Combined wave and wind energy: synergies and implementation

Sharay Astariz Núñez

Supervisors:
Prof. Gregorio Iglesias Rodríguez
Dr. Rodrigo Carballo Sánchez

Tutor:
Dr. Rodrigo Carballo Sánchez

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Sharay Astariz Núñez
Author

Prof. Gregorio Iglesias Rodríguez
Supervisor

Dr. Rodrigo Sánchez Carballo
Supervisor & Tutor

Prof. Gregorio Iglesias Rodríguez,
Professor of Coastal Engineering
Plymouth University

Dr. Rodrigo Sánchez Carballo
Profesor Ayudante Doctor del Departamento Ingeniería Agroforestal
Universidade de Santiago de Compostela

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Abstract

Marine energy is one of the most promising alternatives to fossil fuels due to the enormous energy resource available. However, it is often considered uneconomical and difficult due in part to the initial stage of development of the technology and the harsh marine environment. With this in view, this Thesis proposes combined wave and wind energy farms as a way to enhance marine energy competitiveness by realising the mutual benefits. First, this combination increases the sustainability of both energies by means of a more rational harnessing of the natural resources. Second, combined energy systems result in reduced costs by means of the technological synergies between both renewables. In this sense, the benefits that can be realised by these combined systems are deeply analysed in this Thesis in a holistic way through numerous case studies implemented by third generation models used as a conjunction – SWAN and WAsP. Subsequently, the benefits considered in the different case studies are translated into monetary terms by assessing their impact on the levelised cost of energy (*LCOE*). It is found that the energy cost can be reduced around 50% relative to standalone wave farms. These results confirm the interest of combining wave and wind energy through co-located farms for the purpose of enhancing the economic viability of marine energy.

Keywords: Marine energy; Offshore wind energy; Wave energy; Diversified system; Combined wind-wave farm; Shadow effect; Power variability; Economic assessment; *LCOE*.

Resumen

La energía marina es una de las alternativas más prometedoras al uso de los combustibles fósiles debido a la gran cantidad de recurso disponible. Sin embargo, es a menudo considerada como una fuente de energía de difícil aprovechamiento y de elevado coste debido, en parte, a que la tecnología se encuentra en una etapa inicial de desarrollo y a las duras condiciones del medio marino. En este contexto, en esta Tesis se propone el aprovechamiento conjunto de dos energías renovables, la energía de las olas y la energía eólica *offshore*, como alternativa para aumentar su competitividad y favorecer así su desarrollo. Por un lado, esta combinación resulta en una utilización más racional del recurso existente mejorando así la sostenibilidad. Y por otro lado, estos sistemas combinados ofrecen la posibilidad de reducir el coste de la energía debido a las sinergias tecnológicas que entre ambas renovables se producen. Por tanto, el objetivo de esta Tesis es analizar de manera pormenorizada los beneficios que pueden derivarse del uso de parques combinados de energía eólica y undimotriz. Para ello, se establecen diversos casos de estudio que son implementados en modelos de simulación de tercera generación (SWAN y WAsP). Los resultados obtenidos se expresan, asimismo, en términos económicos para cuantificar el impacto que dichas sinergias tienen en el coste nivelado de la energía (*LCOE*). En base a los resultados, se puede afirmar que este coste se puede reducir en un 50% mediante parques combinados respecto a instalaciones eólicas y del oleaje independientes, situando a estas fuentes de energía en valores mucho más cercanos a los de otras renovables ya consolidadas. Esto confirma las amplias posibilidades que ofrece el aprovechamiento conjunto de la energía eólica y de las olas en aras de realzar la viabilidad económica de la energía marina.

Palabras clave: Energía marina; Energía eólica *offshore*; Energía de las olas; Sistema energético diversificado; Parque eólico y undimotriz combinado; Efecto de Sombra; Variabilidad de la señal de potencia; Análisis Económico; *LCOE*.

Resumo

A enerxía mariña é unha das alternativas máis prometedoras ao uso dos combustibles fósiles debido á gran cantidade de recurso dispoñible. Con todo, é a miúdo considerada como unha fonte de enerxía de difícil aproveitamento e de elevado custo debido, en parte, a que a tecnoloxía atópase nunha etapa inicial de desenvolvemento e ás duras condicións do medio mariño. Neste contexto, esta tese propón o aproveitamento conxunto de dúas enerxías renovables, a enerxía da ondada e a enerxía eólica *offshore*, como xeito para aumentar a súa competitividade. Por unha banda, esta combinación resulta nunha utilización máis racional do recurso existente que mellora a súa sustentabilidade. E doutra banda, estes sistemas combinados ofrecen a posibilidade de reducir o custo da enerxía debido ás sinerxias tecnolóxicas que se producen entre ambas renovables. Neste senso, o obxectivo desta tese é analizar de xeito pormenorizado os beneficios que se poden derivar do uso de parques combinados de enerxía eólica *offshore* e da ondada. Para elo, establécense diversos casos de estudo que son implementados en modelos de simulación de terceira xeración – SWAN e WAsP. Así mesmo, devanditos beneficios exprésanse en termos económicos para cuantificar o seu impacto no custo da enerxía. En base aos resultados, pódese afirmar que este custo pódese reducir nun 50% mediante parques combinados respecto a instalacións eólicas e da ondada independentes, o que situaría a ditas fontes de enerxía en valores moito máis pretos aos de outras renovables xa consolidadas. Isto confirma o interese de combinar a enerxía eólica *offshore* e da ondada en aras de realzar a viabilidade económica da enerxía mariña.

Palabras chave: Enerxía mariña; Enerxía eólica *offshore*; Enerxía da ondada; Sistema enerxético diversificado; Parque eólico e *undimotriz* combinado; Efecto de Sombra; Variabilidade do sinal de potencia; Análise Económica; *LCOE*.

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Symbols and abbreviations

Symbols

AWT_k	percentage of Accessible Wind Turbines during k % of time
b	spacing between the piles of the wind turbines (m)
c_t	transmission coefficient of the offshore wind turbines
c_x	spatial velocities in the x components (ms^{-1})
c_y	spatial velocities in the y components (ms^{-1})
c_θ	rate of change of group velocity which describes the directional (θ) rate of turning due to changes in currents and water depth
c_σ	rate of change of group velocity which describes the frequency (σ) shifting due to changes in currents and water depth
$c(\tau)$	cross-correlation factor at a time lag τ
$c(0)$	instantaneous correlation
c.i.	confidence interval
C_d	drag coefficient of the wind turbine piles
CLF_i	co-Location feasibility index of the i-th site point
d	water depth (m)
D	rotor/pile diameter (m)
D_p	diameter of the wind turbine piles (m)
D_w	mean wind direction (º)
E	energy density (Jm^{-3})
f	wave frequency (s^{-1})

g	gravitational acceleration (ms^{-2})
H	height at which the wind speed is measured (m)
H_i	incident significant wave height (m)
H_{m0}	significant wave height (m)
$\overline{H}_{m0}$	average significant wave height (m)
$H_{m0,max}$	maximum value of the significant wave height (m)
H_s	significant wave height (m)
$(H_{s,b})_I$	significant height incident on the *i*-th wind turbine in the baseline scenario, i.e. without WECs (m)
$(H_{s,W})_I$	significant height incident on the *i*-th wind turbine with co-located WECs (m)
HRA_j	significant wave height reduction along the *j*-th area of wind turbines. This non-dimensional index reflects the wave recovery with increasing distance from the WECs (%)
HRC_j	significant wave height reduction along the *j*-th row of wind turbines. This non-dimensional index reflects the wave recovery with increasing distance from the WECs (%)
HRF	wave height reduction within the farm. It is a nondimensional parameter that provides information about the average wave height reduction within the wind farm (%)
IA	increase in the accessible timeframe for O&M achieved with co-located WECs (%)
J	raw wave power (kWm^{-1})
$\overline{J}$	average raw wave power (kWm^{-1})
J_{farm}	time-averaged power generated by the WECs (kW)
$J_{W,i}$	power generated by the *i*-th WEC (kW)
k	percentage of time during which the wind turbines are accessible
L	distance between the twin bows of a single WaveCat WEC (m)
$LCOE$	Levelised Cost of Energy (€/MWh)
m	number of turbines in the *j*-th row
m_n	spectral moment of order n
n_T	total number of time points

n_W	total number of WECs or wind turbines
N_{WECs}	number of WECs
N	wave action density spectrum (Js)
P	raw wind power (Wm^{-2})
$\bar{P}$	average value of the available raw power (Wm^{-1} or Wm^{-2})
P_{farm}	time-averaged power generated by the wind turbines (W)
$P_{w;i}$	power generated by the *i*-th wind turbine (W)
P_{wave}	wave power per unit crest width (Wm^{-1})
$\bar{P}_{wave}$	average wave power per unit crest width (Wm^{-1})
P_{wind}	wind power density (Wm^{-2})
$\bar{P}_{wind}$	average wind power density (Wm^{-2})
r	rate between the total number of WECs and wind turbines
R^2	coefficient of determination
S_{tot}	energy density source term which describes local changes to the wave spectrum (Js^{-1})
t	a point in time (s)
T	total number of time points considered (s)
T_b	total number of hours per year when H_s within the wind farm is lower or equal to 1.5 m for the baseline scenario, i.e. isolated turbines (h)
T_e	energy period (s)
$\overline{T_e}$	average energy period (s)
$T_{e,max}$	maximum energy period (s)
T_{mo1}	mean wave period (s)
T_p	peak wave period (s)
T_W	total number of hours per year when H_s within the wind farm is lower or equal to 1.5 m with co-located WECs (h)
T_{WECs}	total number of hours per year when H_s within the wind farm is lower or equal to 1.5 m with co-located WECs (h)
U_w	wind speed (ms^{-1})
U_{10m}	wind speed at 10 m above the sea level (ms^{-1})
$\overline{U_{10m}}$	average wind speed 10 m above the sea level (ms^{-1})

$U_{10m,max}$	maximum value of the wind speed 10 m above the sea level (ms^{-1})
x_i	available raw power (Wm^{-1} or Wm^{-2})
z	roughness length (m)
α_x	weighted factor of the parameter *x* when calculating the *CLF* index
Δ	absolute variability index
$\Delta T_{O\&M}$	increase in the accessible timeframe for O&M achieved with co-located WECs (%)
ρ	water density (kgm^{-3})
ρ_a	air density (kgm^{-3})
ρ_w	sea water density (kgm^{-3})
θ	mean wave direction (º)
θ_w	wind direction (º)
$\theta_{wav,mean}$	mean wave direction (º)
$\theta_{wind,mean}$	mean wind direction (º)
σ	standard deviation
σ_J	standard deviation of the wave raw power (Wm^{-1})
σ_p	standard deviation of the wind raw power (Wm^{-2})
τ	time lag (h)
μ	mean value

Abbreviations

BSH	Bundesamt fuer Seeschiffahrt und Hydrographie
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
COP21	21st Conference of the Parties to the United Nations Framework Convention on Climate Change
CS	Case Study
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund

IF	Impact Factor
O&M	Operation & Maintenance
PDA	Peripherally Distributed Array
SET-Plan	European Strategic Energy Technology Plan
SWAN	Simulating WAves Nearshore
UE	European Union (Unión Europea)
WAsP	Wind Atlas Analysis and Application Program
WEC	Wave Energy Converter

I

Introduction

Introduction

1. Motivation and scope of the Thesis

Recently, at the Paris climate conference (COP21) in December 2015 (United Nations, 2015), 195 countries adopted the first-ever universal, legally binding global climate deal. The agreement set out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming. Therefore, reducing carbon emissions and, thus, finding alternatives to fossil fuels is fundamental. In this context, marine energy, as part of the offshore renewable energy family, has a strong potential for development (Bahaj, 2011; Iglesias and Carballo, 2009) and is called to play a key role in the EU energy policy as identified by the European Strategic Energy Technology Plan (SET-Plan). Indeed, the target for 2050 is an installed capacity of some 188 GW for wave and tidal energy and 460 GW for offshore wind energy (EU-OEA, 2010; Moccia et al., 2011).

Nevertheless, being a young industry, marine energy has not yet reached market competitiveness. Offshore wind energy is the most developed ocean renewable, with a relatively mature technology (EWEA, 2012). It is more complex and costly than onshore wind. However, due to a combination of better wind resources and larger turbines, it provides higher energy yields than its counterpart on land. In addition, the sea offers more space and less public resistance (Ramos and Iglesias, 2014; Veigas et al., 2014). Notwithstanding, its levelised cost is still higher than the cost for traditional resources and this may hinder its development and penetration into the electricity market. The economic handicap is even greater in the case of wave and tidal energy (Astariz and Iglesias, 2015a) due to the initial stage of development of the energy converters (Babarit et al., 2012), which are mostly initial prototypes, and the high capital cost involved. Moreover, it is necessary to add the larger costs implied in the Operation and Maintenance (O&M) tasks due to the hard marine environment (Morthorst, 2003) that harms all these offshore installations.

Notwithstanding their environmental benefits, marine renewables have to be economically competitive if they are to attract significant investment (Astariz et al., 2015d; Bucher et al., 2016). To bridge the gap between the project costs and the wholesale electricity price, numerous recovery strategies and fiscal stimulus packages were implemented in several countries around the world. Since then, however, uncertainties and lack of knowledge about actual or expected effects of policies in support of a green energy economy transition have been witnessed and reported in the literature (Astariz et al., 2014). This fact, together with other characteristics inherent to renewables, such as their intermittency (Astariz and Iglesias, 2016a), may hamper the large scale integration of marine energy into the grid.

In recent years, taking advantage of various marine renewables at the same time through combined systems has been regarded as a good solution to promote and accelerate the development of marine energy (Abanades et al., 2014; Carballo and Iglesias, 2013; Kadiri et al., 2012). The combination of offshore wind with wave energy is regarded as one of the most promising options since there are a number of synergies which arise when this combination is considered:

The environmental impacts of wave and offshore wind energy are a major consideration in the development of these renewables (Abanades et al., 2014). The combined option presents an important advantage in environmental terms in that it is likely to have a reduced impact (relative to independent installations), leading to a better utilisation of the natural resources (Lund, 2007). Besides, the combination of both renewables could result in a transfer of knowledge on the environmental impacts from one sector to another.

Moreover, this combination brings about a cost reduction owing to the use of common installations, such as the electric grid infrastructure (Astariz et al., 2015a; Musial and Ram, 2010). Besides, the dimensions and special characteristics of offshore renewable energy projects require the use of expensive specialist marine equipment and facilities, such as port space or installation vessels. A combined project where these elements are shared would also contribute to reducing the costs.

Furthermore, the inherent variability of renewable energy is a problem for developers, since energy markets require dependable (predictable and preferably constant) sources of power (Lund, 2006). A number of studies have been carried out on the large-scale integration of power from renewable into the electricity supply in recent years (Duic and Carvalho, 2004; Østergaard, 2009). Some of them offer the possibility of introducing that *diversity* in the renewable sources mix that may help to reduce the variability and uncertainty in the produced power, so to improve its reliability (Fusco, 2010). In this sense, waves are more predictable and less variable than winds (Veigas et al., 2014) and, consequently, smoothed power output could be obtained by combined wave and wind energy farms.

Despite all these benefits of combining both renewables, at present there are no combined wave-wind devices operating in the sea, and only a few prototypes or concepts have been proposed so far. According to the degree of connectivity between the offshore wind turbines and Wave Energy Converters (WECs) there are different possibilities for a combined wave and wind array (Pérez-Collazo et al., 2015): (i) co-located wind-wave energy farms; (ii) hybrid converters; and (iii) energy islands. The former, i.e. co-located systems (Stoutenburg, 2010), is the most feasible and simplest option at the present stage of development of wave and offshore wind technologies (Borg, 2013), since they combine offshore wind turbines and WECs in the same marine area with independent foundation systems but sharing grid connection, O&M equipment and personnel, port structures, etc. (Pérez-Collazo et al., 2014).

In the same line, only some studies have been carried out in recent years about the synergies between both renewables, and these have always analysed them one by one from a theoretical point of view, focusing on a concrete location and without considering the economic implications of the results obtained in terms of energy competitiveness. In this context, the aim of this Thesis is to assess the benefits of combined wave and wind energy farms in a holistic way and to analyse if co-located wave and wind energy farms result in a more convenient option than individual systems. This objective is achieved through the implementation of numerous case studies by considering the majority of the variables implied and establishing a new tool to select optimum locations for combined wave and wind energy installations.

This purpose is developed through a series of research articles, published in peer-reviewed journals, composing the main body of this Thesis, each of them constituting a fundamental step towards the achievement of the final objective of this work.

2. Justification of the unity and coherence of the Thesis

This Thesis is structured in eight chapters as follows. First, the present Chapter (I – *Introduction*) provides an overall perspective of this work. Then, in Chapter II – *Objectives*, the final and intermediate objectives are briefly presented, the latter being defined according to the different tasks and coherent steps required so as to fulfil the proposed final objective. The four following chapters (Chapters III to VI) correspond to respective publications in peer-reviewed journals constituting the main body of this Thesis. Each of them represents a piece of research whose integration forms a whole through which a holistic assessment of the benefits that would arise from combining wind and wave energy is developed. For this purpose, each of the publications deals with one of the four intermediate objectives as stated in Chapter II.

In Chapter III – *Hybrid wave and offshore wind farms: A comparative case study of co-located layouts*, co-located wave and wind energy farms are proposed as a way to reduce the O&M cost by taking advantage of the *shadow effect* that WECs cause within the wind farm area. On the one hand, offshore installations involve a greater O&M demand due to the harsh marine environment. However, the access of the workboats to the wind farms – the most cost-effective access system (Hassan, 2013) – is only possible when the significant wave height is below 1.5 m (Bierbooms and Bussel, 2002; Hassan, 2013). Thus, while modern onshore wind turbines present accessibility levels of 97% (Henderson and Bussel, 2001), this level can be significantly reduced in offshore installations, even below 60%, resulting in increased maintenance costs (Perveen et al., 2014). In fact, O&M costs of offshore wind farms typically amount to between 20 and 25% of the total lifetime costs of the installation (Hassan, 2013). On the other hand, it is clear that 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 called the *shadow effect* (Carballo and Iglesias, 2013). Therefore, by combining WECs and offshore wind parks at the same location, the *shadow effect* could be used to obtain a milder wave climate inside the park and enlarge the weather windows for accessing the wind turbines for O&M. On this basis, the aim of this chapter is to investigate the feasible increase in the accessibility time to the turbines that could be obtained by means of collocated WECs. The investigation is carried out by implementing and analysing multiple array layouts.

This chapter, which has been published in *International Journal of Marine Energy* in 2016, draws on previous work published in the following articles: (i) *Towards the optimal design of a co-located wind-wave farm* (published in *Energy*, journal indexed in the Journal Citation Reports with an impact factor, *IF,* of 4.292 in the year 2015); (ii) *Co-located wind-wave farm synergies (Operation & Maintenance): A case study* (published in *Energy Conversion and Management*, *IF*: 4.801 in 2015); and (iii) *Improving wind farm accessibility for operation & maintenance through a co-located wave farm: Influence of layout and wave climate* (published in *Energy Conversion and Management*, *IF*: 4.801 in 2015)

In Chapter IV – *Output power smoothing and reduced downtime period by combined wave and wind energy farms*, co-located wave and wind energy farms are proposed as a concrete and realistic solution to the other major handicap of offshore wind energy: the inherent power variability. Given the fluctuating nature of wind resources and their sensitivity to weather patterns, the integration of major offshore wind yields into the existing energy supply infrastructure will be a challenge. The power variability translates into instability in the power system and the associated *balancing costs*: renewable energy installations require higher surplus capacity for supply security reasons (*reliability impact*) due to the source variability and difficulty of prediction, which leads to values of the capacity factor that tend to be lower than those of conventional plants (*balancing impact*) (Eirgrid, 2008). In this context, combining capacity from renewables with uncorrelated or complementary outputs can be of considerable benefit (Freris and Infield, 2008). Precisely, this chapter presents combined wave and offshore wind energy farms as a means of reducing the power fluctuations or, in other words, smoothing the power output. Various locations and mixed installations are considered in this analysis of the *power smoothing effect*. This chapter has been published in *Energy* in 2016 (*IF* : 4.292, year 2015).

In Chapter V – *Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-location Feasibility index*, an *ad hoc* tool to select viable locations for combined offshore renewable energies is defined. As for the global distribution of the wind and wave energy resources, it is apparent that there are some areas with large possibilities for these combined options (Astariz and Iglesias, 2016a). However, optimising the site selection for a combined concept, in order to maximise the synergies between both renewables, involves not only the characterisation of the wave and wind resources but also the computation of other parameters of interest, such as their variability and the correlation between them. Unfortunately, these tasks are generally seen as disconnected and tackled as such, even though they are deeply interrelated and should be treated as two phases of the same procedure. As a consequence, most assessments of wave and wind resources conducted over recent years have considered each energy in an independent way, giving rise to a lack of the elements required for properly conducting the assessment of combined farms. The aforementioned limitation arises from a site selection for combined farms largely dependent on the available resource. Therefore, if accurate and more realistic farm site selection is to be conducted, all the relevant parameters have to be examined in a holistic way. In this sense, the *CLF* (Co-location Feasibility) index is defined in this chapter and proposed as an *ad hoc* tool to encompass and balance wave and wind energy synergies when selecting an optimum location for co-located wave and wind farms. This chapter has been published in *Energy Conversion and Management* in 2016 (*IF*: 4.801, year 2015).

In Chapter VI – *Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study,* the application of the new tool defined in the previous chapter is illustrated by means of a case study off the Danish coast. After selecting a promising location for deploying a combined wave and wind energy by means of the *CLF* index and considering other technical and economic limitations, a co-located farm is defined and implemented to assess the benefits, with regard to standalone installations, that can be achieved thanks to the synergies between wave and wind energy – some of which reviewed in previous chapters, and including other synergies such as common installations and joint maintenance strategies. Subsequently, the results are translated into monetary terms in order to assess the economic competitiveness of the combined wave and wind energy farms. This chapter has also been published in *Energy Conversion and Management* in 2016 (*IF*: 4.801, year 2015).

All in all, the original research articles composing the main body of this Thesis are profoundly connected, each of them constituting a coherent step towards the fulfilment of the intermediate objectives of this research – which in turn leads to the achievement of the final objective – and therefore providing coherence and unity to this Thesis.

Then, in Chapter VII – *General discussion,* an integrated analysis of the results obtained in the preceding chapters (Chapters III to VI) is conducted so as to properly describe their significance within the general context of this work, thereby ensuring the reader’s understanding of the present research as a whole. Finally, in Chapter VIII – *Conclusions*, the main contributions and findings are synthetically presented along with the planned future research, part of which is currently under development.

II

Objectives

Objectives

The overarching objective of the present Thesis is the development of a comprehensive assessment of the benefits that ensue from a co-located wave and offshore wind energy farm, as opposed to independent installations. Co-located farms are proposed as a way to enhance the competitiveness of these promising renewables which, being at an initial stage of development, present similar handicaps that may hinder their penetration into the electricity market. This Thesis is focused on a specific type of combined alternative, the co-location, where a wave energy farm and a conventional offshore wind farm are co-located at the same maritime space sharing common installations and facilities. For attaining this final objective, the following intermediate objectives – each of them corresponding to a publication in a peer-reviewed journal which jointly constitute the main body of this work – are established.

(i). To investigate how the synergy between wave and offshore wind energy, by virtue of the reduction of the significant wave height caused by the WECs extracting part of the energy of the incoming waves (*shadow effect*), leads to enlarged *weather windows* for O&M.

Tasks involved: to investigate the WECs array disposition that maximises the *shadow effect* through a preliminary case study where different hypothetical layouts are considered by implementing them in a third generation wave model (SWAN) under different wave conditions; to extend the study to a wind farm currently in operation modelling the configurations that provided best results in the previous study and considering the total wave spectrum; to establish a sensitivity analysis of the wind farm characteristics (e.g. depth and distance from coast, sea climate and layout); to draw general conclusions about the conditions that enhance accessibility to the wind turbines due to the co-located WECs.

(ii). To analyse the effectiveness of co-located wave and wind farms as a *power smoothing* method, with all the resulting benefits in terms of energy supply security and reduced balancing costs, by assessing the existing correlation between the wind and wave resource at different locations and if the aggregation and combination of both resources can reduce the overall variability of the power produced, one of the greatest handicaps to the penetration of renewables into the electricity market.

Tasks involved: to define the case studies considered in this study selecting two wind farms currently in operation where the correlation between waves and winds is significantly different in order to analyse the influence of this factor on the *power smoothing* effect; to carry out a complete and accurate analysis of wave and wind resource at these locations on the basis of half-hourly measured wave and wind data; to propose different combined wave and wind energy farms and calculate their power output; to determine the non-operational periods, the power variability and the capacity factor in the proposed farms and draw conclusions about the *power smoothing* effect; to translate the results into monetary terms.

(iii). To define a method to identify optimum locations for installing combined wave and wind energy farms and, indeed, where combined parks are more advantageous than independent wave and wind energy farms.

Tasks involved: to define an *ad hoc* tool, the *CLF* index (Co-location Feasibility index), which encompasses and balances the relevant parameters when selecting the location for a combined wave and wind energy farm; to determine a narrow area suitable for co-located farms along the Danish coast by assessing the wave and wind resource by means of third-generation numerical models (SWAN and WAsP) and considering other relevant factors such as the technical limitations and economic concerns; to select the most convenient location for a co-located farm within this area by using the *CLF index* on the basis of annual series of wave and wind data from 2005 to 2015 to obtain consistent results about the validity of the new defined tool; to characterise the wave and wind resource in the selected location.

(iv). To assess the benefits that could be obtained by combining wave and wind energy systems, relative to standalone parks, at a convenient location and in a holistic way, and to evaluate also the impact of these benefits in the *LCOE* to draw conclusions about the competitiveness of combined farms.

Tasks involved: to define a co-located wave and offshore wind energy farm at the site previously selected on the basis of the characteristics of the existing offshore wind farms and the co-located farm layout identified in previous studies as the best option; to implement the defined farm on third-generation numerical models (SWAN and WAsP); to assess the benefits of wave and wind combined systems relative to independent farms on the basis of the model outputs considering hourly wave and wind observations from 2005 to 2015; to compare the power output of the co-located farm with those of wave and wind farms operating as independent installations; to analyse the power smoothing and shadow effects, as well as the decrease in the non-operational periods; to analyse savings on capital and maintenance cost derived from the combined farm; to translate the results into monetary terms to quantify the cost energy reduction involved.

Therefore, these specific objectives allow to characterise the different synergies that materialise when a co-located wave and wind energy farm is considered, constituting intermediate steps towards the final objective of this Thesis: to draw overall conclusions about if co-located farms provide a feasible opportunity to enhance marine energy competitiveness.

III

Hybrid wave and offshore wind farms: A comparative case study of co-located layouts

S. Astariz, C. Perez-Collazo, J. Abanades, G. Iglesias

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IV

Output power smoothing and reduced downtime period by combined wind and wave energy farms

S. Astariz, G. Iglesias

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V

Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-Location Feasibility index

S. Astariz, G. Iglesias

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VI

Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study

S. Astariz, G. Iglesias

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VII

General discussion

General discussion

Combined energy systems, in particular co-located offshore wind turbines and wave energy converters, are presented in this Thesis as a solution to increase the competitiveness of marine energy by taking advantage of the synergies between both renewables. This Thesis develops a holistic assessment of this combination to evaluate its derived benefits relative to standalone installations. For this purpose, the different synergies between both renewables are evaluated in Chapters III, IV, V and VI, each chapter focusing on a particular aspect with the final purpose of drawing general conclusions about the increase in marine energy profitability that can be realised through co-located wave-wind energy farms.

Among the different synergies between wave and offshore wind, Chapter III – ***Hybrid wave and offshore wind farms: A comparative case study of co-located layouts*** − is concerned with the shielding effect of the WECs over the offshore wind farm, the so-called *shadow effect* (Astariz and Iglesias, 2015c). Operation and maintenance (O&M) is a particularly challenging aspect of offshore wind energy. First, the harsh marine environment requires more frequent tasks relative to onshore wind turbines; and second, these tasks can be delayed by difficult sea conditions – in particular, large wave heights, since the operational limit of workboats for O&M tasks is a significant wave height of 1.5 m (Bierbooms and Bussel, 2002), leading to downtime and, consequently, increased costs. Indeed, O&M costs of offshore wind farms typically constitute between 20 and 25% of the total lifetime costs of the installation (Blanco, 2009; Hassan, 2013; Morthorst, 2003).

This handicap of offshore wind farms can be offset in part by combining offshore wind and wave energy systems: wave energy converters adequately deployed extract part of the incoming wave energy, resulting in a milder wave climate within the wind park, and hence better accessibility for maintenance tasks and reduced downtime. On this basis, the aim of this study is to analyse the wave height reduction achieved by deploying co-located WECs and the influence of the layout and wind farm characteristics on the results. This purpose is carried out through various cases studies: a hypothetical wind farm at the WaveHub site, a real wind farm (Alpha Ventus) and a sensitivity analysis comparing different wind farms currently in operation (Alpha Ventus, Bard 1, Horns Rev 1 and Lincs).

In all these case studies the wave model Simulating Wave Nearshore (SWAN) is used to simulate the wave propagation. SWAN is a third generation numerical wave model which computes the evolution of random waves and accounts the refraction, as well as wave generation due to wind, dissipation and non-linear wave-wave interactions (Booij et al., 1999). This model was successfully used to model the propagation of waves, the absorption (transmission) of energy by a wave farm, and the impact of a wave farm on the nearshore wave conditions and the beach profile in its lee (Iglesias and Carballo, 2014). Moreover, the wave model was set up to account the following wave processes: shoaling, refraction due to current and depth, whitecapping, bottom friction and depth induced wave breaking. As for the wave climate, hindcast data from WaveWatch III, a third-generation offshore wave model, are used in conjunction with wave buoy measurements. In all cases, the proper functioning of the nearshore wave propagation model is validated with wave buoy data.

In this work, and in order to obtain high-resolution results without incurring too large computational costs, the model is implemented in the so-called nested mode in all cases, with two computational grids: (i) a coarse grid from offshore to the coast, and (ii) a fine ('nested') grid covering the study site. The high resolution of the nested grid is instrumental in defining the position of the wind turbines and WECs and simulating their individual wakes with accuracy – and the latter ought to be a prerequisite in this kind of analysis (Abanades, 2014). The bathymetric data of each region are interpolated onto this grid.

The wind turbines are represented in the model by a transmission coefficient, whose value can vary in theory from 0% (i.e., 100% of incident wave energy absorbed) to 100% (Ponce de León et al., 2011; Veigas et al., 2014), which is calculated by the method described in (Hayashi and Kano, 2011). For its part, the WEC device used in all case studies is the WaveCat: a floating offshore WEC whose principle of operation is wave overtopping (Iglesias et al., 2011). Its wave transmission coefficient is implemented on the wave propagation model using the results of the laboratory tests carried out by Fernandez et al., 2012.

To analyse the shielding effect of the co-located WECs two groups of parameters are defined: (i) parameters to determine the percentage of reduction of the wave height; and (ii) indices to quantify the increase in the accessibility.

First, a preliminary case study of a co-located wave-wind farm is carried out to get a better understanding of the so-called *shadow effect*. The analysis is carried out by the definition of a hypothetical wind farm at the Wave Hub site. The methodology followed to do this research can be structured in three main pillars: i) the analysis of the location and wave climate; ii) the co-located farms design; and iii) the implementation on the wave propagation model. Thus, three case studies are defined as representative of the wave climate in the area. The wind farm layout is selected on the basis of the operating wind farm Horns Rev 1 and the WECs' disposition is defined considering the restrictions from the wind farm and the predominant wave directions. Indeed, 14 hypothetical co-located farms are analysed with WECs deployed as a peripherally distributed array. Different spacings between devices is considered, as well as different configurations intercepting only prevailing directions and prevailing and secondary directions, and with different layouts considering WECs at an angle of 45º or forming an arc. These configurations are used to evaluate the influence of the layout – spacing and disposition of the devices – on the results.

In the light of the findings, an important wave height reduction is achieved in all cases and configurations, with values of reduction up to 24%. The arrays with lower spacing between converters manage the best results of height reduction. Moreover, adding WECs to face the secondary wave direction contributes considerably to the wave height reduction. Importantly, it is found that the configuration in arc achieves the best results in spite of the fact that it involves fewer converters, which is interesting in monetary terms. All in all, it is demonstrated that WECs deployed as a barrier at the periphery of a wind farm bring in a milder wave climate in the inner part of the farm. However, the effectiveness depends on the layout of the co-located wave-wind energy farm.

When identifying the best layouts in terms of wave height reduction, the study is extended to a real wind farm and considering the total spectrum of the wave climate in order to translate the wave height reduction into the implied increase of the accessibility level to the wind turbines. This investigation is carried out through a case study at the Alpha Ventus wind farm. The co-located WECs layouts are proposed on the basis of the previous results and taking into account the wind farm layout, the wave climate and in particular the prevailing wave direction. In total, 15 layouts are tested using high-resolution numerical modelling and real sea conditions from January to December 2013. The results show that thanks to the wave energy extraction by the WECs, weather windows (hence, access time) increase very significantly. Concretely, in the baseline scenario the wind turbines are accessible 68% of the time over one year, whereas, with co-located farms, this value raises by up to 82%. This represents an increase in the accessibility to the turbines of almost 15%. With regard to the co-located farm layout, the largest results of wave reduction are obtained, as in the preliminary analysis, with the smallest spacing between devices. Moreover, it is observed that the best results are achieved for the configurations with WECs facing not only waves coming from the main direction but also secondary directions, since the latter configurations provide more uniform wave height reduction in the whole area covered by the wind farm. Furthermore, it is worth pointing out that although the largest access to the wind turbines is obtained for the configuration with WEC rows at angle, the configuration in arc achieves a close value, despite of having less number of WECs, which could be an interesting aspect for a future cost-effectiveness study.

Finally, a comparative study considering different wind farms as baseline scenarios (Alpha Ventus, Bard 1, Horns Rev 1 and Lincs) is carried out to investigate how the *shadow effect* can be materialised under different conditions in terms of: (i) location (depth and distance from the coast), (ii) sea climate, and (iii) wind farm layout. First, the wind farm characteristics are analysed, as well as the wave climate at the sites considered. Second, with this information and on the basis of the previous works, two different layouts of the co-located WECs are proposed for each farm and wave propagation is modelled by means of SWAN. Third, the results are analysed through impact indicators quantifying the wave height reduction and the power production.

An important wave height reduction is achieved in all cases, with significant enlargements of the weather windows for O&M. In fact, in the case of Alpha Ventus and Lincs, values around 82% are obtained for the accessibility, which would ensure an availability of the turbines of 90% or higher (Astariz et al., 2015b). All in all, it can be concluded that: (i) co-located WECs increase the availability of the wind farms considerably, which is positive in terms of the cost-competitiveness of the farm; (ii) deploying WECs as a barrier is particularly convenient in wind farms with an energetic sea climate; (iii) better results are achieved in the case of wind farms with a square layout and with smaller spacing between wind turbines, since lower number of co-located WECs are required; and (iv) in the case of small wind farms the ratio between the number of WECs required to achieve the desired wave height reduction and the existing wind turbines is larger, which would involve higher costs.

In summary, co-located wind and wave energy farms are a good alternative to reduce the wave height within a wind farm, achieving more frequent and longer access weather windows, and consequently a lower maintenance cost.

Apart from the higher maintenance cost that marine installations required, offshore wind and wave energy suffer from a common handicap of all renewables: the power fluctuations. All renewable technologies ultimately derive energy from natural sources that vary in their availability over different timescales (Hund, 2006). In this sense, there are growing concerns about the extent to which variable power production impacts power system reliability, efficiency, and the ability to balance the power supply and demand (Østergaard, 2009). In this context, terms such as *balancing responsibility* – the obligation of a power generator to match its forecast electricity output in real-time – or *balancing cost* – the increased cost of maintaining system balance – have proliferated in the studies about the consequences of the penetration of renewables into the electricity market (Musial and Ram, 2010) and, especially, among the arguments against the increased use of "new" renewables such as wind power or marine energy. On the one hand, the rapid growth, especially of wind power, led to significant market share in some countries within a short timeframe thus magnifying grid integration issues. On the other hand, these technologies introduce a new quality of natural cycles in that they can fluctuate over short timescales intra-day and intra-hourly which requires different management strategies than previously established.

Against this background, the option of combining different renewable resources located in a range of areas within the same or in a different energy system (*diversified renewable systems*) (Figueiredo and Martins, 2010) has been recently proposed to manage the variability of renewable power and reduce the system integration costs of renewables (Fusco, 2010). Otherwise, when only one resource is available – wind energy for example – these benefits can only be realised by aggregating the power of geographically disperse sites.

On this basis, Chapter IV – ***Output power smoothing and reduced downtime period by combined wind and wave energy farms*** − focuses on the possibility of combining the power production of wave and offshore wind technologies in the same site to provide a more continuous power output. The analysis is carried out through two case studies, in which two wind farms currently in operation are considered as baseline scenarios: Alpha Ventus and Horns Rev 1. The analysis is conducted on the basis of half-hourly measured wave and wind data provided by the FINO1 research platform for the Alpha Ventus wind farm and by a nearby buoy in the case of the Horns Rev wind farm.

First, a complete and accurate analysis of wave and wind resource is carried out at both locations on the basis of the most characteristics parameters when describing the available wind and wave climate: the wind speed, the significant wave height, the peak period and the wave and wind direction. Representative graphs such as the wave and wind roses or scatter diagrams are obtained and several statistics parameters are used to analyse the waves and winds variability. It is found that both waves and winds present relevant fluctuations along the year, especially during the storm periods, with fluctuations over 7%.

Second, the agreement between wave and winds general patters is analysed since the *power smoothing effect* that can be provided by a diversified systems depends in part on the correlation between the resources considered in the combined installation. Preliminary conclusions are drawn on the basis of the correspondence between the measured and expected waves in view of the existing winds. It is found that expected values are more often than not lower than those observed, which can be ascribed to the contribution to the significant wave height of swells, i.e., waves generated far away by winds unrelated (or little related) to those blowing in the area in question, and therefore not adequately captured by theoretical equations. More accurate conclusions about the correlation between waves and winds are obtained through the cross-correlation factor, $c(\tau)$, which gives the correspondence between two signals at a time lag τ. In this study, the correspondence between wind and wave power at the same point in time, instantaneous correlation $c(0)$, is of particular interest. In both locations, it is found that the peaks of wave height lag behind those of wind speed, a fact that can be used to smooth the power variability and especially to avoid non-operational periods – when the wind speed falls outside the range of power production, wave energy can continue to supply power. However, the correlation is higher at Horns Rev (65%) than at Alpha Ventus (55%).

The above findings provide a glimpse of the potential *power smoothing effect* of combining both sources at the same time. However, and in order to obtain a more comprehensive analysis, the power production from a mix of wave energy converters and wind turbines is assessed. Various hypothetical mixed farms with different percentages of installed wave power are considered. The power output is calculated on the basis of the wind turbines power curves and the performance of the wave devices, analysing the power variability, capacity factor and the non-operational periods (downtime). The selected wave energy converter is the WaveCat (Iglesias et al., 2011), for which laboratory test results are available (Fernandez et al., 2012), along with previous studies on the interactions between devices in co-located farms (Astariz et al, 2015a).

In the case of Alpha Ventus, and in the light of the results, all the mixed farms analysed present less variability of the output power than the corresponding wave and wind farms as independent systems, making the combined exploitable potential larger than the sum of the parts considered in isolation. Therefore, any combination of a WEC with a wind turbine would benefit towards a more continuous production of power compared to the operation of wind turbines as standalone systems. Indeed, the best results are obtained for the mixed farm constituted by 60 MW of the wind farm (baseline scenario) and 30 MW of co-located WECs (50% of the wind farm installed power), in which a reduction in the output power variability of 6% is achieved. This does not happen at Horns Rev, where the output power of all combined farms presents higher fluctuations than in the baseline wind farm. The complementarity between offshore wind turbine and wave energy device is small at Horns Rev due to the higher correlation between these sources; while at Alpha Ventus the presence of a swell superimposed on local wind waves, as it was observed by comparing the observed and expected sea state, reduces the correlation between both resources.

However, good results are achieved for combined farms at both locations in terms of downtime. The combination of wave and wind power reduces the percentage of time that the combined production drops to zero in all the cases analysed, with reductions up to 87% at Horns Rev and 76% at Alpha Ventus. In the same line, the power capacity increases for the combined farms with regard to the standalone energy installations.

When all the above results are assessed in a holistic way and translated into monetary terms, it is found that cost reductions of 5% and 3% per year could be achieved at Alpha Ventus and Horns Rev, respectively, through combined wave and offshore wind energy farms. This finding is far from negligible since the average marginal impact of wind generation on system *balancing costs* has been estimated at about 1-4 €/MWh (Morthorst, 2003).

To sum up, a smooth and highly available power output could be achieved through co-located wave and wind energy farms. However, this study demonstrated that the veracity of the general statement that suggests that the combination with wave energy, with waves having more stable patterns, involves smoother power output depends on the site considered, and especially on the correlation between waves and winds at the site. A consistent lag between peaks in wind and wave power could mean that, when combined, the overall resource is smoother.

Therefore, finding adequate locations for combined farms where the synergies between both renewables are maximised is fundamental to promote the large scale development of wave and wind diversified systems, and consequently boost marine energy competitiveness. However, there is not much research into this issue, and the existing analyses are usually focused on the available resources as independent renewables (e.g. Henfridsson et al., 2007 and Schillings et al. 2012), proposing locations where a large amount of wave and wind resource is available, misleading the analysis of other relevant parameters that have to be considered in order to realise the synergies between wave and offshore wind energy, as was previously proved.

In this context, Chapter V – ***Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-location Feasibility index*** – presents a method to make a joint characterisation of the wave and wind resources when identifying feasible locations for combined wave and offshore wind energy installations. On this basis, the first objective is to define an *ad hoc tool* that encompasses and balances the most relevant factors to characterise a marine region in terms of its convenience for deploying a combined farm on this area: the *Co-Location Feasibility* (*CLF*) index. It comprises the available wave and wind resource, their variability and the correlation between them. Since these factors are not equally important, different weighting factors are assigned for each parameter.

Then, the utility of the new tool is proven by using it in the selection of the best site for a combined wave and wind farm along the Danish coast. This region is selected on the basis of previous analysis that identified Central and Southern North Sea as one of the most promising areas for offshore marine energy parks thanks to the large available resource and the relatively shallow waters – about 40% of this area has a water depth below 50 m (Schillings et al., 2012), in line with the current technological limit. Besides, this sea basin has numerous ports and harbours situated on its coasts, including two of the world’s largest ports − Rotterdam and Hamburg, which is important for the construction of the offshore farms and their maintenance tasks during their lifetime. Nevertheless, currently marine renewable energy is still a marginal sector in the North Sea waters. In fact, only wind power is commercially developed, while there are only some not commercial wave energy installations for research and development. Moreover, significant portions of the North Sea are already used by traditional non-wind functions such as shipping or military activities. In this sense, combined marine energy installations, by increasing the yield per unit of area (Astariz et al. 2015a) emerges as a solution to avoid conflicts derived to the competition for space between the new marine space user that is offshore marine energy and existing users.

The characterisation of the wave and wind resource is made on the basis of hindcast data from WaveWatch III, a third-generation offshore wave model, in conjunction with meteocean data from February 2005 to January 2015 provided by the Horns Rev wind farm. The wind resource assessments are carried out by means of the WAsP (Wind Atlas Analysis and Application Program) software (Mortensen, 2014), which is an implementation of the so-called wind atlas methodology (Troen and Petersen, 1989), and the available wave resource is assessed through the third-generation numerical wave model SWAN as in previous studies. The models’ accuracies are tested by using scatter plots and statistical indicators. First four representative case studies are defined and simulated on the basis of the available wave and wind data to determine a narrow area suitable for co-located farms within the West Danish coast, taking also into account the technical limitations of water depth and distance to coast. Important differences are found between the available wave resource in the north and south sections of the Danish coast, since to achieve similar power output the farm would have to be located much farther offshore in the south section. Therefore, the study is focused on the northern coast, where the wave and wind available resource are evaluated at 60 points through the *CLF* index. The study shows that the locations with larger available resource present also greater variability. However, some of these areas have levels of correlation between waves and winds low enough to bring in reduced fluctuations by combining both resources. The site point with coordinates: 56.65ºN, 8.03ºE is identified as the best location for deploying a co-located farm off the West Danish coast. This point is characterised by a distance to land of around 8 km (a small value, which would involve reduced installation and maintenance costs), northwesterly predominant waves, westerly winds and 11.4 kW/m and 0.64 kW/m^2 as mean wave and wind power, respectively. The low inter-annual variability of wave and wind power at this location would facilitate the annual power output prediction. Moreover, it is found that the lag between waves and winds is around 1 hour, with a cross correlation factor around 67%, which could compensate the fluctuations to some extent and smoothed the power output.

The second part of this study, which is presented in Chapter VI – ***Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study***, corresponds with the implementation of a combined offshore wind and wave energy farm at the site previously selected. The objective is to analyse the validity of the *CLF index* and to assess in a holistic way the benefits that could be obtained by combining wave and wind energy systems, relative to standalone parks. The co-located farm is designed according to the characteristics of current offshore wind energy farms, the future tendencies and the site characteristics. It is composed by 80 turbines erected on a grid of 8 rows with monopiles as foundation structures and a density of 5 MW/km^2. After a comparative analysis between different wind turbines, the Siemens Wind Turbine SWT-3.6-120 is selected. As for the co-located WECs, 56 WECs are deployed as a barrier sheltering the farm from incoming waves to achieve a less energetic climate within the farm and enlarge the weather windows for O&M tasks. The WEC selected is the WaveCat, as in the previous analysis, to be coherent with the studies presented previously and take profit of the results obtained with a view to the optimization of the wave farm layout. The power output, its variability and the downtime periods of the co-located farm are compared to those of the wave and wind farms as individual installations. To this end, wave and wind simulating models (SWAN and WAsP) are implemented in conjunction.

The global energy production of the proposed farm during the study period is around 1,500 GWh/year, with a performance of the wind turbines around 56% (higher than the average) and wake losses of 11% (lower than the average) – which demonstrates the suitability of the proposed layout. The aggregation of the power output of the co-located WECs increases the energy yield per unit area by 3.4%, decreases the downtime periods by 58% and reduces the power output variability by 12.5%. The above benefits of the co-located farm in comparison with standalone wave and wind energy parks are translated into monetary terms. The increase of the energy yield per unit of area by 3.4% reduces the site rental by a hefty 190,000 €/year. The smoother power output implies reductions in the balancing cost of approx. 1 M€/year. Moreover, the enlarged weather windows for O&M achieve by means of the *shadow effect* are quantified. It is found that the accessibility level increased almost 20%, with a good uniform distribution, which involves cost savings around 300,000 €/year in comparison to the wave and wind parks as standalone systems. Besides, thanks to common strategies to the scheduled O&M, the operational expenditures is also significantly reduced by 4 M€/year.

Analysing all these benefits jointly, cost savings around 5.5 M€/year are obtained for the operation costs with the proposed co-located farm. Besides, the capital expenditures are reduced by 17 M€ thanks to common elements and infrastructures. Considering these results jointly, the *Levelised Cost of Energy* (*LCOE*) is reduced by more than 50% relative to standalone wave farms, which ultimately makes it a more attractive option to investors.

These results prove that the defined *CLF* index leads to good results when identifying locations for co-located wave and wind farms and, thus, the approach developed in this work can be applied elsewhere. But above all, the analysis demonstrated that through combined wind-wave systems, offshore wind farms could achieve significant operational benefits that could boost its development, at the same time that the implementation of WECs into offshore wind farms would contribute to the development of wave energy technology and, consequently, to achieve economies of scale. In summary, the reduced energy cost of co-located farms with regard to the independent parks would enhance the competitiveness of marine energy.

VIII

Conclusions

Conclusions

The aim of this Thesis is to provide a comprehensive analysis of the benefits derived from combining wave and wind energy installations to bring about a solution to enhance marine energy competitiveness by taking advantage of the existing synergies between both renewables, particularly through co-located wave-wind farms.

First, this Thesis demonstrates that combined wave and energy farms are a feasible solution to overcome one of the challenges of offshore wind energy: its reduced availability relative to onshore facilities. Sea conditions often cause delays to operation and maintenance tasks, and thereby impact on the availability for power production of the farm. The most immediate consequence is larger non-operational periods, which translate into lower power production and, therefore, a reduction in their economic viability. The shielding effect of WECs over the offshore wind farm showed that *weather windows* (access time) could increase very significantly (over 80%) when the right design of the co-located farm is considered. The savings that could be achieved by enlarging the weather windows for O&M are estimated at 25%; which would lead to a reduction in the overall project cost of energy of 2.3%.

Second, co-located farms prove to be an effective solution to smooth the power output. The inherent variability of renewables causes uncertainties about the demand supplies resulting in market insecurity that may hinder their large scale development. In this Thesis it is demonstrated that, with waves being 10% more predictable than winds, the predictability of the combined wave-wind farm power production is considerably improved. Moreover the variability of the power output can be reduced up to 12% by the aggregation of both renewables because of the existing lag between waves and winds, in such a way that when wind power decreases, wave power output can compensate this peak. However, it is proved that this synergy can be exploited only at locations where wave and winds are low correlated. Therefore, when selecting a feasible location for co-located wave and wind farms it is not enough to anaylse the available resource but also other parameters such as the correlation between them and their variability. In this context, an *ad hoc* tool is defined in this Thesis to encompass and balance all these parameters. Its validity is demonstrated through a case study by means of third generation simulating models, where optimum locations for deploying combined wave and wind energy farms are determined.

Moreover, through the case studies implemented on this Thesis, a reduced capital cost per MW installed is achieved for the combined energy systems because of common elements like the electrical installation. In the same way, cost savings in maintenance tasks are determined due to sharing strategies. Besides, the combination of two different technologies harnessing different sources of energy at a single array site is demonstrated that increases the global energy yield per array unit and thereby contributes to a more sustainable use of the natural resource.

Finally, with the aim of encompassing these substantial benefits in a holistic way and draw general conclusions about the convenience of combining wave and offshore wind energy, the findings of the different case studies implemented throughout this Thesis are translated into monetary terms in a holistic approach by the implementation of a hypothetical co-located farm at a convenient location. The results show that the *LCOE* can be reduced by 50% with regard to standalone parks.

All in all, it is concluded that the benefits derived from co-located wave and wind energy farms, where the climate of the location is appropriate, are too important to be neglected. In brief, wave energy is considered a high risk investment because the technology is unproven. Offshore wind is expensive but proven. Combining them defrays costs in the riskier venture while adding to the potential return on investment from the proven technology. Therefore, co-located farms provide an excellent opportunity to increase the power production from marine renewables in a cost-competitive way and hence their potential to reduce our carbon footprint on the planet.

Despite that, at present there are no co-located or combined wave-wind devices operating in the sea, and only a few prototypes or concepts have been proposed so far. Furthermore, there are no WEC farms or arrays of multiple devices operating in the sea. This technological gap, comparing it with offshore wind systems, gives rise to a number of challenges or technology development issues, e.g. longer development times, accident or manage risk, difficult insurability, etc, which need to be faced to make co-located wave-wind farms becoming a reality. Nevertheless, these challenges present an opportunity to develop new research and technological knowledge which with further development and innovation could lead to an improved future generation of co-located wave-wind farms. With wave energy technology becoming more mature, it will become possible to develop a more complete analysis in which the benefits discerned in this Thesis are integrated, together with the actual costs of the different wave and wind technologies, in a global functional, whose optimisation shall lead to a proper dimensioning and design of offshore combined farms, given the climate of a certain location.

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Appendix

Extended abstract (in Spanish)

La llamada sociedad del bienestar y su crecimiento económico se sustentan en el empleo de combustibles fósiles. Las principales consecuencias de este paradigma son las emisiones de CO_2 asociadas y la dependencia energética de los países productores de petróleo. En este contexto, la Unión Europea (UE) en 2007 adquirió el compromiso de transformar Europa en una economía de alta eficiencia energética y con bajas emisiones de gases de efecto invernadero, comprometiéndose a la reducción del 20% de este tipo de emisiones, al ahorro de un 20% del consumo de energía, y a la consecución de un objetivo del 20% de energía renovable en el consumo total de energía de la UE en 2020 (Hamje et al., 2014). Más recientemente, en la conferencia climática de París (COP21) celebrada en diciembre de 2015 (United Nations, 2015), 195 países adoptaron un acuerdo climático mundial jurídicamente vinculante, que establece un plan de acción global para poner el mundo en vías de evitar un cambio climático peligroso, al limitar el calentamiento global. Para ello, la reducción de las emisiones de CO_2 y la búsqueda de alternativas a los combustibles fósiles es fundamental.

En este contexto, la energía marina está llamada a desempeñar un papel clave en la política energética de la UE debido al recurso existente y su fuerte potencial de desarrollo (Bahaj, 2011; Iglesias y Carballo, 2009). La industria ha establecido, como objetivo para el año 2050, alcanzar una capacidad de potencia instalada de 188 GW de energía de las olas y mareas y 460 GW para la energía eólica *offshore* (UE-OEA, 2010; Moccia et al, 2011). Esta última es la energía marina renovable más desarrollada, con una tecnología relativamente madura (EWEA, 2012). La cantidad de recurso disponible es superior a la que hay en tierra, además de que el mar ofrece más espacio para su desarrollo. Sin embargo, resulta menos competitiva debido en parte a la etapa inicial del desarrollo en la que se encuentra y al hecho de que al ser instalaciones ubicadas en el medio marino precisan mayores labores de mantenimiento (Morthorst, 2003). Esto, junto con otras características inherentes a las energías renovables, como la intermitencia (Astariz and Iglesias, 2016a), puede dificultar la integración a gran escala de esta energía en la red.

En cuanto a otras energías marinas como la energía de las olas, para que su potencial pueda ser aprovechado, es preciso disponer de dispositivos convertidores del oleaje (WECs, *wave energy converters*) eficientes y fiables. Como resultado de la intensa investigación llevada a cabo durante los últimos años para desarrollar WECs, el aprovechamiento de este forma de energía está próximo a ser viable comercialmente, pero presenta todavía importantes incertidumbres, bajos rendimientos y altos costes (Babarit et al., 2012; Falcão, 2010). Dado que el objetivo para 2020 es alcanzar 3,6 GW de potencia instalada para las energías de las olas y las mareas y 40 GW para la energía eólica *offshore*, es evidente que las energías marinas deben sufrir un desarrollo sustancial en los próximos años (UE-OEA, 2010). Sin embargo, su baja competitividad actual puede frenar su introducción a gran escala. Pues, a pesar de sus beneficios ambientales, las energías renovables tienen que ser económicamente competitivas para atraer inversión significativa (Bucher et al., 2016). De otro modo, estarán siempre supeditadas a subsidios y ayudas procedentes de entidades públicas.

Ante esta situación, el aprovechamiento de varias energías renovables marinas al mismo tiempo, a través de lo que se ha denominado sistemas combinados o diversificados de energía, ha sido propuesto como posible solución para promover y acelerar el desarrollo de la energía marina (Figueiredo and Martins, 2010). De entre las posibles opciones, la combinación entre la energía eólica *offshore* y la energía de las olas se presenta como una de las más prometedoras (Pérez-Collazo et al., 2013) debido a las múltiples sinergias que surgen cuando se considera esta combinación.

Por un lado, mediante el aprovechamiento de varios recursos naturales en la misma área se logra una utilización más sostenible del recurso al aumentar la densidad energética (Astariz et al., 2015a). Además, dado que ambas son tecnologías jóvenes y sobre las que existe poca o ninguna información acerca del impacto ambiental que sus instalaciones conllevan, las sinergias entre ambas energías pueden derivar en una transferencia de conocimientos sobre los impactos ambientales de un sector a otro.

Por otra parte, la variabilidad en la señal de potencia inherente de las energías renovables es un problema para su integración en el *mix* energético, ya que los mercados de energía requieren fuentes confiables (predecibles y constantes) de potencia (Denniss 2005). En este sentido, el recurso de las olas es más predecible y menos variable que el recurso eólico (Veigas et al., 2014), por lo que la introducción de convertidores de energía de las olas en parques eólicos marinos puede derivar en una producción más consistente, mejorando su fiabilidad y reduciendo los costes asociados (Fernández Chozas et al., 2013).

Asimismo, con la combinación de ambas renovables se puede conseguir una importante reducción de los costes debido a la utilización conjunta de algunas instalaciones, tales como la infraestructura de la red eléctrica que supone un tercio del presupuesto de todo el proyecto (Musial y Ram, 2010). Además, las dimensiones y las características especiales de los proyectos desarrollados en el mar requieren el uso de equipos marinos especializados e instalaciones tales como espacio de puertos, que en el caso de un proyecto combinado pueden ser compartidos contribuyendo a la reducción de los costes. De igual modo, las condiciones marinas a las que están sometidas este tipo de instalaciones hacen que precisen de frecuentes labores de mantenimiento, que en el caso de instalaciones combinadas, se pueden organizar de modo que el resultado derive en una reducción de los costes implicados.

A pesar de todos estos posibles beneficios, en la actualidad no existen instalaciones de este tipo. En los últimos años, se han realizado algunos estudios sobre las sinergias entre ambas renovables, pero siempre analizando cada una de manera individual, en una localización concreta y sin evaluar su repercusión económica. Por lo tanto, existe un *gap* en la literatura, acerca del beneficio real de implementar instalaciones combinadas de energía eólica y de las olas en lugar de instalaciones de energía independientes. En este contexto, el objetivo de esta Tesis es evaluar todas esas sinergias de una manera holística, y determinar su repercusión en el valor del coste nivelado de la energía (*LCOE*), que es el parámetro comúnmente empleado cuando se compara la competitividad de las distintas fuentes de energía.

De acuerdo con el grado de conectividad entre las turbinas y los convertidores de oleaje, existen diversas formas de implementar una instalación de energía eólica y de las olas combinada (Pérez-Collazo et al., 2015): (i) turbinas eólicas y convertidores de las olas situadas en la misma región pero sin compartir la estructura (en adelante instalaciones co-localizadas); (ii) convertidores híbridos; y (iii) islas de energía. Actualmente, debido al grado de desarrollo de la tecnología eólica y de las olas, los sistemas co-localizados son la opción más conveniente (Stoutenburg, 2010) y en la que se centra esta Tesis. Estos sistemas combinan turbinas eólicas y convertidores de oleaje con sistemas independientes de anclaje, pero que comparten: una misma área, conexión a la red, equipos de operación y mantenimiento y personal, estructuras portuarias, etc.

Esta Tesis se estructura en ocho capítulos, de los cuales los Capítulos III, IV, V y VI se corresponden con sendas publicaciones en revistas científicas y constituyen el cuerpo principal de la Tesis. En primer lugar, en el Capítulo I – *Introduction*, se proporciona una perspectiva general del presente trabajo, y seguidamente, en el Capítulo II – *Objectives*, se indican los objetivos final e intermedios que se pretenden alcanzar. A continuación, en los Capítulos III – *Hybrid wave and offshore wind farms: A comparative case study of co-located layouts*, publicado en International Journal of Marine Energy, IV – *Output power smoothing and reduced downtime period by combined wind and wave energy farms*, publicado en Energy, V – *Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-location Feasibility index*, publicado en Energy Conversion and management y VI – *Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study*, también publicado en Energy Conversion and Managment, se exponen y analizan de forma detallada las sinergias entre la energía eólica y de las olas por medio de diversos casos de estudio, abordándose en cada uno de ellos diferentes aspectos específicos y fundamentales para la consecución del objetivo final de este trabajo de analizar la conveniencia de estas instalaciones combinadas de energía. El Capítulo VII – *General Discussion*, contiene una discusión general común a la Tesis, y finalmente, en el Capítulo VIII – *Conclusions*, se presentan las principales conclusiones obtenidas así como las futuras líneas de investigación a desarrollar. A continuación se resumen los aspectos abordados, así como los resultados y principales conclusiones obtenidas.

Previamente se ha mencionado que el mantenimiento es un aspecto particularmente desafiante de la energía eólica *offshore*. Las duras condiciones marinas hacen que las instalaciones requieran tareas más frecuentes de mantenimiento en comparación, por ejemplo, con las turbinas eólicas en tierra. Pero además, estos trabajos pueden verse retrasados por las condiciones del mar, en particular por valores de altura de las olas elevados, ya que el límite operacional de los barcos de trabajo es una altura de ola significativa de 1,5 m (Bierbooms and Bussel, 2002; Hassan, 2013). Esto conlleva períodos de no operatividad, y por tanto una reducción en el rendimiento del parque eólico. De hecho, mientras que las turbinas eólicas en tierra presenta niveles de accesibilidad del 97% (Henderson and Bussel, 2001), este nivel puede verse reducido significativamente en instalaciones en alta mar, incluso por debajo de 60% (Perveen et al., 2014). El tiempo de inactividad resultante provoca costes significativos que elevan los costes de operación y mantenimiento, que representan entre el 20 y el 25% de los costes totales de la instalación (Hassan, 2013).

En el Capítulo III – ***Hybrid wave and offshore wind farms: A comparative case study of co-located layouts***, se demuestra que la introducción de convertidores de energía de las olas en la periferia de un parque eólico a modo de barrera protectora mejora el acceso a las turbinas. La extracción de energía por parte de los convertidores reduce la altura de ola y crea una estela que modifica el clima del oleaje en el interior del parque (Carballo y Iglesias, 2013), lo que resulta en un clima más suave, y por lo tanto mejora la accesibilidad para el mantenimiento, reduciendo el tiempo de inactividad. El estudio se lleva a cabo por medio de la implementación de diversos casos de estudio: un estudio preliminar en el que se define un parque eólico hipotético, un parque eólico real (AlphaVentus) y un análisis de sensibilidad comparando diferentes parques actualmente en funcionamiento (AlphaVentus, Bard 1, Horns Rev 1 y Lincs). El objetivo es cuantificar la reducción de la altura de ola que se consigue y el aumento de las ventanas temporales de mantenimiento que dicha reducción supone; así como analizar la influencia de las características de diseño de los parques en los resultados.

En todos estos casos, se emplea el modelo de tercera generación SWAN (Simulating WAves Nearshore) para simular la propagación del oleaje. SWAN es un modelo numérico de tercera generación que calcula la evolución de las olas y representa la refracción, así como la generación de olas debido al viento, la disipación y las interacciones de onda de la olas no lineales (Booij et al., 1999). Los datos relativos al recurso y al clima de oleaje se obtuvieron del modelo ola de tercera generación WaveWatch III en combinación con mediciones reales de diversas boyas, que además se emplean para validar los modelos implementados. Asimismo, se utilizan datos reales de batimetría. Las turbinas eólicas y los convertidores se representan en el modelo como obstáculos caracterizados por un coeficiente de transmisión para simular su impacto en el clima del oleaje (Ponce de León et al, 2011; Veigas et al, 2014).

La metodología seguida para realizar esta investigación se puede estructurar en los siguientes pasos: i) caracterización de la ubicación y el clima de las olas; ii) diseño de diferentes configuraciones de granjas co-localizadas; iii) implementación del modelo de propagación; y iv) análisis de los resultados mediante un estudio estadístico detallado. En el primero de los estudios, se analizan un total de 14 parques co-localizados con diferente configuración con el objetivo de evaluar la influencia de la disposición de los convertidores de oleaje y la separación entre ellos en los resultados. A la luz de los datos obtenidos, en todos los casos y configuraciones se logra una importante disminución de altura de las olas, con valores de reducción de hasta el 24%. Las configuraciones con una distancia menor entre los convertidores alcanzan los mejores resultados. Por otra parte, se puede afirmar que la adición de WECs para hacer frente a olas procedentes de direcciones secundarias contribuye considerablemente a la reducción de la altura de las olas en el interior del parque. Es importante destacar que la configuración en arco logra los mejores resultados a pesar de tener un menor número de convertidores, lo que es interesante en términos monetarios.

Tras comprobar la eficacia de los convertidores de olas en términos de reducción de altura del oleaje y de identificar los mejores diseños, se amplía el estudio a un parque eólico actualmente en funcionamiento, Alpha Ventus. Se proponen 15 configuraciones diferentes de granjas co-localizadas en base a los resultados anteriores y teniendo en cuenta la disposición del parque eólico, el clima de las olas y, en particular, la dirección de ola predominante. En este estudio se considera el espectro total del oleaje con el fin de traducir la reducción de la altura de ola en el aumento implícito de la accesibilidad a las turbinas. Los resultados muestran que, gracias a la extracción de energía de las olas por los WECs, el tiempo de acceso a las turbinas aumenta de forma muy significativa. Concretamente, mientras que en el escenario base las turbinas son accesibles el 67% del año, con la granja co-localizada este valor aumenta hasta el 82% (un aumento de casi el 15%). Con respecto a las configuraciones con las que se obtuvieron los mejores resultados, las conclusiones que se derivan son las mismas que en el estudio preliminar.

Por último, y con el fin de analizar la influencia de las características del parque eólico en el aumento de la accesibilidad que se logra al introducir convertidores de oleaje, se realiza un estudio comparativo considerando diferentes parques eólicos (Alpha Ventus, Bard 1, Horns Rev 1 y Lincs). En todos los casos, se obtienen ampliaciones significativas de las ventanas de tiempo para mantenimiento. Lo cual confirma que la implementación conjunta de convertidores de oleaje y turbinas eólicas mejora la accesibilidad a estas últimas y, por tanto, su disponibilidad para generar energía. Si bien, hay factores que maximizan dicho efecto, pues los mejores resultados se obtienen en el caso de parques eólicos con una configuración similar a un cuadrado y con separaciones pequeñas entre las turbinas, ya que requieren de un menor número de convertidores co-localizados para alcanzar un mismo incremento en la accesibilidad.

Aparte de los requisitos de mantenimiento que presentan las instalaciones marinas, otro de los hándicaps para su desarrollo es la variabilidad en la señal de potencia inherente a las energías renovables. En el Capítulo IV – ***Output power smoothing and reduced downtime period by combined wind and wave energy farms***, se propone la combinación de la energía eólica *offshore* y energía del oleaje como sistema para gestionar dicha variabilidad. Con este fin se llevan a cabo sendos estudios en dos parques eólicos *offshore* actualmente en funcionamiento: Alpha Ventus y Horns Rev 1, situados ambos en el Mar del Norte. Se emplean datos de oleaje y de viento medidos cada media hora por la plataforma de investigación FINO1 para el parque eólico Alpha Ventus y por una boya cercana en el caso del parque eólico Horns Rev. En primer lugar, y en base a estos datos, se realiza un análisis completo y preciso del recurso, prestando especial atención a su variabilidad. Se encuentra que las fluctuaciones en ambos recursos son significativas a lo largo de todo el año, pero especialmente durante los períodos de tormenta, con fluctuaciones en torno al 7%. Sin embargo, se determina la existencia de un desfase entre los picos de altura de ola y de los de la velocidad del viento. Un hallazgo que hace pensar que agregar convertidores de oleaje y turbinas eólicas puede suavizar la variabilidad de potencia y sobre todo evitar los períodos no operativos.

Para obtener conclusiones más precisas al respecto se llevan a cabo diversas simulaciones considerando varios parques combinados, con porcentajes de energía de las olas instalada que varían desde 0 al 100%, a incrementos del 10%, en ambas localizaciones. En el caso de Alpha Ventus, todas las explotaciones mixtas analizadas presentan menores fluctuaciones en la potencia de salida en comparación con los sistemas independientes, con una reducción en la variabilidad del 6%. Sin embargo, en Horns Rev la potencia de salida de todas las granjas combinadas presentan fluctuaciones más altas que en el parque eólico de referencia. La causa de esta diferencia entre los dos parques, es que los valores de correlación entre el viento y las olas sólo resultan suficientemente bajos para suavizar la potencia de salida en el caso de Alpha Ventus (en torno al 55%).

A pesar de ello, la combinación de energía de las olas y eólica *offshore* resulta beneficiosa en ambas localizaciones en términos de reducción de los períodos de inoperatividad debidos a velocidades de viento fuera del umbral de producción de las turbinas, con reducciones de hasta el 87% de estos períodos en Horns Rev y 76% en Alpha Ventus. En la misma línea, las granjas combinadas analizadas muestran un incremento en el rendimiento global de la planta.

Todos estos resultados se evalúan de una manera holística y se traducen en términos monetarios. Se concluye que los costes anuales de producción se reducen en un 5% y un 3% en AlphaVentus y Horns Rev, respectivamente, al introducir en los parques eólicos convertidores de oleaje. Por tanto, queda demostrado que otra de las sinergias entre ambas renovables es la de ofrecer una salida de potencia suave y de alta disponibilidad, aunque si bien la materialización de este beneficio se maximiza en aquellas localizaciones donde ambos recursos están poco correlacionados.

En este sentido, es evidente que a la hora de buscar localizaciones adecuadas para plantas combinadas de energía eólica y del oleaje no basta con analizar la cantidad de recurso disponible, sino que si se quiere sacar el máximo provecho de las posibles sinergias entre ambas energías es necesario considerar otros parámetros. Por tanto, si el objetivo de esta Tesis es evaluar los beneficios derivados de combinar la energía eólica offshore y la energía del oleaje, es necesario que este análisis se ubique en zonas adecuadas para que las conclusiones extraídas sean realmente representativas. Teniendo esto en cuenta, junto con el hecho de que la búsqueda de ubicaciones adecuadas para las granjas de olas y energía eólica combinadas es un requisito previo para el despliegue a gran escala de estos sistemas diversificados, el Capítulo V – ***Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-location Feasibility index***, desarrolla una metodología para realizar una caracterización conjunta de los recursos de oleaje y viento basada en el índice *CLF* (*the Co-Location Feasibility index*). Este parámetro comprende la cantidad de recurso de las olas y del viento disponible, su variabilidad y la correlación entre ambos recursos.

Posteriormente, se prueba su utilidad a través de un estudio sobre la selección de una ubicación óptima para una granja combinada a lo largo de la costa danesa. El centro y sur del Mar del Norte ha sido identificado previamente como una de las áreas más prometedoras para parques de energía marina en alta mar gracias a la gran cantidad de recurso disponible y al hecho de que las aguas son relativamente poco profundas de acuerdo con el límite tecnológico actual (Schillings et al., 2012). Sin embargo, no se ha hecho ningún análisis relativo a la idoneidad de esta área para parques combinados.

En el estudio que aquí se plantea, primeramente se efectúa la caracterización del recurso eólico y undimotriz sobre la base de los datos obtenidos a través del modelo WaveWatch III, conjuntamente con series de datos de tres boyas, localizadas en el área de estudio, para el período comprendido entre febrero 2005 y enero 2015. La evaluación del recurso se realiza por medio de dos modelos de simulación de tercera generación: WAsP (Wind Atlas Analysis and Application Program) para el caso de la propagación del viento (Mortensen, 2014) y SWAN, al igual que anteriormente, para la propagación de las olas (Booij et al., 1999). Ambos modelos son previamente validados.

En base a los resultados obtenidos, se observa que las localizaciones con mayor recurso disponible presentan también mayores fluctuaciones en el mismo. Sin embargo, algunas de estas áreas tienen niveles de correlación entre las olas y el viento lo suficientemente bajos como para conseguir suavizar esta variabilidad mediante la combinación de ambos recursos. Tras balancear estos parámetros de modo conjunto a través de la metodología propuesta (*the CLF inde*x), el punto con coordenadas: 56.65ºN, 8.03ºE es identificado como la mejor ubicación para implementar una granja de co-localizada frente a la costa oeste danesa.

La segunda parte de este estudio se recoge en el Capítulo VI – ***Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study,*** en el que se implementa un parque combinado de energía eólica y de las olas en la ubicación determinada anteriormente. El objetivo es analizar la validez del índice *CLF* y evaluar los beneficios que se pueden obtener mediante la combinación de ambas renovables, en comparación con parques independientes, de un modo conjunto y en términos económicos, considerando tanto las sinergias analizadas en capítulos anteriores como las relativas al mejor aprovechamiento del recurso y el uso común de instalaciones y estrategias conjuntas.

Para ello, se define un parque eólico, en base a las características de los parques actuales y las tendencias de los próximos años, y se determina la posición de los convertidores de oleaje de acuerdo con los resultados de los anteriores capítulos, a fin de maximizar el aprovechamiento de las sinergias entre ambas renovables. Se obtiene que la producción global de energía de la planta propuesta es de aprox. 1.500 GWh/año, con un rendimiento de las turbinas en torno al 56% (superior a la media) y pérdidas del 11% debido a la interacción entre las turbinas (menor que la media), lo que demuestra la idoneidad de la disposición propuesta. Además, la producción de energía por unidad de área aumenta en un 3,4% lo que supone una reducción del coste de alquiler de la zona ocupada de 190.000 €/año. Asimismo, los períodos de inactividad se reducen en un 58%, así como las fluctuaciones de la señal de potencia de salida que disminuyen en un 12,5%, lo que implica reducciones de los costes anuales de producción de aprox. 1 M€/año.

Por otra parte, el *efecto de sombra* de las convertidores de oleaje dentro del parque eólico aumenta el nivel de accesibilidad a las turbinas casi un 20%, pasando a presentar valores de accesibilidad cercanos al 70%, lo que deriva en una reducción estimada de los costes de operación y mantenimiento de 300.000 €/año en comparación con parques eólicos y de las olas independientes. Además, gracias a la posibilidad de poder establecer estrategias comunes para realizar las operaciones de mantenimiento programadas, los gastos operativos también se reducen significativamente en aprox. 4 M€/año.

El análisis de todos estos beneficios de forma conjunta, da como resultado una disminución de los costes de explotación anuales de 5,5 M€. A lo que hay que sumarle, una reducción en torno a 17 M€ en el investimento inicial gracias al uso conjunto de elementos comunes de ambas instalaciones como la conexión eléctrica. Teniendo en cuenta estos resultados, el coste nivelado de energía (*LCOE*) se reduce en más de un 50% en relación con las instalaciones de energía individuales, lo que las sitúa en valores mucho más cercanos a los de otras renovables ya consolidadas, aumentando así la competitividad de la energía marina en el mercado.

Por tanto, queda patente que los beneficios potenciales de la integración del recurso eólico y del oleaje, donde el clima del lugar es apropiado, son demasiado importantes como para no tenerlos en consideración en el desarrollo de la energía marina. Por un lado, la energía de las olas se considera una inversión de alto riesgo debido a que la tecnología no está probada. Por otro lado, la energía eólica *offshore* presenta mayor madurez tecnológica pero no es en sí misma competitiva. Sin embargo, la combinación de ambas energías permite combatir las debilidades de la energía eólica *offshore*, a la vez que se favorece e impulsa el desarrollo de la energía de las olas.

De este modo, se puede concluir que los parques combinados de ambas renovables proporcionan una excelente oportunidad para aumentar la producción de energía a partir de fuentes renovables marinas de una manera competitiva y por lo tanto impulsar su desarrollo dentro del paradigma actual de búsqueda de alternativas a los combustibles fósiles.