# The right size for a WEC: a study on the consequences of the most basic design choice.

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***Abstract*-**
This study presents elements of reflection regarding the most basic optimization parameter of any Wave Energy Converter (WEC): what is the right size for a WEC? The question of scale of tank tests and right size for a given WEC concept is a recurrent one, this study challenges to common request to fix at an early stage the WEC "full scale" size, and discuss the broader implications of the WEC size over its commercialization life.
To do so, and in addition to the annual production and capture width ratio, metrics related to the CAPEX utilization, and the impact of maintenance periods on the annual production are introduced. Using the case study of the Sloped IPS buoy, values for these metrics are shown as a function of the WEC scale for four typical wave sites of different characteristics.
The results show that scaling up WECs will indeed be more challenging than scaling up wind turbines, and that the main factor hampering such evolution is the rate of increase of the CAPEX that is superior to the rate of increase of the WEC production with scale. However, the results show that there is an advantage for larger WECs, based on the evolution of the maintenance availability. Larger WECs will benefit from longer predictive maintenance windows in the low season with lower impact on their annual productivity. Large farms of mature devices with lower need for corrective maintenance could benefit from such characteristics. It could therefore be expected that as WECs mature and larger farms are considered, their optimal size for a given resource will increase. Additionally, the results emphasise the fact that simplistic OPEX models are not sufficient to properly assess the size of a WEC for a given project.

***Keywords*-** WEC optimization, scale, maintenance, metrics.

## I. INTRODUCTION

This study presents elements of reflection regarding the most basic optimization parameter of any Wave Energy Converter (WEC): what is the right size for a WEC? Since the start of wave energy sector, different groups have been advocating different solutions, from lots of small units (Laminaria [1], Seabased [2]) to install a given capacity to just a few large single devices (Oyster [2], Wave dragon [3]). Argument for one strategy or the other have been made without ever being decisive, but the consensus tends towards the idea that for a given size, a single optimal size could be found, hence the reference to "full scale" in many communications. This is in stark contrast with the evolution seen in the Wind industry, where turbine rating and dimensions keep increasing, without changing the overall concept.

The question of scale of tank tests and right size for a given WEC concept is a recurrent one, as shown for example by [4]. As most WECs are resonant devices, the scale and size of a WEC are therefore strongly linked to the specificities of the considered deployment site. These can indeed present very different wave period characteristics (see [5]). The scale of a tank test is therefore a relative quantity, which can vary according to the selected site. Additionally, there is no absolute way to define the design wave period of a site. For an identical WEC concept, one could argue for different sizes using perfectly valid arguments in each case and arrive to different conclusions regarding the sizing of this specific WEC. It is only on a case by case basis, when sufficient details are available about a specific project that the right size of a WEC for this project could potentially be defined.

In this study, the topic of the right size of a WEC is explored using the performance curve of a published concept, and the introduction of new metrics.

The metrics are first described, then the WEC on which the case study is based is presented. A methodology section describes how the scale ratio and power matrices are obtained. Finally, the results are presented and a discussion about their implications on the selection of a WEC size concludes the study

## II. OBJECTIVE AND METRICS

The principal objective of this study is to examine the criteria leading to the selection of the size of a WEC in relation to a specific environment. By introducing some new metrics and novel ways to observe the available information from traditional tools, the impact of the WEC size over several aspects of the project will be considered and commented upon. The study also explores the link between the WEC size and the type of market considered, and therefore aims at providing a holistic view to approach the crucial stage of selecting the WEC size.

To achieve this principal objective, the Sloped IPS buoy described in [6] is utilised as a case study. It was important to use a WEC concept which results are known at tank scale, as the process of selecting the WEC size is usually done after the first stage of testing (see [7]), when important decision regarding the basic design of future sea going prototypes are made.

Several metrics are considered within this study, some very generic and well known, and some new ones evolved from previous works and considerations (see [8]). The metrics are presented below with relevant notes and calculation details:

- hydrodynamic Annual Energy Production (hAEP): the total amount of energy made available to the PTO for conversion, considering 100% availability of the WEC. It is estimated using power matrices and scatter diagrams. Expressed in kW.h/year.
- Average annual capture width ratio (a$C_{WR}$): a proxy for characterising the device efficiency. It is the ratio between the hAEP and the average resource $P_{inc}$ in kW.h/m/year, normalised by a characteristics dimension $L$ of the device in m.

$$aC_{WR} = \frac{hAEP}{P_{inc} \cdot L}$$

While not providing an absolute comparison between devices, maximising this metric generally relates to an optimal use of the WEC structure and therefore CAPEX costs.

- Minimum number of days required to produce X% of hAEP at a specific site. It represents the minimum number of days (associated with the most “productive” sea states) required to produce a certain percentage of the hAEP. This is estimated by using the scatter diagram of the site, and the energy production matrix of the device (power matrix multiplied by scatter diagram, expressed in kW.h/year), and obtaining the summary 2D plot of the “Zone matching between scatter diagrams” described in [8].
- Percentage of hAEP available by not producing during the low energy sea states representing X% of the site occurrences. Ordering the sea states from low to high incident power, the sea states which cumulated occurrences represents X% of the annual occurrences are not considered for the hAEP estimation. The metric is the ratio between this and the base hAEP. It reflects the potential production loss by dedicating X% of the time to preventive maintenance for example, during which time the WEC would not produce.

Additionally to these metrics related to power production, a measure of CAPEX utilisation is considered: in [9], a Froude scaling factor of the costs is established for the CorPower technology, giving an indication of how CAPEX costs related to a single WEC should evolve as a function of scale. The method is based on the assessment of the cost driver of each main cost item of the technology and the expected cost of the current prototype. The value obtained is 2.39, and it is specific to the technology. Given a Froude scaling factor λ between a model and prototype, the CAPEX is related as:

$$CAPEX_{prot} = CAPEX_{model} \cdot \lambda^{2.39}$$

The method is of course a simplification and does not accounts for step changes in the costs, but it should be rather indicative.

Assuming a base cost of 1 for the 9s design period device, this method provides a relative evolution of the cost as a function of the scale factor. It is then possible to introduce a normed CAPEX utilisation factor, n$U_{CAPEX.}$ It corresponds to costs divided by hAEP and normalised by the minimum value obtained over the range of scales. A range of cost scaling factor is considered, from 1.5 to 3.

## III. THE WEC

### A. Concept presentation

The WEC concept used for this study is based on the Sloped IPS buoy developed at the University of Edinburgh in the 1990s [10]. It is based on a heaving device originally developed by the Swedish company Inter Project Services AB (the IPS buoy) [11]. The contribution of the University of Edinburgh is the shifting from heaving motion to a sloped intermediate direction between surge and heave. More details on that concept can be found in [6] but for the sakes of convenience, a schematic of the working principle is reproduced in Figure 1 (left).

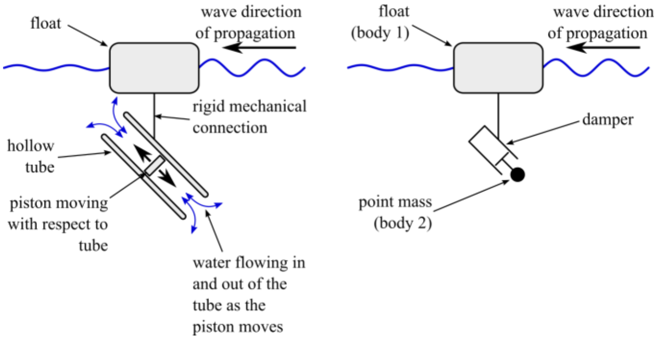

*Figure 1: Schematic of the sloped IPS WEC concept (left). Schematic of the modelling approach (right).*

Incoming waves induce motions of the float which is rigidly connected to the fully submerged PTO tube located below. The wave induced motion is passed on to the tube but the piston sliding inside the tube tends to move less than the tube due to the inertia of the body of water located in the tube. Energy is extracted from the relative motion between the tube and the piston. The concept therefore relies on water inertia for the PTO reference. The sloped direction of the PTO tube makes it possible to exploit not only heave motion but also surge and pitch, hence broadening the wave period range over which the device exhibit a high capture width ratio.

### B. Numerical model and $C_{WR}$

The numerical model used is based on a simplified version of the concept where only the float is subjected to hydrodynamics forces. The PTO tube is approximated by a damper and a point mass as shown in Figure 1 (right). This means that hydrodynamic loads on the PTO are neglected and that the inertia against which the PTO reacts is constant. The float is a cylinder 0.5m in diameter with a 0.5m draft whose mass is 98kg.

The WEC is modelled as a two-body system (the float and the point mass) in the frequency domain using linear potential flow theory. The hydrodynamic coefficients for the float were obtained from WAMIT and the two-body system equations of motion were solved using a bespoke code [6]. The model was used in [6] to carry out parametric investigation of the PTO. The optimum values are the following: mass of the point mass: 98kg, vertical distance between the point mass and the float: 0.25m, damping value: 326Nsm$^{-1}$ and damper slope angle: 50° to the vertical. The capture width ratio of this configuration is shown in Figure 2.

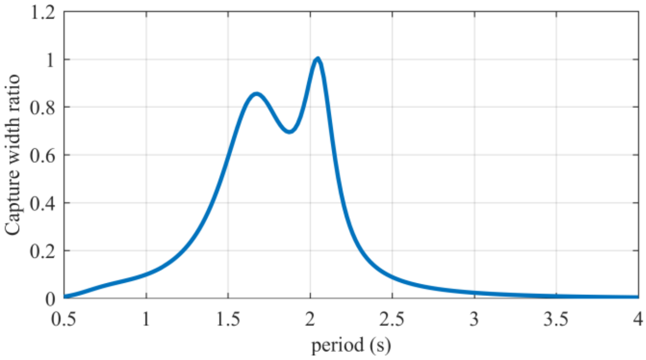

*Figure 2: Capture width ratio plotted against wave period*

## IV. METHODOLOGY

This study scrutinizes the evolution of key metrics (see section II) related to a WEC performance as a function of its size for a given resource. As it is the evolution of these quantities that is essential, the accuracy of the absolute values is not of paramount importance, and results based on linear potential flow theory are deemed acceptable.

The size of the WEC is related to its design period. In this study, the design period is defined as the mean capture width period (TmCW, see [6]). For different target design period, a Froude scaling ratio λ is established as:

$$\lambda = \left(\frac{TmCW_{target}}{TmCW_{base}}\right)^2$$

with $TmCW_{base}$ the mean capture width period of the numerical model (0.5m diameter Sloped IPS buoy).

A range of target design period from 6 seconds to 16 seconds is considered in this study, leading to a range of scale ratio between approximately 10 and 80.

In order not to distort the results in favour of unrealistic performance into highly energetic sea states, a penalty based on sea state steepness is introduced into the power matrices, as described below.

The method utilized to obtain the sought-after metrics is as follow: numerical model is used to obtain the capture width ratio ($C_{WR}$) of the WEC concept at a typical tank testing size (1 to 2 second waves).

For each considered scale ratio, a power matrix of the scaled-up device is created, by scaling up $C_{WR}$ and multiplying it with the sea state spectrum of each cell (a JONSWAP spectra with γ=3.3 is used). A non-linearity penalty is applied: first, the sea state for which the $C_{WR}$ is defined as the sea state with an energy period $T_E$=TmCW and a $H_S$ such as the steepness $S_S$=0.02 (see [12]). This reference sea state is then scaled for each scale ratio. Then, within each power matrix, performance related to sea states with lower steepness are unchanged. For sea state with a higher steepness, the performance is reduced following a linear decrement as a function of steepness. A 0.05 decrement is used in this study.

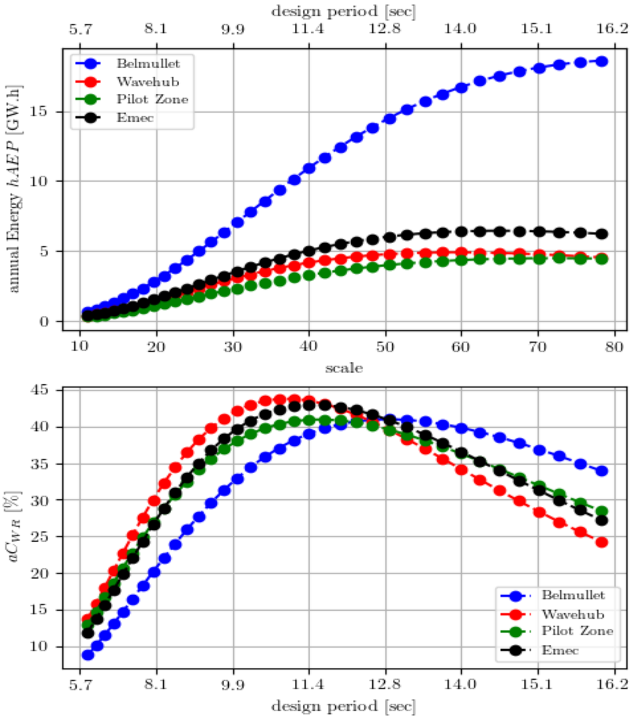

*Figure 3: hAEP and aCWR for the four considered sites.*

Once the power matrix for a given scale ratio is obtained, it can be used in conjunction with the scatter diagram of the considered sites to obtain the metrics defined in section 2.

It is important to note that the process of obtaining the power matrices is not crucial. The power matrices could very conceivably be obtained by scaling up a power matrix obtained experimentally at tank scale or other means, which will already include some of the hydrodynamic non-linearities.

## V. RESULTS

### A. Power production

Figure 3Figure 3 presents the yearly hydrodynamic energy capture and the average capture width ratio of the WEC for the 4 considered sites.

The increase of hAEP is clearly visible for all the sites, albeit it is not peaking at the same period. At the same time, the shape taken by the $aC_{WR}$ curves is interesting: the slope for the increase before the maximum is higher than the slope for the decrease after the peak (large design periods). This indicates that there is less risks of choosing a slightly too large size than a too small one in term of power production and overall hydrodynamic efficiency.

Also, it is interesting to observe that the maximum $aC_{WR}$ at Belmullet is lower than at the other sites, notably Wavehub and Emec. This is influenced by the energy repartition with regard to periods of the energy at each site, but it is especially the product of the linear decrease of $C_{WR}$ as a function of wave steepness in the power matrices.

## B. CAPEX utilization

Figure 4 to Figure 7 show the normed CAPEX utilisation while varying the cost scaling factor from 1.5 to 3.

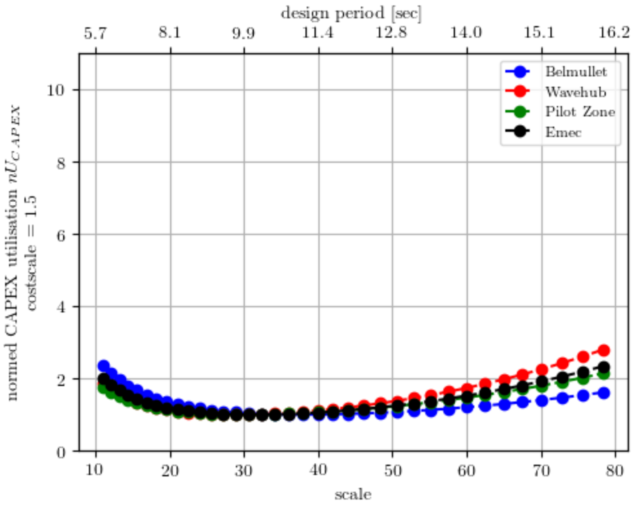

*Figure 4: normed CAPEX utilization with a cost scale factor of 1.5*

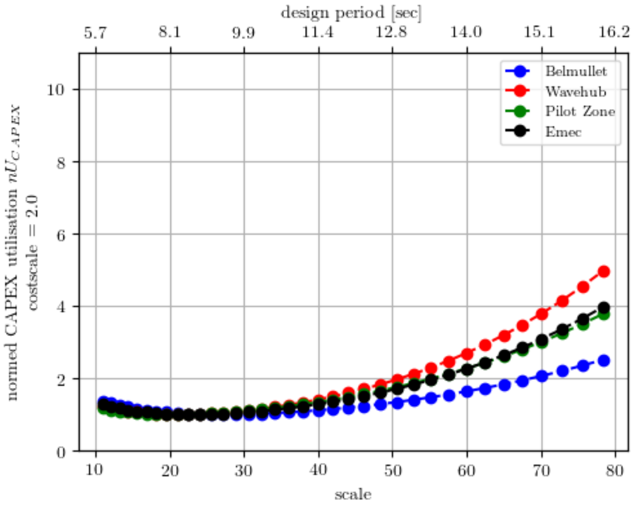

*Figure 5: normed CAPEX utilization with a cost scale factor of 2.0*

The figures show the expected evolution, with a significant increase of $nU_{CAPEX}$ for the larger scale as hAEP increase is slowing down while the device cost is increasing. It should be noted however that in the case of a low-cost scaling factor, it appears possible to reach an optimum close to the usual design periods for WECs, around 8 to 11 seconds. However, if considering a larger cost scaling factor, no optimum at the usual range is available. Therefore, depending on the WEC characteristics, an evaluation of the cost scaling factor might be an early and potent indicator to evaluate the potential of a technology to be scaled up.

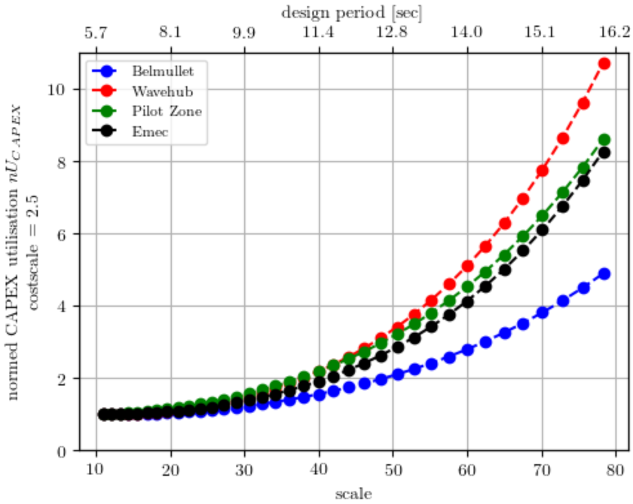

*Figure 6: normed CAPEX utilization with a cost scale factor of 2.5*

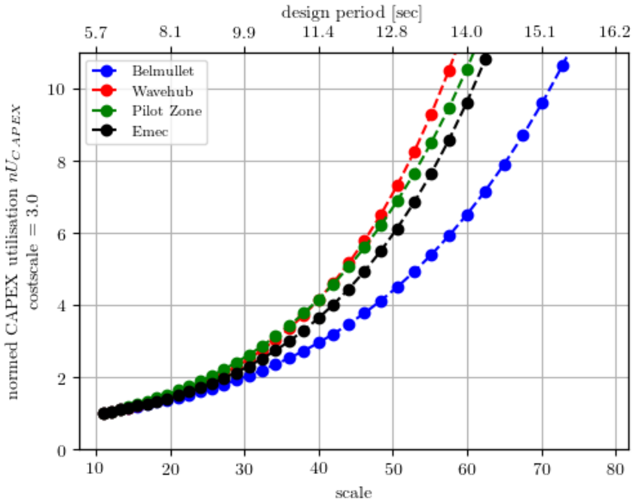

*Figure 7: normed CAPEX utilization with a cost scale factor of 3.0*

While interpreting these figures, it should be noted that the costs considered are only linked to the device itself, and that installation and infrastructure (cables, etc) costs are not taken into account.

## C. AVAILABILITY/OPEX CONSIDERATIONS

Figure 8 shows the Minimum number of days required to produce X% of hAEP as a function of scale, using 75%, 90%, 95% and 98% as threshold levels. The choice of levels is arbitrary and could be altered for the needs of a specific study. These plots quantify and visualize an intuitive characteristics,

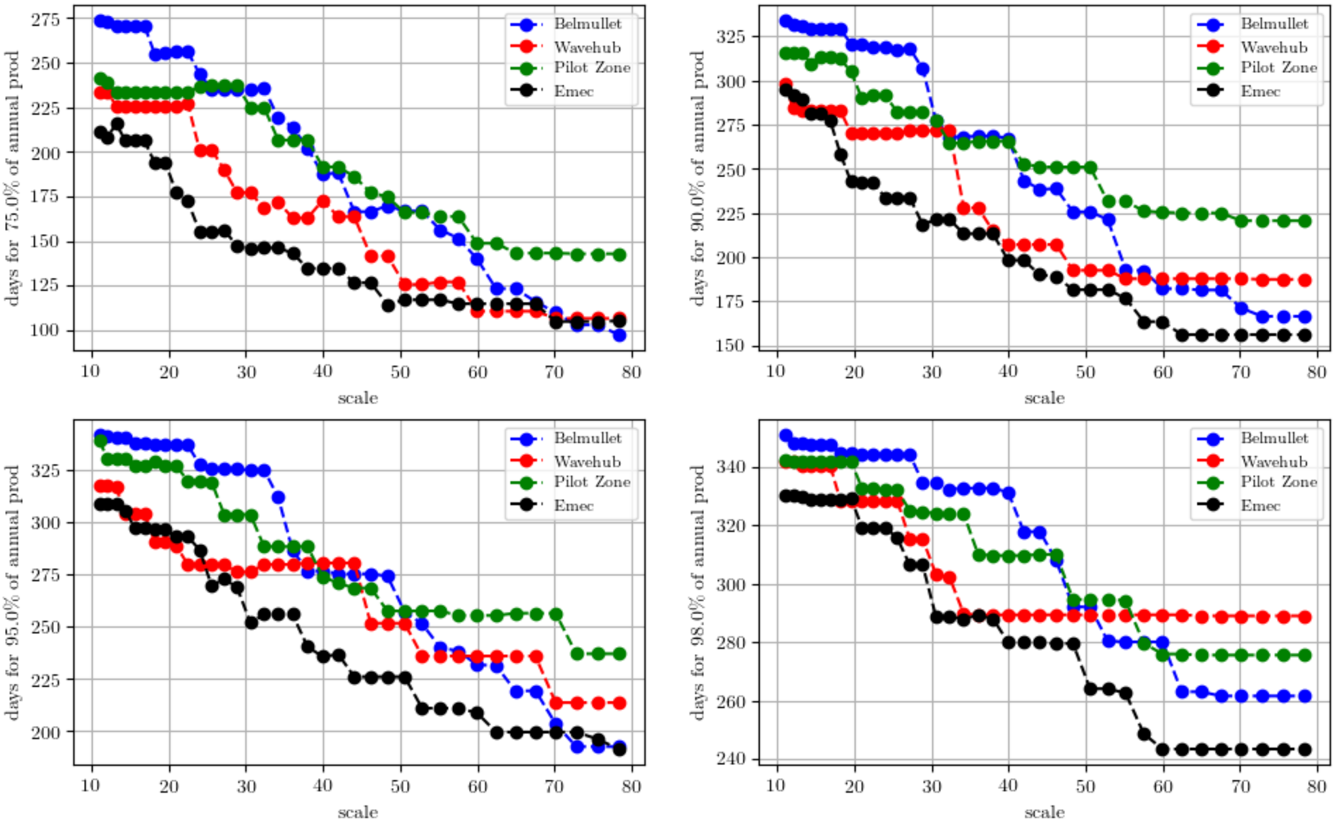

*Figure 8: minimum number of days required to produce X% of annual hAEP.*

i.e. that as the device size increases, it is efficient at the more energetic but less frequenctly occurring sea states, and therefore it will produce more in a limited numbre of sea states than smaller device. This appears to be especially true in the most energetic wave climate such as Belmullet.

The figures show a very significant decrease in the number of days required to produce a given percentage of hAEP for all the sites as the device scale increases. For the 90% level, nearly 300 days are required at the smallest scale (design period of ~6s) falling to less than 225 in all cases for scale >60 (14 second design period). This signifies that up to 75 extra days could potentially be available for maintenance on the larger devices without compromising annual energy production.

On the negative side of scaling up devices, this highlights the fact that larger devices will also produce energy during a smaller proportion of the year, making them less suitable for market requiring constant production. It also introduces a higher risk to the energy production as device scale increases: if a large device is not available when energetic sea states are present, a larger proportion of the hAEP might be lost.

Regarding the impact on maintenance strategy of scaling up a WEC, a secondary set of plots is presented in Figure 9Figure 9**Error! Reference source not found.**, which show the impact of discarding the less energetic sea states. The plots show that up to 20% (up to 73 days) of the sea states can be discarded without significant energy production penalty (98% of hAEP available, which considering low PTO efficiency for the low energy sea states, should translate into even higher percentage of annual energy production) for scales higher than 35 (10 seconds design period).

Looking at discarding up to 30% of the low sea states (109 days), scaling up the device to design periods above 12 seconds signifies that up to 96% of hAEP could potentially be available at all considered sites. These characteristics shows that scaling up the device would provide large amount of flexibility in the planning of maintenance, without significant impact on the energy production. This will require however mature devices with high availability during the productive part of the year.

## VI. DISCUSSION

Selecting the design period of a device or scaling up the design from a tank testing prototype, is shown to be driven by more than just the performance of a given design for a specific resource characteristic. In particular, the metrics introduced in this article are providing insight about which elements should be considered when optimising a WEC size.

- Can a WEC concept be scaled up? It appears that based on performance alone, a WEC concept could be scaled up to a certain extent. A rather large performance plateau is reached for each site within which other consideration could dictate the choice of the WEC size. One of the biggest limitation regarding scaling is probably related to the CAPEX utilisation factor. An early assessment of the CAPEX scaling factor related to a concept will be a very important assessment

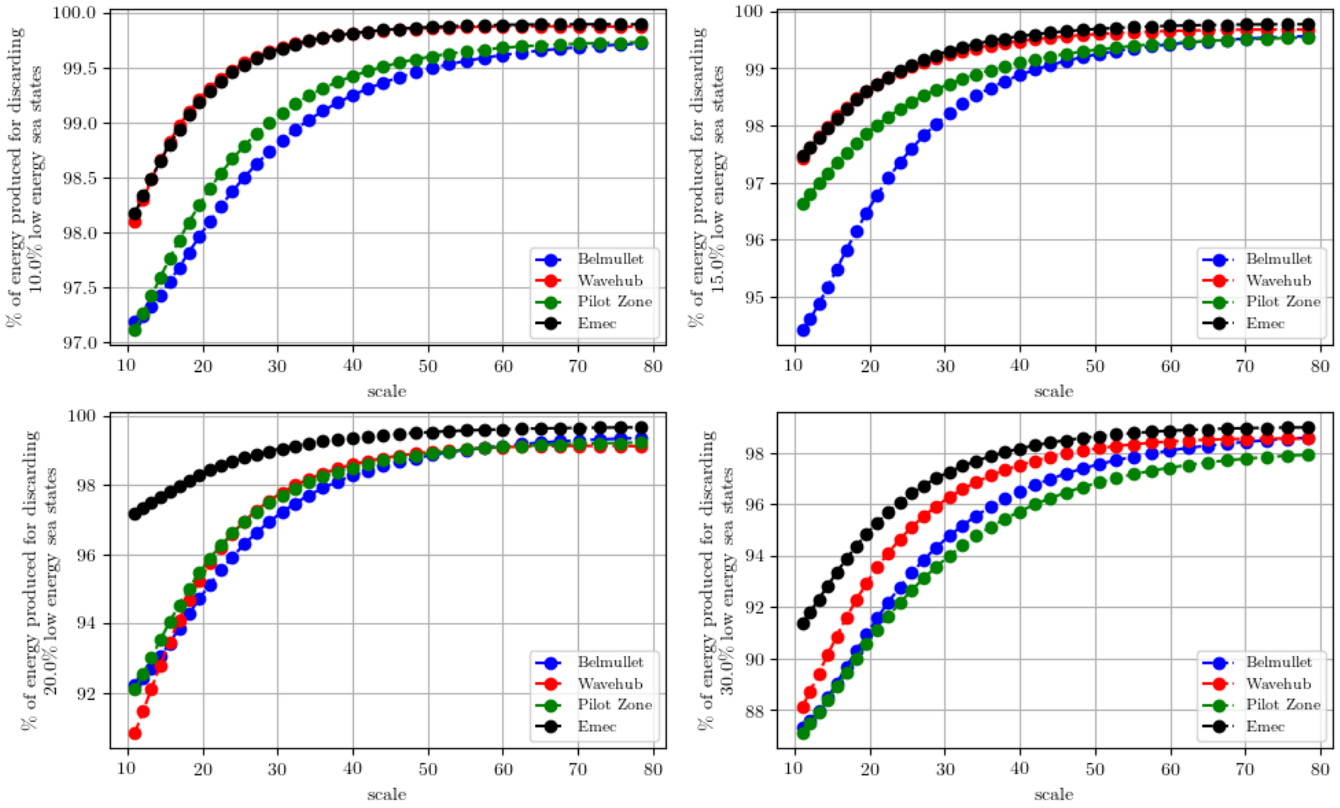

*Figure 9: Percentage of hAEP lost as a function of scale while discarding the low energy sea states representing 10%, 15%, 20% and 30% of the annual occurrences.*

criterion for a given WEC. Design changes, such as moving from a steel structure to a concrete structure could potentially influence this CAPEX scaling factor, and this should be taken into account when evaluating such changes. The analogy with the offshore wind industry, which tends towards ever increasing turbine sizes indicates that the costs of infrastructures and installations should favour the larger devices. This might compensate the reduction in CAPEX utilisation factor for the WEC alone when increasing the WEC size.

- For a specific concept and wave resource, going towards larger WEC size will bring increased flexibility for predictive maintenance operations. A larger WEC hAEP will indeed be less impacted by planned downtime during the summer months, when low energy sea states are present. This characteristic goes hand in hand with the fact that larger WECs will produce a larger share of their hAEP during a smaller number of days. Therefore, the risk over the hAEP of non-predicted downtime is higher for larger WECs.
- Larger WECs will tend to exhibit larger imbalances in the production throughout the year. The importance of energetic sea states into the hAEP increases with WEC size. As energetic sea states are most often concentrated in specific periods of the year, this will tend to increase the production share during such periods and to decrease it in the rest of the year. This might not be an issue when feeding electricity into a larger network and might even match the actual demand pattern over the network through the year. However, WECs or WECs farms connected to a small grid, or even an off-grid load, will tend to provide a significant share of the total demand. An unbalanced production through the year will force the installation of additional generation capacity or storage to compensate for the imbalance and reduce the overall capacity factor of the network.
- The previous elements work together to indicate that the opportunity to increase the size of a WEC for a given resource should be regarded in relation with the level of maturity of a technology, its expected ratio of predictive over corrective maintenance and the target market. A natural path of increasing WEC size emerges where, for a similar resource, the optimal WEC sizes changes as the technology is maturing and becoming more competitive with existing technologies. Early in the commercialisation of the concept, alternative market could be targeted with devices rather small with respect to the resource and still not entirely mature. As the technology matures, larger WECs could be devised to be integrated into larger farms in order to feed large networks. Such large farms will benefit from higher economies of scale regarding the electrical infrastructure when using large device, and the unbalanced yearly production pattern would not be an issue. The longer maintenance window available with larger WECs and smaller amount of corrective maintenance associated with large WECs could potentially allow smaller maintenance team, which will have the time to spread the planned maintenance operations to be carried out on multiple WECs during the low seasons without significant

production penalty. WEC should therefore be expected to grow beyond the size of the first "full scale" prototypes, and this should not be seen as a failure of the design team to properly optimise the WEC in the first place.

- The resource at EMEC is particularly well suited to be a test site. The results indeed show that of the 4 considered sites, EMEC is the one allowing the most downtime through the year without compromising hAEP. This characteristic is particularly well suited for test programs, where developers will consider several periods of maintenance/upgrade through the year. This complement the observations pointing in the same direction made in [8].
- Regarding LCoE modelling, the evidences provided in this study show that simplistic assumptions regarding the OPEX costs and the availability of the device are not appropriate when comparing the impact of the WEC size on the overall cost of energy. With the same level of maturity, larger WECs should indeed exhibits higher overall availability, as the same amount of downtime would have a lower impact on annual power production. The notion of increased risk associated could be considered by increasing the variability of the availability in Monte-Carlo type simulations. Detailed work using a WEC with sufficient maintenance operation data would be necessary to study the impact of the overall WEC size over the LCoE.

## REFERENCES

[1] R. C. R. Pascal, Adrien Combourieu, S. Nauwelaerts, and A. Foschini, "Experimental assessment of an innovative concept for managing mooring load," in *Proceedings of 13th European Wave and Tidal Energy Conference*, 2017.

[2] A. Babarit, J. Hals Todalshaug, M. J. Muliawan, and A. Kurniawan, "Numerical benchmarking study of a selection of wave energy converters," *Renew. Energy*, vol. 41, pp. 44–63, May 2011.

[3] B. Drew, A. R. Plummer, and M. N. Sahinkaya, "A review of wave energy converter technology," *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 223, no. 8, pp. 887–902, Dec. 2009.

[4] A. D. De Andres *et al.*, "Techno-economic related metrics for a wave energy converters feasibility assessment," *Sustainability*, vol. 8, no. 11, p. 1109, 2016.

[5] R. C. R. Pascal, A. Torres Molina, and A. Gonzalez Andreu, "Going further than the scatter diagram : tools for analysing the wave resource and classifying sites," in *Proceedings of the 11th European Wave and Tidal Energy Conference*, 2015, pp. 5–12.

[6] G. S. Payne, R. C. R. Pascal, and G. Vaillant, "On the concept of sloped motion for free-floating wave energy converters," *Proc. R. Soc. A*, vol. 417, no. 2182, 2015.

[7] B. Holmes, K. Nielsen, and S. Barrett, "Wave Energy Development & Evaluation Protocol," in *Proceedings of the 7th European Wave and Tidal Energy Conference*, 2007.

[8] R. C. R. Pascal, A. Torres Molina, and A. Gonzalez Andreu, "Going further than the scatter diagram : tools for analysing the wave resource and classifying sites," in *Proceedings of the 11th European Wave and Tidal Energy Conference*, 2015, pp. 5–12.

[9] A. D. De Andres, J. Maillet, J. Hals Todalshaug, P. Moller, and H. Jeffrey, "On the optimum sizing of a real WEC from a techno-economic perspective," in *Proceedings of the 34th International Conference on Ocean, Offshore and Arctic Engineering*, 2016, p. 11.

[10] S. H. Salter and C.-P. Lin, "The sloped IPS wave energy converter," in *2nd European Wave Energy Conference*, 1995, pp. 337–344.

[11] L. Bergdahl, "Review of research in Sweden," in *Wave energy R&D workshop*, 1992, pp. 129–136.

[12] Det Norske Veritas, "Environmental conditions and environmental loads," *DNVGL -RP-C205*, no. August. DNV GL, p. 259, 2017.

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