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Challenges Posed by the Integration of Wave Power onto the Irish Power System

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***Abstract*— In order to gauge the potential impact of wave power in Ireland, the capacity factor of theoretical wave farms deployed at various locations around the Irish coast is compared to the system-wide capacity factor of wind power generation over the same period. It is shown that wave power off the coast of Ireland experiences a very significant seasonal variation, but with a lower daily variation. This paper presents the results of that analysis and examines certain challenges that will face the Irish power system if a large portfolio of wave power devices is deployed. Issues such as system adequacy and the capacity value of wave power are discussed.**

***Keywords*— Power system operation, wave power generation, wind power generation, wave power resource characterisation, capacity factor.**

I. INTRODUCTION

Of fundamental concern to any power system operator is the maintenance of electrical supply above a predefined level of system reliability. Power systems are designed such that they can handle most contingency events while still being able to supply the electrical demand placed on them. Reserve requirements are drawn up so that loss of the largest single power infeed can be covered by other generators, with the generation adequacy of a system measured by a metric called the loss of load expectation (LOLE). This metric is an important standard when assessing whether there is sufficient generation in place to meet demand and to cover for unit outages. The generation adequacy standard for Ireland is 8 hours loss of load expectation per year, while in Northern Ireland it is 4.9 hours loss of load expectation per year [1]. A generation unit's capacity value, also known as its capacity credit (the capacity which can be reliably depended on to meet the LOLE), is determined by its effective load carrying capability (ELCC) [2]–[4]. It is important to distinguish between capacity value and capacity factor (the average power output of a device divided by its rated capacity), they are separate concepts. While capacity factor is a useful annual metric, other metrics such as capacity value are also relevant.

The ELCC of a generation unit is broadly defined as the additional load on a power system which can be served by that generation unit while maintaining the existing level of security of supply, dependent on the unit's reliability. This probabilistic measure of system adequacy indicates whether sufficient generation is in place to meet future demand requirements, with a predefined LOLE level. It is an effective indicator of the security of supply of a power system, predicting whether enough generation capacity will be available during peak demand periods. The ELCC of a conventional generation unit is dependent on the forced outage rate (FOR) of that unit. However, the ELCC of variable energy resources, such as wind and wave power, is not easy to calculate due to the uncontrollable nature of the energy resource, and also due to uncertain correlations with demand patterns. As such, these generation units need to be treated as an instantaneous negative load on the power system, reducing the overall demand.

The capacity value of wave power in Ireland is of interest. A high capacity value could make wave power an important component of the power system, aiding in system operation, as it would increase the system's ability to meet its peak demand. However, a low capacity value may lead to it being viewed as an energy resource with little to provide in terms of capacity on the power system. Fundamentally, if wave power devices are to have a high capacity value, they must be able to generate consistently in times of elevated demand. This will lead to varying challenges with regard to their system integration in different power systems based on the underlying shape of their demand curves. The Irish power system experiences its peak demand in Winter evenings and minimum demand in Summer nights. A typical daily demand curve in Winter is shown in Figure 1. Hence, from both an operational and an economic perspective it would be preferable for wave power to mirror trends in the system demand curve, both on a daily and a seasonal basis.

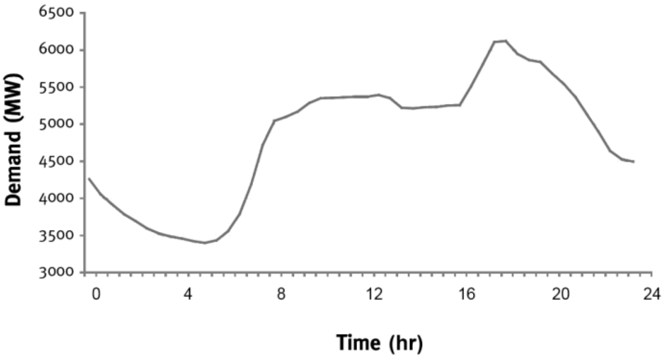

Fig. 1 A typical daily demand curve in Ireland in Winter

This paper examines the temporal and spatial variation of this potential resource with a view to highlighting issues of concern for the Irish power system. The paper also examines how wave power generation may complement the system-wide wind power generation in Ireland, or indeed may exacerbate any variability problems experienced with regard to power system integration. Section II examines the background of wave energy in Ireland, providing the context in which this paper has been created. Wave and wind energy data were examined for a typical year (2008). The data was obtained from a national network of weather buoys, as outlined in Section III. Section IV then examines the concept of a power matrix for a wave energy device, while Section V details the results of the analysis. The potential impact on system operation is discussed in detail in Section VI, with conclusions being drawn in Section VII.

II. WAVE ENERGY IN IRELAND

The west coast of Ireland directly faces some of the most energetic seas in the world. Waves are generated over a large fetch of water in the Atlantic Ocean with the prevailing winds coming from the Americas, southwest across the ocean. This provides a large potential for energy to be extracted from the ocean surface waves off the Irish coast. A target has been set to achieve 500 MW of installed ocean energy capacity by the year 2020 [5], leading to the creation of ocean energy test centres off the west coast of Ireland. It is important to consider the wide-scale impact on the power system that will be experienced if this target is achieved, and how this resource's temporal characteristics will impact on daily system operation and long-term adequacy planning.

The theoretical incident wave energy contained in a particular sea state can be established using Airy wave theory [6]. However, this figure represents the unconstrained theoretical hydrodynamic energy resource. The electrical power that would be generated in each sea state by a particular device is given by that device's power matrix, which describes how a device reacts in various sea states and how its electrical power output fluctuates as a result. Using measured or predicted values for the significant wave height (H_s) and the wave energy period (T_e) a device's power output can be determined, enabling the technical electrical energy resource to be established. Previous research suggests that this value may be reduced from the unconstrained theoretical hydrodynamic energy resource by up to 94% of the original resource [7]. A wave energy resource atlas concluded that the potential wave power which could be harnessed off the coast of Ireland, during the study period, ranged from 0.14 GW to 2.4 GW of accessible electrical power.

Wave energy is not a uniform resource, although some of its temporal variation can be reduced through spatial diversity. However, due to the challenging environment in which these devices will be installed, coupled with other regulatory and environmental constraints, it is unlikely that the devices will be distributed homogenously. A more likely outcome will be the creation of various clusters of devices, an outcome which will limit the spatial diversity which may be achieved.

III. DATA COLLECTION

Wave data around the Irish coast consists of a network of six offshore measurement buoys maintained by the Irish Marine Institute. The six buoys, named M1 - M6, have measured sea states in various locations around the Irish coast for most of the past decade. The buoys were deployed starting in early 2001 with the final buoy being deployed in late 2006. The buoy at location M1 ceased recording in mid-2007 and was subsequently moved to the M6 location. Additional measurement buoys at the two wave energy test centres of Galway Bay (G) on the west coast and at Belmullet (B) on the northwest coast of Ireland were deployed in April 2008 and December 2009 respectively. The approximate location of each buoy is illustrated in Figure 2.

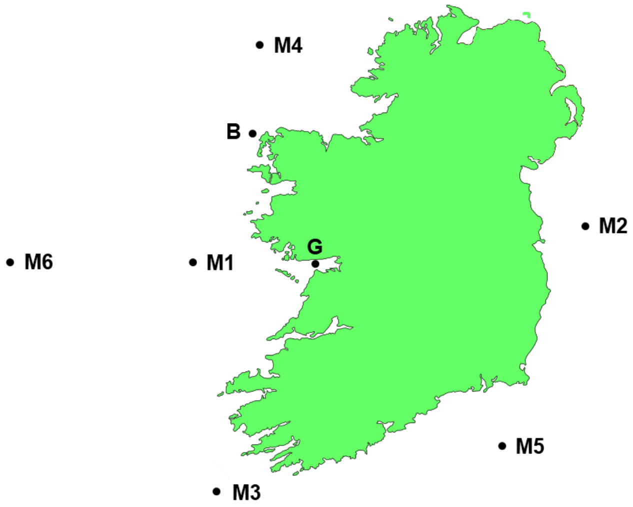

Fig. 2 Irish Marine Institute's offshore measurement buoy network

While it would be desirable to use data from all the buoys in this analysis, buoy data may be missing due to both forced and planned outages. Data is unavailable from the M1 buoy in recent years. Therefore data from M2, M3 and M6 during one year was used for this analysis. This was considered sufficient to represent any spatial diversity. The 'M' buoys measure at an hourly resolution. Due to the inherently slow nature of changes in swell waves in deep water locations, hourly resolution is considered sufficient for this analysis. As recent journal papers suggest, going forward, data analysis should be completed for the buoys not examined in this paper as further data becomes available.

When carrying out an analysis of the potential interaction between Ireland's power system and its wave energy resource, it is important to be aware that devices placed nearer to shore will experience a different wave climate to devices placed further offshore, with frictional effects with the sea bed occurring as a wave approaches the shoreline. Deep water provides an environment where the orbital motion of fluid particles remains generally circular as the wavefront propagates in any direction. As ocean surface waves approach the shoreline and enter shallower seas, the orbital motion of the fluid particles begins to flatten and becomes more elliptical in shape. As such, the waves are modified so that the surge component (the horizontal component) becomes much more significant while the heave component (the vertical component) becomes less significant, as illustrated in Figure 3.

As a result, nearshore (beyond the surf zone, but still influenced by friction with the seabed) wave energy devices, moreso than offshore (no effect from friction with the seabed) wave energy devices, may need to be designed to take advantage of a large surge component in the waves. However, that is not to say that most of the energy available to wave energy devices is lost in the nearshore environment. Folley and Whittaker have postulated that most (over 78%) of the exploitable wave energy at offshore sites is also available for exploitation at nearshore sites [8].

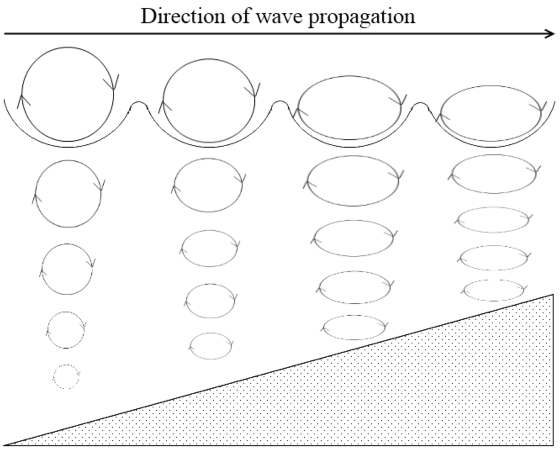

Fig. 3 Impact of friction with the seabed on ocean surface waves

The temporal and spatial variation in the fundamental energy content of offshore waves will be similar to unsheltered nearshore sites, irrespective of changes in the nature of the heave and surge components of those waves [8].

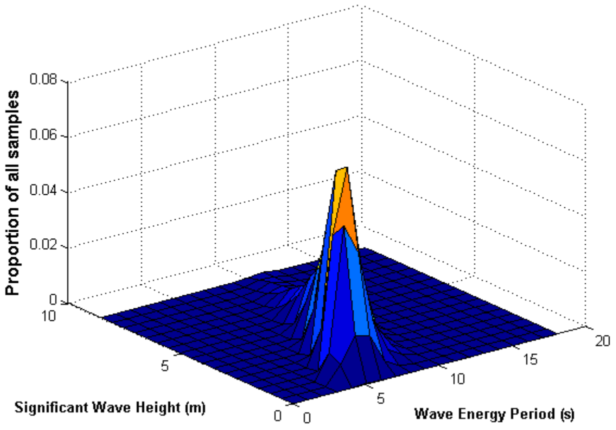

Fig. 4 Typical wave climate experienced across the year at M3

Hence, in terms of measuring or predicting the variation of normalised potential power output from wave energy devices, data from offshore measurement buoys may still be used. Figure 4 illustrates the wave climate experienced in the considered year.

Data for the system-wide wind power generation during the study period was provided by EirGrid. Only wind farms in operation from the start of the study period were considered, with wind power on the Irish system used for this analysis amounting to a total of 828 MW of installed capacity.

IV. DEVICE POWER MATRICES

The electrical power that would be generated in each sea state by a particular wave power device is given by that device's power matrix, using measured or predicted values for H_s and T_e. Pelamis Wave Power Ltd. has made publicly available the power output matrix of their Pelamis wave energy converter [9], which is a long snake-like linear attenuator device, with an articulated structure containing hydraulic power take-off mechanisms.

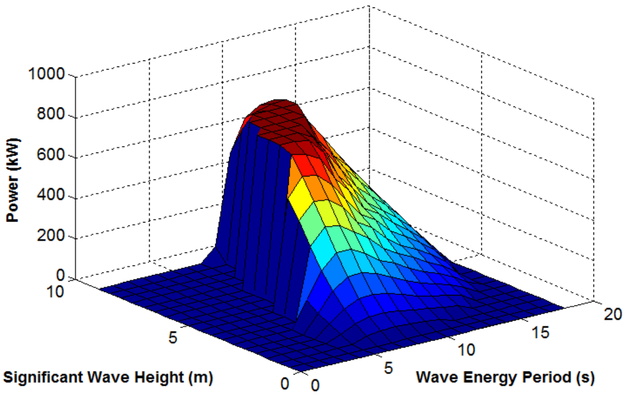

Fig. 5 Electrical power matrix of the Pelamis wave energy converter

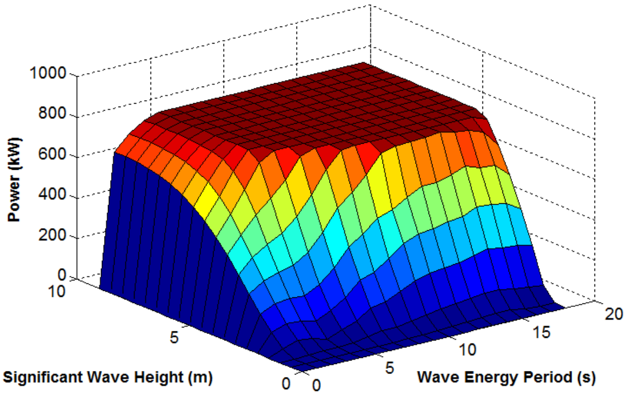

Fig. 6 Electrical power matrix of an electrically downrated device

As can be seen in Figure 5, the Pelamis wave energy converter is not electrically downrated (relatively speaking), reaching less than its maximum power output for many sea states. Its power matrix is widely used in the research community literature, and as such is used here for analysis of the Irish system. For the sake of comparison, a power matrix has also been synthesised for an electrically downrated device, providing some insight into how much of the available wave energy might be gained or lost as a result of electrical downrating. The power matrix of the hypothetical downrated device is illustrated in Figure 6.

V. RESULTS

A. Temporal Variation

This paper employs available data from the network of data measurement buoys to determine the temporal and spatial variation in the capacity factor of wave installations at the buoy locations. These capacity factors are then compared to the system-wide capacity factor of Ireland's wind generation portfolio for the same time period in order to analyse whether the introduction of wave power onto the Irish system may pose any new challenges, or indeed yield net benefits due to complementary variations in wind and wave power output.

1) Monthly Capacity Factors: The M3 buoy (off the southwest coast) is directly exposed to the raw wave energy resource approaching Ireland from the southwest, and so was used for initial analysis. The average electrical power output of a hypothetical wave farm consisting of non-downrated devices located at buoy M3 was determined for one year, and compared to the average national wind power generation in Ireland for the same time period. The capacity factors of both were compared on a per-unit basis. Figure 7 illustrates how a hypothetical wave farm could have made significant contributions (in terms of average power generated) in the Winter months (January, November and December), with an average monthly capacity factor of up to 0.74 pu during January. Figure 7 also illustrates how high capacity factors in Winter and low capacity factors in Summer (as low as 0.05 pu during May) are a characteristic of wave power in Ireland.

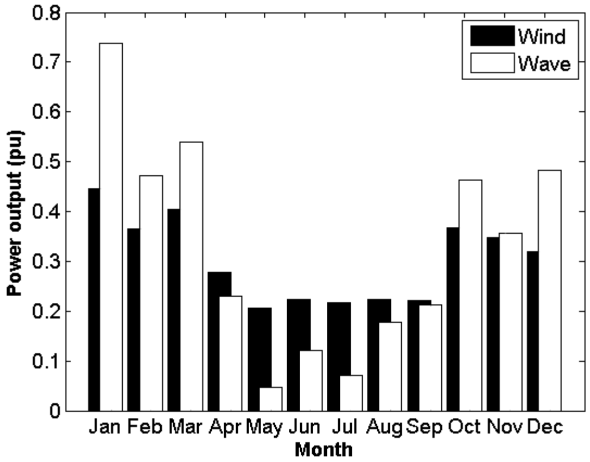

Fig. 7 Average monthly capacity factors of system-wide wind power and a non-downrated device wave farm at buoy M3

Under normal circumstances a power system operator would prefer to experience no variability from generating units which, by their nature, are not dispatchable. While this is certainly not the case with wave energy in Ireland, the negative effects of this variability are at least reduced by the fact that the minimum capacity factors occur in Summer, with maximum capacity factors occurring in Winter. This suits the demand profile in Ireland, with peak demand occurring in Winter and minimum demand occurring in Summer. Conversely, some countries which may experience a similar wave climate may not find the temporal distribution so convenient if they experience alternative load profiles (for instance if their peak demand occurs in Summer and their minimum demand occurs in Winter). This makes Ireland more suited to the grid integration of wave power than many other countries seeking to exploit their wave energy resources.

2) Average Hourly Capacity Factors: It is also of interest to investigate the variation of wind and wave power with time of day. Figures 7 and 8 show the average normalised power from a non-downrated device wave farm at M3 and the corresponding system-wide wind power generation for quarter 1 (January to March) and quarter 2 (April to June). Results for all four quarters are summarised in Table I.

TABLE I
MIN/MAX HOURLY CAPACITY FACTOR FOR SYSTEM-WIDE WIND GENERATION AND A NON-DOWNRATED DEVICE WAVE FARM AT BUOY M3

Quarter	Minimum (wind)	Maximum (wind)	Minimum (wave)	Maximum (wave)
1	0.39 pu	0.43 pu	0.55 pu	0.61 pu
2	0.20 pu	0.29 pu	0.12 pu	0.15 pu
3	0.20 pu	0.25 pu	0.13 pu	0.18 pu
4	0.33 pu	0.37 pu	0.42 pu	0.45 pu

Figure 8 illustrates how a non-downrated device wave farm located at buoy M3 could potentially be a greater resource than an equivalent capacity of wind power generation located onshore during quarter 1. The average hourly variation across the day of a single non-downrated device wave farm has a similar range to the corresponding variation in the system-wide wind power generation during the same period (with the wind profile benefitting from the aggregation of many farms over a wide geographical area). However, the wave farm would have experienced a considerably higher capacity factor (a peak value of 0.61 pu for wave power and an equivalent value of 0.43 pu for wind power). A slight variation in average wave power output occurs across the day, with a trough occurring in the late morning (10:00) and peaks occurring in the evening/night (19:00/01:00), following a gentle rise throughout the afternoon/evening, due to increased wind conditions caused by solar heating during the day. This mirrors a similar trend for the observed wind power generation (with troughs and peaks occurring at 10:00 and 16:00 respectively), with a time lag of two to three hours in evidence.

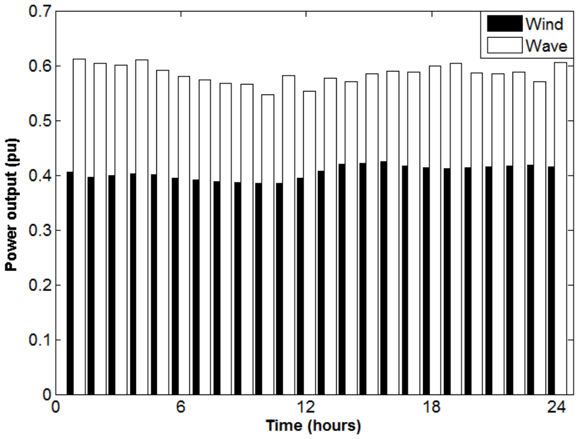

Fig. 8 Average hourly normalised system-wide wind generation and a non-downrated device wave farm at buoy M3 during quarter 1

Figure 9 highlights a defining feature of wave power generation off the Irish coast, namely a large seasonal variation in output, greater than that for wind power generation. As suggested earlier in Section V, this may act to reduce the negative effects of the variability of wave power with respect to its integration onto the Irish power system. The average daily variation of a non-downrated device wave farm located at buoy M3 during quarter 2 (0.03 pu of rated capacity) would have been considerably lower than the corresponding variation in the system-wide wind power generation during the same period (0.09 pu of rated capacity). However, the wave farm would have experienced considerably lower capacity factors. The peak capacity factor of 0.61 pu in quarter 1 has declined to 0.15 pu in quarter 2.

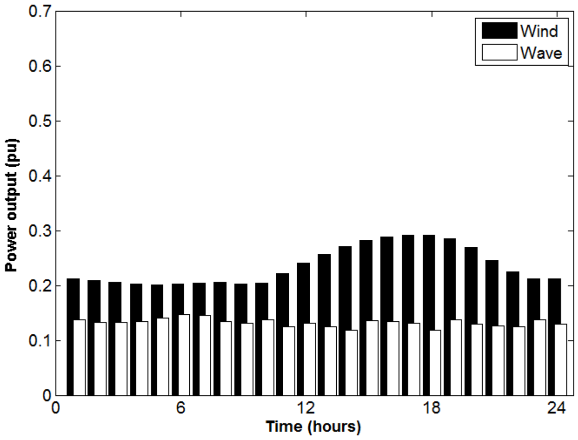

Fig. 9 Average hourly normalised system-wide wind generation and a non-downrated device wave farm at buoy M3 during quarter 2

A very slight variation occurs across the day in this instance, but with the peaks and troughs occurring later than those of the observed wind power generation. While this indicates a low level of average output, from a power system operator's perspective the lower variability is beneficial, with dispatchable plant being used to deal with variations in demand. Unlike wave power, wind power generation during this period experiences noticeable ramping events on average during the afternoon and into the evening due to solar heating during the day, increasing its variability.

During quarter 3 (not shown) a time lag between the peaks and troughs of wind and wave generation is evident. The net effect of this is to balance out the overall average hourly variation of the renewable generation profile. However, capacity factors still remain low with a peak value of 0.18 pu occurring. The average hourly wave power during quarter 4 (not shown) is slightly less variable than the corresponding variation in the system-wide wind power generation during the same period. A return to relatively high capacity factors (over 0.40 pu) for the non-downrated wave device is evident during this quarter. While the average capacity factor for wave power has returned to higher levels than experienced by the system-wide wind power generation, it must be noted that the capacity factors are still considerably lower than those experienced in quarter 1.

3) January vs. May: In order to better understand how much temporal variation occurs the two most extreme months, January and May, were examined further. The average hourly normalised power output of a non-downrated device farm at buoy M3 was determined, as illustrated in Table II.

TABLE II
MIN/MAX HOURLY CAPACITY FACTOR FOR SYSTEM-WIDE WIND GENERATION AND A NON-DOWNRATED DEVICE WAVE FARM AT BUOY M3

Month	Minimum (wind)	Maximum (wind)	Minimum (wave)	Maximum (wave)
January	0.42 pu	0.48 pu	0.65 pu	0.80 pu
May	0.18 pu	0.24 pu	0.03 pu	0.06 pu

The seasonal variation in power output from January's maximum to May's minimum is much greater (up to 0.77 pu of rated capacity) than the corresponding seasonal variation in wind power output. The variation from minimum to maximum capacity factors across a day for wave power is greater in January than in May (0.15 pu and 0.03 pu respectively). Peak hourly capacity factors of 0.80 pu would have been observed in January along with minimum values of 0.65 pu. Wave power output would have been more variable than the corresponding variation in the system-wide wind power generation during the same period. However, that could be expected as this is a comparison of a single wave site during a highly energetic period against wind power aggregated across the entire power system.

While the average hourly wave power output in January experiences noticeable variability, the capacity factors experienced are well in excess of those seen by the system-wide wind portfolio during the same period. Interestingly, while the system-wide wind power portfolio experiences moderate ramping events in the afternoon, the wave farm tends to experience at least two ramping events with peaks occurring in the early morning and early evening.

The average hourly power output of a non-downrated device wave farm at buoy M3 during May would have seen variations in its capacity factor of 0.03 pu (0.03 pu – 0.06 pu). Wave power output would have been less variable than the corresponding variation in the system-wide wind power generation during the same period. The capacity factor of the system-wide wind portfolio would have halved from January, but would not have experienced a similar collapse to the capacity factor of the wave farm. The afternoon ramping events remain for the wind generation, while the wave farm would experience a consistently low output with little variability occurring, hence posing less problems in terms of power system operation.

B. *Spatial Variation*

Thus far the analysis has focused on the wave climate experienced at the M3 buoy. The impact of positioning wave farms at different locations was also determined, namely M2, off the east coast of Ireland in the Irish Sea, and M6, far offshore from the west coast of Ireland in the Atlantic Ocean. The locations of these buoys are shown in Figure 2. These locations were analysed for the months of January and May, the results of which are illustrated in Table III.

TABLE III
MIN/MAX HOURLY CAPACITY FACTOR FOR NON-DOWNRATED DEVICE WAVE FARMS AT BUOYS M2, M3 AND M6

Buoy	Minimum (January)	Maximum (January)	Minimum (May)	Maximum (May)
M2	0.00 pu	0.04 pu	0.00 pu	0.00 pu
M3	0.65 pu	0.80 pu	0.03 pu	0.06 pu
M6	0.75 pu	0.83 pu	0.06 pu	0.12 pu

The average hourly output of a non-downrated device wave farm at buoy M3 would have seen a wider variation than a similar wave farm at buoy M6 in January, as illustrated by Figure 10. However, the wave climate at M6 can be considered to be broadly representative of conditions nearer to shore at locations such as buoy M1. Hourly capacity factors at these locations would have varied on average by 0.15 pu and 0.08 pu across a day in January at M3 and M6 respectively. Hourly capacity factors at buoy M2 would have been very low, with a maximum variation of 0.04 pu on average across a day in January being experienced. Coupled with observed low outputs in all months of the year, this raises the question of whether it will ever be economically feasible to deploy wave energy devices off Ireland's east coast.

Table III illustrates how a wave farm located at buoy M6 would have had a tighter range of capacity factors than a wave farm closer to shore at buoy M3. A time lag of five to six hours was observed between these two locations, with M3 output tending to be more in phase with system demand than M6. May was the least energetic month for wave power output (for buoy M3). All locations experienced low capacity factors in this month, with a maximum of 0.12 pu occurring at buoy M6. Wave farms at M3 and M6 would have experienced very low capacity factors.

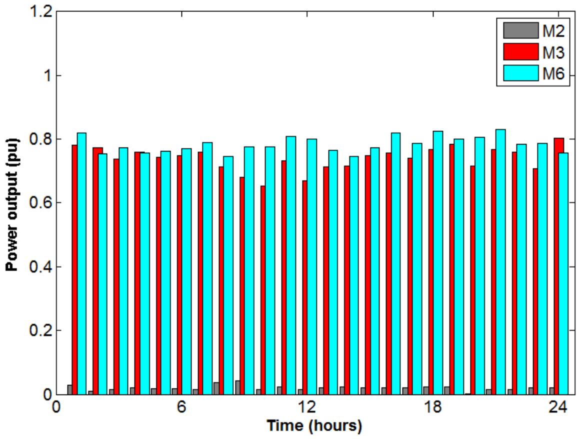

Fig. 10 Average hourly variation of non-downrated device wave farms at buoys M2, M3 and M6 during January

While aggregation over a wide geographic area may act to reduce the overall variability of wave power in Ireland, it must be noted that it is likely, for a variety of reasons (regulatory constraints, environmental constraints, electrical network constraints, etc.), that farms of devices will be deployed in clusters, hence the benefits of aggregation may not be as apparent as for wind energy onshore.

C. *Downrated vs. Non-Downrated Devices*

As indicated in Section III, the Pelamis wave energy converter is a relatively non-electrically downrated device. In order to provide an insight into how much of the available wave energy might be gained/lost as a result of using such a device, a power matrix was synthesised for an electrically downrated device and also used for this analysis assuming devices located at buoys M2, M3 and M6. The same spatial analysis was carried out as before in the extreme months of January and May, as illustrated in Figure 11 and Table IV. Direct comparison can be made with Figure 10 and Table III for the non-downrated device.

TABLE IV
MIN/MAX HOURLY CAPACITY FACTOR FOR THEORETICAL DOWNRATED DEVICE WAVE FARMS AT BUOYS M2, M3 AND M6

Buoy	Minimum (January)	Maximum (January)	Minimum (May)	Maximum (May)
M2	0.06 pu	0.13 pu	0.00 pu	0.01 pu
M3	0.87 pu	0.94 pu	0.06 pu	0.11 pu
M6	0.90 pu	0.97 pu	0.11 pu	0.19 pu

The output of a wave farm consisting of downrated devices at buoy M6 would have experienced a similar low range of hourly capacity factors as a non-downrated device wave farm. However, closer to shore at M3, the range of hourly capacity factors for a non-downrated device would be approaching twice that experienced with a downrated device wave farm. Hourly capacity factors for downrated device wave farms at these locations are higher than non-downrated device wave farms in the same locations, with a range of 0.87 pu to 0.94 pu being experienced at buoy M3, and 0.90 pu to 0.97 pu at buoy M6.

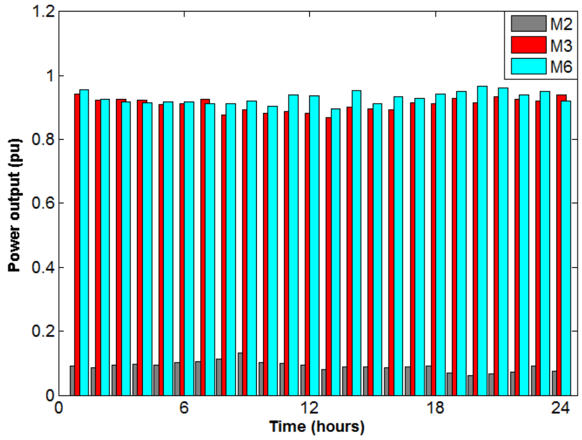

Fig. 11 Average hourly variation of downrated device farms at buoys M2, M3 and M6 during January

The use of a downrated device appears to smooth the profile of the average hourly capacity factors in January (maximum variation of 0.07 pu for the downrated device and 0.15 pu for the non-downrated device). Consistently higher capacity factors would have been experienced with downrated devices, however since the values experienced with non-downrated devices were already quite high, then the relative increase is not so large. Fundamentally, the non-downrated device wave farm would experience greater hourly variation in output, yet would still capture the majority (80%) of the wave energy that the downrated device would capture.

The output of a wave farm consisting of downrated devices at buoy M3 would have experienced similar low average hourly variation to a non-downrated device wave farm in May, albeit with quite low capacity factors. However, these capacity factors are higher than non-downrated device wave farms in the same locations, with a maximum capacity factor of 0.11 pu being experienced at M3, and a maximum capacity factor of 0.19 pu experienced at M6.

So, regardless of which device's power matrix is considered, the average hourly output in May would have been very low. Capacity factors may have almost doubled in many instances at buoys M3 and M6 as a result of using the downrated device's power matrix, however in absolute terms the average hourly capacity factor never exceeds 0.20 pu. The west coast appears to have an abundance of wave power potential during the Winter months, while its output during the Summer months appears to be more influenced by the shape of the individual device's power matrix.

D. Ramp Rates

While the analysis thus far has focussed on the underlying seasonal trends which may affect the variation experienced by wave energy devices, this does not highlight sufficiently the large variations experienced in relatively short time periods (over several hours for instance). Figure 12 illustrates the actual variation experienced across one week in January during the study period, both for an aggregate of wave power at M3 and M6 (50% allocation to each site), and for the system-wide wind power generation over the same period. A three hour moving average was used for analysing the wave data. Similar trends are observed in the variation of system-wide wind power and for the aggregate power output from M3 and M6.

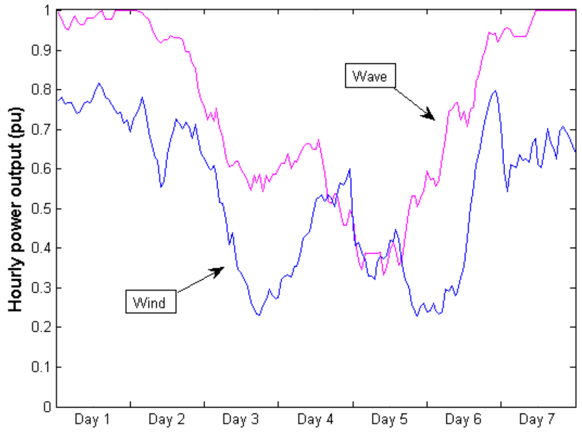

Fig. 12 Hourly variation across one week in January for system-wide wind power generation and for an aggregate of wave data from buoys M3 and M6

Meanwhile, Figure 13 illustrates the hourly ramp rates experienced by the same generation sources over a period of one day in this month (day 4 from Figure 12). This highlights one example of how while wave power experiences broadly similar ramping events to wind power, it doesn't reach the same maximum ramping magnitudes.

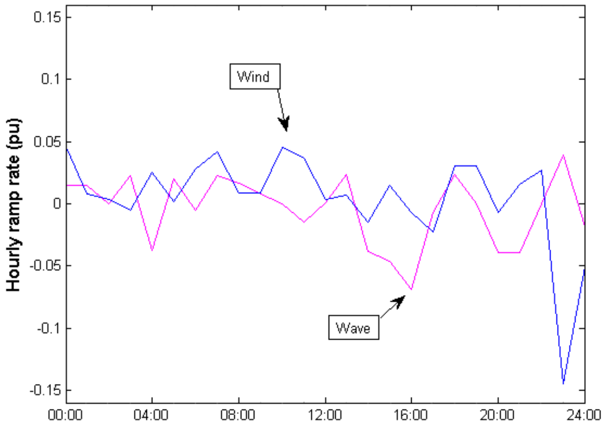

Fig. 13 Hourly variation across one day in January for system-wide wind ramp rates and for an aggregate of wave data from buoys M3 and M6

Whilst wave power experiences large ramp rates along with wind, it doesn't appear to suffer from the exceptionally large ramps which are occasionally experienced by wind power generation. This means that ramping events in the overall renewable generation portfolio may be lessened through an aggregation of wind and wave power across the power system. An example of this is observed on day 5 in Figure 12, with wave power experiencing a large positive ramp while wind power experiences a large negative ramp.

VI. DISCUSSION

The results of this analysis provide a number of interesting conclusions about the potential for wave power in Ireland. Firstly, wave power farms would display a similar seasonal variation, in shape, rather than magnitude, to wind generation on the Irish system. However, the seasonal variation in wave power output is much greater than that for wind power. While the capacity factor for the year as a whole would have been 0.33 pu for a non-downrated device wave farm located at buoy M3, this can mask the fact that average hourly capacity factors in January and May could have varied between 0.80 pu and 0.03 pu in those months respectively. This seasonal variation is not confined to non-downrated devices however as downrated devices would have experienced average hourly capacity factors ranging from 0.94 pu to 0.06 pu at the same location in January and May respectively. Considerable hourly variation is experienced by both wind and wave power generation. Ramping events appear to be less extreme for wave power than for wind power. The ramping events experienced by wind power are lessened as it is the aggregation of many wind farms over a large geographical area. Aggregation over such a wide area would result in very low ramping events for wave power. However, given the likelihood of wave power being deployed as a small number of large clusters of devices, this aggregation benefit may not occur. The resultant variability of these small number of wave device clusters will therefore be comparable to the system-wide wind power variability.

Another variation experienced by wave farms is a spatial one, in relation to whether they are positioned in seas with large swell waves from the Atlantic Ocean, or in seas where the majority of waves are locally generated wind waves. The results presented here suggest that Ireland's eastern seaboard is unsuitable for the installation of wave farms due to its sheltered location from the Atlantic Ocean. Some diversity in output appears to occur from different locations off the west coast of Ireland, however this diversity is relatively small. Through spatial diversity it may be possible to site wave farms such that the hourly variation in their aggregated output is reduced from the perspective of the system operator, also aiding in the forecasting of their combined power output.

Finally, different devices may react differently to similar sea states. As such, it is possible that certain devices can extract more wave energy in certain locations due to their power matrices being more suitable. While a downrated device outperformed the non-downrated device in this study, the non-downrated device still captured most of the same wave energy, while experiencing broadly the same seasonal and hourly variations in output.

Overall, Ireland's wave energy resource can be characterised as having a large seasonal variation, with a low average hourly variation (actual hourly variation is still significant). Selection of wave farm sites and the technology of devices installed may act to minimise seasonal variations. Aside from the obvious economic implications for wave farm owners, such variations will pose many challenges with regard to power system integration, particularly in relation to system reliability in Ireland, as it is a relatively small system with limited interconnection. However, the wave resource peaks during months in which the system demand peaks, with the lower wave resource also coinciding with months of lower demand. As such, wave farms, correctly located, should have a high effective load carrying capability [2]–[4] in comparison with wind power generation from the system operator's perspective. A high capacity value for wave power would indicate that it can provide power when it is required most. Additionally, should aggregated wave power prove to have lower levels of variability than wind power generation, then this could reduce the potential cycling of base load plant. Base load plant are designed to operate under steady conditions with little variation in their power output. Cycling refers to such plant being required to make large changes in power output relatively quickly as a result of short term power requirements on the power system.

VII. CONCLUSIONS

The average capacity factor for both system-wide wind power generation in Ireland and the potential power which could have been generated by wave power farms over the same period has been determined. In terms of temporal variation, wave power has a large seasonal variation, accompanied by a small average hourly variation. The actual hourly variation however can be quite significant, with similar ramping events to wind power generation being experienced. The most extreme ramping events experienced by wind power generation are not however experienced by wave power generation. Wave power has a very large spatial variation, with locations off Ireland's east coast experiencing far less energetic seas than Ireland's west coast. Wave power can potentially provide system operators with a variable energy resource featuring a seasonal characteristic mirroring trends experienced in the system load. The capacity value of wave power is an area meriting further study, as is an investigation into the aggregate effect of introducing spatial diversity to the choice of locations for potential wave farms. Further investigation is also required to assess whether significant annual variation occurs over longer periods of time than that assessed here.

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