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# Performance Assessment of the Wave Dragon Wave Energy Converter Based on the EquiMar Methodology

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**Abstract**— At the present pre-commercial phase of the wave energy sector, device developers are called to provide reliable estimates on power performance and production at possible deployment locations. The EU EquiMar project has proposed a novel approach, where the performance assessment is based mainly on experimental data deriving from sea trials rather than solely on numerical predictions. The study applies this methodology to evaluate the performance of Wave Dragon at two locations in the North Sea, based on the data acquired during the sea trials of a 1:4.5 scale prototype. Indications about power performance and production of the device at the target locations, as well as on the applicability of the methodology, are provided.

**Keywords**— Wave Dragon, Performance assessment, Sea trials, EquiMar, Nissum Bredning, Hanstholm, North Sea, Ekofisk, Wave-to-wire, Wave energy.

## I. INTRODUCTION

The wave energy resource around the globe is very large, with a particularly high potential for extraction along the Western European coast. If properly harnessed, wave energy can become a large-scale contributor to the European electricity mix [1].

At present Wave Energy Converters (WECs) are approaching the commercial stage. In this phase it is very important to provide the energy industry, stakeholders, investors and any other group of interest with a reliable assessment of the performances of full-scale commercial devices.

Numerical modelling is often used to calculate the power performance of a device, mainly due to its flexibility. However, predictions might not always be accurate enough to state the performance of a WEC in real sea conditions since

features like the real-time control of the device and the influence of local conditions might not have been fully considered in the model.

Another possible approach is to assess the performance of a WEC based on data acquired during real sea trials of a reduced-scale prototype. In this case operational issues often neglected by numerical models are taken into consideration. Sea trial results can be up-scaled and fitted to the wave resource at the target location for the deployment of the full-scale devices, limiting the use of numerical models only to complement the experimental data.

This second approach has been recently proposed by the EquiMar project of the European Commission [2]. With this methodology, the EquiMar consortium aims to provide device developers and stakeholders with an equitable and general procedure to assess the performance of any WEC at different scales and locations, based on the results of sea trials.

Encouraging the sea trial of reduced-scale prototypes before reaching the full-scale commercial stage, the methodology also rewards a step-by-step development plan. Within this strategy any new phase of development, with its specific goals and objectives, is justified only by the good results of the previous one.

The adoption of a similar common approach, also known as Technology Readiness Assessment (TRA), would help to reduce capital risks in the product funding programmes [1].

The present study applies the EquiMar methodology to the Wave Dragon (WD) WEC, by assessing its performance at two different locations in the North Sea. These have been selected according to WD on-going and future development plans. The evaluation is based on the data acquired at the 1:4.5

scale prototype tested since 2003 in Nissum Bredning (NB), a benign location in Northern Denmark.

The results, relative to a setup without wave reflectors, show a wave-to-wire non-dimensional performance of 23% at an offshore location having yearly mean wave powers of 6 kW/m. This equals to yearly power productions of 0.64 GWh.

For a high North Sea wave climate of 24 kW/m results show that too few experimental data are available to provide a reliable estimate of the performance for the envisaged device size.

Moreover, some indications will be drawn about the applicability of the proposed methodology, which had not been widely applied yet. Practical considerations on how to plan sea trials in order to increase the applicability will be addressed.

The content of the paper is as follows:

- i) Presentation of WD technology, its development history and plans for future commercialisation;
- ii) Detailed description of EquiMar methodology;
- iii) Power production estimate of WD at two different locations in the North Sea, including the evaluation of its performances at different stages of the wave-to-wire model;
- iv) Discussion of the results regarding the power performances of WD and the applicability of the methodology;
- v) Conclusions and recommended further work.

## II. WAVE DRAGON

The WD is a slack-moored floating WEC of the overtopping type. Incoming waves are focused towards the doubly curved ramp of the device by two wing reflectors, surging it without breaking and overtopping into a reservoir placed at a higher level than the mean water level (Fig. 1).

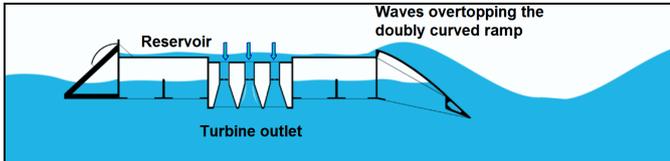


Fig. 1 – The Wave Dragon working principle.

The Power Take-Off (PTO) system of the device consists of several variable speed low-head hydro-turbines directly coupled to Permanent Magnet Generators (PMG). The power production takes place as the water stored in the reservoir is led back to the sea through the turbines.

The turbines are of axial type with fixed propeller blades and guide vanes. The rotational speed of the turbines is controlled in accordance to the available pressure head by means of a back-to back frequency converter system. The turbines are activated in a cascade fashion by the control system depending on the water level in the reservoir. The PTO system has been proved to maintain a very high efficiency across the whole span of working conditions.

### A. Wave-to-wire model

The energy conversion chain from wave-to-wire of WD can be broadly described in four different stages, corresponding to the following power levels:

1) *Overtopping power*: is the potential power of the waves overtopping the ramp crest of the device:

$$P_{crest} \text{ (kW)} = \rho \cdot g \cdot R_c \cdot q \quad (1)$$

It is proportional to the crest level  $R_c$  (m), corresponding to the height of the crest freeboard above the mean water level, and to the overtopping flow  $q$  (m<sup>3</sup>/s).  $\rho = 1025$  kg/m<sup>3</sup> is the salt water density and  $g$  is the gravity acceleration (m/s<sup>2</sup>).

2) *Hydraulic power*: is the potential energy stored in the reservoir that can be effectively harnessed by the turbines:

$$P_{hyd} \text{ (kW)} = \rho \cdot g \cdot H_t \cdot q \quad (2)$$

It is proportional to the working head of the turbines,  $H_t$  (m), defined as the difference between the water level in the reservoir and the mean water level. The power loss with respect to  $P_{crest}$  is due to  $H_t$  being lower than  $R_c$ .

3) *Estimated power*: is the power produced by the turbines assuming they are working at their optimal speed. It is derived from the characteristic curve of the turbines by knowing  $H_t$ . It can be expressed as:

$$P_{est} \text{ (kW)} = P_{hyd} \cdot \eta_{turb} \quad (3)$$

where  $\eta_{turb}$  (-) is the turbine's efficiency.

4) *Actual power*: is the power delivered to the grid. It is a function of the efficiencies of the generators,  $\eta_{PMG}$  (-), and the frequency converters,  $\eta_{fc}$  (-). In case of optimal turbine speed the relation is:

$$P_{act} \text{ (kW)} = P_{est} \cdot \eta_{PMG} \cdot \eta_{fc} \quad (4)$$

### B. Wave Dragon development phases

WD has followed the 5-stage development proposed by the Waveplan project according to the TRA approach [3]. A preliminary phase of extended tank testing of a 1:51.8 scale model carried out at HMRC and Aalborg University served as the proof of concept and to optimize the design of the device [4]. In parallel with it, the WD optimised propeller turbine was developed with EU support and thoroughly tested in the test facility at Technical University Munich.

The results of this phase were used in the up-scaling of the device to the 1:4.5 scale prototype. This has been deployed since 2003 in NB, a benign site in Northern Denmark. The Wave Dragon Nissum Bredning (WD-NB) prototype was the first floating WEC to deliver power to an onshore grid.

Highly instrumented, it also allowed investigating many features impossible to consider at reduced scale. Among these were the control strategy and test of the PTO, the remote monitoring and control system and various issues related to the manufacturing, operation, maintenance and survivability of the device [5].

Currently, WD is involved in various projects to deploy larger scale units at different locations. Among others, the company has recently obtained a national grant to carry out a structural certified design of a 1:1.5 scale North Sea WD to be deployed at the Danish Wave Energy Centre (DanWEC) at Hanstholm, Northern Denmark. Moreover, the feasibility study will also consider full-scale multi-MW WD units to be deployed in the North Sea and the Atlantic Ocean.

### C. WD pre-commercial units

In the following, reference will be made to three different scales of WD: one is the WD-NB, for which the performance data have been recorded, and the remaining two are larger scale devices. These correspond to a 1:1.5 scale device of a North Sea WD, to be deployed at Hanstholm, and to a full-scale North Sea WD.

The main geometrical and power features of the three pre-commercial devices are summarised in Table I.

TABLE I  
SUMMARY OF WAVE DRAGON FEATURES

	Locations		
	Nissum Bredning	DanWEC (Hanstholm)	North Sea (Ekofisk)
Scale ratio	1:4.5	1:1.5	1:1
Wave Climate	0.3-0.6 kW/m	6 kW/m	24 kW/m
Width (with reflectors)	58 m	170 m	260 m
Width (without reflectors)	21.6 m	64.8 m	97.2 m
Length	33.3 m	96 m	150 m
Height	3.6 m	12 m	16 m
Device Rated Power	20 kW	1.5 MW	4 MW

### III. METHODOLOGY USED

The EquiMar methodology aims to use a dataset containing measured power levels at the prototype scale to estimate the power production of the same WEC at different scales and locations.

The ultimate goal of the methodology is to provide a power matrix for the target location, where the power output of the device is defined for every sea state together with an estimate of the accuracy of the stated performance [6, 7].

#### A. Environmental Matrix

The wave climate at the target location is characterised by an environmental matrix. Typically for a WEC this is a 2D matrix including only wave height and period, known as scatter diagram (SD).

In this study, the SD is defined by  $H_{m0}$  (m), significant wave height derived from the frequency domain analysis of a wave record, and  $T_e$  (s), the energy period. The dimension of the matrix bins has been varied depending on the target location considered.

#### B. Performance data derived from the sea trials

The data considered in the study correspond to two datasets, acquired respectively in autumn 2004 and summer 2006 at two different test sites in NB, i.e. Test site 1 and Test site 2 (Fig. 2). The water depth at these locations ranges between 5.3 and 6.1 m, depending on the tide.

Both datasets are relative to data recorded in the absence of the wing reflectors, which were removed at that time due to maintenance. The data recorded at WD-NB include, among others, the wave conditions, floating position, overtopping flow, water level in the reservoir, turbine activity and power delivered to the grid. They consist of 30 minutes long time series acquired at 10 Hz, enough to include in average a number of 1000 waves and allow for a statistical analysis.

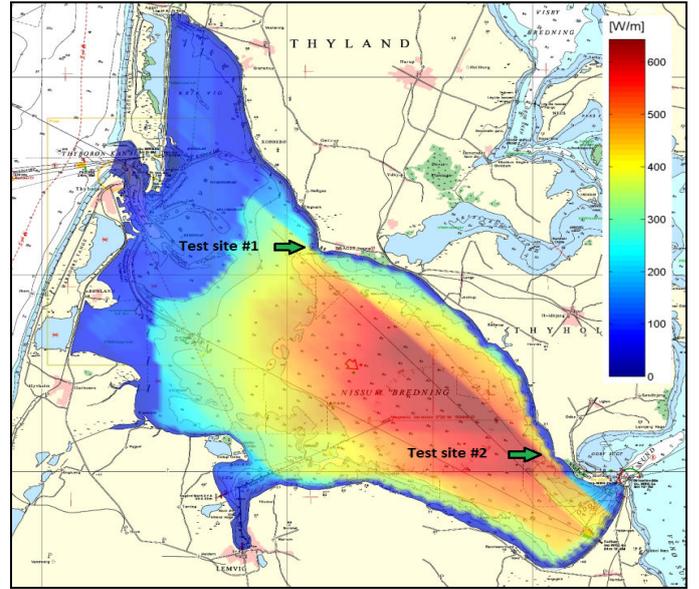


Fig. 2 – Nissum Bredning map with mean energy flux; the position of the two test sites considered is indicated.

The wave features were recorded by using a pressure transducer placed roughly 4 m above the sea bed and 50 m in front of the device, at the anchor pile. From the pressure measurements the wave elevation was derived applying linear wave theory [8].

The wave elevation time series were analysed in the frequency domain and values of significant wave height  $H_{m0}$ , energy period  $T_e$  and peak period  $T_p$  were derived.

The overtopping flow into the reservoir,  $q$ , was measured indirectly: assuming the average volume of water in the reservoir is the same at the start and end of the 30 min of each record, the input, i.e. the overtopping flow, is equal to the output, i.e. the water flow out of the turbines. The latter was calculated by recording the working speed and head of each turbine and by knowing their characteristic curve. The main drawback of this method is that it neglects the spill of water out of the reservoir, which in some cases at WD-NB was significant especially at low crest levels [8]. Water spill can be reduced through the adoption of an appropriate control strategy at full-scale, as it will be discussed ahead in the paper.

The floating level,  $R_c$ , and floating position of the device has been derived from the combined measurements of 4 pressure transducers placed below the platform. The water level in the reservoir, from which the turbine head  $H_t$  has been calculated, has been determined from the measurements of 3 pressure transducers placed on the bottom of the reservoir.

Finally, the working speed of each turbine and the power delivered to the grid ( $P_{act}$ ) by each generator were also recorded.

### C. Zoning

The objective of the methodology is to define the power performance of the device across the whole SD with a reasonable level of accuracy.

The wave states tested during the sea trials have to be up-scaled according to the scale ratio between the prototype and the unit to be deployed at the target location. The extent to which the up-scaled wave conditions cover the SD of the target location determines the accuracy of the estimates.

In principle, it is desirable that the bins of highest wave power contribution at the target location are well covered by performance data. However, since the time of sea trials is limited and the wave conditions cannot be controlled like in a wave tank, enough data might not be available to do so.

In this case, the methodology suggests to group together the bins into zones, for which the average performances are defined. This allows providing an estimate on the performance also for regions in the SD where no or few data have been collected during the trial period. In any case, the zones should be kept as small as possible whenever enough data points are available, in order to have a good resolution of the resulting power matrix.

In regions where too few or no data points are available, the average performance of the zones can be predicted by a numerical model. These zones are hereafter referred to as “numerical zones”, whereas zones where the performance assessment is based on experimental data are called “experimental zones”.

In this study the zoning has been done manually, covering the regions of greater contribution to the total wave power resource of the location.

For both experimental and numerical zones, the dimensions of the zones correspond to one bin of the SD.

### D. Performance assessment and data selection

The performance data acquired at WD-NB was divided by the wave power at the trial location available across the width of WD ramp. These values are called non-dimensional performances  $\eta$  (-).

By using non-dimensional quantities the power performance can be estimated at any location of interest, provided the available wave power is known (i.e. a SD is available) by multiplying the wave power by the respective  $\eta$ .

The estimate of the non-dimensional performance for each zone is the average  $\eta$ , based on all the selected data points for which the wave conditions belong to the zone. In order to describe the accuracy of the estimate, the standard deviation,  $\sigma$  (-), and the confidence interval,  $CI$  (-), for a confidence level of 95% are also calculated for every zone.

The latter is evaluated assuming a Student’s-t distribution:

$$CI = t^* \cdot \sigma / N^{0.5} \quad (5)$$

where  $t^*$  (-) is a statistical parameter depending on the size of the sample considered,  $N$  (-), and the confidence level chosen.

During the sea trials not all recorded data may correspond to optimal performances (the control system may not function well or the control strategy might be improved over time, etc.). Therefore, lower performances are more often recorded than expected at full scale, where every component of the device is expected to work optimally.

In order to have an estimate representative of the performance of a full-scale device, a criterion has to be adopted to account only for those data referring to optimal working conditions. In any case, a minimum amount of data should be considered in every zone and the methodology should reward the increasing number of data considered.

Moreover, the data selection criterion should not only favour the highest  $\eta$  but also the accuracy of the estimate: a balance between considering the optimal  $\eta$  and the lowest  $CI$  should be found.

In this study the minimum amount of data points initially considered for every zone was set to 5. All data points were ordered according to their  $\eta$  and then the 5 highest were initially selected.

Whenever the  $\eta$  of the highest point was more than 10% higher than the following one, that data point was disregarded. This was meant to discard outlier data points which would significantly increase the  $CI$  of the average estimate, being these points too high compared to the rest of the set to be considered reliable.

The first tentative value for the  $\eta$  of a zone is the average between the remaining data points. The number of data points considered in the average is then increased until a 10% drop is achieved in  $\sigma$  of the sample considered. In this way the optimal average  $\eta$  is approached while maintaining a sufficient accuracy of the estimate.

### E. Power contribution and average performance

Each bin of the SD corresponds to a sea state, for which the probability of occurrence,  $prob$  (-), is known and the wave power,  $P_w$  (W/m), can be calculated as:

$$P_w (W / m) = \frac{1}{16} \rho g H_{m0}^2 \cdot C_g \quad (6)$$

where  $C_g (m/s) = \frac{1}{2} \left[ 1 + \frac{2kd}{\sinh(2kd)} \right] \cdot \frac{gT_e}{2\pi} \cdot \tanh(kd)$  is the group velocity,  $k (m^{-1}) = 2\pi/L$  is the wave number,  $L (m)$  the wave length,  $d (m)$  is the water depth.

This value is multiplied by the width of the ramp of WD, in order to consider the total usable wave power.

The contribution of each wave state to the total wave power resource available at the target location can be calculated as:

$$Contr_{bin} = \frac{prob_{bin} \cdot P_{w,bin}}{\sum_{SD} P_{w,bin}} \quad (7)$$

Every parameter characterizing a zone, generically called  $X$  (e.g.  $H_{m0}$ ,  $T_e$ ,  $\eta$ ), is given by the weighted average of  $X$  of the bins belonging to that zone, where the weight is the product  $prob \cdot P_w$  of each bin. This corresponds to:

$$X_{zone} = \sum_{bin} X_{bin} \cdot Contr_{bin} \quad (8)$$

The contribution of each zone is given by the sum of the contribution of each bin of the zone.

The average  $\eta$  of the device at the target location, based on the zones considered in the assessment, is:

$$\eta_{average} = \frac{\sum_{zone=1}^{N_{zones}} (\eta_{zone} \cdot prob_{zone} \cdot P_{w,zone})}{\sum_{zone=1}^{N_{zones}} (prob_{zone} \cdot P_{w,zone})} \quad (9)$$

An unbiased estimate of the average  $\sigma$  can be given by:

$$\sigma_{average} = \sqrt{\sum_{zone=1}^{N_{zones}} (\eta_{zone}^2 + \sigma_{zone}^2) \cdot Contr_{zone} - \left( \sum_{zone=1}^{N_{zones}} \eta_{zone} \cdot Contr_{zone} \right)^2} \quad (10)$$

#### F. Numerical Complementation

When the performance data are not abundant enough in regions of the SD with a significant wave power contribution to the overall resource, the experimental data can be complemented by the predictions of numerical models.

In this case, the average numerical performance is called  $\eta_{num}$  and its accuracy is defined by the accuracy of the numerical model used.

Performance values derived numerically have to be well distinguished from those drawn from experimental data, the use of the latter being the main objective of the methodology.

In this study, the numerical model used allows for predictions of the overtopping flow  $q$ , depending on the environmental features and on the setup of WD.

The numerical model has been adapted from a general overtopping model suitable for high crest applications [9],

which has been updated to suit the specific case of WD after the tank testing of a reduced-scale model of it [10]. Features of the model include the description of the effect of the reduced crest height and limited draft of the device, of the wave steepness and of the specific geometry of WD. However, the model does not account for the effect of the hydrodynamic response of the WD.

The model can be applied whether or not wing reflectors are present. For the case considered in this study (no reflectors) the accuracy of the predictions with respect to the experimental data of the tank tests is  $\pm 5\%$ .

Constant ratios  $H_{m0}/R_c$  and  $R_c/H_t$  are considered for all wave conditions, in order to provide numerical estimates of  $P_{crest}$  and  $P_{hyd}$ , according to Eq. 1 and 2 respectively. These ratios are calculated as mean values, based on the data points selected in all the experimental zones.

Then,  $P_{est}$  and  $P_{act}$  are derived according to Eq. 3 and 4 by assuming constant efficiencies of the various components of the PTO system:  $\eta_{turb} = 0.91$ ,  $\eta_{PMG} = 0.94$  and  $\eta_{jc} = 0.98$  [11].

#### G. Target locations for the study

The target locations considered in the study are Hanstholm and Ekofisk, both located in the North Sea off the west coast of Jutland, Denmark (Fig. 3).

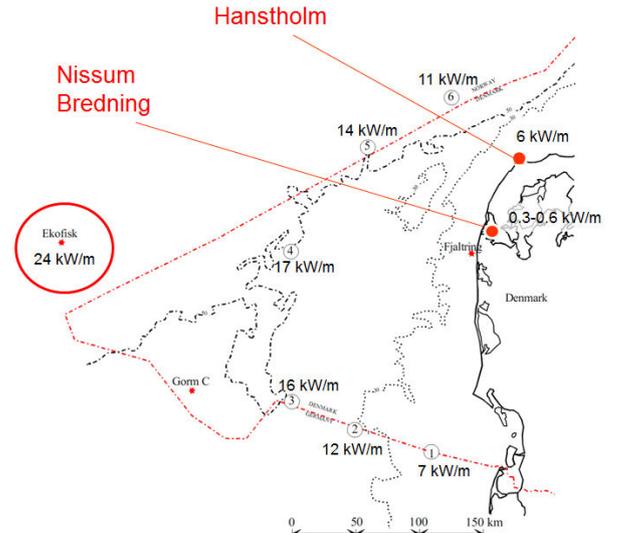


Fig. 3 Map of the Danish part of the North Sea including the locations considered in the study and their relative mean wave energy fluxes. In NB this corresponds to 0.3 kW/m at test site #1 and 0.6 kW/m at test site #2.

At Hanstholm the mean energy flux is 6 kW/m at  $d = 12-30$  m [12]. The wave climate is characterized by a wind sea on top of a non-constant swell coming from the Atlantic Ocean.

Hanstholm wave climate is suitable for the deployment of a 1:1.5 North Sea WD unit, rated at 1.5 MW.

Due to this, the location has been considered very useful to evaluate the feasibility of the device at an intermediate step between the reduced-scale prototype and the multi-MW WD versions. The deployment of the 1.5 MW unit would in every

case prove the economic feasibility of the device and its power production capabilities.

Moreover, Hanstholm is the location of a new developed wave energy test site, DanWEC, where two other devices are being tested [13].

Structural design work for the 1:1.5 scale WD is currently ongoing.

Ekofisk, at  $d = 70$  m, has a mean annual wave power resource of 24 kW/m, suitable for a full-scale WD rated at 4 MW. Ekofisk is reasonably close to the Danish part of the North Sea, which gives the reason for considering the possible power performance of a Wave Dragon in this scenario.

Moreover, the location presents the interesting opportunity of working with combinations of wave energy plants and offshore oil and gas platforms and wind farms, an option that has already been evaluated for the near future [14].

In addition, a similar wave climate as Ekofisk can be found further north along the British coast and also near the southern Norwegian coast.

#### IV. RESULTS

The four power levels listed in section II-A have been recorded at WD-NB. However, the described methodology is applied only to the first two of them,  $P_{crest}$  and  $P_{hyd}$ .

$P_{est}$  and  $P_{act}$  are estimated from  $P_{hyd}$  (see Eq. 3 and 4), along with the provided efficiencies of the PTO components:  $\eta_{nurb} = 0.91$ ,  $\eta_{PMG} = 0.94$  and  $\eta_{fc} = 0.98$ .

This is meant to give figures representative of the performance of a large-scale device in optimal working conditions, whereas the recorded values of  $P_{est}$  and  $P_{act}$  at WD-NB were not as such.

Indeed, the values of  $P_{est}$  measured at WD-NB were affected by scale effects caused by the small-sized turbines used, mainly due to high friction at the rotor axis, as well as by the effect of marine growth in the draft tubes. The resulting recorded efficiencies of the turbine were in most operational situations around 60%.

The same affected the measurements of  $P_{act}$ , which in addition corresponded at WD-NB often to non-optimal working speeds of the turbines, whereas a commercial full-scale WD would work at optimal speeds.

In optimal conditions, provided the control strategy would ensure a constant PTO efficiency for different wave states,  $\eta_{est}$  and  $\eta_{act}$  are proportional to  $\eta_{hyd}$ . Therefore, it is possible to refer to the hydraulic power level in order to draw indications about the trend of the non-dimensional performance and power production of WD for different wave conditions.

However, the estimates on the power production should be referred to  $\eta_{act}$ , which represents the wave-to-wire non-dimensional performance of WD.

##### A. Hanstholm

A WD to be deployed in Hanstholm would be three times larger in size than WD-NB. It would be deployed at a water

depth  $d = 30$  m, reachable within a few kilometres offshore, and rated at 1.5 MW with a set of 8 turbines of 185 kW each.

The SD considered has been discretized into bins of 0.5 m in  $H_{m0}$  and 0.474 s in  $T_e$ .

The zoning process revealed to be quite easy, since the wave climate at Hanstholm is very consistent with the one characterizing the test location, i.e. NB. In these conditions, a good overlap between the up-scaled performance data and the higher probability wave states has been found, reducing the number of numerical predictions required (Fig. 4).

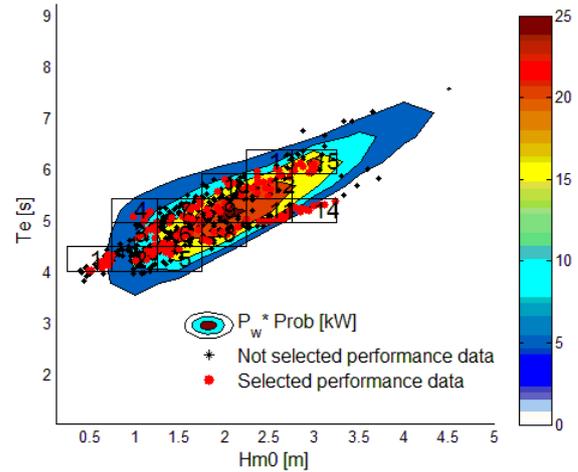


Fig. 4 – Scatter Diagram at Hanstholm including wave power resource, up-scaled performance data points and zones. The dominant wind sea has a peak in wave power at  $H_{m0} = 2$  m and  $T_e = 5.2$  s [12].

The performance assessment includes 15 experimental zones and 19 numerical zones. The latter have been used mainly in those regions of high wave resource that were not available for testing during the sea trials (Fig. 5).

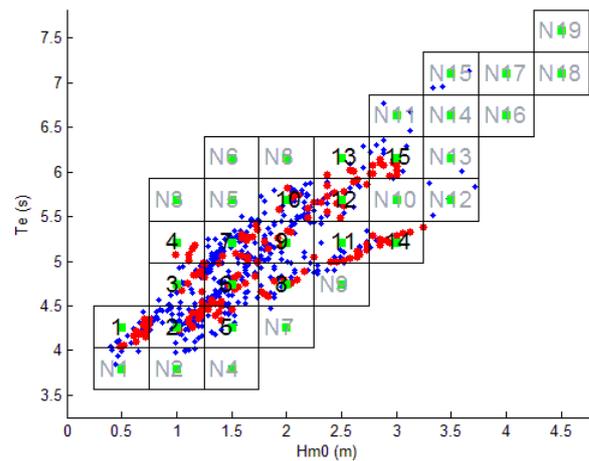


Fig. 5 – Zoning at Hanstholm: the regular zones are named in black and the numerical ones in light grey. Performance data points are marked in blue and the selected data points in red. A green square identifies the representative wave state for each zone.

The experimental zones correspond to 60.2% of the total wave resource at the location. A total of 150 performance data points have been selected in the performance assessment according to the procedure outlined in section III-D.

In these zones it has been possible to estimate the accuracy of the hydraulic non-dimensional performances through  $\sigma$ .

Table II summarizes the results at Hanstholm. The influence of including the numerical zones on the assessment of the yearly power production, based on  $P_{act}$ , can be noticed.

TABLE II  
SUMMARY OF WD PERFORMANCE AT HANSTHOLM

	Experimental Zones		Experimental and Numerical Zones	
	Mean value	Standard Deviation	Mean value	Standard Deviation
<b>Contr. (%)</b>	60.2		88	
$\eta_{hyd}$ (-)	0.32	0.043	0.27	-
$\eta_{act}$ (-)	0.27	-	0.23	-
$P_{hvd}$ (kW)	116	16	99	-
$P_{act}$ (kW)	97	-	83	-
<b>Power Production (MWh/year)</b>	514	-	642	-

Since Hanstholm is the location that has proved to fit better with the experimental data, its results are discussed in detail.

The trend of the non-dimensional performance of WD in the experimental zones, based on the crest and hydraulic power level, is visualized in Fig. 6. The ratio between the two  $\eta$ , representing the conversion efficiency between  $P_{crest}$  and  $P_{hvd}$ , is also displayed.

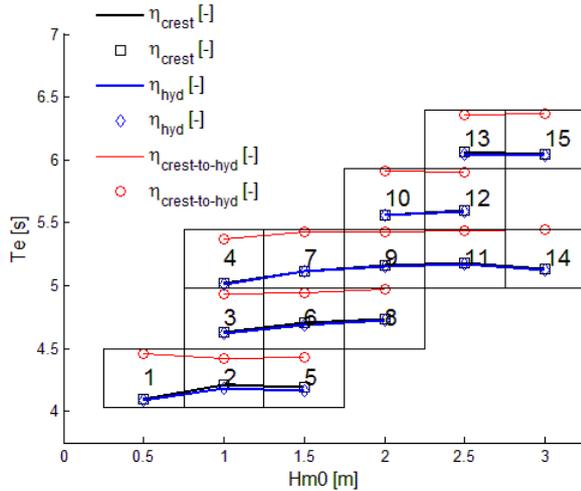


Fig. 6 – Estimates of  $\eta_{crest}$  and  $\eta_{hyd}$  of WD deriving from the application of the EquiMar methodology, shown over experimental zones with the same  $T_e$ . Conversion efficiency between  $\eta_{crest}$  and  $\eta_{hyd}$  is shown in red. The zero for each  $\eta$  is the lower bound in the y-axis of the zone. This trend is due to a non-optimal control caused by the lack of operating turbines at WD-NB, which led to often fill the reservoir causing spill losses.

Fig. 8 is an overview of the power contribution of each zone (experimental and numerical), as well as the wave-to-wire performance of WD in each zone both in terms of  $\eta_{act}$  and  $P_{act}$ . The latter (Fig. 8c) is the power matrix.

## B. Ekofisk

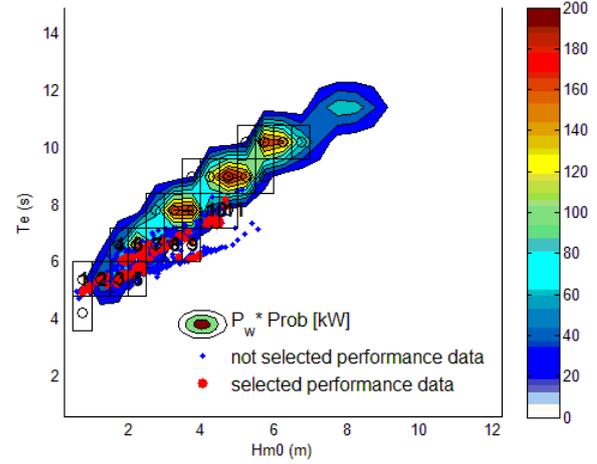


Fig. 7 – SD of Ekofisk including wave power resource, up-scaled performance data points and zones. The experimental zones (numbered) leave almost uncovered the most energetic parts of the SD, so several numerical zones (un-numbered) have been added.

A WD to be deployed at Ekofisk ( $d = 70$  m), often referred to as a North Sea WD, would be a full-scale device 4.5 times larger in size than WD-NB. It would be rated at 4 MW with a set of 16 turbines of 250 kW each.

The SD considered has been discretized into bins of 0.5 m in  $H_{m0}$  and 1.2 s in  $T_e$ .

In this case the zoning process revealed to be more difficult than at Hanstholm. Indeed, the wave resource at the target location is generally characterized by waves with relative longer  $T_e$  than in NB. Therefore, the regions with the highest power contribution of the SD were covered by performance data only to a minor extent and an extensive use of the numerical predictions had to be done (Fig. 7).

A total of 11 experimental zones and 13 numerical zones have been considered. The former covered 21.3% of the total wave power resource, including 111 selected performance data points. After adding the numerical zones the energy coverage increased to 82.2%. Results are shown in Table III.

TABLE III  
SUMMARY OF WD PERFORMANCE AT EKOFISK

	Experimental Zones		Experimental and Numerical Zones	
	Mean value	Standard Deviation	Mean value	Standard Deviation
<b>Contr. (%)</b>	21.3		82.2	
$\eta_{hvd}$ (-)	0.26	0.026	0.18	-
$\eta_{act}$ (-)	0.22	-	0.15	-
$P_{hvd}$ (kW)	633	62	424	-
$P_{act}$ (kW)	532	-	356	-
<b>Power Production (MWh/year)</b>	992	-	2562	-

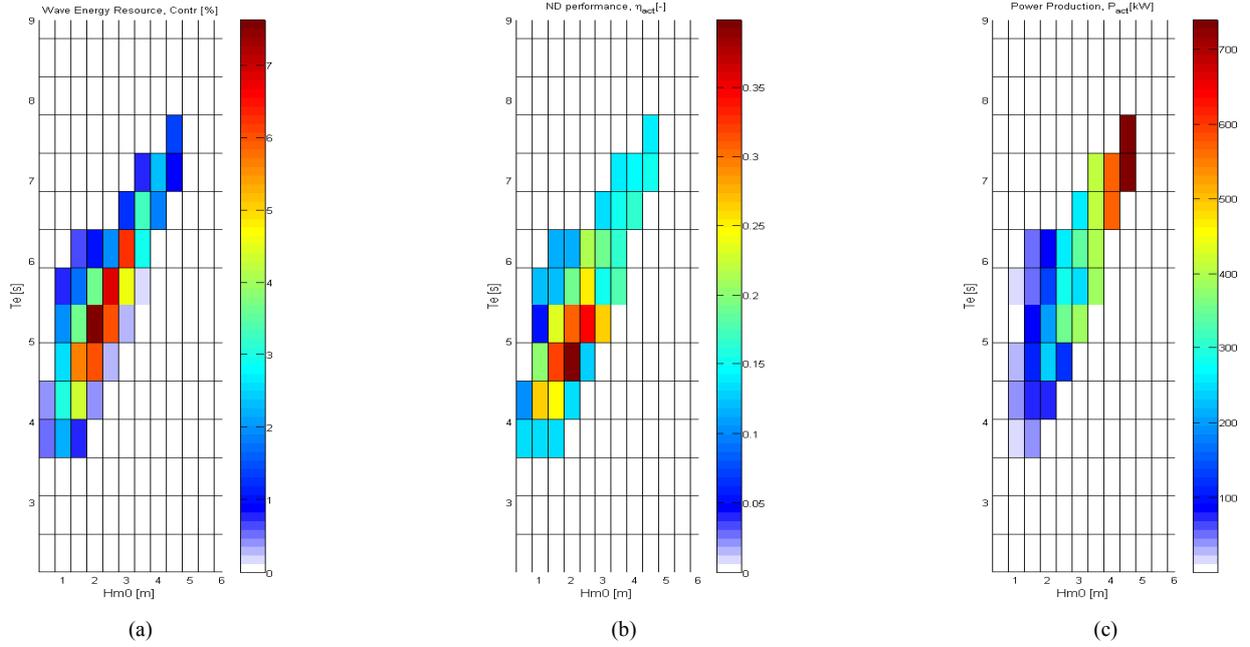


Fig. 8 - Matrices of (a) contribution of each zone to the total power resource (b)  $\eta_{act}$  of WD and (c)  $P_{act}$  of WD, at all zones considered at Hanstholm. The latter is the power matrix.

## V. DISCUSSION

### A. Data selection and accuracy of results

The results shown are influenced by the criterion of data point selection, but only to a minor extent.

If the proposed criterion had to be adjusted increasing the  $\sigma$  of the estimate, it is suggested to include more of the highest data points rather than of the lowest.

In the first case, the accuracy of the estimate would decrease, but its mean value would increase towards the optimal one; in the second case, both values would decrease, having an overall negative effect on the quality of the results.

### B. Average performance of WD at the target locations

Wave-to-wire average non-dimensional performances of 23% and 15% respectively at Hanstholm and Ekofisk have been found.

These correspond to yearly power productions of 0.64 GWh at Hanstholm and 2.56 GWh at Ekofisk. However it should be noticed that the results at Ekofisk are to a very high degree based on the predictions of the numerical model, which has not yet been calibrated with real sea data.

These figures are conservatives, referring to a configuration without the wave reflectors. It has been estimated that the average increase in annual wave power flux provided by the reflectors would be of 30% [15].

As shown in Fig. 8, the highest wave power contribution is given by zone 9 ( $H_{m0} = 2$  m,  $T_e = 5.2$  s), with 7.6% of the overall available wave power; values above 5% are also given in zones 6, 8, 11, 12 and 15.

The highest  $\eta_{act} = 0.4$  is achieved by far in zone 8 ( $H_{m0} = 2$  m,  $T_e = 4.74$  s); values of  $\eta_{act}$  above 0.25 are also achieved in zones 2, 6, 9, 11, 12 and 14.

$P_{act}$  increases with  $H_{m0}$ , showing a fairly clear dependency, while it is quite constant over  $T_e$ . Maximum values are reached in the numerical zones N18 ( $H_{m0} = 4.5$  m,  $T_e = 7.1$  s) and N19 ( $H_{m0} = 4.5$  m,  $T_e = 7.6$  s), corresponding respectively to  $P_{act}$  of 739 kW and 733 kW.

### C. Wave-to-wire energy conversion

Fig. 7 shows the evolution of the non-dimensional performances relative to the crest and hydraulic power levels over the experimental zones.

The same trend can be observed for  $\eta_{crest}$  and  $\eta_{hyd}$ , which grow with  $H_{m0}$ , determining the conversion efficiency  $\eta_{crest-to-hyd}$  to be very high and constant and meaning that the reservoir at WD-NB was close to be full in most of the cases considered. This is due to the fact that the data selected correspond to the optimal hydraulic performance of the device, when the turbines were not able to process the large overtopping volumes incoming in the reservoir.

At full-scale, once the optimal control strategy has been implemented, this trend would actually be the opposite,  $\eta_{hyd}$  and  $\eta_{crest-to-hyd}$  decreasing with  $H_{m0}$ . With the aim of reducing the spill losses, the water level in the reservoir will be lowered in wave conditions with high  $H_{m0}$  indeed, so to be able to accommodate the next incoming wave group and therefore increase the power production.

This kind of strategy would be favoured by the adoption of wave-by-wave predictive algorithms, which have already shown to be possible through the use of digital filters [8].

Using the  $\eta_{wave-to-wire}$  resulting from the study, the different conversion efficiencies along the WD energy conversion

chain have been analysed, provided the PTO efficiencies are known and the  $\eta_{crest-to-hyd}$  has also been estimated.

Table IV summarizes the wave-to-wire conversion efficiencies of WD at the two tested locations. The given figures are only based on the results of the experimental zones so to be more reliable, being not influenced by the limitations of the numerical model which has shown a tendency to underestimate the overtopping flow measured.

TABLE IV  
SUMMARY OF WD ENERGY CONVERSION EFFICIENCIES

	Hanstholm	Ekofisk
$\eta_{wave-to-crest}$	35%	28%
$\eta_{crest-to-hyd}$	92%	93%
$\eta_{hyd-to-est} = \eta_{turb}$	91%	91%
$\eta_{est-to-act} = \eta_{PMG} \cdot \eta_{fc}$	92%	92%
$\eta_{wave-to-wire} = \eta_{act}$	27%	22%

The lower overtopping efficiency at Ekofisk is against expectations, but can be explained by the fact that zones with high  $\eta$  at WD-NB correspond to a low probability sea states at the target location, limiting the average non-dimensional performance. This is more evident where the correspondence between the two wave climates is not very good, such as at Ekofisk.

Table IV shows that the primary energy conversion, i.e. the overtopping efficiency, limits the wave-to-wire conversion efficiency. With respect to this, it has already been mentioned that the adoption of the optimal control strategy would reduce the water spill and increase the overtopping efficiency, decreasing in turn  $\eta_{crest-to-hyd}$ .

#### D. Applicability of the methodology to WD-NB

The applicability of the methodology has been found to highly rely on the correspondence between the high probability wave conditions at the sea trials and those at the target location.

When the correspondence is good (e.g. Hanstholm) a higher number of performance data points can be used in the performance assessment. This allows providing more reliable estimates, for which figures on the accuracy can also be given.

On the other hand, when the wave conditions at the sea trial location do not correlate well with the wave climate of the target location (e.g. Ekofisk) the use of experimental data is possible only in a reduced number of zones, requiring an increasing use of numerical predictions and limiting the reliability of the results.

Therefore, the correct choice of the sea trial location is essential to apply this methodology. Whenever possible, this should be based on the detailed wave climate of the target location for future deployment rather than only on its mean annual wave power.

NB, the location of the sea trials used in the study, is an inlet sea with locally generated, fetch-limited wind seas, which cannot represent well the wave conditions in the deep

parts of the North Sea. Here waves are generally longer due to swells, limiting the scalability of the performance found in NB.

As a consequence, the performance estimates provided at Ekofisk are mostly based on numerical predictions. Due to the limitations shown by the numerical model in predicting the overtopping flow, a drop in the  $\eta_{hyd}$  of 8% can be observed when the estimate includes the numerical zones. This also indicates that the numerical model still needs to be calibrated by large scale tests in real sea.

#### E. Indications for further WD performance assessment

Future plans for commercialization of WD include the deployment of full-scale units in the Atlantic Ocean off Wales and Portugal [3]. In the performance assessment of WD at these locations, characterized by swells longer than in the North Sea, it would be difficult to use the EquiMar methodology with the current dataset. Therefore, at present the performance assessment of WD at these locations is likely to be derived almost entirely through numerical models.

However, the deployment and test of a large-scale WD at Hanstholm would provide a better basis for the performance assessment at Ekofisk or Atlantic locations based on experimental data, making the DanWEC test centre very useful.

## VI. CONCLUSIONS AND FURTHER WORK

WD is now in a pre-commercial phase. At this stage, it is very important to be able to provide reliable estimates on the performance of large-scale commercial devices at possible target locations.

The EU project EquiMar has proposed a methodology to assess the performance of WECs at target locations in an equitable way and based on real sea trials of prototypes. The methodology allows estimating the non-dimensional and power performance in different zones of the SD at the target location based on experimental data, providing also a measure of the related uncertainty. Average non-dimensional performances can also be derived, based on the contribution of each zone to the overall wave power resource of the location.

The present study applies this methodology to the WD WEC. Performances are estimated for a 1:1.5 scale WD rated at 1.5 MW to be deployed at Hanstholm in the Danish part of the North Sea (at the DanWEC test centre) and of a full-scale 4 MW unit deployed at Ekofisk, in the offshore North Sea.

The study is based on performance data measured during the sea trials of a 1:4.5 scale pre-commercial demonstrator deployed between 2003 and 2006 in Nissum Bredning, a benign site in Northern Denmark. The dataset considered is relative to a setup of WD without wave reflectors.

The performance assessment has been mainly based on experimental data at Hanstholm, whereas at Ekofisk a significant number of numerical predictions has been required. This is due to the fact that the wave climate at Ekofisk did not fit very well with the one at the sea trials test at NB, location characterized by wind driven seas only.

The overtopping model used for the numerical predictions was developed through the tank testing of a small-scaled model of WD at Aalborg University.

The study considered 4 different power levels characterizing the wave-to-wire model of WD: the potential power derived from the overtopping flow over the crest of the ramp, the potential power corresponding to the water level in the reservoir, the estimated power produced in the case of optimal working conditions of the turbines and the actual power delivered to the grid.

The efficiencies along the wave-to-wire energy conversion chain of WD have been analysed. It does not come as a surprise that the stage most limiting the wave-to-wire performance is the conversion efficiency from the kinetic and potential energy mix of the waves to pure potential energy in water in the reservoir ("power level 1").

However, this can be further optimised at full-scale through the adoption of the already well defined turbine control strategy.

Since a scale effect limited the values of the wave-to-wire non-dimensional performances  $\eta_{est}$  and  $\eta_{act}$  measured at WD-NB, these have been derived from the measured  $\eta_{hyd}$  through the well-known efficiencies of the PTO components. In any case, this highlights the importance of being aware of the consequences of scale effects whenever the measured performance refers to small-size prototypes.

The average non-dimensional performance of WD has been found to be 23% at Hanstholm and 15% at Ekofisk. These figures are considered highly conservative as they refer to a setup without wave reflectors.

The average  $\eta$  achieved at Ekofisk has been found to be lower than at Hanstholm. An explanation has been found in the non-optimal correspondence between the wave climates at NB and Ekofisk, leading to a lower average  $\eta$  when some of the higher performances recorded at WD-NB correspond to low probability of occurrence at the target location.

Even though the use of numerical predictions allowed considering in both cases the major part of the wave power resource in the performance assessment (88% at Hanstholm and 82.2% at Ekofisk), a large use of numerical calculations goes against the stated objective of the EquiMar methodology of relying mostly on experimental data. In this case, the uncertainty of the estimates increases and cannot be quantified, depending more on the reliability of the numerical model than on the statistical treatment of the experimental data.

On the other hand, an availability of 95% can be generally expected from WD, so that also in this sense the figures given can be considered conservative.

The poor correspondence between the wave climate experienced at WD-NB and those characterizing possible deployment locations in the Atlantic Ocean limits the application of the used methodology, as the performance

assessments here would primarily be based on numerical predictions.

Further work can be expected to assess the performances of WD at these locations. In light of this, the update of the numerical model used and its calibration on data coming from real sea trials would increase the reliability of the provided estimates.

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