Statistical analysis of power production from OWC type wave energy converters

L. Martinelli[1], B. Zanuttigh[1] and J. P. Kofoed[2]

[1] DISTART,
University of Bologna,
Viale Risorgimento 2, 40136 Bologna, Italy
E-mail: luca.martinelli@mail.ing.unibo.it, barbara.zanuttigh@unibo.it

[2] Wave Energy Research Group, Department of Civil Engineering,
Aalborg University,
Sohngaardsholmsvej 57, 9000 Aalborg, Denmark
E-mail: jpk@civil.aau.dk

Abstract

Oscillating Water Column based wave energy plants built so far have experienced a low efficiency in the conversion of the bidirectional oscillating flow. A new concept is considered here, the LeanCon Wave Energy Converter (WEC), that unifies the flow direction by use of non-return valves, into a unidirectional flow, making the use of more efficient air turbines possible. Hereby, a more steady flow is also obtained.

The general objective of this note is to examine, the power take off (PTO) efficiency under irregular wave conditions, for WECs with flow redirection. Final practical aim is to identify a method that allows the choice of the optimal power generation capacity for which the device should be designed, when subjected to any given wave climate.

The analysis is based on the experimental results of existing tests carried out in the 3D deep water wave tank at Aalborg University, Denmark.

First, the power measured at the modelled PTO is compared with the available incident wave power in order to examine the overall system response in a scale-independent manner. Then, the power production density function is fitted to a simplified shape, whose parameters are related to the tested sea state conditions (wave period, wave height). Average performance and stochastic variability is thus obtained for any sea state and therefore also for the annual wave climate of interest.

An example application of a LeanCon unit is carried out for a location off-shore Cagliari (Italy).

Conclusions provide economic criteria for estimating the optimal value of power for which the PTO should be designed.

Keywords: power production, oscillating water column, statistic distribution.

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List of symbols

d	=	OWC draft
g	=	gravity acceleration
H_s	=	significant wave height
L_o	=	wave length based on T_{m-1}
p	=	pressure
P	=	power produced by the OWC
P_W	=	wave power
s_o	=	wave steepness based on T_{m-1}
T_{m-1}	=	spectral wave period
T_p	=	peak wave period
v	=	air velocity
t	=	time
g	=	parameter of the lognormal distribution
l	=	parameter of the lognormal distribution
μ	=	average value of the lognormal distribution
r	=	water density
s	=	variance of the lognormal distribution

Subscripts

d	=	daily value
e	=	exit
i	=	in
m	=	mean value
y	=	yearly value

Superscripts

$'$	=	non dimensional value (with the average power)

1 Introduction

This note addresses a class of floating wave energy converters (WEC) of the oscillating water column (OWC) type, that unifies the flow direction by use of non-return valves, into a unidirectional flow, making the use of more efficient air turbines possible. Hereby, a more steady flow is also obtained. The specific concept under investigation is the LeanCon (www.leancon.com).

In most WECs, a power take-off (PTO) equipment is present that converts an irregular oscillatory energy flux into electricity.

The PTO is a key element in the device economic performance [1], and is considered as a significant barrier to commercialising.

The unsteady wave induced energy results in an electrical output that often is variable in voltage and frequency. Power conditioning is the tool that extracts the energy from the generator and, to suit the grid connection requirements, inverts it into a given constant value of voltage and frequency.

For OWC types, due to the necessity to cope with the unsteady wave oscillation, Wells turbines are used, e.g. at the LIMPET plant on Islay [2] or PICO, Azores [3].

In order to increase efficiency, recent research is dedicated to rectification and stabilisation of the flow. Simultaneously, a different concept of turbine is considered [4], possibly similar to the conventional impulse one, which takes considerable advantage from the flow stabilisation.

What are the methods used to rectify the flow?

1) one approach is based on a system of non-return valves (as proposed by [5]).

2) the other is to average in space the available energy. The optimal solution also requires a large storage capacity, such as for the TAPCHAN device [6], but for offshore WECs the reservoir is necessarily limited, as for the case of the WaveDragon [7].

Off-shore WEC concepts that tend to rectify the flow (LeanCon, WaveMaster, MRC, Sea Bredth, and others) combine the two approaches. Air or water is channelled from different points into a single duct by means of non-return valves, taking advantage of the different phases of the waves in different locations.

So far, the only attempt to provide a statistical representation of the power production was given by [8] for shore fixed OWC only, that are simpler to model. They propose a method for random waves, by essentially deriving the variance and the probability distribution of the PICO plant, using the transfer function for fixed OWC developed by [9] and assuming a linear relation between turbine flow rate and pressure head. The same approach cannot be easily extended to more difficult systems, with several degrees of freedom. In these cases, the PTO response can only be predicted experimentally.

Purpose of this note is to describe the stochastic nature of the power performance related to a complex device, focusing on the OWC type and on the LeanCon in particular. The analysis is based on existing 3D tests of the hydraulic performance of this device.

The practical aims of the paper are:

- to derive a tool for the evaluation of the power that can be extracted for any wave condition, so that it will be possible to extend the results to any wave climate and any scale.
- to identify the optimal power generation capacity for which the device should be designed. Such design value is necessarily greater than the average power and lower than the highest peak, certainly infrequent and therefore contributing very little to the overall power production.
- to give suggestions on what should be the strategy with respect to the wave conditions greater than the design one: on the basis of the amount of energy harvested in these conditions, it will be decided if it is worth while to keep the device running or switch it off, putting it in safe mode.

The approach followed here is to describe the measured power in terms of efficiency, in order to by-pass the problem of scaling. Then, each value of measured produced power is conceptually associated to the cause that generated it, i.e. the wave with its own height and period. Actually the wave to wave fitting is based on a probabilistic approach, which considers a probability distribution and its essential parameters, average and variance. The fitting is therefore limited to these parameters.

No actual investigation on the effect of the mooring system is looked for, nor on the possible presence of any natural resonance which has been theoretically and experimentally proved to be a very efficient mechanism ([10]; [11]).

The paper is organized as follows.

In section 2, the WEC model and its hydrodynamic functioning concept are briefly described. In Section 3, tests are presented, focusing on the results of interest for the turbine, i.e. the pressure and discharge. Section 4 presents the analysis of the power production. The variance and the probability distribution of the air pressure inside the main pipes are computed in Section 5 for a number of sea states. A hypothetical application to a location off-shore Cagliari (Italy) in Section 6 shows the usefulness of the given statistics. A comparison with other concept in Section 7 allows a judgment on the efficiency of the tested device.

2 The device

The tested OWC is the LeanCon WEC, a multi chamber, floating device, working in near-shore and off-shore conditions.

The model is formed by a floating V-shaped slender structure, with two arms oblique 40° with respect to the incident wave front (Fig. 1). The reference full scale device is 240 m wide, intended for deployment in the Danish part of the North Sea. The model of the device is realized in fiberglass, and it is 6 m wide (scale 1:40).

The floating beams are equipped, in the bottom submerged half, by two rows of cylindrical chambers(each may be considered to be an OWC). Fig 2 shows a cross-section.

In the model each chamber is channeled via flexible hoses toward two larger ducts, lying parallel to the arm. One duct is kept at high pressure, the other one at low pressure. In full scale these ducts and hoses is integrated into the structure.

As the wave travels across the structure, the air present in the chambers over the crest is pressurized and it opens the relative non-return valves. The air is therefore forced to enter into the high pressure duct, and from here to the turbine. After the generator, the air, at a pressure below the atmospheric one, is gathered at the second duct and from here it is sucked out of the system by the pipes placed at the wave troughs, again flowing past non-return valves.

The structure beam is therefore divided into high pressure zones, connected to chambers that redirect the air toward the main inlet duct and from here toward the turbine, and low pressure aspiration zones, where the chambers suck air from the outflow duct. In an ideal condition, two rows of 60 pipes blow air into the pressurized inlet duct, and two rows of 60 pipes suck the air from the outflow duct (Fig. 2). During every wave period, each pipe completes a cycle and blows air when the waves rise and sucks air when the wave falls.

The 120 non-return valves are delicate parts, as they are necessary to force the air in a single direction. Since the flow is surely uni-directional, a different and more efficient turbine than the Wells type may be used.

During the wave period, the beam is subjected to an upward and downward force which is in general lower than in absence of pipes.

Should the beam extend for a length which is similar to one (or multiples hereof) wavelength, the vertical forces would tend to be small in average, thus avoiding that the WEC is raised by the waves. This allows the realization of a light structure and reduces costs. Further, in this ideal condition, the pressure in the pressurized inlet duct and in the aspiration outlet duct is almost constant, and so is the flow discharge through the turbines and, in last analysis, the produced power.

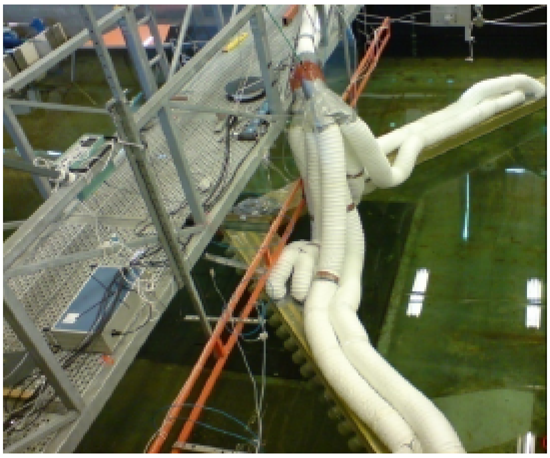

Figure 1: Picture showing the OWC device.

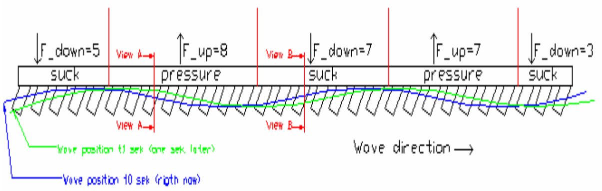

Figure 2: Cross-section of the arm of the OWC device.

3 The tests

Tests were carried out in the wave basin of the laboratory at Aalborg University (DK) by the Wave Energy Research Group [12].

The basin is 8.5 m wide, 15.7 m long and 1.5 m deep.

Long-crested waves are generated by means of an irregular wave-maker with active wave absorption switched off. Waves are absorbed laterally by metallic gabions (minimizing cross waves in the basin) and, in the end opposite to the wave-maker, by a 1:4 sloping beach made of sea stones.

Water depth in the basin at rest is 0.73 m and the bed is flat.

The model floats and is anchored in a single point, at the tip of the V by means of a spring board. (Fig. 3).

A parameter which is believed to strongly influence the device efficiency is the draft. The draft is modified by placing some polystyrene foam inside the duct, and therefore a greater buoyancy is associated to a reduction of the pipe diameter.

Tests considered here are those with a fixed 7 cm draft, assumed as the optimal value on the basis of previous testing.

The tested wave conditions are 5 irregular waves, with JONSWAP spectrum (peak enhancement factor 3.3), assumed as representative of the conditions typical of the North Sea. Tab. 1 presents the values of H_s (significant wave height) and T_p (peak wave period) that characterize each sea state.

WS	H_s [m]	T_p [s]
1	0.024	0.89
2	0.054	1.11
3	0.078	1.33
4	0.106	1.55
5	0.146	1.77

Table 1: Wave states tested in the laboratory (model scale).

Resistive wave gauges were used to measure surface elevation: two arrays of 4 gauges were used, and placed in front of one of the arms. One array was positioned in the usual way, along the wave direction, aiming at the measure of incident wave condition and reflection. The other array was rotated in order to be perpendicular to the to the wave direction (and to the wave-maker) in order to assess the decay of the wave along the arm.

Logging frequency was 25 Hz and test duration was approximately of 30 mins.

In order to (indirectly) "measure" the absorbed power in time, the pressure and the flow were monitored. More specifically, the pressure was measured in the inlet $p_e(t)$ and outlet $p_i(t)$ ducts, whereas the air velocity $v(t)$ was measured only in the latter.

The "measured" produced power $P(t)$ in time is obtained as:

$$P(t)= (p_e(t)-p_i(t))\cdot v(t)$$

and is given in *W*.

Pressure measurements were carried out by means of extremely sensible cells, covering the range 0-500 Pa. Velocity was acquired by means of a thermal flow meter working in the range (0-10 m/s), accurately calibrated in the section of duct under exam.

The flow meter appeared to have a lower accuracy at low speed, and therefore the low values of measured wave power production are expected to be less accurate.

Figure 3: Picture showing the OWC device moored with a spring board and the position of the wave gauges.

4 Analysis of power production

Fig. 4 shows the curves giving the probability distribution of the measured power. The order of magnitude of the generated power is several watts (up to 12, as shown in the Figure), which is something quite appreciable and the concept capability of harvesting energy is thus proved behind doubts.

Two considerations can be observed, and agree with what was expected, proving that the measured quantities are reasonable. For each sea-state, the encounter probability is maximum for the lower sea-state, and decreases as the measured power increases. As the severity of the sea states increases, the average measured power increases.

Fig. 5 compares the efficiency measured by the different sea-states. A progressive reduction of efficiency is seen as the sea states becomes more intense. This is rather counter-intuitive, since efficiency should be probably greater for longer waves, when the wavelength tends to the structure length therefore inducing a uniform flow. One possible reason is that greater sea-states induce greater dissipation in general, an other is that the air chambers size was too small. The intuitive observation is expected to hold only when the structure is fixed, as for instance when it is anchored on piles. On the other hand a fixed structure is believed to be less convenient due to the increased cost of the foundation.

The efficiency given in Fig. 5 is obtained as the ratio between the measured and available power.
The available power P_W is obtained as

$$P_W = \frac{r g^2 H_s^2 T_{m-1}}{64 \cdot p} \text{ W}$$

where the terms have the usual meaning: *r* is the water density, *g* is the acceleration of gravity, T_{m-1} is the wave energy period, *W* is the width of the structure (wings aperture).

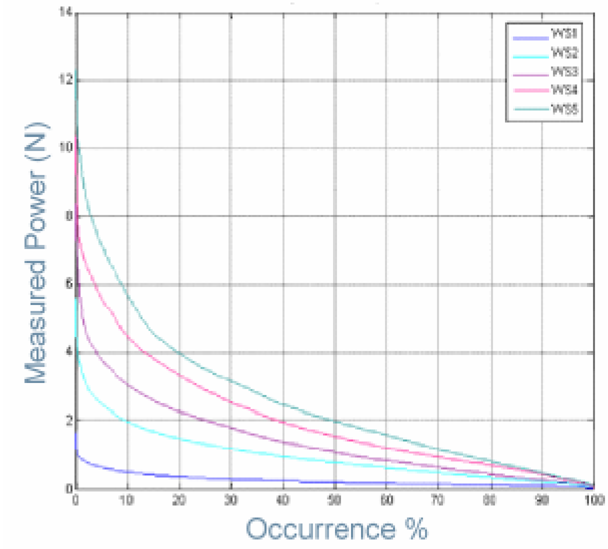

Figure 4: Power production versus its probability.

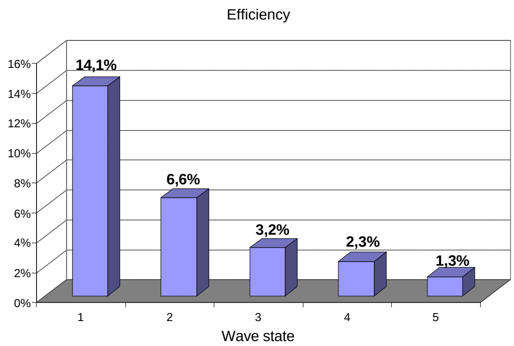

Figure 5: Measured efficiency of the power conversion.

The reason for assuming deep-water conditions for evaluation of the available power derives by the desire of comparing different concepts, from off-shore to near-shore, using the same term of reference. Note that in this case the device is meant to be placed at a depth of the order of half the wavelength, and therefore in condition close to the off-shore ones.

As usual, the concept of scaling is based on the assumption that efficiency is scale-independent, and consequently power scales with $\lambda^{3.5}$, λ being the scale factor of lengths.

5 Statistical distribution of power production

For each sea state, the oscillating signal of the wave power has been recognized and fitted to a triangular shape with known maximum and duration. The values of power intensities were ordered and an experimental distribution of encounter probability was obtained.

The theoretical distribution that resulted most suited to the experimental one was the log-normal, given in Fig. 6. The accuracy of the fitting is not critical in the analysis, since any two-parameters distribution would do. Anyway, it should be mentioned that, although all cases appear to be log-normal distributed, for the first sea state such behavior is evident, becoming less so as the intensity of the sea state increases.

For each sea state, the characteristics parameters of the lognormal distribution l and g were obtained (Tab. 2). They are related to the average m and variance s^2 of the sample by the:

$$m = \exp(l + \frac{g^2}{2})$$

$$s^2 = \exp(2l + 2g^2) - \exp(2l + g^2)$$

The fittings of l and g were based on the maximum likelihood method. Some deviations are therefore expected between average of the measured power derived by such parameters (using the eq.s above) and the average and standard deviation of the sample. The correspondence of such values gives an insight on the quality of the fitting, and this is given in Tab. 2.

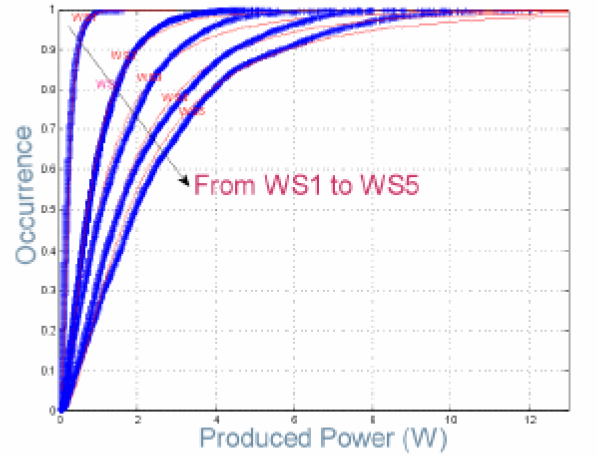

Figure 6: Approximation of the measured power distribution with a lognormal distribution, for each sea state.

For each sea state, the mean μ and the standard deviation σ are non-dimensionalized by the value of the average available powers, thus obtaining the average efficiency m' and an index of its variability s'. The relative non-dimensional values of l' and g' are computed from such non-dimensional average and standard deviation, inverting the eq. above.

Therefore l' and g' define a non-dimensional lognormal distribution of the produced power.

Then, the analysis is directed toward the definition of a relation among such non-dimensional values and the parameters characterizing the sea states, such as H_s and T_p.

Indeed, thanks to the relation among l and g (or alternatively μ and s^2) with H_s and T_p, it is possible to derive the statistics of the power produced in correspondence of any sea state and any scale (obviously assuming the device scales accordingly and efficiency is preserved).

The selected non-dimensional parameters, recognized as representative of the sea states, account for the intensity or amount of energy, and for the wavelength. They are the ratios between wave height and draft (note that draft is fixed for the test under consideration) d_H and the offshore wave steepness s_o:

$$s_o = \frac{H_s}{L_o}, \; d_H = \frac{H_s}{d}$$

The term off-shore indicates that the wave length is computed with the deepwater approximation: $L_o = 1.56 \cdot T_{m-1}^2$ in SI units, T_{m-1} being, again, the spectral energy period (in seconds).

WS	m [W]	σ [W]	P_m [W]	λ' [-]	γ' [-]
1	0.26	0.18	0.26	-1.77	0.62
2	1.00	0.95	0.97	-2.41	0.79
3	1.53	1.76	1.44	-3.01	0.92
4	2.18	2.39	2.07	-3.38	0.88
5	2.74	3.19	2.57	-3.95	0.91

Table 2: Dimensional and non dimensional parameters of the power distribution function. The mean of the distribution, μ, is compared with the measured mean power, P_m.

The scale-independent relations between the terms l' and g' (describing the PTO statistics) with the terms d_H and s_o (describing the sea state) are given by:

$$l' = -1.251 \cdot d_h - 1.4473, \; g' = 21.45 \cdot s_o + 0.0679$$

and shown in Fig. 6. Given the reduced number of experiments only the linear fitting was considered, which anyway seems to be rather accurate as can be seen from the figure.

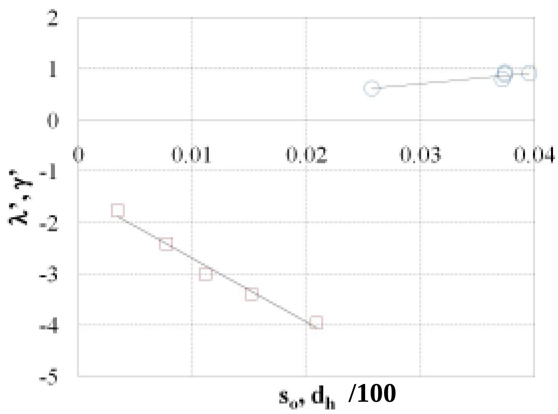

Figure 6: Approximation of non-dimensionalised parameters of the log-normal power distribution with the non-dimensionalised parameters representative of wave attack. Note that $\lambda'(d_h)$ is negative and $\gamma'(s_o)$ is positive.

6 Hypothetical application in Cagliari, IT

In the previous Section, it is shown that for any sea state (H_s, T_p) it is possible to derive the statistical distribution of the produced power.

As an example application, we decided to check the amount of energy production that should be expected in a hypothetical park of LeanCon devices placed off-shore the port of Cagliari, in the Sardegna island (Italy).

Water depth cannot be independent from conditions already tested in the Lab. It is indeed obvious that the wave devices need to be as close to the shore as possible in order to optimize costs of grid connections, but still sufficiently far in order to extract the wave energy before significant losses due to wave-bottom interaction. This occurs where the depth is half of the average wavelength.

The source of the wave climate is the "MEDATLAS", which provides a series of wind and wave data on a grid of points in the Mediterranean Sea, produced by the Istituto di Scienze Marine - Consiglio Nazionale delle Ricerche (ISMAR-CNR) di Venezia. The MEDATLAS project synthesizes the information gathered from several sources, including wave buoys, satellites and numerical models. All grid-points with the wave information are placed off-shore. Among the grid-point available for the chosen location, the selected one has geographical coordinates 38 N- 10 E (see Fig. 7). The winds blowing on Cagliari are the so-called "Maestrale" (prevalent and dominant) from NW and "Scirocco", from SE.

The data were first briefly analyzed and a preliminary decision of the suited water depth and therefore scale of the device was taken. This decision may be revised and subject to iterative procedure aiming at optimizing the cost-benefit ratio. In the end, a water depth of 30 m was considered, a little bit higher than the optimal, in order to be consistent with the design prototype scale (40 times greater than the tested model).

Once the scale is set, the draft (2.8 m) and the V-shaped structures aperture (240 m) are also defined.

MEDATLAS wave climate was given on a water depth of 100 m. Given the mild slope of the bed the off-shore values did not change significantly after the wave transformation from -100 to -30 m. The detailed table was slightly simplified, aggregating the occurrence probability relatively to classes with similar characteristics. The wave height value of the aggregated center class is the average wave height, and the period is computed in a way that assures the same amount of energy of the aggregation. The obtained period is therefore a weighted period where the weights are the occurring probabilities multiplied by the square of the wave height.

The reason for this simplification is a greater clarity of presentation, since a few figures are more simple to understand, control and interpret than a long 17x19 table.

Figure 7: Position of Cagliari and of the hypothetic wave buoy used for reconstructing wave climate.

The simplified wave climate representative of a location off-shore Cagliari is given in Tab. 3, and presents the occurrence probabilities summing up to 100% since wave condition 1 also includes the calms.

For each of the sea states, the parameters d_h and s_o, are evaluated (draft = 2.8 m). Then, by using the linear equations given above for λ' and γ, the expected scale-independent efficiency μ' and variance σ' are obtained. The expected produced power is given for each sea state by the available energy multiplied by the efficiency and prototype structure width (240 m at full scale).

Table 3: Simplified wave climate in Cagliari with available wave energy per meter width.

WS	H_s [m]	T_p [s]	*Prob* [%]	*Available Energy* [W/m/year]
calm	>0.5	-	19,2%	-
wave 1	0,75	4,8	24,3%	273
wave 2	0,75	8,1	8,3%	166
wave 3	1,38	4,8	12,2%	463
wave 4	1,38	7,0	9,6%	537
wave 5	1,38	9,2	4,9%	397
wave 6	2,30	6,7	10,1%	1'508
wave 7	2,30	9,6	5,3%	1'260
wave 8	3,50	8,5	2,9%	1'349
wave 9	3,50	10,8	1,1%	709
wave 10	4,50	10,2	1,5%	1'484
wave 11	6,13	10,7	0,6%	1'177
			100%	**9'324**

The sea states are sorted from 1 to 11 following the criterion of increasing wave height. The power associated to each sea-state increases as expected from sea-state 1 to 11 but, due to the wave period of sea state 9, the power associated to this sea state is lower (see Tab 3).

Fig. 8 shows the predicted average power generated by the device with increasing wave state.

Fig. 9 shows that efficiency is maximum for sea state 1 and decreases until it is minimum for sea state 11, with exception of sea state 3.

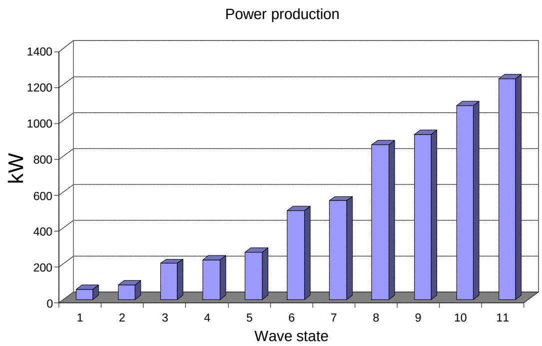

Figure 8: Power production for the different wave states.

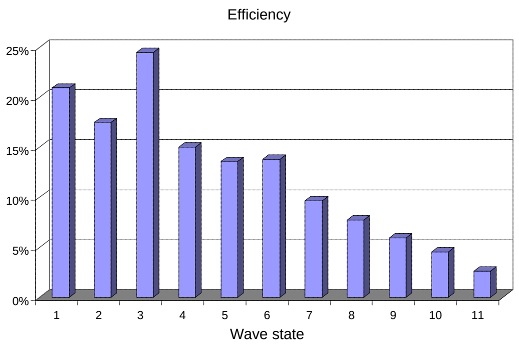

Figure 9: Power conversion efficiency for the different wave states.

The following analysis evaluates the expected available and produced energy for each sea state. Efficiency ranges from 1 to 25%.

As anticipated, the practical question of interest is to find what is the reference value of power for which the PTO should be designed. Although the maximum sea state has a potential for 2-3 MW, it looks like such turbine would be not economical in the chosen location.

By looking at Tab 4, it is evident that a turbine designed for 500 kW with a cost of the order of half of the previous one, can extract a large fraction of the available energy.

Knowledge of the statistic distribution allows the evaluation of the amount of energy extracted from each sea states by an under designed PTO. The economic consequences of switching the system in "safe mode" after some threshold may also be investigated.

The effect of different strategies is analyzed comparing cost and benefits.

Considering:

- the cost of the PTO proportional (with proportionality constant α) to the design power W_d,
- the benefit proportional (β) to the expected produced energy function of the sea states i,
- the remaining costs (C_o) independent from the choice of the PTO,

we have:

$$\text{Cost}=\alpha\, W_d + C_o$$

$$\text{Benefit}= \Sigma\, \beta\, W_i\, T_i + C_o \text{ (sum over i <d)}$$

Selection of the design power W_d is essential: if W_d is the power related to the 1st sea state, then the cost of the PTO will be small but the WEC will not produce energy for sea states greater than condition 1. The other extreme is a PTO designed for maximum power W_{11}, so that the WEC will always produce energy but the total cost may be excessive.

Since this investigation cannot enter into the details of the real values of α and β, the study will assume arbitrary values of α, β, and C_o, leaving to the designer to find his specific case. Order of magnitude of costs are derived from [1].

For our purposes, a convenient chioce of α/β is given by the condition that the yield is null when $W_d=W_{11}$ (W_{11} is associated to the maximum power). Similarly the cost of the WEC may be related to the cost of the PTO, say the cost of the PTO for wave condition 11:

$$C_o=\alpha\, W_{11}$$

We will see the alternatives to the choice of $W_d=W_{11}$ based on simple reasoning.

The yield may be defiend as (Benefit-Cost)/Cost.

From the definitions of Cost and Benefit given above, we obtain:

$$y= (\Sigma\, \beta\, W_i\, T_i - \alpha\, W_{11} - \alpha\, W_d)/(\alpha\, (W_d + W_{11}))$$

If we also substitute T_i by the total time within the year T multiplied by the probability of occurrence of a sea state i (p_i).

We have:

$$y= (\Sigma\, \beta/\alpha\, W_i/W_d\, p_i\, T - W_{11}/W_d - 1)/(W_{11}/W_d + 1)$$

with the condition on β/α that y=0 for $W_d=W_{11}$.

The maximum return is obtained selecting the design power W_d which maximises the yield.

Tab. 4 shows the average power P_g, the standard deviation, efficiency, the average annual E_y energy produced by the device, accounting for the available energy in each sea state.

Table 4: Mean generated power P_g and corresponding standard deviation for each wave condition, efficiency of power conversion, yearly produced power E_y.

WS	P_g [kW]	σ_P [kW]	*Efficiency*	E_y [MWh]
1	56	42	20,9%	120
2	84	24	17,5%	61
3	223	366	24,5%	238
4	202	127	15,0%	170
5	264	98	13,6%	113
6	495	645	13,8%	438
7	551	310	9,7%	256
8	864	1046	7,7%	219
9	922	626	6,0%	89
10	1081	1129	4,6%	142
11	1230	1713	2,6%	65
TOT	**5972**	**6126**	**9,8%**	**1'911**

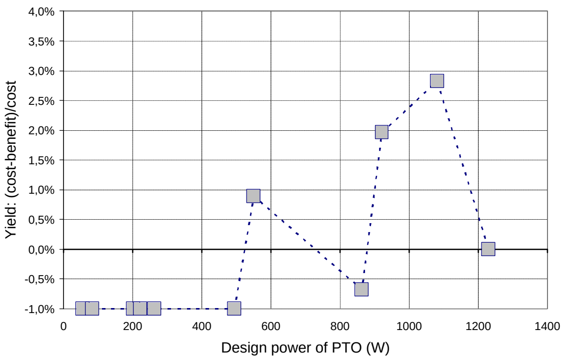

Figure 10: Yield of the project as function of the power used for PTO design.

Obviuosly within the costs one should include the fixed cost for the WEC itself. The cost curve will vary from the formulation given above and become greater of a fixed quantity. The yield optimisation will therefore be shifted and the maximum will become a higher sea-state.

It is clear from Figure 10 that the maximum profit is given by a PTO designed on wave condition 10, but a design of the PTO based on wave condition 7 can be a good alternative (since the PTO would be only approximately 500 KW).

Fig.11 shows the yearly production of wave energy for each sea state. Design of the PTO for sea state 10 will harvest 97% of the wave energy converted by the device, for a total of 1.85 GWh. The under-design of the turbine is associated to a greater economic yield.

In total the produced energy is merely the 10% of the available one (9.3 kW/m).

It is of course evident that up-scaling of small scale tests to prototype dimension may lead to considerable errors in the estimate of the result. Main points of concerns are related to the absence of a real mooring system and of multidimensional waves. Nevertheless it is expected that these aspects will be sorted out at the proper time and that the overall efficiency will be preserved as much as possible.

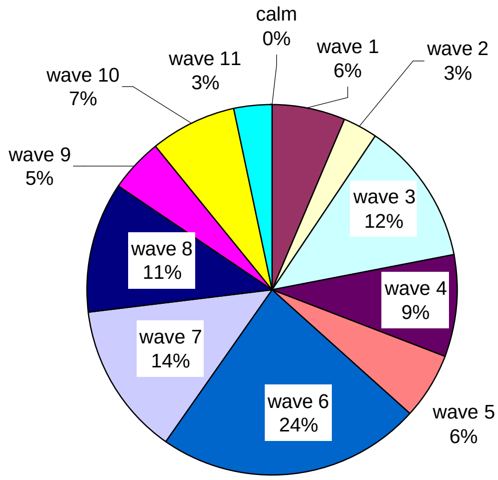

Figure 11: Yearly production of wave energy for each wave state.

6.1 Comparison with other concepts

In order to have a quantitative feeling of the results, the amount of energy per year produced by the tested concept is compared to others concepts. For this purpose, a comparison is made with a wind turbine installed in the wind park in Nurri, which is located only 60 km from Cagliari.

The park is equipped with 26 machines of the VESTAS-V52 type, 55 m height and nominal power of 850 kW. The assessed annual power production (web source) is approximately 1.7 GWh each.

We see that the expected yearly power production of the analyzed OWC concept is not much different from that of a wind turbine.

Note that both the considered OWC device and the turbine are designed to be deployed in parks.

In conclusion, it is expected that a park of OWC may have a similar energetic output of a wind park, with obvious advantages in terms of landscape impact. This result is general and should not be considered to be restricted to the specific tested device (LeanCon). It is seen that in Cagliari, which is not the most energetic Italian one, a possible application aiming at harvesting wave energy has is significant and proportioned to the needs of the site (of the same magnitude of existing plants based on other technologies).

7 Conclusions

The problem of interest here is the quantitative derivation of the possible produced power under any wave condition and at prototype scale, generalising the small scale experimental results obtained in the wave basin at Aalborg University (DK), on a floating OWC device named LeanCon .

It is found that the measured power may be approximated by a two parameter lognormal distribution. The average and standard deviation of the distribution are related to selected parameters, namely the ratio between wave height and draft and the wave steepness. Therefore, the power production can be predicted at any location under any wave climate.

The method can be used also to determine what is the most economical reference power for which a PTO should be designed.

The method is applied to an hypothetical study site, placed off-shore the coast of Cagliari, where the actual available average energy is 9.3 kW/m. A single 240 m long OWC, with a PTO of 1.1 MW, designed to extract 97% of the convertible wave power, harvests 1.9 GWh/year, i.e. approximately 10% of the available energy.

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