Wave Resources in South Wales and a Comparison with Wave Climate at the Wave Hub

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Executive Summary

A variety of resource assessments have calculated available areas, constraints and possible installed capacities for wave energy in Wales. While these are useful from a strategic point of view, from an operational or project planning point of view, analysis of measured wave statistics is required. This work presents data from wave buoys within and close to the Pembrokeshire resource areas. The viability of three types of wave energy converters, an attenuator, point absorber and an offshore overtopping device, are considered based on data measured at the Turbot Bank (51.603N, 5.1W) buoy and the Aberporth (52.3N, 4.5W) buoy. Comparison between the measured Welsh resource and data collected at the Wave Hub site in Cornwall is presented. Both Wales and Cornwall have similar wave resources with differences in device capacity factor of between 0-2%. This makes Pembrokeshire a very attractive location for the deployment of wave energy converters in the UK, especially given the proximity to large port facilities for maintenance and population centres along the M4 corridor for electricity use.

1 Introduction

The marine energy resources in Wales are focused on Pembrokeshire (wave and tidal), Anglesey (tidal) and the Severn Estuary (tidal). In a recent policy statement (WAG, 2010), a target of 4GW installed wave and tidal generation capacity by 2025 was set. In recent years, disparity in electricity prices (dictated by ROC's) has seen UK marine energy developments focus on Scotland. However, the planned re-structuring of ROC's (Pelmore and Nind, 2011) in England and Wales should increase the rate of development in these regions.

Two main marine energy resource assessments have been conducted for Wales: The Wales Marine Site Selection Report (PMSS, 2006) and the Marine Renewable Energy Strategic Framework (RPS, 2011). Both reports identified significant wave resources off the Pembrokeshire Coast. The PMSS (2006) report suggested a capacity for deep water wave energy converters in Pembrokeshire of 5.6GW. The MRESF (RPS, 2011), suggested a range of installed capacity between 1-6GW, it is worth noting that the MRESF suggests that the wave climate in Wales is unsuitable for attenuator wave energy converters such as Pelamis. The wave resource area suggested by RPS (2011) is presented in Figure 1. Work by Fairley et al. (2011) used technological constraints from PMSS (2010) and macro-scale constraints such as shipping areas, wind farms and military areas to suggest three wave energy converter deployment areas in Welsh waters (Figure 2). The key difference between the RPS report and the work by Fairley *et al.* (2011) is the area further west. This relates to the 50km offshore region in Fairley *et al.* (2011) including islands in the calculation which artificially extends the available area. Therefore it can be assumed that the central area in Figure 2 is the most likely deployment region of the three presented. The area to the east is less likely to be developed given the lower wave energy and location behind the proposed Atlantic array.

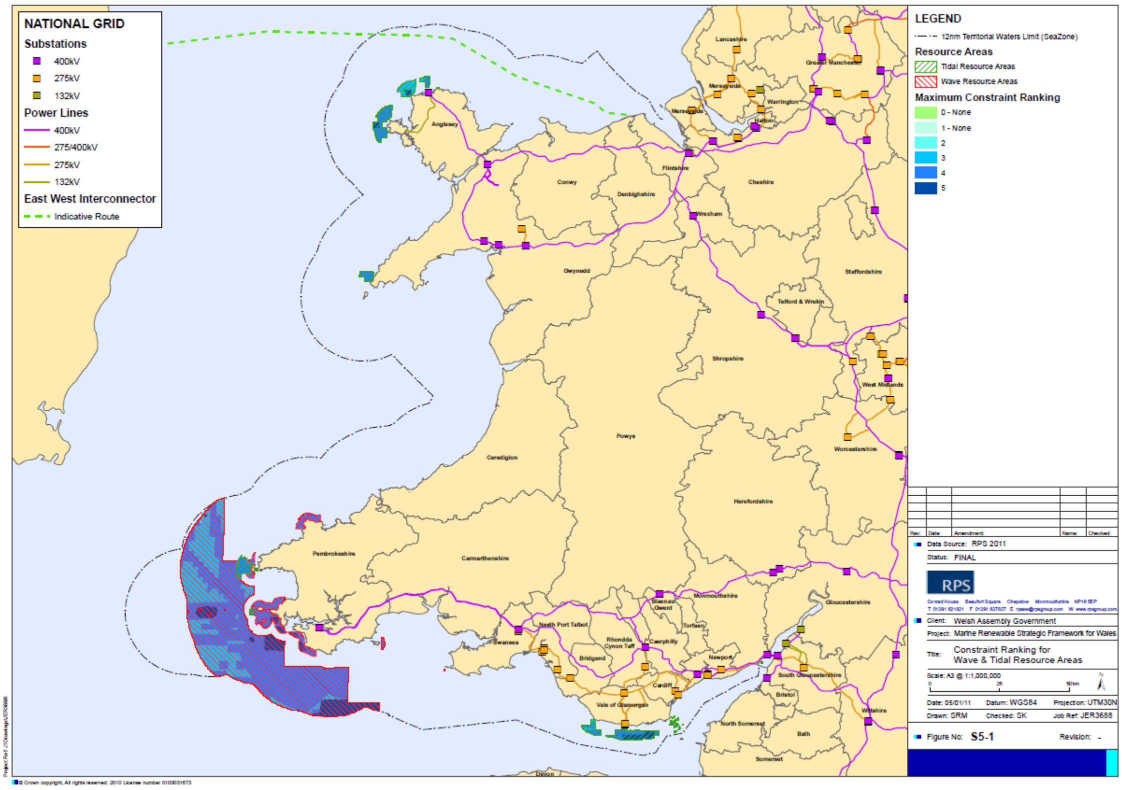

Figure 1: A map show wave and tidal resource areas reproduced from RPS (2011)

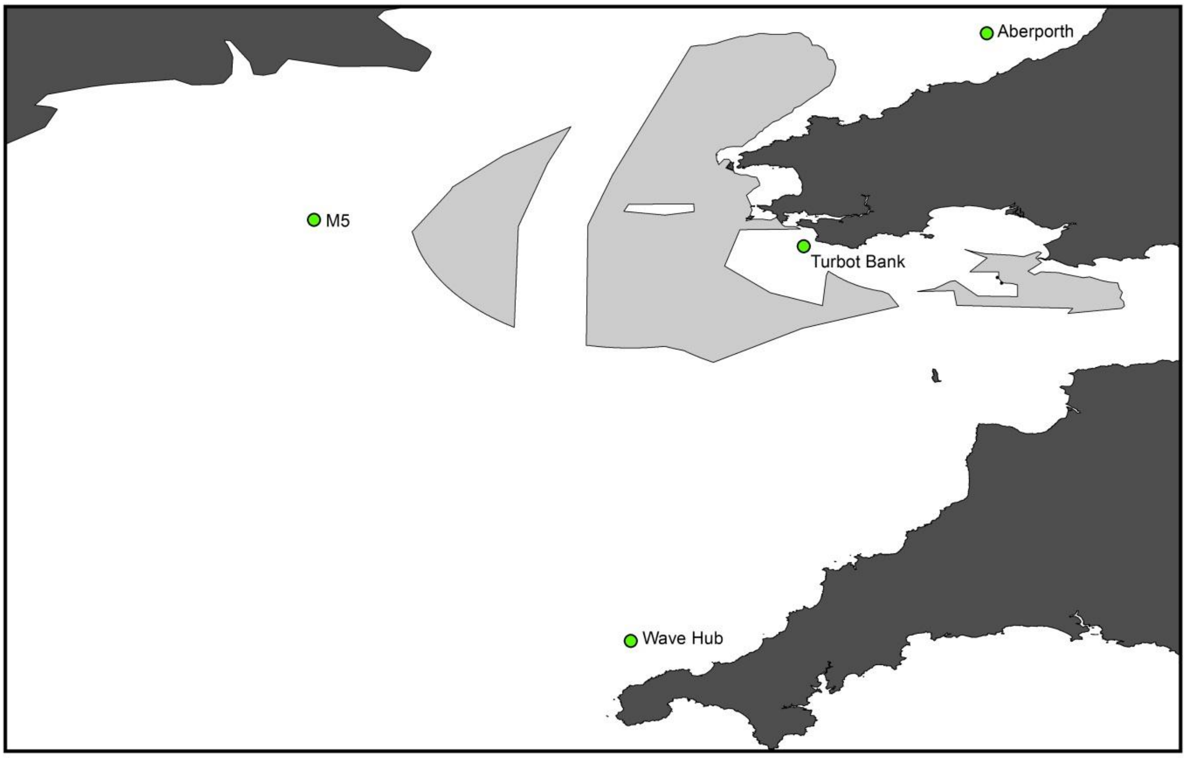

Figure 2: Areas available for wave farm deployment from Fairley et al (2011), the locations of the four wave buoys are also displayed.

All three mentioned studies give suggested deployment locations for wave energy converters. To attract developers and investment to the region quantification of available resource is required. Measured data is preferable to modelled data due to lesser uncertainty in results. This work looks at data from wave buoys at three locations close to the Welsh deployment areas and, for comparison, at data from a buoy at the Wave Hub location in Cornwall. For any area to be attractive to investors, comparison with known wave energy deployment sites is useful. In this study the resource in South West Wales is compared to the resource at the Wave Hub in Cornwall. The Wave Hub is a grid-connected facility in a location considered favourable for wave energy converters (Wave Hub, 2012).

Wave energy converters typically extract differing amounts of power depending on wave height and period. The information about device performance is summarised in a power matrix. This is commonly commercially sensitive data, however in this study three matrices are utilised. The matrix for the Pelamis 700kW P1 device, an attenuator, has been presented in a variety in publications (e.g. Dunnett and Wallace, 2009), the power matrix for a point absorber, the 250kW Aqua Buoy, was replicated from Dunnett and Wallace (2009), the power matrix for the 7MW Wave Dragon, an offshore overtopping device, was obtained directly from Wave Dragon but is also published in Dunnett and Wallace (2009). These three devices represent three of the most common types of device. The Pelamis device is one of the more commercially ready wave energy converters, however it is an attenuator device which means that, according to the MRESF (RPS, 2011) the device would not be suitable for Welsh waters. These matrices are used in combination with the wave statistic time series is used to estimate power output for the three wave energy converters. This allows comparison both of the different sites and of the performance of the different technologies at these sites.

2 Methodology

Data for three wave buoys, the Turbot Bank buoy, the M5 buoy and the Aberporth buoy were obtained from the UK Met Office for a period from 01/01/2005 to 31/12/2009. Data from a wave buoy at the Wave Hub site covering a time period from 16/10/2009 to 31/10/2010 was obtained from the Primare at the University of Exeter. While the time periods are different, Figure 9 (Discussion) shows that the one year of data from the Wave Hub is representative of the wave climate in that region. The locations of these buoys are shown in Figure 2. The M5, Turbot Bank and Aberporth buoys are close to the wave resource areas in Pembrokeshire. Matrices of percentage occurrence of H_s-T_z combinations have been calculated and presented. Monthly means of wave height and period have also been calculated and are presented graphically.

Power outputs for the three devices were calculated for the three buoy locations. An example power matrix, the Pelamis power matrix (Pelamis Wave Power, 2011), is displayed in Figure 3. The Power Matrices are used as a look up table against wave height and period to calculated power output for the different devices. Where an H_s-T combination is outside of the range of the power matrix, the power output is set to zero: for sea states with energy below the lower bound of the matrix it is assumed there is insufficient energy available to generate power; for sea states with energy over the upper bound of the matrix it is assumed the device is in a survival mode and hence would not generate power. The Pelamis matrix uses the energy period, a period representative of the energy in the whole spectrum, whilst the Wave Dragon and aqua buoy matrices utilise the peak period. For the Wave Hub buoy the mean wave period and the energy periods are available whilst for the other buoys only the mean wave period is available. Therefore the energy period and peak periods have to be calculated using two ratios. A ratio between the energy period (T_e) and the zero up-crossing period (T_z) can be derived from consideration of the Bretschnieder Spectrum as:

$T_e = 1.12\ T_z$.

Consideration of the Jonswap spectrum gives an equation for T_p from T_z as:

$T_p = T_z\ [1.30301 - (0.01698 * \gamma) + (0.12102 / \gamma)]$

Where γ is the peakedness factor that determines the concentration of energy about the peak frequency, γ=1 to give a Bretschnider spectrum. Therefore:

$T_p = 1.4 T_z$.

The power time series is used to calculate monthly mean power output, mean power over the time period and the device capacity factor. The capacity factor is calculated as:

$$Capacity\ Factor = \frac{Power\ generated\ over\ time\ period}{Power\ generated\ if\ running\ at\ full\ capacity}$$

Additionally, the percentage time that the devices operate at or above a power threshold is calculated and displayed graphically. This allows the characteristics of the power matrix – wave climate combination to be understood better.

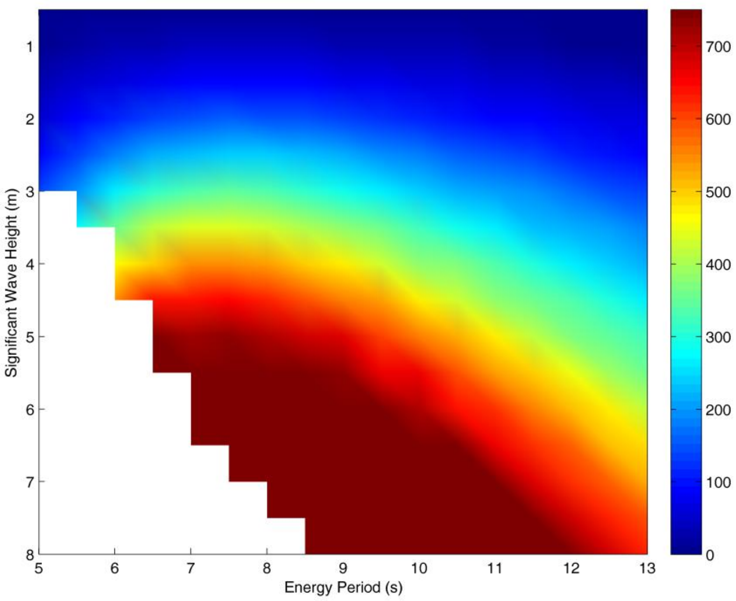

Figure 3: The Pelamis power matrix used in the study.

3 Results

Figure 4 shows the percentage occurrence matrix for H_s-T_z pairs for the four buoys. It can be seen that all four buoys have similar joint probability distributions which is backed by the similarity in monthly means (Figure 5). The spread in probabilities is greater for the Turbot Bank and Wave Hub buoys than the other buoys, indicating their wider exposure to a variety of wave conditions.

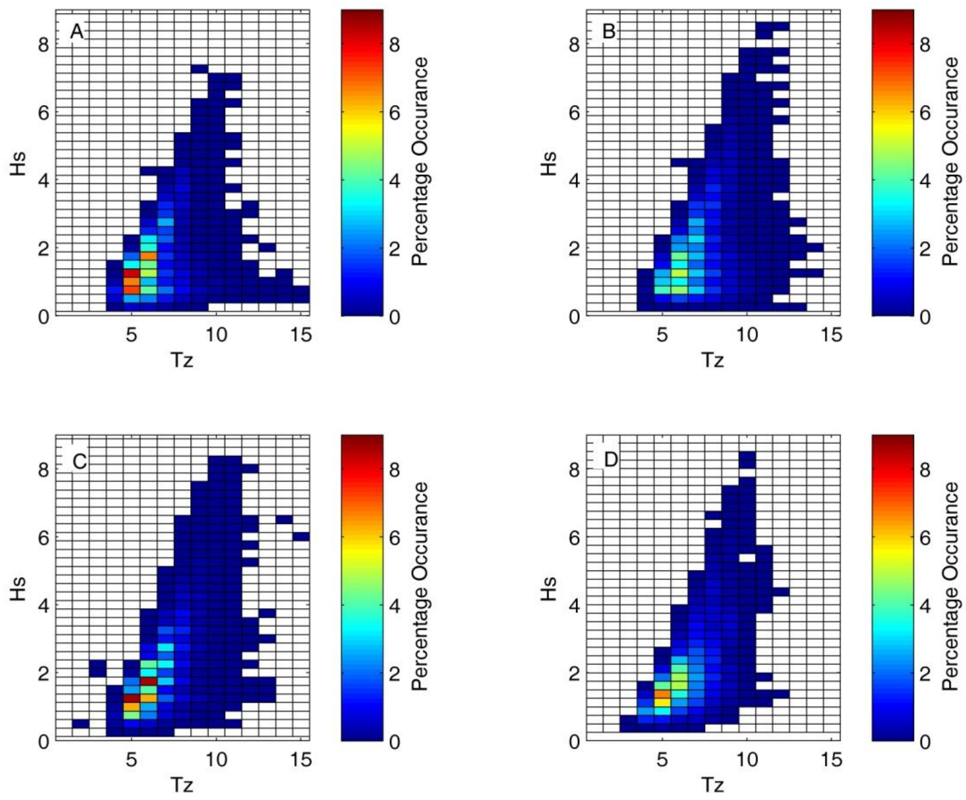

Figure 4: Percentage occurrence plots for a) The Aberporth buoy, b) the Turbot Bank buoy, c) the M5 buoy and d) the Wave Hub buoy.

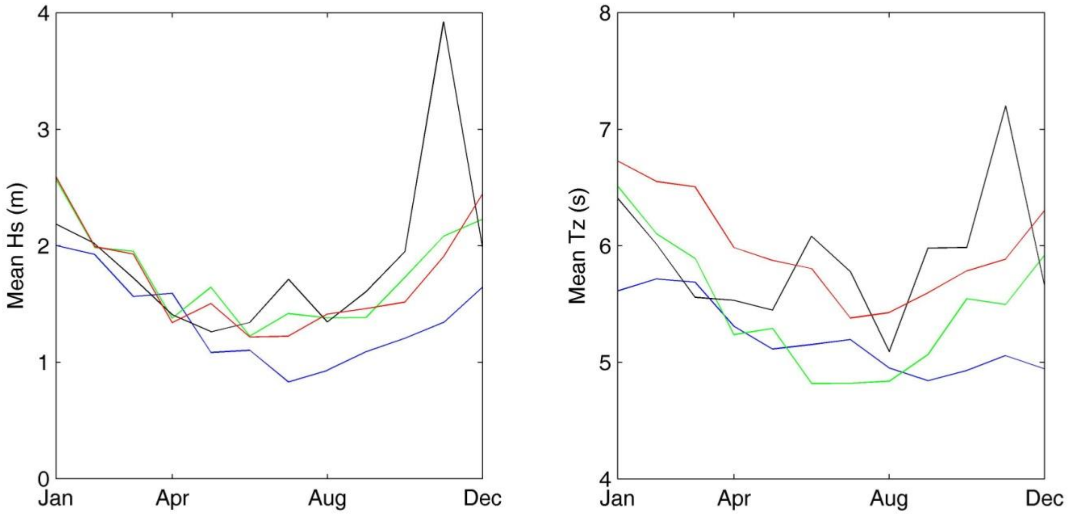

Figure 5: A plot of monthly mean wave height (a) and period (b) for the Wave Hub buoy (black), Turbot Bank buoy (red), the Aberporth buoy (blue) and the M5 buoy (green) showing seasonal variation

Figure 5 shows monthly means for significant wave height and period for the four buoys with standard deviation in parameters also shown. It can be seen that all buoys are similar although there is a large peak in the Wave Hub buoy for November, probably due the one year record duration meaning monthly averages can be skewed by one large storm event. Wave heights are slightly lower for the Aberporth buoy than for the other buoys. The Aberporth buoy is in Cardigan Bay and hence the swell window is smaller than for the other buoys and the fetch for locally generated waves in the predominant south west wind is limited by the St David's peninsula. Wave periods are again similar with the Turbot Bank buoy and Wave Hub sites displaying slightly longer periods due to their greater exposure to long period swells from the North Atlantic (other buoys are sheltered from West and North West swells by Ireland).

Power matrices for the three devices were used to calculate time series of power output at the Turbot Bank buoy, the Aberporth Buoy and the Wave Hub buoy. An example time series is shown in Figure 6. Monthly average power outputs are shown all locations and devices are shown in Figure 7. As is to be expected, mean monthly power output is greater in the winter months than in the summer months. Both locations show similar outputs through much of the year, although there is a large peak in output for November at the Wave Hub site, again due to the large storm.

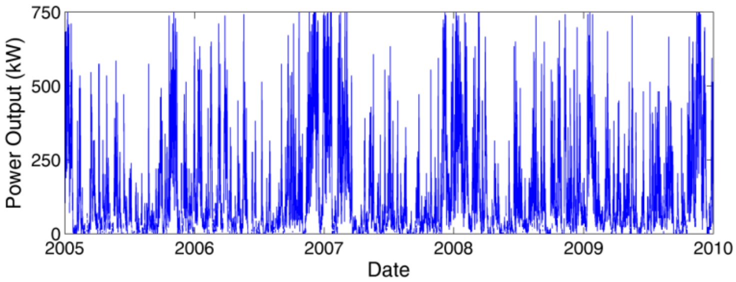

Figure 6: A time series of power output for the Pelamis device at the Turbot Bank buoy location.

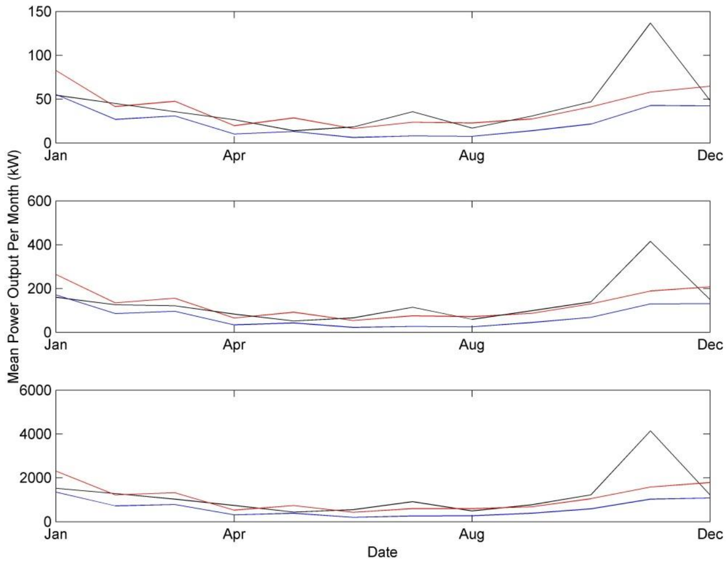

Figure 7: Monthly mean power outputs at the Turbot Bank buoy location (red), the Aberporth location (blue) and the Wave Hub site (black) for a) an AquaBuoy, b) a Pelamis and c) a Wave Dragon.

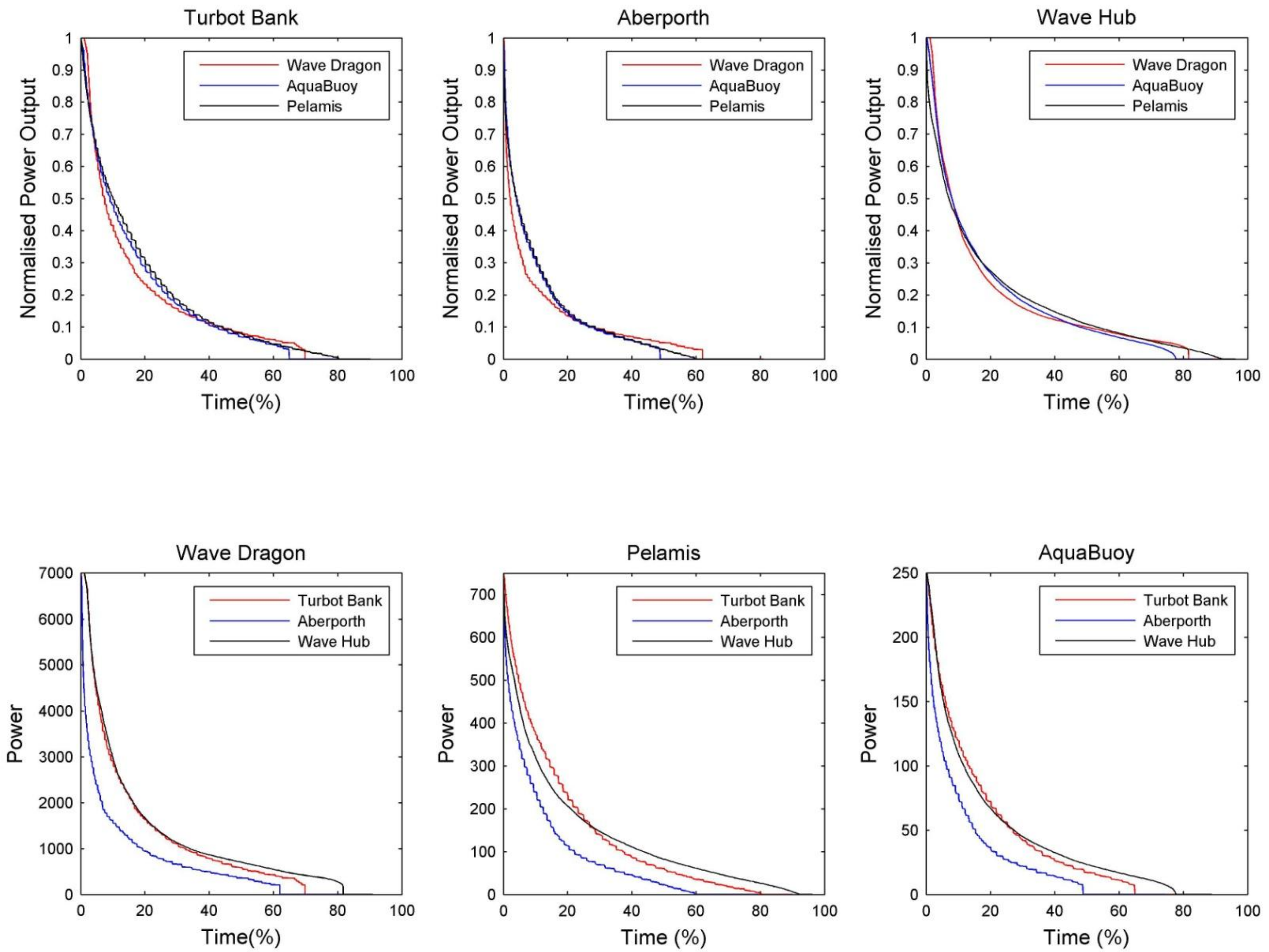

Figure 8: Plots showing percentage time that the devices would be producing over a certain power value for the different locations

Figure 8 shows a plot of the percentage time that the devices are producing over a certain power level for all locations. Considering the different devices at one location (upper three panels), it can be seen that Aberporth (b) performs less well than the other sites, with no power output for 40% of the time and less time at full output. The Turbot Bank location and the Wave Hub location are similar. The Wave Dragon device outputs at high capacity for longer but tails off through the mid power range and is similar again at lower powers.

In the lower three panels (d-f) the curves are displayed for the three sites for each device. Curves for each site are similar for all devices. The Aberporth site behaves least well, with high power output for little time. The Wave Dragon and Pelamis devices do not produce power for 40% of the time, this goes up to 50% of the time for the AquaBuoy. Output curves are similar for the Wave Hub site and Turbot Bank for the Wave Dragon device, although power is produced for less time at the lower power levels for the Turbot Bank site. For both Pelamis and AquaBuoy, output curves at the Turbot Bank site show a greater percentage of time at higher output compared to the Wave Hub site but less time producing at the lower power levels, therefore the percentage of time idle is greater at the Turbot Bank site.

Table 1 shows the mean power and capacity factors over the records for the different devices and locations. It is interesting to note the similarity in capacity factors between the different devices at each site. At the Wave Hub, all devices have the same capacity factor, at Turbot Bank the variation is 2% and at Aberporth the variation is 1%. A key consideration in this work is the difference in productivity between the Wave Hub site and the Turbot Bank site. The Pelamis device has an equal capacity factor at the Wave Hub and the Turbot bank site, the AquaBuoy is 1% lower and the Wave Dragon 2% lower at the Turbot Bank site.

Table 1: Mean Powers and capacity factors for the three devices at the three sites

	Wave Dragon		Pelamis		AquaBuoy	
	Mean power (kW)	Capacity factor (%)	Mean power (kW)	Capacity factor (%)	Mean power (kW)	Capacity factor (%)
Turbot Bank	1068	15%	127	17%	39	16%
Wave Hub	1168	17%	129	17%	42	17%
Aberporth	616	9%	73	10%	23	9%

4 Discussion

The available record for the Wave Hub site is shorter than for the Turbot Bank buoy (1 year instead of 5). Figure 9 shows a four year record from a nearby shallow water wave buoy at Perranporth (REF CCO), the time period covered by the Wave Hub Buoy is marked with a thicker line. It can be seen that the available year has a similar wave climate to the other years and hence, whilst the one year record is shorter than desirable, it should represent the wave climate sufficiently well to allow meaningful comparisons to be drawn. Different types of buoy were used at Turbot Bank and the Wave Hub. The Wave Hub buoy recorded spectra which allowed calculation of the energy period (Te). For the other sites the energy period had to be estimated using a standard equation. This may lead to inaccuracies in calculation. For all sites, the peak period was estimated by a simple multiplication. Again this may lead to inaccuracies if the spectral shape does not conform to the standard spectra used to determine the co-efficients. The Turbot Bank buoy is not quite in the prime location for wave energy converter deployment in Wales and so the climate experienced deployed converters will differ slightly. The only way to determine power outputs exactly would be to deploy a state-of the-art wave buoy capable of recording wave spectra in the planned deployment location. Despite this shortcoming in the data, given the similarity between outputs at the M5, Turbot Bank and Wave Hub buoy, one can assume the representation of wave climate is reasonable and that the conclusions drawn are valid.

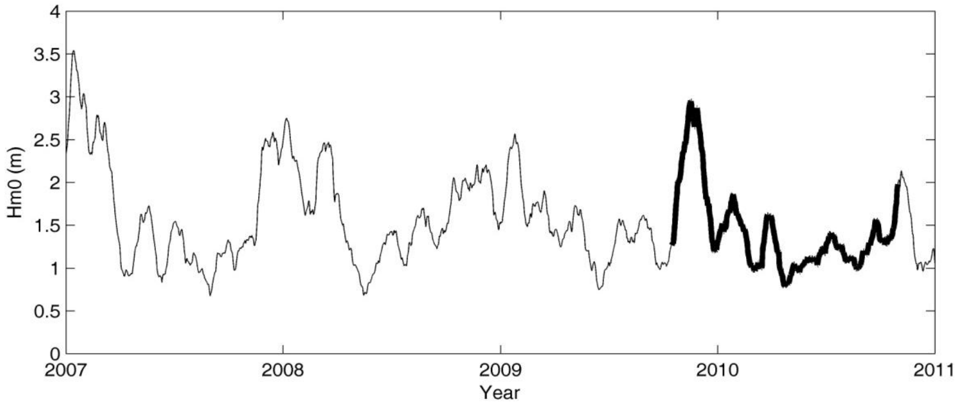

Figure 9: A wave height time series for Perranporth with the Wave Hub buoy time period in bold.

The power matrices used were standard power matrices. It is likely that devices would be tuned to perform most efficiently at specific wave climates which would increase the capacity factors of deployed devices. The Wave Dragon power matrix available to the research was the 7MW device. There is a Wave Dragon rated 4MW for lower energy seas and it may be that that device would perform better. Capacity factors were around 17% (less for Aberporth). Pelamis suggest a capacity factor of between 25% to 40% for their device. Capacity factors for Wave Dragon have been quoted as 34% for various states in America (Prevesic *et al.* 2004). Research into two locations off the off the west coast of Canada, one of the world's most energetic regions, suggested capacity factors for Pelamis of 51% and 59% and for Wave Dragon of 21% and 30% (Robertson, 2010), the lower capacity of the Wave Dragon device caused by near-shore siting in the study. However, other research has presented general wave energy capacity factors of 22% to 29% for farms off the California Coast (Stoutenburg *et al.* 2010).

In order to consider differences between devices, normalised power output has been investigated. However, the devices all have different power ratings, the largest is the Wave Dragon device at 7MW, and it would take 9.33 750kW Pelamis or 28 AquaBuoys (250kW) to provide the same amount of energy. The increase in numbers of devices affects cost of deployment in terms of additional cabling, mooring systems and ship time for deployment and maintenance. An advantage of multiple instruments is that failure of one unit will less affect power output. An economic analysis is required to determine which types of device are most suitable for deployment in Welsh waters.

Wave climates are similar for the Wave Hub location and the Turbot Bank Buoy. Whilst the Turbot Bank buoy is not in the exact location of potential developments, the wave climate will be similar. Given that developments are likely to be further offshore than the Turbot Bank buoy the wave climate may even be greater. It could be argued that the support services for wave energy converter deployment are better in Pembrokeshire than in Cornwall. The large deepwater port of Milford Haven is close to the deployment areas allowing for easy installation and maintenance. South Wales has a strong manufacturing heritage and therefore good fabrication facilities. Equally important is the proximity to large population centres along the M4 corridor with high electricity demand.

5 Conclusion

The wave climate in Pembrokeshire is very similar to the Wave Hub site. Capacity factors for the three devices varied by 0-2%. In general capacity factors were lower than others reported in the literature. Despite the RPS report suggesting attenuator devices should not be used in Welsh waters, this research suggests it would be feasible to do so. Given the similarity in resource to the wave hub site, and excellent port facilities close to the resource areas Pembrokeshire is a very attractive location for the deployment of wave energy converters.

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