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ON DESIGN LOAD, FATIGUE LIFE AND SITE-SPECIFIC ECONOMIC VALUATION OF WAVE ENERGY PROJECTS

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ABSTRACT

Normative formulae are applied to estimate two climate-dependent cost drivers for WECs: design load for steel structures and fatigue life of components. There are significant uncertainties arising in particular from the lack of field-tested method to calculate instant loads on devices that seek to maximize, rather than, as other marine structures, minimize interaction with waves. However, applying very different hypothesis for design and fatigue loads, it was found that although results for a given wave climate can differ by a factor of two or more, relative changes between two climates depend far less on the chosen method to calculate loads. Between a quiescent location of design significant wave height of 7 m, such as the Western Mediterranean or the Canary Islands, and one with a design significant wave height of 20 m, as appropriate for parts of the North Atlantic storm belt, we find that a cylindrical hull's weight of steel must increase by 20 to 50%, depending on its shape and on design load cases assumptions. Fatigue life for bearings of a particular WEC was found to decrease typically by a factor of two between these locations. Concerning the cost of wave energy in rough or mild wave climates, these results suggest that (a) structure weight and fatigue life of components will significantly reduce the advantage of operating a WEC in energetic seas, but that (b) these losses are significantly smaller than gains in harvestable energy found in recent work [1], and (c) these losses are several times smaller than losses due to lower capacity factor [2] and significantly smaller than those due to lower accessibility found for energetic sites [3] .

INTRODUCTION

Most estimates of ocean wave energy situate their potential contribution to electricity generation at some 15% of current demand [4]. Mechanisms to tap this vast flux of relatively well organised mechanical energy before it dissipates on our shores have been proposed since the 18th century, but now as then, the central challenge remains to ensure device survivability and operation at-sea in cost-effective ways.

Generally speaking, it is in the high latitudes of the western sides of continents that the highest energy flux is found. While it is certainly desirable that the technology emerges to harvest these daunting waves, the flux reaching the shores of lower latitudes is significant as well, generally of the same order of magnitude as that of better endowed coasts, and for isolated areas, a welcome opportunity for new energy options.

[5] and more recently [6] argue that as revenue from wave energy projects should correlate well with the average energy flux, while costs will primarily correlate with extreme values, a useful indicator of the cost of energy in specific locations, then, is the ratio of mean to extreme values of wave heights. The map of this "Figure of

Merit" actually exhibits lowest (best) values in the low latitudes of large ocean basins. High energy sites of the southern hemisphere (Australia, Chile) and mid-ocean islands score well, while low energy sites of semi-enclosed seas such as the Mediterranean generally do not have favourable values of this indicator. A very different picture emerges, thus, than from maps of average mean energy flux alone.

Needless to say, it is not sufficient information to determine the location providing the best trade-off between revenue and cost. Taking the example of the North-Eastern Atlantic coasts, which fare rather poorly with this indicator despite their abundant wave resource, a practical question that comes to mind is: will design cost really increase so much that it will offset gains in harvestable energy?

While precise figures will depend on which WEC is being considered, and in particular on its mechanism for storm protection, it seems worthwhile to investigate what first order, generic information can be obtained on this question from the application of methods commonly used in naval and offshore engineering that have been time-tested in some of the roughest seas.

We look at what such methods tell us about two of the main drivers of cost increase that are influenced by the wave climate: increase in the weight of steel needed to face higher extreme waves, and changes in fatigue life of WEC components from operation in rougher weather. These results should be considered together with other climate-dependent cost drivers, such as the availability of weather windows for maintenance operation [3] or the regularity of the resource [2].

EXTREME WAVE HEIGHTS AND WEIGHT OF STEEL

Cost and power absorption performance may differ greatly for various WECs and their tuning to a particular wave climate. However, generic indicators of cost of energy can provide useful comparative information on various approaches to harvesting wave energy [1] [7]. One such indicator is the absorbed power normalised by the weight of steel. Structural complexity should be factored in [8], but overall steel remains an important part of the initial cost of most WECs. Device weight will also greatly influence the difficulty and cost of installation and maintenance.

Depending on the particular WEC and its conditions of operation, significant steel may be used for anchoring and/or the power take-off mechanism, but the hull will generally be the largest mass. The hull's weight for marine structures is usually primarily a function of the structural strength that is required from it, which in turn is usually calculated from the most demanding weather the structure is likely to encounter.

Hulls for different WECs can differ greatly, but for a rather large number of them their shape can be approximated by either a vertical or a horizontal cylinder. Results for the case of a vertical cylinder are presented here. The calculations were repeated for a large range of cylinder dimensions, aspect ratios, submerged and non-submerged heights; varying these parameters didn't significantly change our main conclusions. Once design loads are computed as detailed below, the required plate thickness and dimensions of the reinforcing stiffeners and girders to provide the adequate hull strength are then obtained following [9] and [10] with load and resistance factor with the ultimate limit state as design basis.

We compared results for a variety of configurations for the reinforcing stiffeners, girders, and bulkheads. In general, the more framing, the less steel needed to obtain the required strength, but improvement is slow past the scantling commonly used in naval architecture, while welding costs would keep increasing with structural complexity. Weight sensitivity to the design wave height decreases somewhat with framing complexity, but unless the number of beams becomes unrealistically large, at which point significant costs would be incurred from the structural complexity, sensitivities remain within the range presented below.

Several design load cases were tested. Static wave pressure and drag and inertial forces are calculated with a hydrostatic approximation and the Morison equation, valid for a cylinder much smaller than the design wavelength. These are fairly well established in the offshore and naval fields and perhaps applicable without too much modification to our case.

There is far more uncertainty on the appropriate formulation wave impact loads for a WEC: breaking and broken wave, wave slap, wave slap and wave run-up. Various design cases and methods were considered for these. In the most optimistic design case normative formula for wave impacts on the decks of small ships are used [11]. In this case loads are dominated by wave static pressure. In the most conservative design case, the most unfavourable relative velocities between WEC and water are assumed. Slamming pressures on the side of the cylinder are then estimated with normative formula for offshore engineering [12]:

$$p_{slamm} = \frac{1}{2\pi}\rho C_s u^2$$

where u is the relative velocity horizontal velocity between the breaking wave and the cylinder, and the impact coefficient Cs has a value of 5.15. Slamming pressure on the top side of the cylinder is computed in one case with the formula above, in which we add the free fall acceleration to orbital velocities. Another formulation from standard practice in offshore engineering [13] for breaking and broken wave loads is also considered, which focuses instead on the phase velocity of the extreme wave:

$$p_{slamm} = 1.643\rho\left(\frac{gT}{2\pi}\right)$$

where we take a wave period T of 25 seconds. We note that all this could still underestimate the instant loads that would result from fully non-linear plunging breakers impacting a WEC [14], which may be the appropriate design case for certain deployments. However, the focus here is not on loads estimation, but rather on how they may influence the relative change in hull weight between different wave climates. As expected the hull weight varies quite significantly between optimistic and conservative configurations for the design load, by a factor of three or more depending on the sea-state considered. However, the relative change in hull weight between two different locations remains remarkably similar, although it does increase somewhat with more conservative assumptions for design loads.

Table 1 shows the percentage change in the steel mass needed for different design wave heights and periods, relative to that for a reference design sea-state of significant height (H_s) of 7 meters and peak period (T_p) of 11 seconds. The calculations are for a cylinder with a radius of 3 m, total height of 6 m of which 2 m are non-submerged, primary reinforcement (along cylinder axis) every 1.6 m and secondary every 50 cm. The hull weight obtained for this configuration and this design sea-state is 15 metric tons.

The reference sea-state approximates the 225 year storm for Barcelona [15] in the Western Mediterranean (225 years and longer return values have been requested by insurance companies prior to deployment of marine renewable energy devices). This is one area where the average wave energy flux is low – but would the cost of steel be so much less there that the final cost of energy would be more interesting than in more energetic seas? Table 1 suggest otherwise as detailed below.

Results for this site are compared with those for an estimated 225 year storm with H_s = 6.96 m and T_p = 14.24 s (Canary Islands) [16], H_s = 10.11 m and T_p = 16.57 s at 53 m depth near Bilbao in the Bay of Biscay [17], and H_s = 16.28 m, T_p=16.6 s near Bilbao but at 600 m depth [18] [19]. For more comparison, the 80 year Hs at 50 m depth in Belmullet in Western Ireland is estimated as 16.3 m [20] while further offshore in the North Atlantic

Table 1: increase in hull steel weight from a design significant wave height of 7 m, period 11 s. Sea-states approximating design waves for sites mentioned in text highlighted with light blue borders.

		Peak Period (s)										
		10.	11.	12.	13.	14.	15.	16.	17.	18.	19.	20.
Significant height (m)	20.	73%	64%	55%	55%	45%	45%	36%	36%	36%	36%	27%
	19.	64%	55%	55%	55%	45%	36%	36%	36%	27%	27%	27%
	18.	64%	55%	45%	45%	36%	36%	36%	27%	27%	27%	27%
	17.	55%	45%	45%	45%	36%	36%	27%	27%	27%	18%	27%
	16.	55%	45%	45%	36%	27%	27%	27%	18%	18%	18%	27%
	15.	45%	45%	36%	36%	27%	27%	27%	18%	18%	18%	27%
	14.	45%	36%	27%	27%	27%	18%	18%	18%	18%	18%	27%
	13.	36%	36%	27%	27%	18%	18%	18%	9%	18%	18%	18%
	12.	36%	27%	18%	18%	18%	9%	9%	9%	18%	18%	18%
	11.	27%	27%	18%	18%	9%	9%	9%	9%	18%	18%	18%
	10.	18%	18%	18%	9%	9%	9%	9%	9%	18%	18%	18%
	9.	18%	18%	9%	9%	0%	0%	9%	9%	18%	18%	18%
	8.	18%	9%	9%	0%	0%	0%	9%	9%	9%	18%	18%
	7.	9%	0%	0%	0%	0%	0%	9%	9%	9%	18%	18%
	6.	0%	0%	0%	0%	0%	0%	9%	9%	9%	18%	18%
	5.	0%	-9%	-9%	-9%	0%	0%	0%	9%	9%	18%	18%

100 year return values of Hs well above 20 meters are found [21]. On the other end, 100 year H_s in the equatorial Atlantic are below 5 meters [21].

Table 1 suggests that the amount of steel required for this hull is of the same order for the wave climate of the Mediterranean, the Canary Islands or West-Central Africa and some 30% higher for the Northern Atlantic storm belt. Depending on load cases and cylinder dimensions and scantling, this relative change was found to vary between 20% and 50%.

It should be mentioned that although the formula used here have been time-tested in ship-building and offshore engineering, there is much less field experience concerning their applicability to WECs. Unlike existing marine structures, WECs are specifically designed to maximise, rather than avoid, resonance with waves. This may give rise to yet insufficiently known failure modes [22], and may underlie some of the repeated failures at-sea of earlier WECs. This issue is discussed further in the last section.

How important would be the impact of such changes in hull weight in terms of a wave energy project economics? Estimates found in the literature of WEC structural costs, of which steel would often be a major part, put this figure between 10% and 50% of initial costs [3] [23] [24]. [1] compared absorbed energy per characteristic mass for 8 different WEC technologies (ignoring changes in steel weight for different locations), and finds an increase between 30% and 100% between Lisbon and Belmullet, depending on the WEC, and a factor of three or more up from more sheltered areas. These figures are significantly higher but of the same order as the increase in steel weight found here. Thus, subject to the aforementioned uncertainties, the results above suggest that for most WECs absorbed energy per characteristic mass would still increase from a mild to an energetic wave climate, but that this gain will be significantly reduced by the increased amount of steel needed to withstand the higher extremes. On the other hand, recent work suggests that lower capacity factor for operation in storm belts [2], or less frequent weather windows for maintenance operations [3] could decrease economic returns by a factor of two or more. Hence the influence of hull weight, although significant, may well be less important than both gains in harvestable energy and loss from lower capacity factor and accessibility when operating in more energetic seas.

It should be mentioned here that other parts than the hull will also be dimensioned differently in different weather. The mooring system may become a significant expenditure for WECs that operate in deeper sites [25]. Cost per meter seems to increase more or less linearly with minimum breaking load [26], but mooring loads will depend on many other factors than wave height and period, and it appears even more difficult to draw any general conclusions on their climate-dependent costs than it is for hulls.

WAVE CLIMATE AND FATIGUE LIFE

For fatigue life even more than for structural costs, given the wide variety of proposed WECs and their components it is impossible to get results that could be generalised to all of them. It was chosen to illustrate the application of standard fatigue calculations to a particular WEC.

The OCEANTEC WEC considered here is a floating offshore device which can be classified as a linear absorber or attenuator, with all moving parts protected and kept dry within the hull. Its capture principle is based on the relative inertial movement produced by a gyroscopic system. The conservation of the flywheel angular momentum converts wave-induced pitch in an alternating precession motion in the longitudinal axis, which is then used to drive a generator. The WEC is designed to minimize wind drag so as to ensure alignment with the dominant wave propagation, maximize the excitation force and resonance with the most common wave, and reduce hydrodynamic damping. [27] provides a more detailed description of this device.

It was determined that under current design, the replacement schedule for one bearing will be the upper limit to the servicing interval. This part supports the gyroscopic mechanism of this WEC, hence rotation velocities are higher than those of bearings in many other power take off mechanisms. In addition the bearing is housed inside the hull and bearing life will thus be quite different for outside moving parts exposed to corrosion, bio-fouling, lubricant contamination, etc.

Bearing in mind these limitations to the scope of the conclusions hereafter, it should be mentioned nonetheless that the calculation were repeated for different types of bearing under very different loads, and the *relative* changes in service life between different sea-states and climates were rather similar. Bearing fatigue is a constraint on maintenance that may be expected to be shared by many WECs. These parts will be chosen so that loads are within their rated operating range, within which fatigue life equations describing the propagation of cracks in steel

Table 2: Bearing fatigue life in years for different sea-states.

		Peak period (s)											
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**17**	**20**
Significant height (m)	**0,5**	72,0	67,0	52,4	38,5	35,7	36,0	38,0	39,1	44,8	49,1	54,0	58,2
	1	69,8	60,6	38,1	21,8	18,5	19,0	21,0	23,3	28,0	33,2	39,5	45,9
	1,5	67,4	54,4	28,0	12,5	10,2	11,2	12,1	13,9	18,6	23,4	30,0	37,0
	2	65,3	49,3	21,0	8,2	6,4	7,2	7,9	9,3	12,1	16,9	23,5	29,4
	2,5	63,2	45,2	16,5	5,6	4,3	4,6	5,6	6,3	9,2	12,2	18,0	24,2
	3	61,7	40,6	12,2	4,0	3,0	6,4	7,7	4,9	6,7	9,5	14,6	19,8
	3,5	59,6	37,4	10,0	3,0	4,1	10,3	9,2	6,8	5,0	7,2	11,6	16,9
	4	57,7	33,8	8,3	2,2	3,1	8,3	8,2	9,1	3,9	5,8	9,4	12,9
	4,5	54,9	30,9	6,8	1,6	3,9	7,1	7,3	7,1	6,3	4,6	7,8	11,7
	5	53,6	28,5	5,5	2,6	3,4	5,9	6,4	6,4	7,6	3,7	6,8	10,2
	5,5	52,6	26,0	4,6	2,1	2,9	5,1	5,8	5,1	6,4	3,0	5,5	8,8

under cyclic stress (S-N curves) will have some common features. Hence the conclusions presented herewith on what established procedures may predict concerning the influence of the wave climate on cost of energy through fatigue life may be of use for a variety of WEC components.

Hull accelerations and flywheel response are calculated with a time-domain hydrodynamic model making use of Cummins' equation for pitch only [28] which has been calibrated and tuned by tank tests [27]. RMS axial and radial loads on the bearing for different sea-states are obtained with this model, and from there equivalent load on the bearing computed following manufacturer recommendations.

As it is difficult at this point to estimate instant loads that will result from operation in irregular seas, the bearing is chosen multiplying RMS loads by a security coefficient of 4. Sensitivity to different loads assumptions was also examined. For example, multiplying bearing loads by 10 greatly diminished expected bearing life, which became some ten thousand times shorter, for most sea-states. But the relative change between each site, again, was found to be much less sensitive: it decreases only by a factor of two or so even in this extreme case. Certainly, the proper way to predict fatigue life would make use of complete histograms of load cycles in real-seas including transient loads. Such data will probably become available within a few years with the rapidly increasing number of at-sea trials of WECs.

The manufacturer rates a minimum service life as a function of operating conditions as represented by parameters such as equivalent load, rotation velocity, lubricant temperature, viscosity and contamination. The (H_s, T_p) scatter diagram can thus be converted to a histogram of applied stress. From there, the service life for operation in a particular wave climate is obtained with the Palmgren-Miner rule, a cumulative damage model widely used in offshore engineering (e.g., [29]).

In effect, this approximates that damage in the material accumulates linearly with time of operation in one sea-state, that this can be represented by the fraction of the fatigue life predicted for that sea-state, and that the total damage is the linear sum of the damage contributed from each sea-state. Fatigue failure is expected to occur when this sum (Miner's sum) approaches unity. This approach has been validated in many fields including for marine structures, however, its reliability depends critically on a good representation of load cycles including load extremes [30].

For storm protection, this WEC is equipped with a shutdown mechanism that slows bearing rotation when accelerations become large, and beyond H_s = 6 m, stops it and relieves it of static loads. It is assumed to protect the bearing sufficiently well that fatigue damage contributed from rare events of H_s > 6 m can be neglected. With these assumptions it is found that in general extreme sea-states are not the main contributors of fatigue damage – that is, as long as the component is dimensioned correctly, applied stresses remain within operating range and the more rapid damage occurring during storms do not compensate for their rarity. Hence, unlike design loads, fatigue life is primarily a function of the mean rather than the extreme regime. However, progress in accounting for transient loads that result from operation in irregular seas may yield very different results. Not accounting

Table 3: Fatigue life in different sites

Site	Estimated service life, years
Belmullet M4 Buoy	6.9
Belmullet, 50 m depth	9.7
Bilbao, 600 m depth	11.7
Gran Canaria	10.2
Barcelona	22.6

properly for these transient loads may result in unexpectedly early fatigue failure at sea, as was observed with the first operations of wind turbines a couple decades ago [30].

Table 2 shows service life in years calculated with this method for each of the sea-states (H_s, T_p). Combining this with published data and scatter diagrams ([31], [32], [18], [16], [15]), the Miner's sums can be calculated and hence service lives in various wave climates are obtained. Those results are presented in Table 3.

Clearly, the changes shown in Table 3 between energetic and more benign seas are significant. The question of relevance to decision-making here is: by how much increased fatigue life could compensate for lower harvested energy between a high energy site and more benign operating conditions (or conversely). A good indicator would be the energy harvested during each service life. The proper way to estimate this indicator would be to use the device power matrix, if available and publishable, but first order information can be obtained by simply considering the total energy flux during service life.

The deep-water approximation with a relationship between the energy-mean period and the peak period for a JONSWAP spectrum as indicated in [33] yields the following relationship between (H_s, T_p) pairs and omnidirectional wave power in kW/m:

$$P \approx \frac{\rho g^2}{64\pi} H_{mo}{}^2 T_e \approx \frac{\rho g^2}{64\pi} H_s{}^2 (0.9 T_p) \qquad (1)$$

Significant differences between this approximation and calculations with finite depth have been reported [20], and in general full spectral information is certainly preferable for accurate energy calculation, but for the purpose of a first order comparison this is a useful approximation. The element by element product of this function with the service lives shown in Table 2 is the total energy flux per service life, which is shown in Table 4.

Table 4 shows that, subject to the assumptions discussed above, for this component harvestable energy increases with wave height more rapidly than fatigue life decreases, so that the best trade-off in this case is obtained for the largest wave heights. That is, even assuming that all operating costs in a wave farm would be increasing in direct proportion to the number of servicing requirements due to component replacement (and this is clearly an overestimate as there are fixed and non-climate dependent costs), in our model the operating cost per kWh due to fatigue life alone is still smaller for the more energetic seas.

The extent to which fatigue life changes will decrease gains from increased harvestable energy will depend on the detailed breakdown of costs. A significant part of operating expenditures for a wave farm, such as ship time, will increase more or less in proportion to the average number of servicing operations needed per year, and hence in inverse proportion to the critical component fatigue life. Alternatively a larger bearing can be purchased for operations in rougher seas, and costs would thus be transferred to capital expenditures instead.

At any rate, for this type of WEC component, and with the important caveat that at the moment no adequate knowledge of extreme loads from operating in real is available, standard calculations show that decrease in fatigue life is important between a milder and a more energetic wave climate, by a factor of two or more, and this should be taken into account for more accurately comparing the economic feasibility of wave energy projects in different wave climates.

CONCLUSIONS

Standard methods were applied to estimate how WECs' hulls weight of steel and components fatigue life may vary with wave climate. While results suggest that it is unlikely that they could by themselves cancel gains in harvestable energy between a vigorous wave climate and a more quiescent site, the changes are significant and should be taken into account when examining economic feasibility. Together with other climate-driven costs such as availability [3] and regularity [2], they may render wave energy project in more benign weather more attractive.

Conversely, these results also argue for WECs that are precisely tailor-designed for the site in which they are to operate. As the cost of steel may

Table 4: Cumulative energy flux during bearing service life for different sea-states, MWh.

		Peak period (s)											
		3	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**14**	**17**	**20**
Significant height (m)	**0.5**	204	253	247	218	236	272	323	369	508	649	866	1099
	1	791	916	719	495	490	573	715	880	1269	1754	2537	3466
	1.5	1720	1851	1191	638	606	758	928	1185	1894	2781	4328	6282
	2	2960	2981	1589	741	677	869	1077	1408	2202	3584	6032	8874
	2.5	4473	4271	1946	798	709	869	1179	1490	2598	4027	7242	11438
	3	6292	5525	2072	822	707	1730	2353	1649	2730	4513	8439	13479
	3.5	8270	6929	2323	819	1341	3817	3836	3124	2755	4678	9142	15671
	4	10458	8166	2494	787	1329	3994	4434	5507	2844	4942	9670	15620
	4.5	12610	9462	2609	748	2099	4346	4992	5424	5793	4873	10184	17948
	5	15191	10764	2616	1456	2235	4428	5423	6083	8569	4827	10951	19193
	5.5	18035	11886	2640	1413	2304	4626	5986	5783	8805	4752	10705	20183

severely impair economic, it would not make sense to design WECs hulls with the same strength in mild climates as they would need for operation in the storm belt. It has been reported earlier that other characteristics such as size [7] and resonance periods [34] [35] should be changed significantly to make the best use of the waves of a particular site, and that different devices will perform comparably better in energetic seas while others in calmer ones [32]. It may be that wave energy will necessitate a greater diversity of devices to suit the diversity of site-specific conditions, than, for example, wind energy, where the design of all large turbines eventually converged to the same type, at least for now.

Current WEC design in large part relies on know-how inherited from the engineering of existing marine structures, mainly naval and offshore. While it is worthwhile to report on what these methods predict concerning the cost of energy in different wave climates, some important differences should be recalled. Unlike ships, WECs will likely remain in the same site throughout their operating life, and hence can and should be fitted exactly to the site's specificities. Unlike ships and offshore oil structure, WEC failure will not involve loss of life or enormous environmental risk. And finally income generated per tonne of steel may differ greatly as well and may be orders of magnitude smaller than for offshore oil.

For these reasons, WEC design may have to be fitted more closely to the strictly needed for a specific location than in naval and offshore engineering. A consequence is that existing formula may be tested beyond their currently field-proven applicability. This must be considered together with the fact that unlike all other marine structures, WECs are typically designed specifically to resonate and interact with waves as much as possible per structural weight and dimensions.

Hence it may be expected that new knowledge and know-how on marine engineering specific to WECs will emerge. This may well include updated methods to estimate hull weight and fatigue life, so that the results presented herein may need major updates within a few years. With the unprecedented number of WECs being now deployed at-sea, it is likely that the coming years will see much new developments in this area. No doubt that this new branch of at-sea engineering would develop at much greater pace, and the cost of wave power be reduced correspondingly, if experience is shared in time and mistakes are not repeated needlessly in such areas as dimensioning hulls and analysing and predicting new modes of fatigue failure.

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