Offsetting of wave and wind resource and resultant economic benefits: a GB case study

Shona Pennock, Nieraj R. K. Bharathi, David Crooks, Henry Jeffrey, Patrik Möller

Abstract—**This paper presents a comparative analysis of historical wind power generation, wave resource and day ahead wholesale prices for GB for a three year period from 2015-2017. A hypothetical historical wave power generation time series is constructed for this period using resource data from six spatially diverse sites and a power matrix from an active wave energy developer. Comparing the potential revenues per MW installed capacity for wind and wave generation from this time period has shown a considerable temporal variation in market revenues between months and years, with a regular pattern of comparatively higher revenues from wave generation during the spring and autumn months. Over the three year period explored, wave generation gained a total of 2.36% greater revenues compared with wind generation, ranging from -0.27% to 3.61% annually and from -29.63% to 70.60% monthly. A sensitivity analysis has also been undertaken to explore the sensitivity of these results to the comparative capacity factors of wind and wave generation. This analysis supports a wider discussion that the offsetting of resource between wind and wave generation could result in various benefits in terms of economics, socioeconomics and system operation.**

Keywords—**Wave energy, marine energy, electricity markets, energy economics, time series analysis**

I. Introduction

A diverse mix of renewable generation technologies will be necessary to meet ambitious European and global carbon reduction targets whilst meeting the 'energy trilemma' conditions of sustainability, affordability and security of supply. Wave energy, with a large potential global resource and locational offsetting with wind resource, could play a key role in meeting these targets whilst maintaining system reliability.

Including wave energy as part of a diverse electricity mix has the potential to provide various economic and socio-economic benefits. Ideal sites for marine energy development often coincide with fragile coastal communities, which could benefit greatly from the additional jobs and opportunities associated with the marine energy sectors [1], [2]. Remote coastal areas can also benefit from the additional interconnection to the grid and from the associated reduction in cost of supplying electricity to such areas.

Socio-economic metrics currently used to provide quantifiable benefits to installing renewable energy technologies include the number of jobs supported and the Gross Value Added (GVA) [3]. Both of these metrics are used to represent the additional benefit to the economy, based on total project spend and using input-output analysis to illustrate how this spend impacts on all sectors of the economy. However, these metrics do not capture all of the various system benefits of including wave energy as part of the current electricity mix.

The Waveboost project [4] is a European Commission funded research and innovation action, aiming to develop a PTO with high efficiency and reliability and integrate it within the CorPower Ocean (CPO) point absorber wave energy converter (WEC). This module is intended to allow for increased operability and survivability within extreme sea states, as well as increased efficiency and reduced cost of both manufacturing and operation. The work presented in this paper forms part of the economic analysis work package of the Waveboost project, in which the economic, socio-economic and environmental impact of wave energy developments are investigated.

This paper incorporates both qualitative and quantitative analysis to explore the concept that wave energy can provide additional value to power systems and markets alongside the deployment of other, more developed, stochastic renewable generation technologies. An analysis of historical time series of spot prices, wind generation and wave resource is presented in order to illustrate the offsetting of wave and wind resource and the short-term market benefits that could result from

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developing wave energy generation. The results are presented as part of a wider discussion of the potential added technical, economic and socio-economic value that wave energy generation could bring to electricity systems with high penetrations of renewable energy.

The following sections are structured as follows: Section II outlines the background to this work in terms of literature produced focusing on wave and wind resource prediction, offsetting of wave and wind generation and the potential additional benefits of including wave generation as part of the electricity mix. Section III details the data and methodology involved with the time series analysis and Section IV the time series analysis results in terms of comparative market revenues accessible by wind and wave generation. Section V presents a discussion of the results and of the winder benefits in terms of technical, economic and social value that wave energy generation could bring to electricity systems with high penetrations of renewable energy. Finally, section VI presents key conclusions and discusses potential future work.

II. Background

In Europe, explicit individual targets to member states for renewable generation have resulted in implicit mechanisms to encourage investment in renewable energy, such as technology-specific subsidies (e.g. feed-in-tariffs) and priority dispatch. This has resulted in a large uptake of wind and solar installed capacity in Europe, with 157.7GW of wind and 107.3GW of solar PV installed in Europe between 2000 and 2017 [5]. Various member states are now experiencing issues with the interaction between these renewable technologies and the operation of power systems. For example, Germany's priority dispatch mechanism and high penetration of wind installed capacity in the north and high load in the south has resulted in loop flows, causing transmission congestion in surrounding countries [6]. Further to this, Ireland had to limit the amount of wind dispatch at any one time to 60% in 2016 due to potential system reliability issues [7].

From a market perspective, some markets with high penetrations of non-dispatchable renewables such as wind and solar generation have been experiencing price spikes at times of high demand and low renewable resource [8], [9]. GB has also seen a large amount of installed wind capacity in the past five years, which has been found to result in higher instances of price spikes at times of low wind resource and network stress [10]. This issue could escalate with increasing penetration of wind generation, as shown in the literature: Green and Vasilakos found that price volatility will increase when modelling expected wind generation capacity and demand for 2020 [11].

An answer to meeting renewable generation and carbon reduction targets while minimising network stress could be to combine the current renewable generation deployment with other forms of renewable generation which have a production profile with a low correlation to wind and solar, such as wave energy.

Previous work has shown that wave resource is more predictable than wind resource [12] and is often temporally offset [13]. Saskai [12] found that wave resource can be predicted with a prediction error of <20% with a lead time of three days in most areas of ocean world-wide, rising up to nine days in advance in the tropical ocean. This work found wind power predictability to be consistently lower compared to that of wave power.

Fairley et al [14] investigated the spatio-temporal variation of wave power by modelling arrays of devices over spatially separated regional, national and Europe-wide sites, finding in all cases that increasing the number of sites decreases the step-change in generated power and the percentage of time with zero generation.

Further to this, several studies have undertaken an analysis of combined wave and wind resource at set locations [13], [15]–[19]. Kalogeri et al [13] found that the offshore areas of western Europe were most suitable for combined wave-wind farms due to the low correlation of resource, resulting in lower variation in power output and lower instances of zero power output. Stoutenburg and Jacobson [17] investigated the optimal transmission capacity of a combined wind and wave farm using resource data off the California coast, finding that costs of transmission infrastructure per energy delivered could be heavily reduced compared with individual wind and wave developments.

A 2009 analysis by Repoint Energy Limited for the British Wind Energy Association [20] used a Monte Carlo market dispatch model to represent energy mixes including varying proportions of wind, wave and tidal stream generation for a hypothetical future year. It was found that a reduction of £200M in cost of backup capacity, 2.5TWh of energy spill and over 2Mt of CO_2 emissions per year for the scenario in which 30% of the renewable generation came from marine energy. It also found that a £1.4bn increase in total market revenues could be possible if the 120TWh annual renewable generation was produced by a 60%:40% wind:marine mix, compared with 100% wind.

A 2012 analysis by Chozas et al [21] explored the economic benefit of combining wave and wind power production in terms of balancing costs. Forecasted and actual resource were compared for several months of waverider buoy and weather station data at Hanstholm, Denmark and found that the extrapolated balancing costs of wave converters are up to 47% smaller than a wind-only scenario.

While there are several comparative studies on wave and wind resource variability and predictability, there is very little recent analysis beyond those mentioned above on the future deployment of wave energy in terms of potential interactions with electricity markets. Another limitation of the literature is the availability of data on power conversion of WECs currently in development.

Much of the analysis of wave energy exploitation within the literature is using power matrices for outdated devices and does not account for the current progression in the field. This work explores the comparative potential revenues of wave and wind generation using historical time series data of wind generation, wave resource and day-ahead wholesale electricity prices, using an up to date power matrix developed by a current wave energy developer, CorPower Ocean.

III. Methodology

The following sections outline the time series analysis methodology, detailing the data sources used for this work and then derivation of the generation and market revenue time series. Three years of historical wind generation, wave resource and day ahead wholesale market prices have been used to compare potential revenues of wind and wave generation between 2015-2017. For a direct comparison, the wind and wave time series generation data have been normalised to give generation and revenues per MW and also scaled to a capacity factor of 35%.

The key aim of the time series analysis is to investigate if there is a clear offset in wind and wave resource in GB and if this could lead to a difference in the revenues which wind and wave generation could receive from the spot market. It should be noted that since Ireland has its own single market, GB is being referred to here in terms of the power system and markets relating to Scotland, England and Wales.

A. Market Price Data

Three years of historical time series data were used from 1st January 2015 to 31st December 2017. Hourly market price data (in £/MWh) was taken from the N2EX historical data library [22]. N2EX historical GB data represents wholesale day-ahead electricity trading within the N2EX platform, which is an auction-based market.

Figures 1 and 2 show two example weeks of this data in winter (January 2015) and summer (June 2015). Electricity market prices are highly sensitive to the available generation capacity and system demand. It can be seen that clear peaks in price occur each day in the winter and clear troughs occurs each night in the summer. This is due to the UKs higher energy requirements in the winter months.

Market prices can also be affected by extreme weather conditions as well as plant or transmission outages. An example of this occurred in last few months of 2016, in which there were French Nuclear plant outages and the French interconnector (Interconnexion France-Angleterre (IFA) Link) was operating at half of its usual available capacity [23]. This also coincided with the higher demand peaks associated with winter in GB. The GB system operator, National grid, issued two capacity market notices for times of potential system stress during this period [24] and balancing market prices rose to above £1500/MWh on the 8th November [25]. The impact of these factors on UK wholesale market prices can be seen in the N2EX market data, which has 117 instances of market prices rising over £100/MWh in 2016 (108 of which are between September and December 2016), compared with 6 instances in 2015 and 27 instances in 2017. The highest N2EX price within all of the data occurs in September 2016 at £999/MWh. Figure 3 shows the N2EX wholesale market data from 1st September 2016 until 31st December 2016.

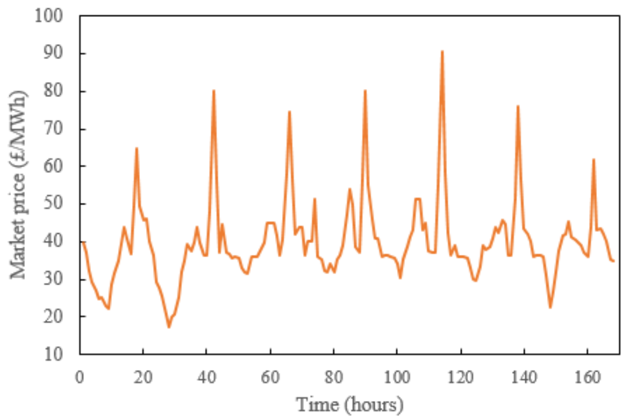

Fig. 1. N2EX market data, example winter week (Jan 1st – 7th 2015).

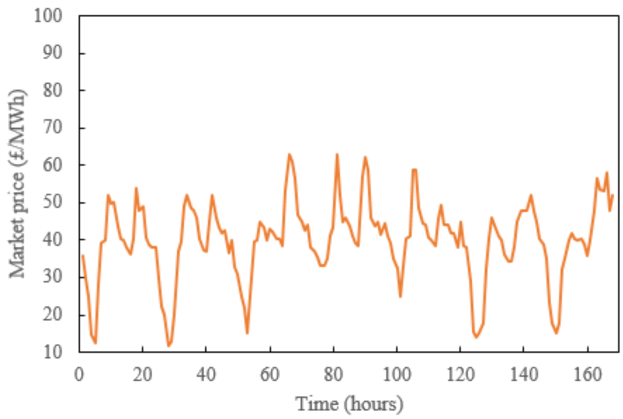

Fig. 2. N2EX market data, example summer week (June 1st – 7th 2015).

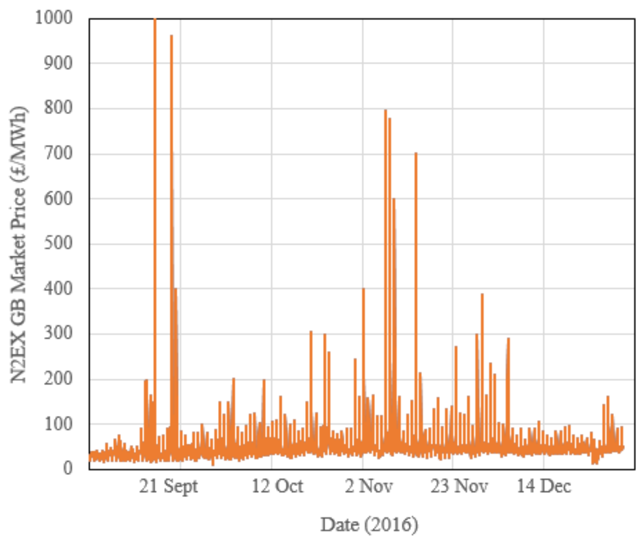

Fig. 3. Hourly N2EX GB market price data 1st September – 31st December 2016

B. Wind Data

Two years and ten months of historical time series data were used from 22nd February 2015 to 31st December 2017, 22nd of February being the first date at which these data are available. Half-hourly GB transmission-connected wind generation data (in MW) was taken from the Elexon portal (generation by fuel type) [26]. Figure 4 and Figure 5 show an example winter month (January 2016) and an example summer month (June 2016) of these data respectively. Both of these example months illustrate times of high and low wind generation in GB, with the winter peak and the overall winter average being much higher than the summer peak and the overall summer average generation. The difference in y-axis scale should be noted between these graphs.

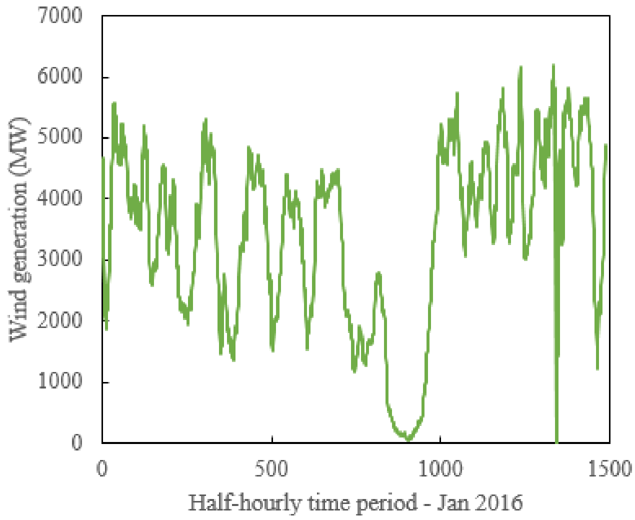

Fig. 4. Wind generation time series for example winter month (January 2016).

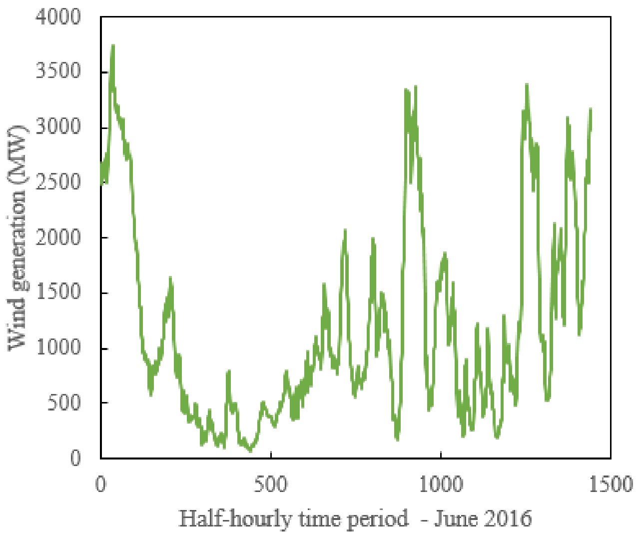

Fig. 5. Wind generation time series for example summer month (June 2016).

Figure 6 compares the wind generation time series with the N2EX market price data for January 2016. It can be seen that during the period of consistently low wind generation there are high spikes in market price at times of high demand, reaching almost £250/MWh in one instance.

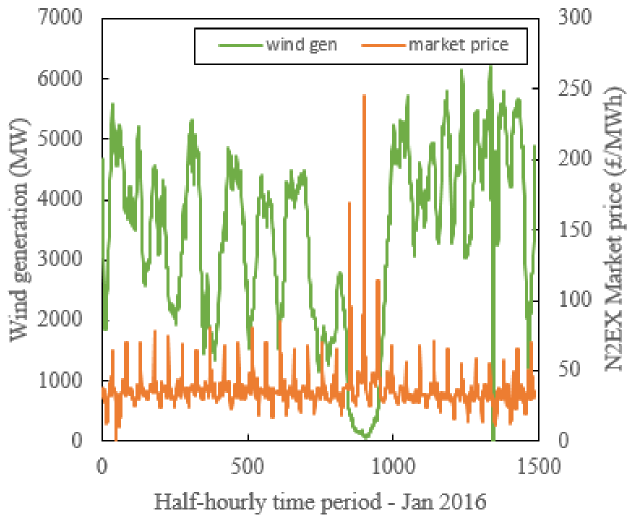

Fig. 6. Wind generation and N2EX market revenue comparison time series for example winter month (January 2016).

C. Wave Data

Three years of historical time series data for wave resource were used from January 1st 2015 to December 31st 2017. These have been taken from two sources:

1. Half-hourly Datawell Waverider MkIII data of Hs and Tp from the Billia Croo site in Orkney was supplied by the European Marine Energy Centre [27] as part of the Waveboost project.
2. Half-hourly Datawell Waverider MkIII data of Hs and Tp from Moray Firth, Western Hebrides, Blackstone, Firth of Forth and West Pembrokeshire from the Cefas WaveNet database [28].

Figure 7 illustrates the six locations for the Waverider buoy data used for this study. In addition to the historical time series data, a WEC power matrix from CorPower Ocean was used to convert half-hourly Hs and Tp time series data into a wave power generation time series. This power matrix represents a WEC with a rated power of 300kw. Power generation was averaged over the six sites to form a time series representing the hypothetical generation in GB which could have occurred based on the historical wave resource data.

Figure 8 and Figure 9 show an example winter month (January 2016) and an example summer month (June 2016) of these time series data respectively. Both of these example months illustrate times of high and low wave generation in GB, with the winter peak and the overall winter average being much higher than the summer peak and the overall summer average generation.

Fig. 7. Locations of wave data buoys.

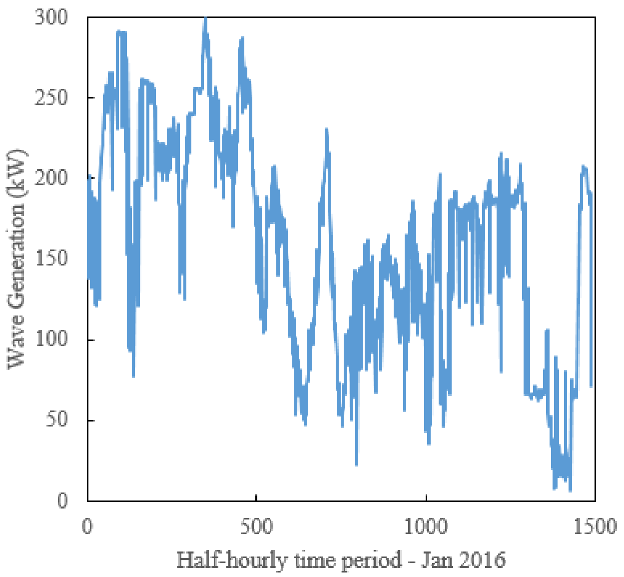

Fig. 8. Wave generation hypothetical time series for example winter month (January 2016).

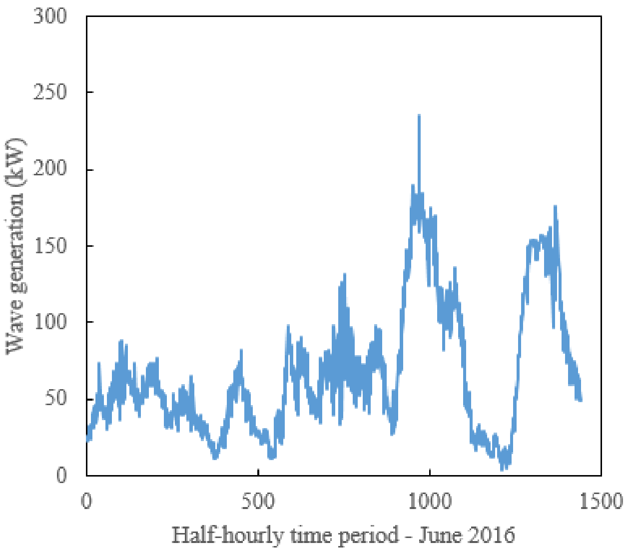

Fig. 9. Wave generation hypothetical time series for example summer month (June 2016).

Figure 10 shows the weekly average normalised power output from both wind and wave using the 2016 data. This illustrates the seasonal variation of both wind and wave resource, with a marked dip in power output in the summer months. It also highlights the offset between wind and wave generation, as there are various occasions at which there is a difference in generation output. Weeks 5-15 for example, have a considerably higher wave power output than wind.

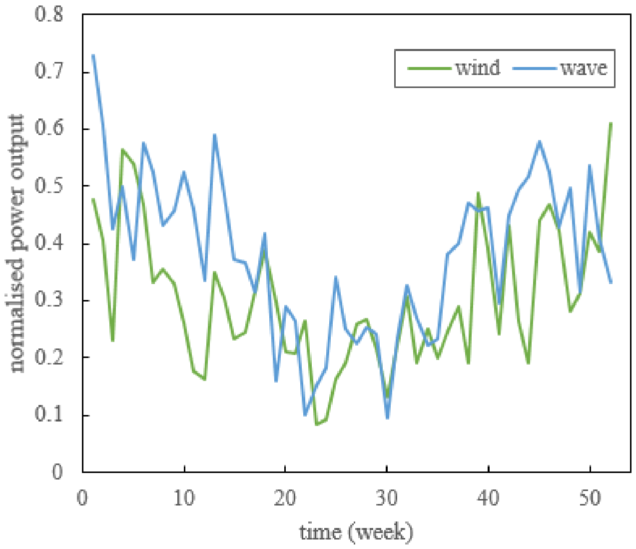

Fig. 10. Weekly averaged normalised power output for wind and wave generation time series, 2016.

D. *Time series analysis*

The time series data discussed above has been used to compare revenues for potential wave generation with historical wind generation over the three-year time period for this study. As such, the wave resource data and wind generation data was converted into time series representing the potential generation and revenues per MW of wind or wave generation with a 35% capacity factor. This has been done to directly compare the potential revenues per MW of installed capacity of both wind and wave, and as historical market prices are used it is assumed that the penetration of wave energy in the system is small enough that it does not impact on market prices.

To create a time series of wholesale market revenues from the half-hourly wind generation data, an average wind generation output was calculated for each hour from the two half-hourly generation outputs and then each year of data was normalised to the annual peak wind output. A limitation of the GB wind generation data is that a significant amount of wind generation has come on to the system over the 3-year time period. As such, when normalising and adjusting data for a 35% capacity factor this is done annually rather than over the 3-year time period.

The normalised wind generation data was scaled to an overall wind energy output at a 35% capacity factor, which represents the average capacity factor of GB wind in 2015 [29]. This scaled hourly wind generation time series was then multiplied by the market price from the N2EX data corresponding to the appropriate date and hour. This produced a representative time series of wholesale market revenues for wind generation per MW of installed capacity.

A very similar methodology was used to create a time series of wholesale market revenues from the hypothetical half-hourly wave generation data. Again, an hourly average power output was calculated to correspond to the hourly market revenue data. On this occasion, the power matrix used is capped at 300kW, so the power output time series was normalised using this value. Once averaged and normalised, the wave energy output was also scaled to an annual capacity factor of 35% to be directly comparable with the wind energy output data. This scaled energy output was then multiplied by the N2EX wholesale market price data for the appropriate date and time to produce a time series of market revenues for wave generation per MW installed capacity.

A sensitivity analysis was also undertaken to investigate the impact of the relative capacity factors of wind and wave generation on the difference in revenues per MW installed capacity. Wind capacity factor scaling was varied from 30% to 40% in 1% increments whilst keeping wave capacity factor scaling at 35% and vice versa.

IV. RESULTS

This section outlines the comparative results of wind and wave hypothetical historical wholesale market revenues, based on historical wind generation and wave resource between 2015 and 2017. Results are shown per MW installed capacity and with generation scaled to a 35% capacity factor and are thus intended to directly compare the time-dependent resource and resultant relationship to market prices.

Table I displays the total annual wholesale market revenues for wind and wave generation per MW installed capacity, as well as the cumulative total over the three years of data. As wind data for 2015 was only available from 22nd of February, wholesale market revenues for both wind and wave have been calculated from this date onwards. It can be seen that in 2016 and 2017 the total revenues for wind and wave were very similar, with 3.18% and 3.61% percentage difference respectively. The 2015 data, however, shows a decrease in revenues for wave generation compared with wind generation of 0.27%.

Table II displays the monthly total market revenues per MW installed capacity for wind and wave generation over the time period studied, as well as the percentage differences between the two. In this table positive percentage differences indicate months where market revenues for wave generation are greater than market revenues for wind generation. It can be seen that the percentage difference in wind and wave revenues differs greatly from month to month. The month with the highest revenues for both wind and wave was November 2016, and the months with the lowest revenues for wind and wave were April 2015 and July 2015 respectively. The month with the highest percentage difference in revenues in favour of wave was April 2015, in which wave had 70.60% higher revenues than wind. The month with the highest percentage difference in revenues in favour of wind was July 2015, with 29.63% higher revenues for wind generation compared with wave generation.

TABLE I
ANNUAL TOTAL REVENUES AND PERCENTAGE DIFFERENCES

Year	Total revenues - wind (£k/MW)	Total revenues – wave (£k/MW)	Percentage difference (wave – wind)
2015	£98.8k	£98.5k	-0.27%
2016	£122.1k	£126.0k	3.18%
2017	£126.9k	£131.5k	3.61%
Total	£347.8k	£356.0k	2.36%

TABLE II
MONTHLY REVENUES AND PERCENTAGE DIFFERENCE (WAVE – WIND)

MONTH	2015			2016			2017		
	WIND REVENUES (£K/MW)	WAVE REVENUES (£K/MW)	PERCENTAGE DIFFERENCE	WIND REVENUES (£K/MW)	WAVE REVENUES (£K/MW)	PERCENTAGE DIFFERENCE	WIND REVENUES (£K/MW)	WAVE REVENUES (£K/MW)	PERCENTAGE DIFFERENCE
JANUARY	N/A	N/A	N/A	£12.93K	£13.27K	2.58%	£12.44K	£17.64K	41.80%
FEBRUARY	N/A	N/A	N/A	£9.85K	£10.43K	5.96%	£13.49K	£15.72K	16.56%
MARCH	£12.32	£12.30K	-0.14%	£7.49K	£11.10K	48.29%	£10.68K	£15.35K	43.75%
APRIL	£8.11K	£13.84K	70.60%	£7.51K	£8.15K	8.51%	£8.70K	£11.07K	27.35%
MAY	£11.34K	£10.56K	-6.88%	£7.79K	£5.86K	-24.69%	£7.31K	£6.04K	-17.34%
JUNE	£7.74K	£7.63K	-1.40%	£4.48K	£5.66K	26.48%	£8.02K	£7.48K	-6.76%
JULY	£8.42K	£5.93K	-29.63%	£6.62K	£4.89K	-26.01%	£6.84K	£5.70K	-16.68%
AUGUST	£8.90K	£6.72K	-16.97%	£7.09K	£6.30K	-11.09%	£7.31K	£5.62K	-23.04%
SEPTEMBER	£7.15K	£7.62K	6.55%	£9.65K	£12.85K	33.19%	£10.47K	£10.21K	-2.48%
OCTOBER	£7.71K	£10.62K	37.70%	£12.34K	£14.56K	17.97%	£16.24K	£13.72K	-15.51%
NOVEMBER	£13.32K	£12.00K	-9.94%	£18.87K	£19.54K	3.53%	£17.41K	£15.88K	-8.80%
DECEMBER	£14.57K	£11.30K	-22.43%	£17.53	£13.40K	-23.54%	£8.00K	£7.04K	-12.03%

Figure 11 shows the comparative wind and wave market revenues for each hourly time period in April 2015, the month in which wave had the highest percentage difference in revenues over wind. It can be seen that there were a couple of periods within April 2015 which had low wind resource but higher wave resource, meaning that wave generation was able to gain a greater amount of wholesale market revenues.

Figure 12 shows the comparative wind and wave market revenues for each hourly time period in July 2015, the month in which wind has the highest percentage difference in revenues over wave. It can be seen that there are several periods in which wind resource is greater than wave resource, meaning that wind generation was able to gain a greater amount of wholesale market revenues fairly consistently over the month.

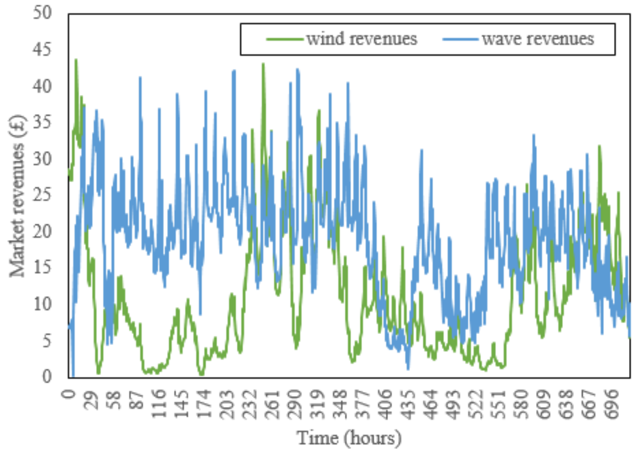

Fig. 11. Resultant hourly market revenues for wind and wave generation per MW installed capacity, April 2015.

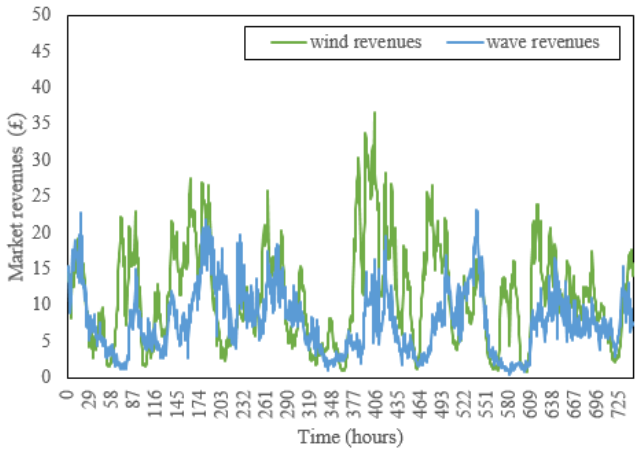

Fig. 12. Resultant hourly market revenues for wind and wave generation per MW installed capacity, July 2015.

Figure 13 shows the monthly percentage difference in revenues between wave and wind generation for each of the three years of data, as tabulated in Table II. This figure shows the clear seasonal relationship of this percentage difference, with consistently higher revenues for wave compared with wind in the spring (March and April) and in the autumn (September and October). The summer months (May – August) show consistently greater revenues for wind compared with wave over all three years of data, with the exception of June 2016.

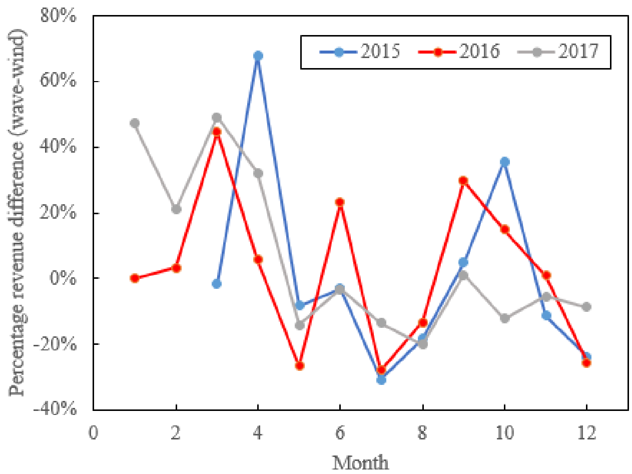

Fig. 13. Monthly percentage difference in revenues (wave-wind).

Figure 14 shows the results from the sensitivity analysis, in which the scaled normalised wind generation time series was kept at a capacity factor of 35% and the scaled normalised wave generation time series capacity factor was varied from 30% to 40% and vice-versa. It can be seen for the analysis where the capacity factor of wind was kept static at 35%, the point where the percentage difference in revenues is zero, and wave and wind gain equal revenues over the three year time period, is where wave generation has a capacity factor of 34%. Similarly in the analysis where the capacity factor of wave was kept static at 35%, the point where the percentage difference in revenues is zero, and wave and wind gain equal revenues over the three year time period, is where wind generation has a capacity factor of 36%. This shows that the point at which wind and wave generation gain equal revenues over the three year time period occurs when wave has a capacity factor of 1% less than the capacity factor of wind.

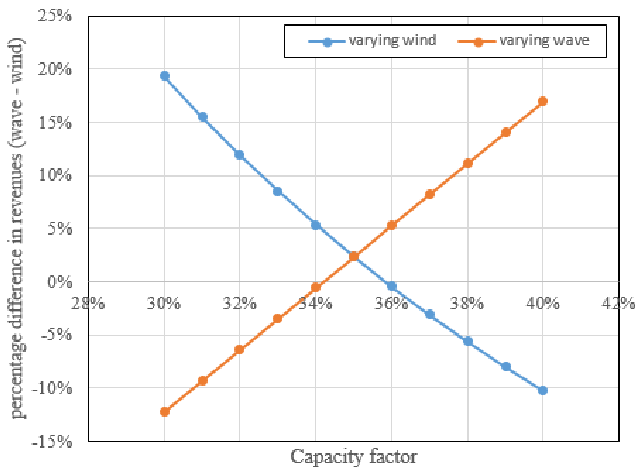

Fig. 14. Sensitivity results on percentage revenue difference (wave-wind).

V. Discussion

Results have shown that for these data, on average wave generation is gaining higher annual revenues than wind, with the 2017 analysis in particular resulting in over 3.6% greater revenues for wave generation compared with wind generation. This suggests that in a system with a high penetration of wind impacting on market prices, the temporal offset in wave and wind generation could result in a difference in market revenues for wave generation compared with wind generation. This is based on the assumption that small amounts of wave generation on the system would not make a large impact on the wholesale market price, and thus wave can access market prices without impacting on them. The resultant offset in wave and wind generation means that wave can take advantage of price spikes at times of low wind resource.

However, the results also show the annual percentage difference in revenues results from the three years of data varying significantly, from -0.27% to 3.61%. This perhaps indicates that three years of data is not enough from which to draw robust conclusions.

A particularly interesting further result was that wave and wind comparative revenues have a high seasonal correlation. Significantly higher revenues in the spring and autumn months were seen for wave generation consistently over the three years of data analysed. This could provide the basis of some interesting future work involving optimising planned maintenance strategies for wave energy converters to maximise market revenues.

The sensitivity analysis highlighted that for these data, the point at which wind and wave generation gain equal revenues occurs when wave generation has approximately a 1% lower capacity factor than wind generation.

E. *Assumptions and Limitations*

The time series analysis undertaken in this work is intended to illustrate the offset in potential production of wind and wave technologies within the UK and the potential impact of this offset in resource on market revenues. There are of course limitations involved with this historical analysis and various assumptions have been made in order to keep the time series analysis relatively straightforward. For example, data from a single wave buoy at six sites around GB has been used for wave resource data when ideally multiple wave buoys at multiple sites around GB would provide a more representative idea of the potential future GB wave generation output. The averaging of the six sites does allow for a spatial variation in resource, however.

A limitation associated with the wind generation time series creation was that each year of data was normalised to the highest value, however this most likely does not represent the installed capacity for transmission connected wind in GB exactly.

In both wind and wave time series creation the averaging and normalisation processes resulted in a time series with a relatively high capacity factor – between 36-39%, and this was scaled down to 35% to represent the current average capacity factor of wind in GB. A sensitivity analysis has also been undertaken to further investigate the impact of the comparative capacity factor of wind and wave generation on the total revenue output results.

It should be recognised that comparing actual historical wind generation with potential generation from wave based on historical resource means that in this study it is assumed that this potential wave generation can capture wholesale market prices without impacting on them. Revenues calculated are assuming that only a small amount of wave generation is present and as such historical market prices represent both wind and wave revenues, when in reality having significant wave generation on the system would impact on market prices.

It is also worth noting that historically in GB the short term wholesale market has been relatively illiquid, with a large proportion of bilateral trading through the use of power purchase agreements. As such, this analysis does not give a complete picture of the probable potential revenue streams of marine generation in future market conditions where the cost of balancing the grid may increase substantially, offering opportunities for higher revenues for energy sources that can supply electricity at times when demand exceeds supply. In addition to this, the current UK support mechanism for low-carbon electricity generation takes the form of a contract for difference (CfD), where generators are paid the difference between the market price for electricity and a competitively allocated strike price [30]. This means that renewable generation with a CfD is separated from market price signals to a certain extent, and is incentivised to secure long term power purchase agreements rather than participate in wholesale electricity markets.

F. *Wider benefits of the integration of marine renewables*

As Europe works towards legally binding carbon reduction targets which are steadily becoming more ambitious, the system impacts of high penetrations of renewable generation are becoming a significantly more important issue. The importance of renewable integration to power systems will only increase as the move towards electrification of heat and transport sectors is realised. There is an argument for a diverse mix of renewable electricity generation sources, including marine energy, to maintain security of supply and to allow for effective system balancing.

The UK in particular has a large proportion of Europe's wave resource, and is also at a latitude in which the seasonal variability results in a higher wave resource in the winter months, coinciding with times of greater energy demand. Wind resource follows a similar seasonal output to wave resource, and thus also delivers generation output within the months of highest demand. However, within an hourly resolution there is a noticeable offset on wind and wave resource. The installed capacity of wind within the GB power system already impacts on wholesale electricity market prices, driving prices down at times of high wind resource and resulting in price spikes at times of low wind resource and high demand. Such trends can be expected to increase in future markets where intermittent sources (wind and solar PV) provide high proportions of generation capacity. This work has shown that the offset in wave and wind resource could mean that wave generation is able to capture these price spikes and gain greater market revenues in the short term. In the long term, if wave generation were to make up a larger proportion of the electricity mix, then it would be conceivable that these price spikes could be mitigated by the more frequent occurrence of available renewable generation. The combination of various renewable generation technologies could improve system security and reduce reserve requirements whilst also reducing carbon emissions from electricity generation. This will be especially important as the penetration of renewables increases within the energy mix.

Marine generation also has additional socioeconomic benefits when installed within a diverse renewables mix. As mentioned previously, ideal sites for wave resource are often sited close to fragile coastal communities, which benefit considerably from the additional job creation and additional induced effects within the economy.

VI. CONCLUSION

Projections for the growth of the marine energy sector result in significant cost reductions as marine energy technologies become more mature. As socioeconomic indicators depend on project costs, these also tend to reduce with time. However, these metrics do not capture the additional socioeconomic and system value of developing marine energy technologies due to their location, predictability and offsetting of resource with other renewable technologies.

A time series analysis of historical wave and wind resource has been undertaken in this paper to illustrate the offsetting of resource and the potential short-term economic benefits to wave developers. It has shown that small amounts of wave generation which do not impact on system prices could gain greater overall revenues than wind generation, as at times of low wind resource wave generation can capture price spikes at times of high demand. This work has also shown a significant temporal variation in comparative wind and wave market revenues, at both monthly and yearly scales. A regular pattern emerged over the three years of data analysed, producing significantly higher revenues for wave generation in the spring and autumn months and for wind generation in the summer months.

Additional research is needed in order to quantify the potential value of installing and dispatching marine energy to both the developer and the system. Further work could include modelling the impact of installing higher penetrations of wave generation on market prices, and the further impact of this on captured market revenues.

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