main active direction** is the principal dimension of the WEC, this means the distance measured in metres of the extraction of the energy from waves it extracts the energy from waves. For Wave Dragon it corresponds to the front width, for Wavebob to the floater diameter and for Wavestar to the floater diameter times the number of floaters.
- **Capture width** is a measure of the performance of the WECs, and it measures the ratio between the absorbed energy from the device and the total wave energy available per metre of wave front [19].
- **Shielding potential coefficient (regular operation),** this coefficient assigns an analytical value to measure the shielding potential of the WECs in standard operational conditions.
- **Shielding potential coefficient (storm operation),** this coefficient, like the previous one, assigns an analytical value to measure the shielding potential of the WECs under storm conditions.

Table 1: Main reference parameters for each one of the WECs considered for this work.

WEC name	WEC main active dimension [m]	Capture width [-]	Shielding potential coefficient (regular operation) [-]	Shielding potential coefficient (storm operation) [-]
Wave Dragon	260	0.23	0.6	0.5
Wavebob	15	0.42	0.3	0.2
Wavestar	100	0.40	0.6	-

4. *The case studies*

a) **First case study: co-located wave and offshore wind turbines**
A co-located wave-wind array has been considered for this case study, where the WECs are distributed between the wind turbines at the periphery of the array, facing the incoming waves. This approach takes advantage of the shielding capability of the WECs to extract energy from waves and consequently reducing the wave high at the inner part of the array. The selected WEC for this case is Wavebob, due to its small size in comparison with the spacing between wind turbines.

b) **Hybrid wave-wind energy converters**
For this second case study, a hybrid wave-wind device has been selected. This hybrid device shares the same substructure with the wind turbine. Like in the previous case the hybrid devices are placed at the periphery of the array, facing the incoming waves, and acting as wave shields. The selected WEC for this hybrid device is Wavestar.

c) **Combination of a) and b)**
The last case study combines both previous solutions, by introducing small point absorbers at the inner area of the array (using for that the Wavebob option), and also including the Wavestar hybrid. Also some periphery wind turbines are removed to install large WEC like Wave Dragon, to drastically increase the shielding effect.

IV. Results

In this section, the three case studies proposed on the previous section were compared by taking into consideration the different parameters and characteristics defined also in previous section. To proceed with this comparison, a set of weighing coefficients have been proposed. These coefficients are aimed to compare the influence of the synergies and characteristics defined in previous sections for each one of the three case studies proposed. The coefficients have been divided into two main categories, savings and costs, depending on the influence over the whole project that the combination of wave energy has.

Table 2 shows the different weighing coefficient values that have been assigned for each one of the case studies. There a set of coefficients are defined giving a maximum value of 0.2 to the category with the higher weigh and 0.02 to the one with the smaller weigh.

Table 2: Comparative analysis between the three case studies proposed.

Case Study Solution		**1**	**2**	**3**
	Savings			
Initial Savings	Grid connection	0,10	0,10	0,10
	Licensing	0,05	0,05	0,05
	Substructure	0	0,05	0,03
Lifetime Savings	O&M	0,02	0,02	0,02
	O&M Weather Window	0,20	0,10	0,30
Shared Costs Total		*0,37*	*0,32*	*0,50*
	Costs			
Loss of WEC Power	Shielding/Turbulence	0	0	0,05
	Wave Climate	0,05	0,05	0,05
Loss Total		*0,05*	*0,05*	*0,10*
Total Savings		**0,32**	**0,30**	**0,40**

The savings category has been subdivided into initial and lifetime savings. The initial savings evaluate those parameters that have a direct influence over the capital cost of the project, such as: **the grid connection**, which has been considered constant for the three case studies and with a high relative weight, as this is one of the more important costs for an offshore project; **the licensing**, this is the cost reduction linked with the smaller application and licensing times of presenting one combined project instead of two. This cost is also considered as uniform and with a relative weigh of 0.05; and **the substructure**, this cost is only applicable to case studies 2) and 3) as it is there where hybrid wave-wind devices are considered, and it is especially relevant for case 2) where only hybrid devices were used.

Lifetime savings are those that have an effect over the variable cost of a project and which are distributed during its whole life, for this analysis two were considered: **the O&M**, sharing the same specialised personnel to perform the maintenance and the operation of the combined farms will mean a cost reduction, however the increased technical complexity due to the addition of the wave devices will mean that this reduction will not be extremely effective; and **weather windows for O&M,** the shield effect of the WECs over the combined farm will end on increasing the weather windows for O&M to the combined farm, this will end reducing such as costs. This saving has been considering bigger for cases 1) and ·3), as the weak area produced for the WECs is expected to be bigger than for case 3).

An analysis of the costs, incurred due to the loss of wave power, was also considered. This loss of wave power is due to that the array has been optimized to increase the wake area and not the energy production. These costs can be divided in two categories: **wave climate**, where this loss of wave power is due to that the farms has not been optimised for energy production. This loss has been considered uniform for all the three cases; and **shielding,** which is the loss due to the reduced performance of the WECs at the inner part of the combined farm caused due to the shield effect.

In summary, and after considering the savings and the costs detailed before, this qualitative analysis comes up highlighting case 3) as the one with highest saves and cases 1) and 2) shows some similar values, with a slightly higher value for case 1) due to its biggest shielding effect. However, if a risk analysis is performed, analysing the risk commented in section II, it can be concluded that case 3) it is also the one with higher risks and case 2) the one with the small risk. This is due to that in case 2) is used a bottom-fix hybrid device, solution that reduces significantly the risks (especially the collision risk).

V. Conclusions

This work goes through the synergies for a wave-wind energy concept. As first step, the synergies between wave and offshore wind technologies have been presented. These synergies are strong and make from the combined wave-wind energy a real alternative. From these synergies, the one regarding to the shadow effects should be considered with special detail and further research should be conducted to understand the interaction between the weak of the WECs within the farm array and the find turbines substructures.

A number of risks have been identified for combined wave-wind projects. These risks are mostly due to the early stage of development of wave energy or for the reduced of experience on full scale projects. Even though there are risks, the identified synergies are strong and justify to proceed with further research and to set new challenges to make that combined wave-wind farms became a reality.

Three case studies have been proposed to illustrate how the synergies and risks identified previously would affect to a combined wave-wind farm. It has been identified that there are WECs that are susceptible for combining considering their actual development status. Furthermore, for the three case studies analysed has been found that the case number three is the most convenient in terms of savings but it is also the one with the higher risk.

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