Methods for identifying attractive wave energy scenarios

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***Abstract*— The wave energy sector is currently in a prototyping stage. During this conceptual phase method are needed for identifying promising concepts which warrant further investigation. This paper focuses on the development of a model for assessing wave energy scenarios, combination of site, WEC and project specifications, on their commercial attractiveness. Quantitative evaluation is challenging due to the high degree of uncertainty at such an early development stage and the lack of design consensus within the sector. The methods presented here highlight some of the ways this uncertainty can be reduced even with high-level input parameters to the model.**

***Keywords*— Structured innovation, wave energy, techno-economic assessment.**

I. Introduction

The Wave Energy Sector is currently in a conceptual, prototyping stage. Funding bodies are searching for promising innovations through programmes designed to add structure to the development process [1]–[3]. The failure of several developers to reach commercialisation, despite demonstrating high technology readiness levels, has motivated this structured innovation approach to development [4].

Structured innovation refers to a systematic process of identifying, developing and validating novel technology [4]. A key component of this approach is techno-economic assessment. Even at an early stage of development, performance targets, based on the full lifecycle functional requirements of a wave energy converter (WEC), are deemed necessary [5]. This reduces the agility of innovation but enables funding bodies and research institutions to focus resources on concepts with commercial potential whilst avoiding the pitfalls suffered by previous developers.

The wave energy sector has simultaneously suffered from both a fixation on sub-optimal designs and a lack of design consensus leading to a lack of sector focus. During the conceptual phase of technology development, promising concepts which warrant further investigation, need to be identified. Lessons can be learnt from other, more established sectors, such as defence which has very stringent requirements but which produces relatively few units and the automotive sector which has high quality standards and serial production. Within these sectors methods are employed to search a wide design space when looking for the best solution to an engineering problem [6].

The purpose of this work is to develop methods for ranking alternative wave energy designs. So that no potential 'winner' is overlooked, the widest possible parameter space need to be assessed and the limits of WEC design options established. To this end, two scoring metrics are proposed. Firstly, a score for 'commercial attractiveness', used to assess economic viability, and secondly, a score for 'technical achievability' used to assess technical risk and feasibility.

Previous studies, investigating the techno-economics of wave energy, have focused on certain design aspects. Whether that be hydrodynamic performance [7], the optimal geometry or size of a WEC [8][9], the layout of farm-scale arrays [10], electrical and connection set-up [11], operation and maintenance (O&M) cost [12], or the location and resource characteristics which provide the greatest returns [13].

Certain studies include the modelling of manufacturing and operational costs to assess large, farm-scale deployment [14][15], along with site characteristics to inform device availability and accessibility [15], [16].

The majority of these studies have centred their investigation on one particular WEC concept, whether that be attenuators [9][12], point absorbers [8][10][17] or oscillating water columns (OWC) [13], as defined in [18], for example.

This work aims to differ from this previous work in two ways. Firstly, whereas other studies focus on certain aspects of wave energy, this work aims to develop tools which enable the combination of deployment site selection, WEC design, project scale and market to be evaluated. Secondly, these tools will allow for high-level comparisons – when development is at an early stage, with the option of comparing detailed design choices once it becomes necessary. Existing techno-economic tools do not allow for this level of dexterity, [15] and [19] require knowledge of sea states and device performance, for example.

This paper focuses on the development of the model used to assess the commercial attractiveness of site, WEC and project design characteristics which are combined as hypothetical scenarios. The challenges to this approach are highlighted throughout the text.

The paper is divided as follows. Section II provides an overview of the economic model, including a description of the inputs and assumptions. Section III explains how commercial attractiveness is scored. Initial analysis is based upon a point absorber, which is currently the most widely researched type of wave energy converter and preliminary results are shown in section IV to provide an example of the model output. Finally, section V summarises the main conclusions.

II. Economic Model

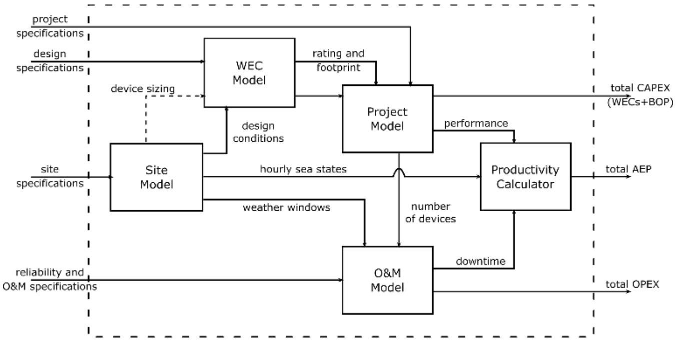

Fig 1: Schematic to describe the calculation of commercial attractiveness from CAPEX, AEP and OPEX for a wave energy project. Adapted from [15].

Fig 1 provides a schematic of the economic model used to assess commercial attractiveness. The design of the model is such that it allows for a high-level comparison of WEC and project architecture without the need for more technical details. When there is a need for a more advanced comparison more technical detail can then be included. TABLE I provides an example of these high-level inputs.

It has been noted from the literature, for instance in [7] and [8], that optimal WEC scale and configuration is dependent on the resource characteristics at the deployment site. Therefore, the inclusion of the site model, provides a measure of WEC versatility.

It is important to consider the full project or farm scale context, even at an early stage of WEC development [5], when evaluating the commercial attractiveness. Project specification are therefore included to determine the number of WECs in the required array. Cost for electrical infrastructure and O&M can then be calculated more accurately to provide a total CAPEX and annual operational expenditure (OPEX) costs. The inclusion of these project scale factors has a large impact on optimal sizing of the individual WEC for example.

The rest of this section is split according the parts of the model as shown in Fig 1, in the following order:

1. The site model, which characterises the resource, including the probability of occurrence matrix and design conditions.
2. The WEC model which calculates the performance of the WEC in different sea states as a power matrix and calculates the CAPEX based on the design conditions supplied by the site model. There is also the option of scaling the device according to the resource characteristics to optimise for cost per energy production.
3. The project model which calculates the number of WECs in the array, their spacing and layout and the electrical infrastructure costs based on the design of the individual WEC.
4. The O&M model which calculates the OPEX costs based on the reliability and vessel specifications as well as the characteristics of the resource provided by the site model.

TABLE I
High Level Site, Device and Project Design Specifications

Site Specifications	**Example**
Location:	Europe: North Sea
Average Available Resource:	25 kW/m
Water Depth:	100 m
Device Specifications	**Example**
Scale:	W: 10m L:10m
Structural Material:	Steel
PTO Type:	Hydraulic
Station Keeping:	3 Mooring Lines
Project Specifications	**Example**
Farm Capacity	10 MW
Farm Area (seafloor)	5 km^2
Distance from Shore	25 km

A. *Site Model*

1) Hourly Sea States: In the model sites are characterised by the power level (PL), defined as the annual average mean power per meter crest length, in kW/m, and geographic zone. To provide an accurate value for AEP a method is needed to relate these specifications to the hourly distribution of sea states, combinations of significant wave height (H_s) and wave period (T_z), across a year.

The location is an input to the model, as the nature of this joint probability distribution is highly dependent on factors such as the distance from the wave source. To give a first approximation broad ocean areas can be generalised, for example, the global wave statistic database (GWS) provides the joint model parameters for 104 oceanic zones. However these provide no variability for PL within each zone.

Different models of H_s and T_z joint distribution exist. In [20], a linear relationship is found for the parameters of the Ochi joint distribution ([21]) and the PL of a site. The bivariate log-normal Ochi model is relatively simple and gave relatively poor results when the method presented in [20] was replicated. In particular there were large errors of up to +/-30% in the PL when fitting the model to reference occurrence matrices taken from [19].

To improve on these results, the same method was used for the Weibull and conditional log-normal distribution, as recommended in the standards relating to offshore structures [22]. The distribution of Hs is described in Eq. 1 where α, β and γ are the scale, shape and location parameters.

$$f_{H_s}(h) = \frac{\alpha}{\beta}\left(\frac{h-\gamma}{\alpha}\right)^{\beta-1} \cdot \exp\left\{-\left(\frac{h-\gamma}{\alpha}\right)^{\beta}\right\} \tag{1}$$

The distribution of Tz conditional on Hs is then modelled according to Eq. 2 where σ and μ are the location and scale parameters which are functions of Hs.

$$f_{T_z|H_s}(t) = \frac{1}{\sigma t\sqrt{2\pi}} \cdot \exp\left\{-\frac{(\ln t - \mu)^2}{2\sigma^2}\right\} \qquad (2)$$

According to [22], for a two-parameter Weibull distribution $(\gamma = 0)$, μ and σ can reasonably be given by:

$$\gamma = 0 \qquad (3)$$
$$\mu = 0.70 + a_1 {H_s}^{a_2} \quad \sigma = 0.07 + b_1 {H_s}^{b_2}$$

The CMA model was fitted to reference occurrence matrices from [19] (15 sites) and also to hindcast numerical-simulation datasets from [23] (62 sites) for five zones in Europe as shown in Fig 2.

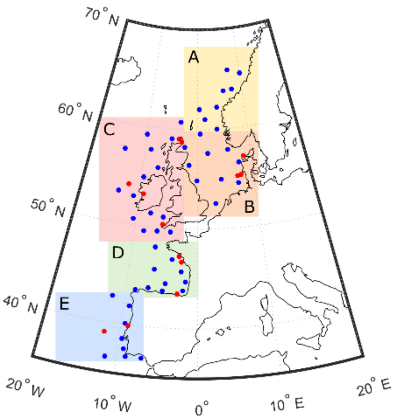

Fig 2: Reference data sites split into five zones, A to E. Blue dots from [23], red dots from [19].

Linear regression was then performed on the fitting results, as shown in Fig 3 and Fig 4. This provided four constants which characterise this linear relationship between the distribution of H_s and power level for each zone. This relationship is given by:

$$\alpha = c_1 + c_2 \cdot RL \qquad (4)$$
$$\beta = c_3 + c_4 \cdot RL$$

Where c1, c2, c3, c4 are zone dependent constants and PL is the annual average resource in kW/m. As the distribution of T_z is conditional on H_s, only the Weibull distribution of H_s needs to be scaled for the PL, and average values can be used for the lognormal distribution of T_z. Values for zone C are given in TABLE II.

TABLE III shows the results for the joint distribution model using these values when fitted for sites in zone C. Both the average fit error (root of the sum of the squares (RSSE)) and PL error show improvements on using the Ochi model, particularly the RL error. An example of the model fit is given in Fig 2, for a site of the coast of Portugal (zone E).

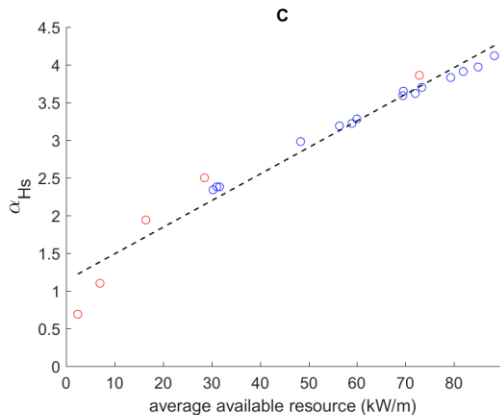

Fig 3: Linear relationship approximation of α and PL. Red circles are calculated from [19] datasets and blue circles are calculated from [23] datasets.

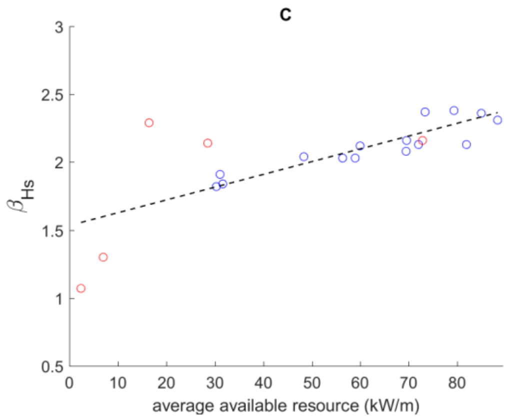

Fig 4: Linear relationship approximation of β and PL. Red circles are calculated from [19] datasets and blue circles are calculated from [23] datasets.

TABLE II
GENERIC JOINT DISTRIBUTION MODEL FOR ZONE C

Weibull Parameters	α		β	
	c1	**c2**	**c3**	**c4**
	1.7344	0.0269	1.7047	0.0067
Lognormal parameters	**a1**	**a2**	**b1**	**b2**
	1.1970	0.1770	0.0585	-0.0056

TABLE III
COMPARISON OF RESULTS FOR TWO JOINT DISTRIBUTION MODELS

Joint Distribution	RSSE*		PL Error	
	Av.	**Std. Dev.**	**Av.**	**Std. Dev.**
Ochi	0.10	0.03	9.98%	5.96%
CMA	0.07	0.01	4.25%	1.69%

*Root sum of the squared errors

The model can be used to provide a first approximation of probability of occurrence of hourly sea states across a year with minimal inputs. This is more accurate than a constant hourly incident power based upon the PL, which produces an uncertainty of +/-50% in the annual energy production (AEP) calculation [24]. By including the variation for geographic location, the accuracy is improved and the influence of the distribution of sea states on commercial attractiveness can be examined.

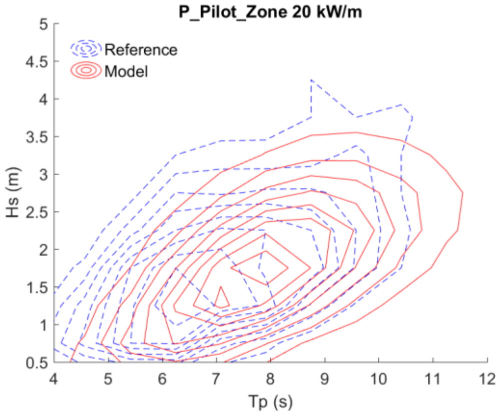

Fig 5: CMA joint probability model fit. Contours represent constant probability of occurrence. Reference data taken from [19].

2) Design Conditions: From the joint probability distribution, the design conditions, extreme events for a given return period can be calculated. These are then used to inform the WEC design. Typically for offshore structures a return period of either 50 or 100 years [22] is used.

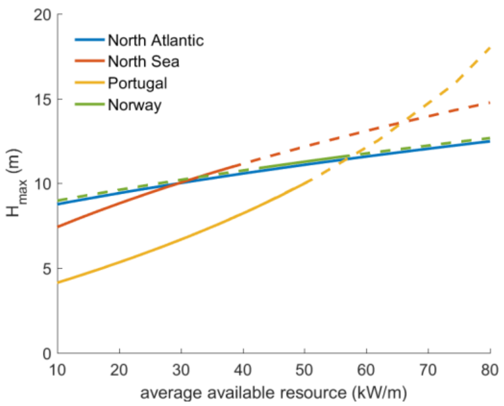

Fig 6: Extreme wave height with PL, for a return period of 100 years.

Fig 6 shows how extreme wave height varies with PL for the five zones included in the model, based on their H_s distribution parameters. For every 20% increase in PL, extreme wave height increases by 3%, 6%, 13% and 3% for the North Atlantic, North Sea, Portugal and Norway respectively. The design conditions are then used to inform WEC CAPEX in the WEC model.

B. WEC Model

The WEC model takes the design specification inputs listed in TABLE I and calculates a power matrix. This requires and approximation of both whole WEC hydrodynamics and sub-system performance across different sea states.

The CAPEX calculation for the WEC is made up of the cost of three subsystems: the structure, PTO and the station keeping. According to [15] these account for 72% of WEC cost including fabrication (28%, 20% and 24% respectively), which is deemed sufficient for approximating cost variation at this stage.

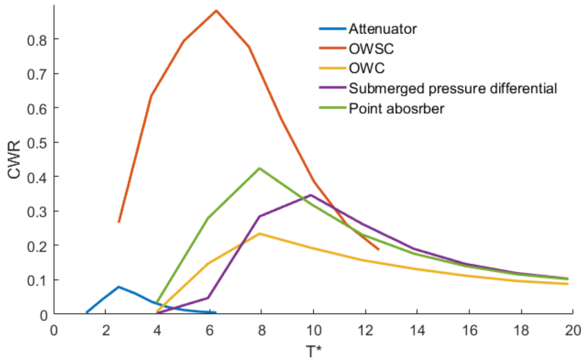

Fig 7: CWR against non-dimensional wave period.

1) Energy Capture: Hydrodynamic efficiency is commonly quantified as the capture width (CW), the length of the wave crest absorbed by the WEC, or the capture width ratio (CWR), the ratio of CW to a characteristic dimension of the WEC. Typical CWR and characteristic dimensions for different types of WEC are presented in [7] and these can be used for approximating the AEP of a WEC, such as in [25].

Using a fixed value of efficiency based on WEC type neglects the relationship between the WEC and the resource. Alternatively, Fig 7 displays variable CWR for five types of WEC, details of which can be found in [26]. For a purely linear system CWR can be plotted against non-dimensional period and taken as of Hs. The non-dimensional period is defined as:

$$T^* = T_p\sqrt{\frac{g}{D}} \tag{5}$$

Where T_p is the wave peak period, g is acceleration due to gravity and D is the characteristic dimension of the device. This is used to characterise hydrodynamic performance regardless of device scale, assuming a constant geometry.

2) Energy Conversion: For PTO performance a representative efficiency value can be used. TABLE IV provides values for four types of PTO taken from [26]. However, using a fixed efficiency value from the literature is problematic, firstly, because each PTO type has different associated components and secondly because PTOs will also have a load dependent efficiency and WECs will mostly be operating at partial load.

TABLE IV
REPRESENTATIVE VALUES FOR DIFFERENT PTO TYPES [26].

PTO Type	Efficiency (%)	Cost (€/kW)	Maintenance cost (% total)
Hydraulic	70	800	5
Air Turbine	60	1000	3
Linear Generator	70	600	8
Mechanical Drive	80	1400	10

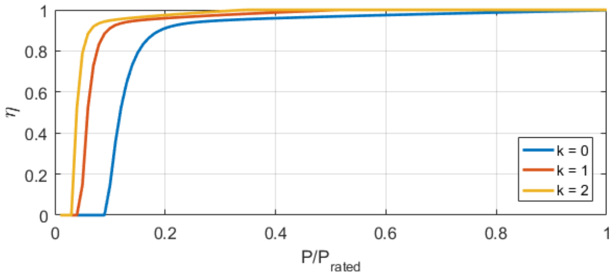

Fig 8: Plot of Eq. 6 for different values of part load capability, k.

Taken from [27], Eq. 6 provides a description of the relationship between the PTO efficiency, size and part load performance. The equation is formulated from analysis of typical wind turbine efficiency curves, with adjustments made to reflect the relative immaturity of wave energy technology (reduction in performance). The study compares different configuration of PTO, and determines a part load capability score of k = 0, 1 or 2. The total efficiency of the PTO is given by:

$$\eta = \eta_{\text{base}} \cdot 0.9\tanh\left\{11.18\sqrt{(1+k)\cdot\frac{P}{P_{\text{rated}}} - 0.05} - 2.5\right\} + 0.1008\sqrt{(1+k)\cdot\frac{P}{P_{\text{rated}}} - 0.05} \quad (6)$$

$$k = 0,1,2$$

Where P/P_{rated} represents the partial load and η_{base} is the efficiency at rated power. This equation is plotted in Fig 8 for each of the three values of k, showing the difference in part load performance. In all three cases efficiency increases rapidly at low loads and is then sustained as the load increases.

3) Operating limits: To complete the power matrix the limits of operation are also required. Two operating strategies can be used which relate the WEC survival mode (point at which operation stops to protect from extreme loads) to the rated power. The difference in the two strategies is described in Fig 9.

a. At rated power the WEC enters a survival mode. The WEC does not operate above rated incident power (Fig 9 red dotted line).
b. The WEC has load shedding capabilities and for above rated power the power capture is held constant. The WEC enters a survival mode at some threshold beyond rated power. In the model this may be determined by a maximum operating wave height or as a % of rated power (Fig 9, blue line).

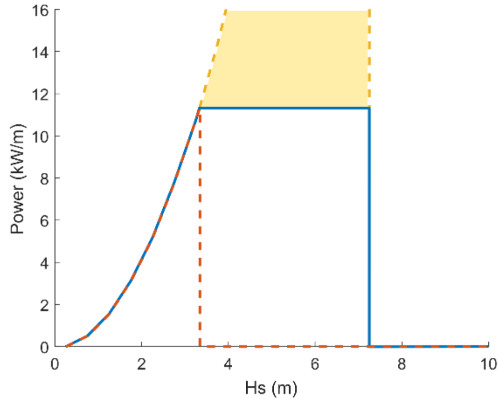

Fig 9: Indicative power curves for two operating strategy options. Red dotted line = option 1 and blue line = option 2.

Option b implies that there is an implementation of a more sophisticated active control system. Therefore, the choice between the two strategies is a trade-off between cost (both CAPEX and OPEX) and energy capture. In Fig 9, the yellow shaded area indicates the incident power mitigated by the control system. A minimum operating threshold (P_{min}) is taken from Eq. 6 when η = 0.

4) WEC scale: The scale of the device can either be specified as an input, or it can be optimised. The choice of optimisation is important, optimising for CAPEX, OPEX or AEP leads to a different outcome. The ideal size will depend on the weighting of each of the three components when evaluating commercial attractiveness. Optimising scale relies on the assumption that a developer would always size their WEC to match the resource, but it allows a fairer comparison of the other design choices.

5) WEC Power Rating: The power rating of the WEC is based upon the rating of the PTO. Two different options can be used to determine the PTO rating. Firstly, the PTO can be sized to maximise capacity factor defined as:

$$C_f = \frac{J_{\text{mean}}}{J_{\text{max}}} \quad (10)$$

Where J_{mean} is, the annual average power absorbed by the WEC and J_{max} is the maximum absorbed power. A PTO rating chosen for maximum capacity factor is generally optimal in terms of the subsystem cost per energy produced. However, on a device or project level the optimal rating will also be dependent on OPEX and balance of plant (BOP) costs. For this reason, the model allows for the WEC rating to be set as a resource probability threshold (P_{rated}) (e.g. at 80% of available energy) with constraints for PTO size relating to the WEC dimensions and PTO type.

TABLE V
COMPARISON OF PRIMARY MATERIALS FOR THE PELAMIS WEC HULL [28].

	Steel tube	GRP sandwich	Post-tensioned concrete	Wood-epoxy
Segment cost (based on min. WT and volume manufacture):	£34.3k	£32.5k	£30k	-
Coating cost:	£13.7k	Included	Included	-
Fatigue capability:	Worst	Best	Middle	-
Bending rigidity:	Excellent	Good	Excellent	-
Buckling rigidity:	Poor	Poor	Excellent	-
Ballast requirement (ratio of dry weight):	1.8-3.0	11-16	0.2-0.7	-
Minimum wall thickness (as function of key failure criteria)	20mm	12mm	62mm	49mm

6) Structural Cost: The most important factors in determining cost of the main WEC hull are the scale and the choice of primary material. For some materials manufacturing cost may also be dependent on the complexity of the hull shape. Sharp decreases in manufacturing costs are typical for up scales in production, so hull complexity is not seen as a crucial factor in assessing commercial attractiveness. However, some materials, such as concrete, will be more constrained when it comes to WEC geometry due to their physical properties.

To a lesser extent, the structural cost may be affected by the PL as the structure will be built to withstand environmental loads. In [29] the effect of extreme wave height on primary steel weight is modelled for the PelaStar floating wind turbine foundation. First order wave loads are calculated for wave heights from 7m to 16m and the analysis shows that on average a 20% increase in extreme wave height leads to an increase in primary steel weight of 4.2% and an increase in total cost of 3.35%.

In the model a minimum hull-wall thickness and the total required mass of steel is calculated based on the buckling strength of the hull and the design conditions. For a more robust assessment, a fatigue analysis is also required. In [28], for instance, fatigue is identified as the most important factor in determining the wall thickness of a steel hull.

Assessing the required quantity of primary material for different material types is complex as different materials have different limiting properties. In [28] four materials are assessed for the cylindrical hulls of the Pelamis wave power device: rolled steel, glass reinforced plastic, wood-epoxy laminate, and concrete. Some of the results of this study are shown in Table V, including the minimum required wall thickness of each material dependent on the load type most critical to their failure. The different characteristics of each material indicate the challenge in comparing materials like for like.

7) PTO Cost: PTO costs are taken from the literature, such as those presented in TABLE IV, which assume that costs are proportional to the power rating. These values are based on experience. A better assessment of how costs scale with the requirements of the PTO system would require a detailed analysis of the PTO configuration.

8) Mooring Cost: The calculation of mooring cost is based upon the choice of mooring line layout, the water depth and the environmental design load acting on the WEC. The design load is calculated based on the PL of the site and scale of the device from the drift, current and wind forces. Inputs to the model are the safety factor and the number of mooring lines. As a first approximation it is then assumed that all the mooring lines are designed to the strength requirements of the most loaded line.

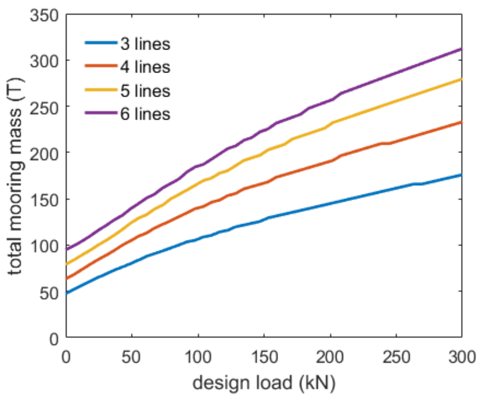

Fig. 10: Parameterised model of the mooring system as described in [30].

The total required mass of the mooring system is calculated from a parameterised model of elastic catenary moorings following the methodology outlined in [30]. In the model moorings lines are characterised by their weight and the model is scalable with water depth. The model assumes a circular cross section so that changes in the weight per unit length implies a proportional change in line stiffness or cross sectional area. Firstly, combinations of line weight and length are calculated which meet the depth and load requirements, then the combination providing the lowest total mass is selected. Fig. 10 gives results for a 100m depth site for layouts of 3 to 6 mooring lines. A restriction on horizontal offset (as a percentage of water depth) can also be applied, which constrains the length of the mooring lines. With the total mass of the mooring lines a fixed price per kg is then applied to find the total cost.

Fig 11 gives a plan view of the mooring arrangement from above, as calculated for a 75m deep site with a PL of 30 kW/m and three, 150 kg/m mooring lines. The minimum horizontal scope represents the suspended line radius when the WEC is in its original position and the maximum horizontal scope represents the suspended line radius when the design load (aligned with one of the mooring lines) is applied to the WEC.

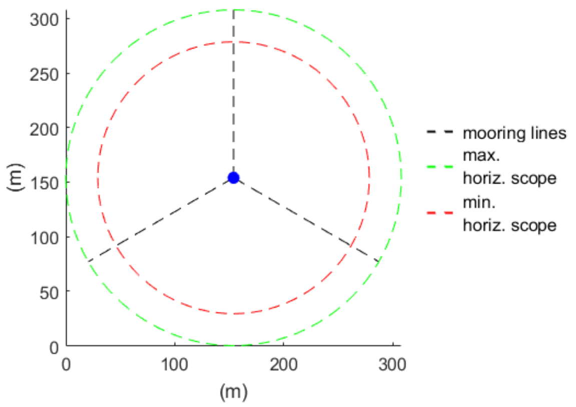

Fig 11: Calculation of the mooring footprint.

C. *Project Model*

1) Number of Devices: The number of devices that make up the project scale wave farm can be determined from two options.

- Maximum seafloor area: The WEC model outputs the length of the mooring lines, from which the horizontal scope of each line can be determined, providing a footprint (Fig 11). The permissible number of devices is then calculated by basing the device spacing on this footprint.
- Maximum farm capacity: The number of devices is calculated from the PTO rating calculated in the WEC model.

2) Device spacing: Several factors could influence device spacing including mooring area, inter-device cabling, space required for operations or the effect of hydrodynamic interaction on energy yields. In the project model the device spacing is calculated based upon the minimum suspended length of the mooring lines which provides a seafloor footprint, as shown in Fig 11. It is assumed that this distance is also sufficient to avoid hydrodynamic interference with minimal impact on energy yield [31], and sufficient for maintenance operations.

3) Electrical Infrastructure Cost: The total cabling cost is taken as the sum of the intra-array cabling and the export cabling. Offshore substation costs may only be considered if HVAC export cabling is required for very large wave farms. In each case the cost per meter of cable is calculated from the voltage rating and cross sectional area (CSA). In [11] a normalised model for installed costs is provided based on these parameters with the assumption that installation accounts for 75% of the electrical system cost.

The model selects cost-optimal voltage and CSA based upon the device rating and industry standard cable sizes. The maximum power capability of the cable is based upon the values for ampacity and CSA provided in [32] and minimum and maximum values for CSA are taken from [33].

A voltage rating of 10kV is generally sufficient for the intra-array cabling. The length of cable required between each WEC is then calculated as the WEC spacing plus twice the depth, as would be the case for a radially laid out wind farm [33]. For the export cabling, higher voltage levels may be required and this is determined from the total capacity of the farm. The length of export cable is taken as the distance to shore.

A more in depth analysis should consider alternative transmission technology such as HVDC, although this has been shown to only be cost effective for distances beyond 50km.

D. *O&M Model*

1) Downtime: The total downtime of each WEC is based on preventative maintenance, and calculated from the number of required maintenance operations and the length of time required for each operation including delays due to the weather. The downtime is then used to reduce the AEP to account for availability. Planned, preventative type maintenance could also be considered but this would likely only take place during periods of calm seas when WEC energy capture is low and therefore have little effect on productivity.

The site model provides an average wait period, the time until a sufficient weather window, based upon the occurrence matrix calculated from the PL. A weather window is sufficient if H_s is below the maximum, and for a duration long enough, for the operation. Average wait period is found using the relationship shown in Eq. 9, where t_{wait} is the wait period in days and A^* is the accessibility of the site.

$$t_{\text{wait}} = c_1 \cdot \exp(c_2 \cdot A^*) \tag{9}$$

The constants c1 and c2 were determined by fitting Eq. 9 to the results from [16] which provides average wait periods for 7 sites with varying PL (Denmark, Ireland, Chile, Spain, Portugal, Scotland and Australia). Fig 12, shows the fit of Eq. 9 for the $H_s < 1.5$m results, with the values of c1 and c2 given in Table VI. Each of the dotted lines is calculated from the c1 and c2 values for a 6 hour, 12 hour and 24 hour weather window duration. Although there is a good fit for 6 locations, the wait period values for Chile (accessibility 9%) are clearly in disagreement with the otherwise linear trend, owing to the much lower seasonality of Chile's wave energy resource.

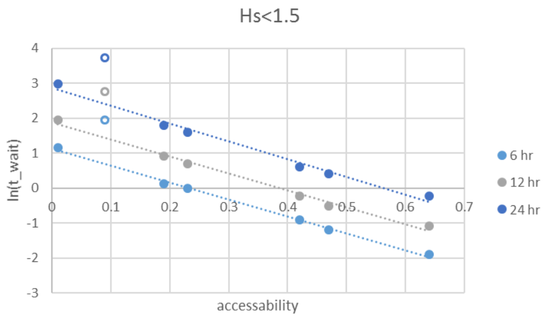

Fig 12: Log of the wait period against accessibility for 3 weather window durations.

TABLE VI
FIT RESULTS FOR EQ. 9 AND HS < 1.5

work time (hrs)	c1	c2	R^2
6	3.08	-4.84	1.00
12	6.52	-4.85	0.99
24	17.53	-5.10	0.99

2) O&M Costs: O&M costs are calculated based on values taken from the literature for vessel hire. In [16] the vessel costs are specified as:

- 7000 € mobilization fee,
- 625 €/hr cost of keeping vessel waiting,
- 1250 €/hr cost whilst operation is underway.

Operations cost are highly variable from one source to another, partly owing to the sensitivity of vessel costs to other industries so, although it might be possible to use a more complicated breakdown of costs (including labour and insurance costs for example), it makes sense to keep these parameters relatively simple. A relative cost for spare parts is approximated from the choice of PTO type, reflecting their initial cost, as outlined in Table IV.

III. COMMERCIAL ATTRACTIVENESS

To score commercial attractiveness on a project scale a calculation is needed which combines the CAPEX, OPEX and AEP values. Typically, a levelised cost of energy (LCOE) is used, a metric widely used for comparisons in the energy generation sector. This is defined in Eq. 7, where PV indicated the present value.

$$\mathrm{LCOE} = \frac{\mathrm{PV(CAPEX)} + \mathrm{PV(OPEX)}}{\mathrm{PV(AEP)}} \tag{7}$$

The LCOE is sensitive to both the lifetime of the project and the chosen discount rate and so these are both fixed at 25 years and 12% respectively. The aim of the work is to identify promising concepts and, given that wave energy is at such a nascent stage, it is the ranking of business cases which is important rather than the absolute LCOE value. However, key to this approach is to check that the weighting of each LCOE component on the final score is valid.

Further work will also look at the technical achievability of scenarios based on risk. For example improvements in conversion efficiency or cost might be possible for some types of PTO depending on the maturity of the technology. The inclusion of a metric to represent risk will allow for a fuller assessment of economic viability.

IV. RESULTS

To provide an example of the output of the model, initial analysis was based upon a point absorber, which is currently the most widely researched type of wave energy converter owing to its relative simplicity.

Results are shown for three scenarios, detailed in TABLE VII to TABLE IX. In each scenario one design specification was left variable with four options, giving a total of 12 combinations. All the results are normalised for the maximum of the 12 different combinations to provide a relative ranking. All three scenarios are for an array scale project made up of 10 WECs. In each case the size of the point absorber was scaled for optimum LCOE to allow a fairer comparison. The average diameter of the point absorber for the 12 combination was 14.25m with a standard deviation of 0.44m. On average the OPEX as a percentage of CAPEX was 10% with a standard deviation of 2%.

TABLE VII
SCENARIO 1

Design Specifications	
Zone: E	**Structural Material:** Steel
Site PL: Variable	**PTO Type:** Hydraulic
Scale: Optimised for LCOE	**Station Keeping:** 4 lines
PTO Rating: 80% available energy	**Failure rate:** 5 per year

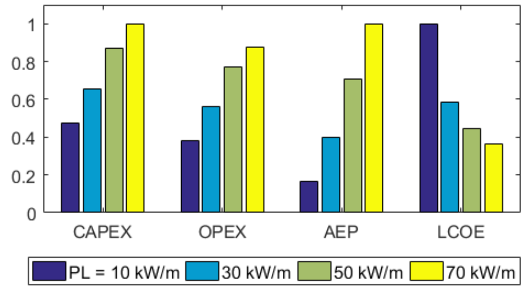

Fig 13: Results for scenario 1.

Fig 13 show the results of scenario 1 where the PL was variable. It is clear from the graphs that the LCOE is very sensitive to PL, decreasing as PL increases suggesting that sites with higher available energy are more attractive. The 'pay-off' however, decreases with increasing PL as the improvements in AEP are counteracted by bigger increases in cost, although this trend will vary according to location.

Fig 14 shows the results for scenario 2, where the WEC failure rate, in events per year, was variable. The OPEX in particular is sensitive to changing failure rate, and this impacts on the optimal scale of the WEC. Resultantly there is in an increase in CAPEX and the impact of the lower availability on AEP is reduced.

TABLE VIII
SCENARIO 2

Design Specifications	
Zone: B	**Structural Material:** Steel
Site PL: 50 kW/m	**PTO Type:** Hydraulic
Scale: Optimised for LCOE	**Station Keeping:** 4 lines
PTO Rating: 80% available energy	**Failure rate:** Variable

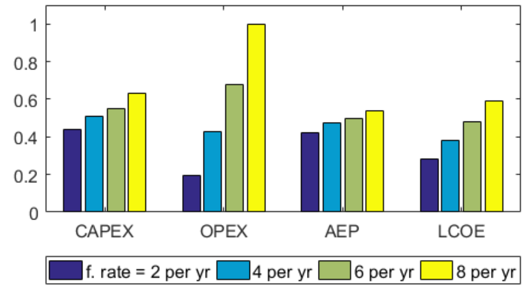

Fig 14: Results for scenario 2.

TABLE IX
SCENARIO 3

Design Specifications	
Zone: C	**Structural Material:** Steel
Site PL: 50 kW/m	**PTO Type:** Variable
Scale: Optimised for LCOE	**Station Keeping:** 4 lines
PTO Rating: 80% available energy	**Failure rate:** 5 per year

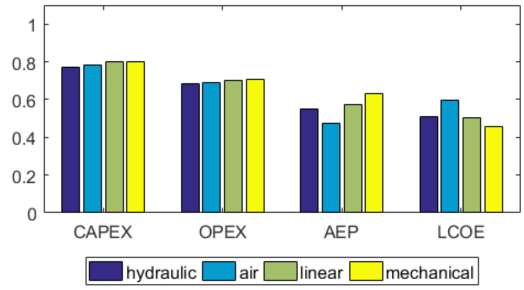

Fig 15: Results for scenario 3.

Fig 15 shows the results for scenario 3 in which the PTO choice is varied. The LCOE is less sensitive to the parameter changes associated with the PTO (within the ranges presented in TABLE **IV**) than with the PL and failure rate. The mechanical drive PTO gives the best LCOE for this scenario, despite a much higher cost, suggesting that the pricing of the subsystems, which has a high degree of uncertainty, has minimal impact on the final results.

As discussed in section III the inclusion of a technical achievability metric to account for risk will allow for a greater parameter range to be evaluated.

V. CONCLUSIONS

The work presented here provides an overview of the development a model for assessing the commercial attractiveness of wave energy scenarios, combination of site, WEC and project specifications. The challenges of the approach have been highlighted, in particular allowing for the lack of design consensus and high degree of uncertainty in the wave energy sector. The work identifies some of the ways uncertainty can be reduced even with high-level input parameters to the model. Further work will be to increase the flexibility of the model to although for a greater range of design options to be explored.

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