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Inter-annual variability of potential power production from wave energy converters

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Abstract

Estimation of the variability in the electrical power production and performance over the lifetime of wave energy converters (WEC) is paramount for the economic viability of potential wave farm projects. In this work, the significance of the inter-annual variability in the potential power production (PPP) is demonstrated, using power conversion matrices of ten pre-commercial WEC devices and an existing 31-year wave hindcast case study from the central shelf of New South Wales, Australia. The variability in the PPP over the intra- and inter-annual time scales is found to be comparable, hence indicating that making predictions merely based on annual and monthly averages could be misleading and that inter-annual fluctuations should be considered in future analysis. The results also show that inter-annual variations in WEC production performance can be significantly higher than that of the wave energy resource (WER) due to the efficiency of different WECs relative to the local sea state conditions. We also demonstrate that optimisation of WEC performance for the local sea state can not only lead to improved power yields but also a decrease in the intra- and inter-annual variability in PPP.

Keywords: Wave power conversion; Wave power variability; Power production; WEC performance;

1. Introduction

Global concerns about reducing anthropogenic greenhouse gas emissions and the need to assist with more sustainable development, has led to both the expansion in renewable energy investments and the establishment of renewable energy directives for the share of future carbon-free energy. In 2015, the United Nations Framework Convention for Climate Change formulated the Paris Climate Agreement [1] where a commitment to limit global warming to well below 2° was agreed. With electricity generation accounting for 25% of greenhouse gas (GHG) emissions globally [2], the transition to renewable energy generation is seen as a critical component to meet this objective. Wave energy is an early stage technology which has attracted notable investment (e.g. [3–5]). Technologies to exploit the largely untapped wave energy resource (WER) have the potential to contribute to the required future reductions of GHG concentrations, as part of the future global energy mix [6]. However, progress from pre-commercial, full-scale prototype testing to commercialization of wave energy converters (WEC) has been relatively slow [7]. This has been partly due to the financial risks associated with the variability of the WER and subsequent potential production performance (PPP) throughout the expected lifetime of the projects [8]. Hence, analysing both the intra and inter-annual performance of WEC technologies might be required prior to the installation of a WEC farm, even though the latter has received minimal attention [9].

It is widely accepted that the available WER is inherently variable on multiple time scales such as intra- and inter-annual, which play a key role in the cost-efficiency of WEC projects [10]. It is also regarded as a key factor for selecting optimal locations for wave farm development from a technical viewpoint [11]. Therefore, assessing the economic viability of a WEC farm projects assuming stationary annual (or seasonal) average power yields, will likely lead to inefficient implementation of wave projects [11,12]. In addition, without detailed information about the variability in the energy output from WEC farms, the electrical utilities will be unable to undertake adequate long-term planning for the inclusion of wave-generated electricity in the energy mix.

The performance characteristics of a given WEC technology is typically specified by manufactures in terms of a power generation matrix which relates power generation to a given sea state condition as defined by the significant wave height (H_s) and wave energy period (T_e). The actual power production is subsequently determined by how this matrix compares with the WER characterisation matrix [11,12]. In contrast with other renewables, there is not one single established WEC that consistently presents the best performance globally. Rather, a wide variety of different devices exists, that have been optimized for a specific range of sea states [13]. Therefore, the selection of the optimum site-WEC combination should be based on a thorough analysis of the

PPP of different site-WEC combinations over their expected lifetime (at least at the intra- and inter-annual level).

To date, much of the research focus has been on assessing both the availability and variability in the available wave energy resource (e.g. [14–25]), with assessments of the electrical energy yield from WECs being yet relatively limited. Some studies have provided an analysis of potential production and performance of WEC technologies [26–37], nevertheless, most of these assessments have been performed on the basis of annual (or seasonal) averaged quantities [26–33] and have hence neglected any variability in the potential energy yield. The few appraisals that have addressed the variability in WEC performance are limited to intra-annual analyses, thus neglecting inter-annual fluctuations [34–37]. Moreover, these assessments only included one to three WECs in their analysis which is fairly limited given the number of different technologies, with different power conversion efficiencies, that currently exist. The aims of this paper are thus: (1) to determine the significance of the long-term variability in the PPP in relation to that which exists in the available WER; (2) to assess the influence of WEC optimization by scaling on the PPP variability and (3) to expand on the number of WECs that have been considered previously.

This research provides, for the first time, an integrated assessment of the intra- and inter-annual variability in both the WER and the PPP of ten different WEC devices. In doing so, it addresses the shortcomings of these previous studies by: 1) assessing the inter-annual variability in the PPP; 2) analysing the importance of quantifying the inter-annual variations in PPP relative to the more commonly examined intra-annual fluctuations and 3) investigating the importance of designing and optimizing WEC technologies for the local sea state to not only maximize PPP but also minimize the variability. To this end, a case study in the central coast of New South Wales in the Southeast Australian Shelf (SEAS) (Fig. 1) is developed, on the basis of an existing 31-year wave hindcast for the region [38].

The paper is organized as follows. The study region is introduced and the source of data is considered in section 2. In Section 3, the variability of the available WER is determined and discussed. In section 4, the methodology to develop the monthly and annual characterization matrices is described followed by the analysis of the inter-annual variability in the power conversion of different WEC devices. Section 5 describes the downscaling of the selected WEC devices to maximize the PPP. Finally, in Section 6, the main conclusions are drawn.

2. Study area and wave data

2.1. Study area

The central coast of New South Wales (Fig. 1) is characterized by a fairly steep and narrow continental shelf, with the 80 m depth contour only 8 km from the shoreline

in places. This region experiences a highly variable multimodal wave climate, driven by six typical meteorological systems in, or peripheral to, the Tasman and Coral Seas [39]. These are namely tropical lows, tropical cyclones, anti-cyclonic intensification, east coast lows, southern Tasman lows and also Southern Ocean lows [39]. The WER across the inner-mid shelf boasts time-averaged power levels of approximately 8 to 16 kW/m, which is similar to that of the South Cornish Coast in the UK [40] and Gran Canaria in Spain [41]. Moreover, around 85% of the total population in this region is situated within 50 km from the coast [42]. This strengthens the need to facilitate the development of WEC farm projects within proximity to energy demand centres, such as Sydney and Newcastle, whilst decreasing the high dependence on fossil fuels for electricity production in NSW.

Figure 1 – Central coastal shelf of New South Wales in Southeast Australia (the inset box in the top left). The black squares '□' indicate the locations proposed for wave energy exploitation and the black circles '○' the nearest port infrastructures. The high-resolution computational model grid (up to 500 m) from where the wave data was derived from and corresponding bathymetry are also shown.

2.2 Wave data

The wave dataset for the present study is the 31-year hourly wave hindcast (1979 to 2010) described in detail by Morim et al. [38]. This hindcast was developed with the shallow water wave energy transformation model SWAN [43] and accounts for the effects of the various depth-dependent processes involved in the cross-shelf wave energy transformation at high-spatial resolution (down to 500 m at the coast). The dataset has been validated against historical wave rider buoy observations at multiple locations with up to 31-year record lengths. For a detailed description of the wave hindcast, calibration and validation, the reader is referred to Morim et al. [38]. The full description of the equations employed here for the computation of the wave energy transport and wave sea states parameters are described in the SWAN scientific and technical documentation [44].

3. Variability in the wave power resource

3.1 Intra-annual variability

Fig 2 shows the intra-annual variability of the monthly mean wave power resource averaged over 31 years (1979–2010). The monthly average wave power is highest during autumn (March to May) and winter (June to August), reaching ca. 13–20 kW/m on the inner-mid shelf. Spring (September to November) and summer (December to February) experience a relatively lower monthly mean wave power between ca. 8–12 kW/m. June is the most energetic month with ca. 16–20 kW/m across the shelf, whilst December has the lowest wave power level with less than ca. 8 kW/m. Intra-annual variability is clearly evident with June and July exhibiting monthly average wave powers that are twice as large as those experienced in early-mid summer (December and January). However, this degree of WER variability is relatively stable compared to the more energetic south and southwest shelf regions of Australia (e.g. [14]), where the power in the most energetic months can be up to a factor 3 greater than in calmer months.

Figure 2 – Spatial distribution of the intra-annual variability in the monthly mean wave power resource (kW/m) for the central coast of NSW (1979–2010).

3.2 Inter-annual variability

In order to assess the inter-annual variability of the WER, the normalised standard deviation NSD (Appendix D) was calculated as the standard deviation of the monthly mean wave powers across the 31-years normalized against the 31-year mean. Fig. 3 shows that the greatest inter-annual variability in the WER occurs in April, May and also August, with a NSD ranging from ca. 35–50%. Relatively moderate inter-annual variations in the WER are seen in January, June, July, September and October across much of area of study, with the NSD ranging from ca. 30–35%. The periods with the

lowest inter-annual variability in the mean monthly wave power are November, December and February with a NSD of approximately 25%. This degree of inter-annual variability is similar to that of other energetic coastal shelf areas such as the Orkney Archipelago (Scotland) [19] and is partly explained by the relatively large year-to-year variability found in the cumulative monthly storm energy in the present region of study [45]. It is worth noticing that the inter-annual variations in the monthly mean wave power (Fig. 3) is ca. 5–10% greater than the inter-annual variability in the monthly mean H_s found by Hemer et al. [46] for the SEAS using several wave datasets covering the Australian region. It is also noticed that the spatial distribution of the NSD is fairly uniform across the NSW central coastal region for all the months. The implications of this inter-annual variability on the inter-annual variations in the WEC performance are assessed in section 4.

Figure 3 – Spatial distribution of the normalized standard deviation of the monthly means (%) which is a measure of the inter-annual variability for the central coast of NSW based on 31 years of wave hindcast data.

The NSD of the annual mean wave power was also analysed (Fig. A1 in Appendix A shows the inter-annual variability across the central coast of NSW and the full SEAS) and found to be ca. 8–12 % being thus: 1) significantly less than those of the monthly averages discussed previously which ranged from ca. 30 to 50% and also 2) smaller than the inter-annual variation observed across the other parts of the SEAS. The smaller variations at the inter-annual scale is mainly due to the WER fluctuating at shorter time scales (i.e. months) which are effectively smoothed out when averaging over a year. Hence, analysis of the inter-annual variability should be conducted at the least at monthly mean level in order to capture a more accurate assessment of the variability.

4. Variability in the potential power production

4.1 Site selection

Two hotspots were determined by Morim et al. [38] considering maximum annual wave power as well as water depth, proximity to electricity grid and access to port infrastructure. In addition, a new site off the coast from Sydney, was added to make a total of three potential WEC sites to which were used to examine the intra- and inter-annual variability in PPP from ten WEC devices. The first site, located in 10 m water depth (shallow water) off the coast of Seal Rocks (Fig. 1), provides the highest time-averaged wave power across the entire shelf [38]. The second location is located in 22 m depth (intermediate water) close to the port of Newcastle (Fig. 1) and the third location is located at 54 m depth (deep water), offshore from the port of Sydney. The range of water depths were selected to allow the consideration of a wider range of WEC devices which have been designed for deployment in different water depths.

4.2 Potential production performance (PPP)

In this section, the intra and inter-annual electrical power output and performance of ten different technologies are investigated. The choice of WEC was based on the following: (1) the considered WECs are at an advanced stage of development having undertaken ocean trials, (2) the power generation matrices of the WECs are publicly accessible and (3) the WECs have different operating mechanisms. The performance of the different technologies was only considered at the locations where the water depth was consistent with the water depths they have been developed for (Table 1), which resulted in a total of 14 site-WEC combinations. The main characteristics of the considered WEC devices are summarized in Table 1.

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Technology	Rated power [kW]	Classification	Installation depth [m]	Power matrix resolution [$H_s \times T_e$]
OWC ¹ [31]	85	Terminator	Nearshore (< 20)	1.0 m × 1.1 s
Oyster [48]	290	Terminator	Nearshore (10–25)	0.5 m × 1.0 s
WaveRoller [49]	1000	Point absorber	Nearshore (10–25)	1.0 m × 1.0 s
Wave Star C6 [50]	600	Point absorber	Nearshore (10–30)	0.5 m × 1.0 s
CETO ² [51]	260	Point absorber	Near-Offshore (20–50)	0.5 m × 0.5 s
Wave Dragon [31]	7000	Terminator	Near-Offshore (> 20)	0.5 m × 0.5 s
Archimedes [31]	2500	Point absorber	Offshore (> 50)	0.5 m × 0.5 s
Wavebob [51]	1000	Point absorber	Offshore (> 50)	0.5 m × 0.5 s
AquaBuOY [48,51]	250	Point absorber	Offshore (50–60)	0.5 m × 1.0 s
Pelamis [48,51]	750	Attenuator	Offshore (50–70)	0.5 m × 0.5 s

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242 **Table 1** – Main characteristics of the wave conversion technologies considered.

243 ¹ Oscillating Water Column (OWC) prototype [47]

244 ² Cylindrical Energy Transfer Oscillating

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246 The potential power production of the WEC devices was determined by combining
 247 the WER characterization matrix at the sites of interests, with the power conversion
 248 matrix of the devices. The WER monthly and annual characterization matrices were
 249 derived from the wave hindcast data (see section 2.2) with a resolution matching the
 250 bin sizes (ΔT) × (ΔH_s) of the power matrices of the different WEC technologies for
 251 consistency (see Appendix B, Fig. B1-3). The WER monthly characterization matrices
 252 at the location 1 are given in Fig. 4 (matrices for the other two locations are provided
 253 in Appendix C). Wave directionality was not considered in this analysis, since there
 254 is no information currently available regarding the variation of WEC's performance
 255 according to the variation of the direction of the waves (manufactures specify a

WEC's performance solely as a function of (T and H_s). In addition, it should be noted that 6 of the WEC devices examined here are axi-symmetric, being therefore able to naturally absorb wave energy from any direction, and the Pelamis is designed to align itself with the direction of highest incoming wave energy flux. In terms of survivability, it is assumed that the devices are only expected to operate within the range of sea states specified in their power matrices. Therefore, sea states above the maximum specified H_s for each device have not been considered. In this part of the SEAS, there is a low probability of waves exceeding the threshold of survivability of these devices (typically >5 m) and thus only a small chance of WECs having to cope with such extreme loading scenarios [38]. Whilst it is possible that a WEC device might be damaged during storm events it is assumed here that the device will be immediately repaired or replaced.

The potential monthly and annual energy production (in MWh) for each of the WEC devices at each site was hence calculated according to (e.g. [32]):

$$E_0 = \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} P_{ij} \quad (1)$$

where p_{ij} is the occurrences of each wave sea state and P_{ij} represents the electrical power yield provided by each WEC for the same energy bin.

Given that the monthly and annual power generated by the different WEC devices is dependent on their rated power (P_m), the production performance was quantified in terms of energy production E_0 (in MWh) per (device) maximum rated power P_m (in MW) according to (as in [32]):

$$R_h = \frac{E_0}{P_m} \quad (2)$$

This ratio when expressed in units of time (h) is known as full load hours and has been widely used for studying the profitability of other renewables, such as wind and solar energy [52].

Figure 4 – Omni-directional monthly wave energy characterization matrices at the nearshore site 1 derived from 31-years of wave data (For simplicity, only one in two months is displayed). The colour band indicates the contribution of each energy bin to the total (monthly) energy (MWh/m) and the numbers represent the occurrence of the different sea states in hours per month

4.3 Intra-annual variability of power production

R_h values at the three locations of interest are shown in Figs. 5 to 7 (the plots of monthly average-energy production E_0 are provided in Appendix D). The observed intra-annual variability at all locations is generally consistent with the annual cycle of monthly mean wave power previously discussed in section 3. Nonetheless, certain WECs are indeed more sensitive to the intra-annual variations of the WER (Fig. 4) than others owing to their efficiency in sampling the different sea states. It is worth mentioning that the WEC devices with largest E_0 are not necessarily the ones with the largest R_h .

Fig. 5 shows that the OWC converter with a rated power of 85 kW, exhibits the best performance during the year for site 1. R_h values are between 474 to 542 MWh/MW, two to three times larger than those of other devices. In addition, the OWC exhibits the lowest variability in both R_h and E_0 , with the monthly figures falling closer to the monthly average value, compared to the remaining WECs. The Oyster exhibits an R_h of ca. 140–219 MWh/MW, followed by the Wave Star and WaveRoller with 140–186 and 47–83 MWh/MW, respectively. It is worth mentioning that, the WaveRoller has the highest capacity of 1 MW, but the lowest values of R_h during the year. According to Fig. 5, in June, the Oyster has the highest values of R_h and E_0 with 219 MWh/MW whilst that of WaveRoller is ca. 83 MWh/MW. March is the best month for the OWC and the Wave Star with ca. 542 and 183 MWh/MW, respectively. These values are ca. 36%, 43%, 12% and 24% greater than in the month with the lowest R_h (December), respectively. It should be also noted that the OWC and Wave Star provide a higher R_h in March than June and July when the WER is highest. This is because the conversion efficiency of the OWC decreases substantially in sea states above 2.5 m–9.5 s (almost half compared to its efficiency in wave sea states with 0.5 m–5 s, Fig. 4), which often occurs during winter (see Fig. 4 and Appendix B). In the case of the Wave Star, it is incapable of harvesting sea states above 4 m for storminess protection.

Regarding the nearshore site 2, Fig. 6 shows that the pattern in the intra-annual variability of R_h is fairly similar to that of location 1 (Fig. 5), but with slightly smaller magnitudes, as the latter experiences a higher resource availability [38]. The highest R_h value during the year is provided by the Oyster with ca. 140 and 219 MWh/MW, followed by the Wave Star, with ca. 140–186 MWh/MW. These values are, in general, two to four times larger than those of WaveRoller (47–83 MWh/MW), Wave Dragon (30–46 MWh/MW) and CETO (19–28 MWh/MW). The largest values of R_h are found in June and March, whereas the lowest in December, when the monthly WER reaches its minimum.

In the case of the offshore site, Fig. 7 shows that the highest R_h are provided by the Pelamis and AquaBuOY with 38–54 and 25–54 MWh/MW, respectively; followed by the Wave Dragon with 30–46 MWh/MW, Wavebob with 25–46 MWh/MW and the

Archimedes with 14–35 MWh/MW. However, they present a fairly similar pattern of intra-annual variability and maintain their relative differences in R_h throughout the year. According to Fig. 7, the change in their relative differences only occurs from May to August, where the R_h values of the AquaBuOY slightly exceed those of the Pelamis. This pattern in the intra-annual variability of R_h is similar to that previously observed at the other two sites (Fig. 5 and 6). The greatest value of R_h is obtained in June for all the technologies, which is consistent with the month of highest WER availability (Fig. 2). The exception is the Pelamis, which achieves its maximum R_h in March. In June, the Aqua Buoy, Wave Dragon, Wavebob and Archimedes provide R_h ca. 50%, 34%, 44% and 59% higher than those found in December, respectively.

Figure 5 – Monthly average performance in terms of R_h at the nearshore hotspot 1 (10.2 m depth) for the Oyster, OWC, WaveRoller and Wave Star technologies

Figure 6 – Monthly average performance in terms of R_h at the nearshore hotspot 2 (22 m depth) for the Wave Dragon, Oyster, CETO, WaveRoller, AquaBuOY and Wave Star technologies

Figure 7 – Monthly average performance in terms of R_h at the offshore (54 m depth) for the Wave Dragon, Archimedes, Wavebob, Pelamis and the AquaBuOY technologies

4.1 Inter-annual variability of power production

In Figs. 8 to 10, the normalized standard deviations (NDS) of the monthly energy production per rated power (R_h) are plotted for the different WEC technologies at the three selected sites. It can be observed that R_h presents a significant inter-annual variability of up to 67%, indicating that the monthly average power production is not stationary. In fact, the production performance of the selected WEC technologies (R_h) in each month varies significantly from year to year (Fig. 8 to 10 and Appendix D4-D5). Furthermore, the pattern of inter-annual variability in R_h for all the three locations resembles the pattern in the inter-annual variability of the available WER.

For nearshore site 1 (10.2 m), Fig. 8 shows that the level of inter-annual variability ranges from approximately 5% up to 40%, depending on the device and the month. The WEC exhibiting the lowest inter-annual variations regardless of the month is the OWC with ca. 5 to 12%, which is considerably lower than those of other devices. This implies that much of the inter-annual variability in the WER occurs across a range of sea states for which the OWC device is not optimized to and so these variations do not significantly affect the power production from the device. On the other hand, the Waveroller exhibits a relatively greater inter-annual variability between ca. 25–37%, followed by the Oyster and Wave Star with 20–30% and 15–27% respectively. Fig. 8

also shows that the inter-annual variability of the electrical power production can be indeed larger than that of the WER, as seen for the WaveRoller.

Fig. 9 shows that at site 2 (22 m depth), the Wave Star and the CETO devices have the lowest inter-annual variability in terms of monthly R_h values, with 19–33% and 20–34%, respectively. On the other hand, the Wave Dragon and WaveRoller exhibit the largest inter-annual variability in the monthly R_h , with 28–40% and 28–43% of the monthly means, followed by the Oyster with 26–38%. Fig. 10 also discloses that the year-to-year variations in the monthly energy production E_0 of the Wave Dragon and the WaveRoller are larger than the inter-annual variability seen in the WER, which is explained by the inherent filtering effect of these WECs in converting the local sea states.

The results for the offshore location with a depth of 54 m (Fig. 10) show that the offshore devices exhibit a higher inter-annual variability in R_h compared to the other locations. In addition, the inter-annual variability in R_h for these devices are higher than the inter-annual variability found in the WER. For example, in the case of the Archimedes, R_h shows inter-annual variations of 45–65% while the variability in the WER ranges between 25–40% (i.e. almost half as much). Fig. 11 also shows that the R_h values of all WEC devices show a fairly similar inter-annual pattern consistent with the WER. The Pelamis, closely followed by the Wave Dragon, displays the lowest inter-annual variability in R_h with ca. 25 to 39% and 32 to 46%, respectively; whereas the Archimedes and Aqua BuOY show the greatest variations with 45–57% and 39–58%, respectively.

Figure 8 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the nearshore hotspot 1 (10.2 m depth) for the Oyster, OWC, WaveRoller and Wave Star technologies.

Figure 9 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the nearshore hotspot 1 (22 m depth) for the Wave Dragon, Oyster, CETO, WaveRoller, AquaBuOY and Wave Star technologies (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Figure 10 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the offshore site (54 m depth) for the Wave Dragon, Archimedes, Wavebob, Aqua BuOY and Pelamis technologies.

5. Scaling to optimise WEC performance

The findings presented in section 4.1 suggest that the potential power productions of some of the considered WECs are comparatively low compared to those obtained for the same converters around the world. For instance, if installed at a depth of 20 m offshore from Port of San Ciprian in Spain, the Oyster could potentially generate 75 MWh/MW annually [35], compared to respectively ca. 37 and 52 MWh/MW at the nearshore locations 1 and 2 in the present study. Likewise, the Archimedes and Pelamis installed offshore of Northern Spain, could possibly generate approximately 195 and 102 MWh/MW [35] compared to approximately 34 and 50 MWh/MW respectively at site 3. These comparisons, along with results presented in Fig. 6 to 8, suggest that these wave conversion technologies have been optimized for different wave climates (i.e. characteristic wave heights and wave periods of a location). By comparing the characterization matrices of the WER at each of the selected sites (Fig. 4 and Appendix C), with the power matrices of the WECs shown in Appendix B, it can be seen that the devices (excluding the OWC) are operating far below their optimal rating for most of the sea states in the present study region. This is also verified for the other devices according to their published power matrices in the literature (see Table 1).

In order to optimize the WEC performance at the three sites being examined here, the original efficiency matrices of each of the WEC devices were downscaled using Froude similitude [53] as performed by Bozzi et al. [37]. Froude's scaling law implies that given the geometric scale λ , the period scale is $\lambda^{1/2}$, the power scale is $\lambda^{7/2}$ and the significant wave height scale is λ [53]. For each WEC, the annual average energy output (E_0) and corresponding conversion performance ratio (R_h), were examined for a range of geometric scalings, assuming that such devices could accommodate a proper downscaling.

Fig. 11 shows that by downscaling the devices, R_h increases considerably, from two to eight times the values of the full scale WEC. The exception is the OWC, which achieves its maximum R_h at full scale, suggesting that this device is optimized for a wind-wave climate with a similar WER characterization to the present study region. Furthermore, Fig. 11 shows that the geometric scales maximizing R_h range from ca. 0.25 to 0.35 for the offshore site, 0.4 to 0.6 for the nearshore site 1 and 0.3 to 0.6 for nearshore site 2. In general, these results suggest that besides the OWC device, the considered devices are oversized for the present study region and a more efficient power conversion could be reached by downscaling the WEC devices. In addition, these results also show that the offshore WEC devices are generally more oversized in relation to the local sea state compared with the nearshore devices. By site-specific downscaling of these devices, their wave power conversion performance R_h become similar to those estimated for Northern Spain [35] and also Portugal [51].

Figure 11 – Annual R_h (MWh/MW) at nearshore site 1 (top), nearshore site 2 (middle) and offshore site (bottom) as a function of the geometric scale λ for the different wave energy converters.

Furthermore, the downscaling of the WECs leads to a lower intra- and inter-annual variability in R_h and E_o . Fig. 12 shows the ratio between the NSD of the (monthly and annual) mean R_h for each WEC at an optimized scale to that at the full scale (or $\lambda = 1$). Relative to the variability in PPP from the full-scale WEC devices the optimization of WEC performance via downscaling decreases the intra-annual variability by ca. 28 to 82% and the inter-annual variations by ca. 11–78% (i.e. depending on the WEC device and site). Similar results are observed at the monthly level, where the inter-annual variability of the R_h monthly averages (and energy production) significantly decreases compared to the full-size prototypes (Appendix D, D6-D8). We show that with downscaled devices (in contrasted with full-scale prototypes), the magnitude of the inter-annual variations is generally lower than that of the WEC. These results are consistent with the findings presented by Bozzi et al. [37] for the western coast of Sardinia and along the Sicily Strait (Italy). This means that the smaller-rated WECs exhibit a more consistent energy production E_o , and performance R_h , throughout the year and between years, as they now operate closer to their rated power P_m . More specifically, the WEC devices can now more efficiently capture the energy of the lower sea states ($H_s < 3$) throughout the year, which would otherwise be filtered out by the full-scale WECs. The exception is the OWC whose full-scale configuration is more suitable for the local sea states at the studied sites.

Figure 12 – Ratio between the normalized standard deviation of the 12 monthly mean R_h values (i.e. intra-annual variability) for each WEC at optimized scale and at full scale (top figure) and ratio between the normalized standard deviation of the 31 annual mean R_h values (i.e. inter-annual variability) for each WEC at optimized scale and at full scale (bottom figure).

6. Discussion

The abovementioned results show that the analysis of the intra- and inter-annual performance of different technologies at different locations is a key aspect so as to define the most suitable WEC-site combination for harnessing the WER in a coastal

region. We show that intra-annual variations in the monthly mean P_o and R_h reach up to ca. 60%, depending on site and WEC device, while the variations in monthly E_o and R_h between years reach ca. 65%. The efficiencies of different WEC devices play a key role in the quality and variability of their power production performance. This was confirmed by noticing the technologies with the largest rated power P_m and thus greater E_o , were not necessarily the ones with the largest R_h . In fact, the OWC had a R_h approximately 2-3 times greater than the R_h of any other considered WEC, which suggests this device is designed for exploiting local sea states similar to the present area of study. We conclude the efficiency of a particular WEC in sampling the local wave climate has a significant impact on the magnitude and intra- and inter-annual variability of E_o and R_h and therefore should be considered when selecting the most suitable WEC for a given site. On the basis of such results, the OWC device was found to provide the greatest and most consistent performance with a total annual power output of ca. 512MWh at nearshore site 1. This is twice the annual power production provided by the same device at the Port of San Cibrao in Northeastern Spain (ca. 220 MWh), a site where a wave farm has been proposed for development [31].

We suggest that a much higher power production performance could be obtained with smaller versions (dimensions) of the same WEC technologies, if they could be downscaled according to the local sea state conditions. Results suggest nine of the selected WECs are oversized for the local wave sea states in the present study area and they operate far beyond their maximum rated powers. The geometric scaling factor which maximized the WEC production performance ranged from 0.25–0.35 at the offshore site 3, 0.4 to 0.6 at the nearshore location 1 and from 0.3 to 0.6 at the nearshore location 2. The downscaling of the WEC devices to the optimal size led to a substantial increase in R_h of two to eight times the R_h at full scale, depending on the WEC. Furthermore, it is also shown that reducing the size of the WECs results in a significant decrease in both the intra- and inter annual variability of R_h (28 to 82% and 11 to 78%, respectively). This means the smaller rated devices will have a much better performance R_h with overall less variability since they now operate closer to their maximum rated power P_m . Furthermore, using downscaled devices, the year to year variations in power production (and performance) are generally lower (<30%) than the natural inter-annual fluctuations of the wave resource (in contrast with the full-size devices). The results suggest wave energy exploitation at the site proposed for wave energy farming could be more cost-effective using WEC devices specifically designed and tuned for the central coast of New South Wales. However, it should be acknowledged that further research will be required to understand the survivability of the downscaled WEC devices (i.e. how the structural design will withstand

extreme wave events) under the local wave regimes and also how well the efficiency of the mechanical to electrical energy conversion scales.

7. Conclusion

Estimation of the variability in the electrical power production and performance over the lifetime of wave energy converters (WECs) is paramount for the economic feasibility of potential wave farm projects. However, to date, analyses of wave power production have drawn conclusions from stationary annually or seasonally averaged values for a few select devices, thus neglecting intra- and inter-annual fluctuations. In this work, the significance of the intra/inter-annual fluctuations in the potential power production (PPP) (i.e. relative to the fluctuations inherent in the wave energy resource (WER) itself) is thoroughly evaluated, using power conversion matrices of 10 pre-commercial WEC devices and an existing 31-year wave hindcast case study from the central shelf of Southeast Australia. As part of this analysis, we explored the viability of potential wave energy exploitation off the Australian southeast shelf and the influence of WEC optimization the PPP variability.

We show that the level of intra- and inter-annual variability in the available WER along the central coast of NSW is comparable to that of other energetic shelf regions considered suitable for wave farm development (e.g. Orkney Islands [19]). In terms of power production, we show that the intra- and inter-annual variability in the WER leads to notable variability in the energy production (E_0) and performance (R_h) of all the WECs. In particular, we show that inter-annual fluctuations in the performance of WECs can exceed the inter-annual variability in the WER, thus demonstrating the importance of considering the PPP at the inter-annual level. Furthermore, we show that variations in PPP on the inter-annual time scale can be as high as intra-annual variations depending on the WEC. Thus, we conclude that making predictions solely based on annual and/or monthly averages obtained for a specific WEC could, in fact, be misleading in terms of anticipating the revenue of a wave farm. Lastly, we show that a more efficient power conversion (higher production and less variability) could be possibly attained if site-specific WECs could be designed for the Australian Seas.

In this study, we have examined the feasibility of the WEC devices at only three promising sites. The required spectral wave parameters to carry out this analysis are available with high-spatial resolution over the whole considered coastal zone, and the method could be readily implemented at any other site of interest. Furthermore, it can also applied to any other coastal region where a large, high-resolution dataset is available. We recommend intra- and inter-annual variations in both the wave energy resource and the energy production from any considered WEC be considered in future wave energy feasibility studies.

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Appendix A

Figure A1 – Spatial distribution of the normalized standard deviation of the annual means (%) which is a measure of the inter-annual variability for the SEAS (including the central coast of NSW) based on 31 years of wave hindcast data (~10 km to 1 km) [38]. The locations of interest are marked with black circles.

Appendix B – Wave power conversion matrices

Figure B1 – Wave conversion efficiency matrices (ΔT (s) $\times$ ΔH_s (m)) of the nearshore devices - OWC prototype 85 kW, Oyster 260 kW, WaveRoller 1000 kW, Wave Star C6 1000 kW.

Figure B2 – Wave conversion efficiency matrices (ΔT (s) $\times$ ΔH_s (m)) of the near-offshore devices –Wave Dragon 7000 kW and CETO 260 kW.

Figure B3 – Wave conversion efficiency matrices (ΔT (s) $\times$ ΔH_s (m)) of the offshore devices – Wavebob 1000 kW, Aqua Buoy 250 kW, Pelamis 750 kW and Archimedes 2500 kW

Appendix C – Bivariate distributions of wave energy

1071 **Figure C1** – Omni-directional monthly wave energy characterization matrices at the
 1072 nearshore site 2 derived from 31-years of wave data (For simplicity, only one in two
 1073 months is displayed). The colour band indicates the contribution of each energy bin
 1074 to the total (monthly) energy (MWh/m) and the numbers represent the occurrence
 1075 of the different sea states in hours per month

1076 **Figure C2** – Omni-directional monthly wave energy characterization matrices at the
 1077 offshore site derived from 31-years of wave data (For simplicity, only one in two
 1078 months is displayed). The colour band indicates the contribution of each energy bin

to the total (monthly) energy (MWh/m) and the numbers represent the occurrence of the different sea states in hours per month

Appendix D – Monthly and annual energy production

Figure D1 – Monthly average energy production E_0 at the nearshore hotspot 1 (10.2 m depth) for the Oyster, OWC, WaveRoller and Wave Star technologies.

Figure D2 – Monthly average energy production E_0 at the nearshore hotspot 2 (22 m depth) for the Wave Dragon, Oyster, CETO, WaveRoller, AquaBuOY and Wave Star technologies.

Figure D3 – Monthly average energy production E_0 at the offshore hotspot (54 m depth) for the Wave Dragon, Archimedes, Wavebob, Aqua BuOY and Pelamis technologies.

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Figure D4 – Monthly average energy production E_0 at the nearshore hotspot 1 (10.2 m depth) for the Oyster, OWC, WaveRoller and Wave Star technologies

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Figure D6 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the nearshore hotspot 1 (10.2 m depth) for the optimized Oyster, OWC, WaveRoller and Wave Star technologies.

Figure D7 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the nearshore hotspot 2 (22 m depth) for the optimized Wave Dragon, Oyster, CETO and Waveroller and Wave Star technologies.

Figure D8 – Normalized standard deviation (%) of the monthly performance in terms of R_h and monthly wave power at the offshore hotspot 3 (54 m depth) for the optimized Wave Dragon, Archimedes, Wavebob and Pelamis and Aqua BuOY technologies.

Appendix E

The normalized standard deviation was calculated as follow:

$$NSD = \frac{\sqrt{\frac{1}{N-1} \sum_{i=1}^N |P_i - \mu|}}{\mu} \quad (1)$$

where N is the number of values, P_i represents the mean wave power of a year or month i and μ is the mean of P .

- A 31-year wave hindcast has been analysed to quantify the intra- and inter-annual variability of the available wave energy resource
- The intra- and inter-annual variability in the performance of ten wave energy converters is investigated
- Inter-annual fluctuations in WEC production performance can be considerably higher than that of the wave resource
- It is shown that inter-annual variability can be as significant as that of intra-annual variability of power production
- Wave energy converter performance can be significantly improved with devices downscaled to local sea conditions