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Preliminary load assessment: UMBRA's 250kW EMG power take-off

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Abstract— **This paper summarises the key outcomes of WP2 of the IMAGINE project, which aimed to provide technical specifications that can assist in the definition of the load environment for a novel 250kW Electro-Mechanical Generator (EMG) Power Take-Off (PTO). A series of complex, yet realistic, design situations were considered, namely those involving operational and parked scenarios, framed in a shortlist of design load cases (DLCs). A range of wave energy converter (WEC) types and target sites were covered, aiming to maximise the range of applicability of the PTO.**

Fully coupled WEC-Sim models were created to obtain estimates of key metrics that allow the definition of the loading environment affecting the PTO. The coupling of the environmental conditions with the type of WEC (and its operational state) strongly conditions the WEC loading, and thus EMG PTO loading. ULS and FLS metrics were derived, to characterise extreme and fatigue loads affecting the PTO.

The analysis allows a range of key findings to be derived. These include generic findings with implications to WEC and / or WEC subsystem design, and that are applicable in a wider context to the wave energy field. In particular, the methodology followed to quantify e.g. ULS loads provides insight into the applicability and robustness of different numerical approaches. In future work, it is also foreseeable that the developed WEC models will be integrated in a hardware-in-the-loop (HWIL) environment to allow representative load inputs to be recreated in controlled, onshore based, real-time tests involving a physical EMG PTO.

Keywords—**concept design, fully coupled assessment, load analysis, numerical modelling, Power Take-Off (PTO), Wave Energy Converter (WEC).**

I. Introduction

THE IMAGINE project, led by UMBRAGROUP spa, aims to contribute to the development of a new Electro-Mechanical Generator (EMG) for wave energy applications, following the efforts described in e.g. [1]. The EMG basically consists of a ballscrew-based device capable of converting reciprocating, linear motion into three-phase electricity which has the overall ambition of significantly reducing the CAPEX of current power take-off (PTO) technologies, increasing the PTO efficiency and extending the PTO design life.

The project brings together UMBRAGROUP spa, a leading original equipment manufacturer (OEM), an independent marine renewables engineering consultancy (Cruz Atcheson Consulting Engineers, now part of K2 Management), control systems experts (Norges Teknisk-Naturvitenskapelige Universitet, NTNU), a classification society (Bureau Veritas), test bench manufacturer experts (VGA), and leading socio-economic impact researchers (University of Edinburgh), to complete a range of desktop, numerical and experimental activities related to the design, development, fabrication and testing of a 250kW EMG prototype.

The EMG testing will make use of a novel HWIL test bench, to emulate the interaction of the EMG with different wave energy converter (WEC) concepts in representative environments. To frame the testing, a series of preliminary activities have to be conducted, to ensure that the physical characterisation can cover the widest range of possible options. Firstly, a range of WEC concepts was reviewed and a WEC numerical model database was created [2]. The review aimed to identify the concept(s) that may be best suited for the EMG PTO, recognising that it may be unfeasible to suit all sizes and types of WECs. Secondly, the typical environmental conditions that representative WECs are exposed to, namely the wave climate, were characterised for European locations [3]. The coupling of the environmental conditions with the type of WEC (and its operational state) dominates the WEC loading, and thus the EMG PTO loading. Recognising this coupling and the desire to fit a range of sites and WECs, the concept of a WEC class introduced in [4] and [5] becomes relevant. This concept aims to recognise that sites with different environmental characteristics may have different design requirements. In such context, the WEC class scheme may

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assist technology developers to focus their efforts on issues that are critical to their specific designs. The acceptance of such methodology can also contribute to the conceptualisation of a design that is applicable to a range of sites. The concept of a WEC class was therefore revisited in this assessment as a means to explore the potential to design a critical WEC component on a non site-specific basis.

This paper describes the above-mentioned initial tasks conducted under the IMAGINE project to define a representative range of WECs and deployment sites. Additionally, the paper also presents the key results from a preliminary load calculations exercise that enables the definition of the load environment affecting the WECs, contributing to the technical specification of the EMG. A series of complex, yet realistic, design situations were considered, namely those involving operational and parked situations, in the form of representative design load cases (DLCs). Fully coupled WEC-Sim models were used to estimate the response of the different WEC types at the target deployment sites, alongside key metrics that allow the definition of the loading environment affecting the PTO.

Finally, the paper explores the potential to adopt a standardised approach to the design of key WEC sub-systems, namely the PTO, using a design-class approach with key target metrics, assisting in the transition from concept to detail design. Future work may explore the applicability of the same design principles to other critical components / interfaces in a typical WEC.

II. METHODOLOGY

A. Overview

In order to outline the EMG technical specifications, the loading environment that the PTO will be subject to during the design life of a WEC needs to be characterised.

A generalised workflow diagram illustrating the WEC design process is presented in Fig. 1. The workflow is based on a design framework for a 20-year EMG life, where suitable characteristic loads are of interest. Fig. 1 also illustrates some of the key steps when determining the characteristic loads for a WEC which are followed in the IMAGINE project

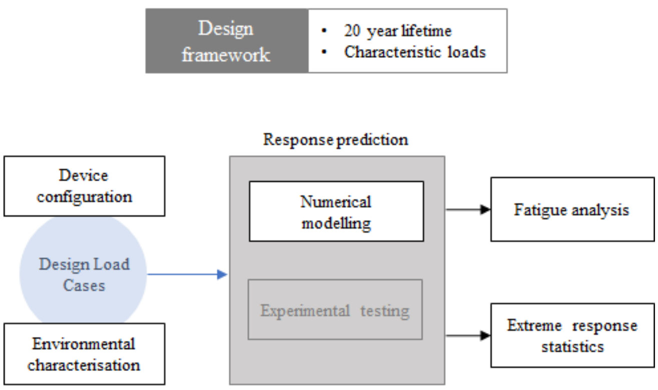
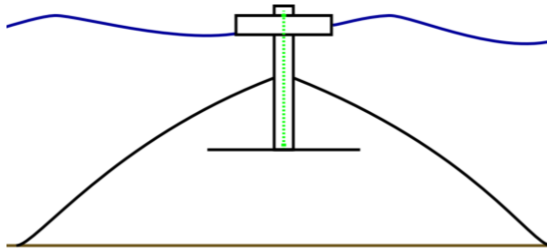
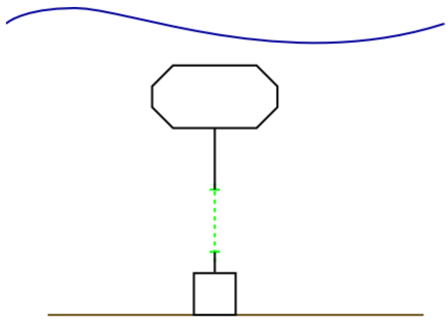


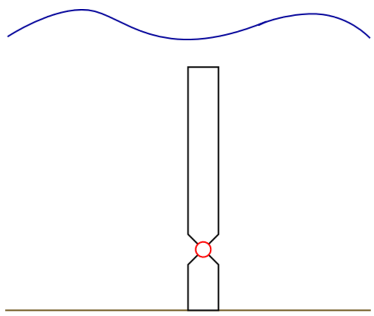
Fig. 1. General WEC design workflow; adapted from [6].



PA 2: Point absorber (PA) WEC type, self referenced, two-body



PA 3: Pressure differential / PA WEC type, bottom referenced, single body



OWSC 2: Oscillating wave surge converter (OWSC) WEC type, bottom mounted, submerged

Fig. 2. Illustrations of the WEC types in the IMAGINE WEC models database (not to scale) [2].

An overview of the IMAGINE EMG design brief is provided in sections II.B to II.E, covering:

- The WEC types included in the IMAGINE WEC model database [2].
- The environmental characterisation of the target deployment locations selected in [3].
- The priority DLCs selected for the preliminary load assessment.
- The data post-processing methodologies, including extreme response statistics and fatigue load analysis approaches.

B. WEC Database

Publicly available information for WEC devices was used to create an IMAGINE WEC model database [2]. The WEC model database provides a representative range of WEC types that are potentially suitable for integration with the 250kW EMG PTO developed within IMAGINE.

TABLE I
LOCATION AND KEY CHARACTERISTICS OF THE IMAGINE TARGET DEPLOYMENT SITES [3]

#	SITE LOCATION	COORDINATES	MEAN WAVE POWER FLUX, P (kW/m)	EST. DEPTH (m)
1	FRANCE	45N, 2.5W	43.8	100+
2	SW ENGLAND	49.8N, 5W	31.3	50
3	NORWAY	62.5N, 5.5E	34.1	50

In [2], a shortlist of generic WEC types were selected for inclusion in the IMAGINE WEC models database. The shortlisted WEC types include a bottom-referenced point absorber, a submerged pressure differential device, and a bottom mounted oscillating wave surge converter (OWSC). Using a Froude scaling approach compatible with the target power rating, numerical models for each of these WECs were developed in WEC-Sim. The reference WEC models used in the preliminary design are illustrated schematically in Fig. 2.

C. *Site Assessment*

Prior to initiating the load calculation exercise, suitable deployment sites were selected, and representative environmental characteristics were defined. The dominant environmental conditions at a site from a WEC design perspective, i.e. the wave conditions, were addressed. To define the long-term representative conditions of the target deployment sites, hindcasts based on outputs from the WAVEWATCH III model [7] were used, driven by winds from the US National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR). The data covers the period between January 1979 and December 2009, i.e. 30 years, allowing long-term statistics to be estimated, including:

- Probability of occurrence of each H_s, T_p pair (long-term averages).
- Directional spectra.
- Environmental contours (long-term return periods).
- Probability of exceedance (for relevant spectral parameters).

Table I summarises the key characteristics of the IMAGINE target deployment sites. Based on the rationale detailed in [3], three Class II, target deployment sites were selected for analysis in the IMAGINE project, see Fig. 3. A summary of the wave conditions at each site is also presented in Appendix A. The chosen target deployment sites are intended to represent a range of different environmental conditions across Class II, aiming to provide a WEC response envelope representative of the inter-class variability – see also [4] and [5].

D. *Load Case Definitions*

Design load cases (DLCs) combine the environmental conditions at a site and relevant design situations for a WEC. A table of DLCs as a function of environmental

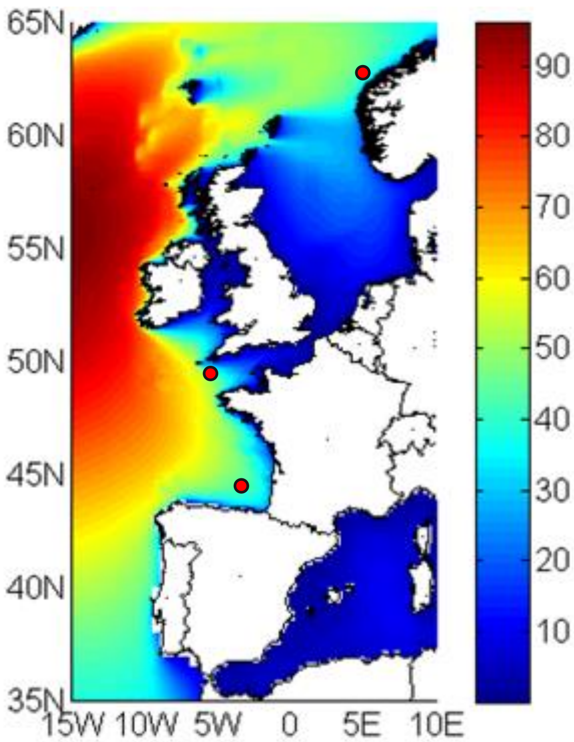


Fig. 3. Annual mean wave power flux (kW/m). Approximate location of target deployment sites illustrated by red circles [3].

conditions and relevant design situations is proposed in [8]. Further guidance can be found in e.g. [9].

The design of the EMG PTO is a multi-stage process. The initial phase represents a preliminary step that aims to provide the overall technical specifications. This preliminary design step therefore aims to define load '*goal posts*' derived from a priority list of DLCs, using available information and baseline assumptions. Following an internal workshop, the DLC prioritisation was based on a set of key assumptions regarding the environmental conditions and the most relevant design situations, namely:

- It was assumed that the wave conditions are the dominant environmental conditions at the deployment sites from a PTO design perspective.
- In general, there is a relatively narrow spread with waves approaching the three target deployment sites. Therefore and as an initial assumption, the load analysis was conducted for a single head-on wave direction. The influence of spread seas in the response of the WECs may be considered in future work (namely for the OWSC 2 WEC).
- Power production load cases are seen as particularly relevant for the demonstration of many of the IMAGINE project aims, e.g. representing load conditions that occur most frequently to allow demonstration of efficiency and fatigue investigations on the EMG PTO, which will provide information relating to the design life of the EMG.
- A subset of parked design situations allows a first investigation of potential high-loading events associated with each WEC. As the PTO is locked in

TABLE II
PRIORITY LOAD CASES

DESIGN SITUATION	DLC	WAVE CONDITIONS	PTO CONDITIONS	F / U
POWER PRODUCTION	1.1	*NSS*	POWER PRODUCTION	F / U
PARKED (STANDSTILL OR IDLING)	6.1	*ESS H_{S1}*	PARKED	U
	6.2	*ESS H_{S50}*		U
	6.4	*NSS*		F

a parked design situation, the loads are not influenced by specific PTO and / or controller settings.

- Faults, start-up, shut-down and emergency shut-down design situations are likely to be very dependent on the control strategy. These design situations may be considered during the iterative design phase of the IMAGINE project, if deemed relevant (see also V).

Following the above detailed rationale, the list of the priority DLCs is summarised in Table II, where *NSS* and *ESS* refer to normal and extreme sea states, respectively. Although WEC performance and other high-level metrics can be derived from the resulting simulations, the focus on PTO design warrants the assessment of long-term, statistical design metrics that affect the PTO. References to the type of analysis – U: Ultimate loads; F: fatigue loads – are also made in Table II (see also II. E).

E. Load Post-Processing

1) Extreme Load Analysis (ULS)

An extreme load analysis of the relevant WEC load data was conducted to characterise the extreme response of a given WEC. Two types of sampling methods were considered: a contour approach, where a reduced number of samples were taken from each environmental contour; and a full environmental characterisation, where a larger number of samples (circa 200) were taken within the 100-year contour. At the expense of computational effort, the latter approach has the advantage of making no assumptions regarding the specific environmental conditions leading to the highest loads.

Both approaches used the WEC Design Response Toolbox (WDRT) developed by Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) [10], following the environmental characterisation process described below. Firstly, environmental contours were used to define extreme sea state conditions. In such representation, each contour represents the extreme environmental conditions for a given return period. The environmental contour for a 1-, 50-, and 100-year return periods were determined based on the Inverse First-Order Reliability Method (I-FORM) approach, following [11] and using the Extreme Sea State Contour module of the WDRT toolbox. For example, Fig. 4

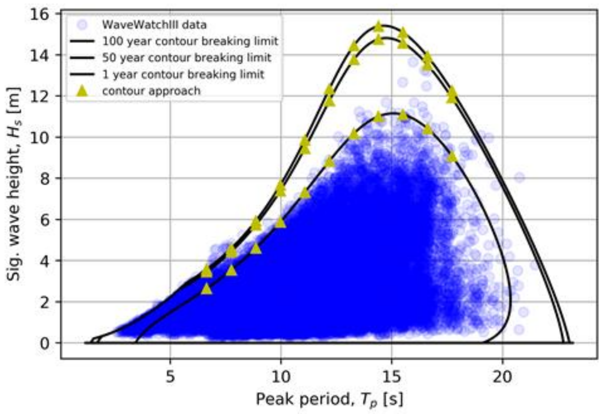


Fig. 4. Environmental contours for Site #1: France (45N, 2.5W).

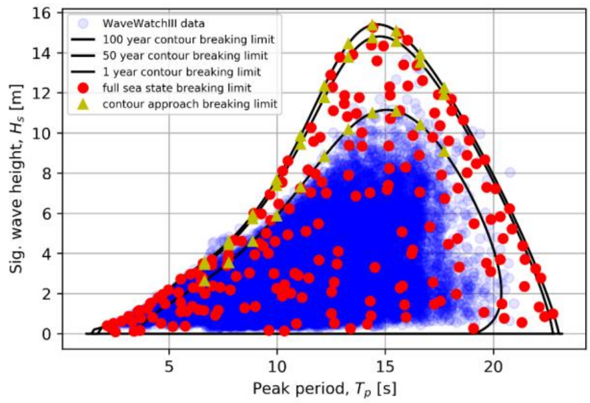


Fig. 5. Full environmental characterisation for Site #1: France (45N, 2.5W).

illustrates the environmental contours for return periods of 1-year, 50-years and 100-years at deployment site #1 in France (45N, 2.5W). Secondly, a full environmental characterisation was also completed for DLC 1.1. This approach is more rigorous than the contour approach, but it requires more substantial computational effort. Approximately 200 sea states were selected from within the 100-year contour at each site. Fig. 5 illustrates the sea states selected for the full environmental characterisation at deployment site #1 in France (45N, 2.5W).

The key steps in the extreme load analysis methodology can be summarised as follows:

- Run load model simulations (3-hour) for all relevant sea states defined for each deployment site and DLC.
- Analyse the resulting time-series (initial pre-screening), focusing initially on the PTO axial force.
- Extract the positive peaks (or negative peaks, in the PA 3 case) from the time-series data, and order them in ascending order to approximate an empirical peak distribution as:

$$F'(x_i) = \frac{i}{N+1} \quad (1)$$

where x_i is the i_{th}-ordered sample and N is the number of peaks.

- Fit a probability distribution function (e.g. Gumbel) to the time-series of peaks, $F(x)$. The selection of the type of distribution was based on quality of the fit, by comparing the cumulative density function (CDF) with the empirical CDF.

- Using $F(x)$, the short-term extreme distribution can be estimated by:

$$F_e(x) = F(x)^n \tag{2}$$

where n is the expected number of waves associated with each 3-hour simulation.

Depending on the type of analysis (contour approach or full environmental characterisation), the methodology is concluded by:

- *Contour approach*: using $F_e(x)$, the characteristic load value(s) for the variable(s) of interest can be estimated as e.g. the 98% quantile of the associated $F_e(x)$ CDF, as a representation of the 50-year return load value(s). The environmental and machine conditions leading to the highest characteristic load values can then be selected. It is noted that (2) is only applicable if $F(x)$ has been derived with *ESS* H_{s1} as input – otherwise an appropriate adaptation to target quantiles must be considered.
- *Full environmental characterisation*: the collection of short-term extreme results is used to create a complementary cumulative distribution function (CCDF), also referred to as *survival function*, to obtain long-term target estimates for a range of long-term return periods. Unlike the contour approach, the full environmental characterisation method does not assume that the highest loads are necessarily associated with a specific environmental (extreme) contour, and thus account for the possibility that these may be relevant to any event within a long-term environmental contour.

The above methodology targets ultimate limit states (ULS) and follows DNVGL-RP-C205 [12]. The ULS estimates can be typically related to the maximum load carrying capacity and directly related to structural failure modes.

2) *Fatigue Load Analysis (FLS)*

Marine environments typically present highly variable loads, and as such a PTO must withstand considerable fatigue loading during its design life. Typically, fatigue life can be reported in terms of a *S-N* curve, usually resulting from empirical results, that relates the number of load cycles to failure N to a given constant load amplitude S (see Fig. 6). The curve can be expressed mathematically as

$$\log(N) = \log(K) - m\log(S) \tag{3}$$

with K being an empirical material constant and m the slope of the *S-N* curve.

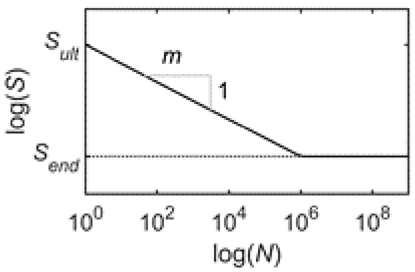


Fig. 6. Typical *S-N* curve profile for most common materials (source: WDRT website http://wec-sim.github.io/WDRT/).

The WDRT toolbox has been used in the fatigue load analysis. The toolbox uses the Palmgren-Miner rule to predict the cumulative damage for variable loading. The Palmgren-Miner rule is based on the assumption that the cumulative damage of each load cycle is sequentially independent, allowing the calculation of the total damage equivalent load (DEL) as a linear summation of the distributed load ranges. The DEL is described in a generic sense by S_N, in (4).

$$S_N = \left(\sum \frac{S_i^m n_i}{N}\right)^{\frac{1}{m}} \tag{4}$$

The main steps followed in the fatigue calculations are summarised below:

1) Simulations were completed for DLC 1.1. The resulting loads time-series were recorded.
2) A *S-N* curve slope, m, was selected.
3) The average number of cycles for a 1h time frame was calculated as:

$$N_{cycles,1h} = \sum_{i=H_s}\sum_{j=T_p} \frac{n_{occ_{i,j}} * 3600}{\gamma_{pz} * T_{p_j}} \tag{5}$$

with $n_{occi,j}$ representing the fraction of occurrence of sea state i, j, T_{pj} the peak period of sea state i, j and γ_{pz} the coefficient of proportionality relating the peak and the mean zero up-crossing periods (1.285^{-1} for JONSWAP spectra; 1.405^{-1} for Bretschneider spectra).

4) The number of cycles for a 1y time frame $N_{cycles,1y}$ is given by $N_{cycles,1h}$ multiplied by 8760 (number of hours in a year).
5) Following the estimation of the 1h DELs for each sea state, $S_{eq_{1h}i,j}$, the 1y DEL, S_{eq1y}, can be derived via:

$$S_{eq_{1y}} = \left(\frac{\sum_{i=H_s}\sum_{j=T_p} S^m_{eq_{1h}i,j} * N_{cycles,1h} * n_{occ_{i,j}}}{N_{cycles,1y}}\right)^{\frac{1}{m}} \tag{6}$$

6) Finally, DELs were derived for additional reference periods (e.g. 10y, 50y) to assess the evolution of the DELs with increasing life requirements.

III. Model Setup

The numerical simulations described in this paper were carried out using WEC-Sim (Wave Energy Converter SIMulator), an open-source WEC simulation software. A high-level description of WEC-Sim can be found in e.g. [13]. The derived PTO (point) loads were considered.

Multiple sets of simulations were conducted for the DLCs specified in II.D. All simulations included a ramp-up time to reach a steady state response. A summary of the WEC-Sim simulation parameters applied is presented in Table III. These parameters e.g. time-step and convolution integral interval were adjusted for each WEC model to

TABLE III
SUMMARY OF THE WEC-SIM SETUP

WEC-SIM VERSION		V3.0
WATER DENSITY		1,025 kg/m^3
CONVOLUTION INTEGRAL INTERVAL (OWSC 2, PA 2, PA 3)		15S, 30S, 20S
SIMULATION TIME-STEP (OWSC 2, PA 2, PA 3)		0.05S, 0.005S, 0.005S
RAMP-UP TIME (OWSC 2, PA 2, PA 3)		15S, 30S, 20S
SIMULATION LENGTH	NSS	1,800S
	$ESS\ H_{s1}$	10,800S + RAMP-UP

provide stable results while optimising the computational time.

The setup process also involved the development and integration of an EMG PTO model in the overall WEC models. The total EMG reaction force is composed by an electrical damping force and a mechanical friction force, and the IMAGINE EMG design criteria defines a peak instantaneous electrical power of 250kW. The key design parameters for the EMG PTO are summarised in Table IV.

A power capped control logic was implemented to ensure that the damping variable ($k_{current}$) leads to an instantaneous electrical power ≤250kW. The control logic can be summarised as follows:

a) Check PTO velocity ($\dot{x}$):
- If $|\dot{x}| < 0.001$, then $k_{current} = k_{PTO}$
- Else: $k_{current}$ is calculated using Equation 1

b) Apply saturation to $k_{current}$:

$$0 \leq k_{current} \leq k_{PTO}$$

$$k_{current} = \frac{P_{inst}}{|\dot{x}|^2} \quad (7)$$

Step a) is applied when the PTO velocity is too small to avoid overflow errors during simulations. The final step applied in the power capped control logic (step b), ensures that the resulting damping variable ($k_{current}$) leads to an electrical power within the admissible limits.

Given that the control logic has a direct influence in the EMG setup, an iterative approach is required to optimise the PTO setup. A preliminary optimisation exercise was conducted for each WEC at each of the target deployment sites prior to running load case simulations. As a preliminary step, the pre-optimised damping value k_{PTO} is always used when the power threshold is not reached.

IV. RESULTS

A. *Extreme Load Analysis*

A long-term extreme load analysis of the PTO design load data was conducted to characterise the extreme response as a function of the type of WEC and deployment location. The PTO force (F_{PTO}) time-series was selected as the key variable of interest, although other load sources and further kinematic variables (e.g. motion, velocity) are also outputs of the coupled simulations. Following the recommendations listed in e.g. [9], characteristic values associated with a 50-year return period were derived, using the methodologies detailed in II.E. 1). The sensitivity of the derived metrics to the methodology implemented to obtain them was also addressed, namely the influence of the type of extreme value distribution and of the type of analysis (contour approach vs. full environmental characterisation). Although the results are specific to the IMAGINE project, the latter investigation is expected to be relevant in a wider WEC design context.

Extreme load estimates related to DLCs 1.1, 6.1 and 6.2 were derived for all WEC types and for the three target sites. For each of the two methods of deriving the ULS estimates two types of extreme value distribution (Gumbel and Weibull tail) were also used.

Table V details the ULS estimates associated with the PTO force affecting the OWSC 2 WEC for DLC 1.1. An example of a related survival function is also given in Fig. 7. The results demonstrate a degree of site dependency, representative of inter-class variations (recalling that in [3] all three sites were associated with a specific WEC class).

TABLE IV
KEY DESIGN PARAMETERS FOR THE EMG PTO

INSTANTANEOUS ELECTRICAL POWER (P_{inst})	250kW
POWER RATIO ($R_{power} = \frac{inst.\ Power}{P_{rated}}$)	1
TARGET STROKE RANGE (PTO_{stroke})	5m

TABLE V
OWSC 2 – DLC 1.1 ULS PTO FORCE

F_{PTO} (MN)	Contour approach		Full environmental characterisation	
	Gumbel distribution	Weibull tail distribution	Gumbel distribution	Weibull tail distribution
Site #1 – France	0.76	0.64	0.77	0.65
Site #2 – SW England	0.56	0.50	0.60	0.51
Site #3 – Norway	0.86	0.74	0.89	0.78

TABLE VI
OWSC 2 – RELATIVE DIFFERENCE BETWEEN THE CONTOUR APPROACH AND FULL ENVIRONMENTAL CHARACTERISATION (DLC 1.1 ULS PTO FORCE)

Relative difference (%)	Gumbel distribution	Weibull tail distribution
Site #1 – France	1.64	0.60
Site #2 – SW England	6.46	2.73
Site #3 – Norway	3.28	5.04

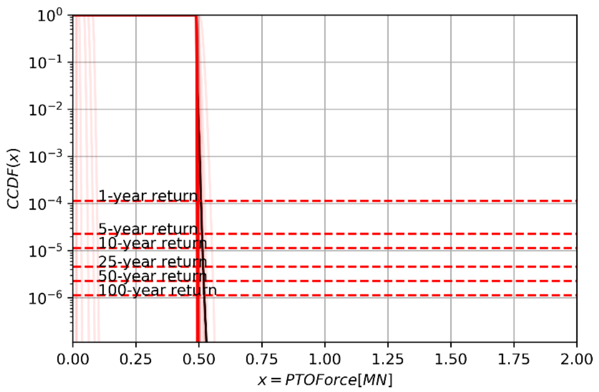


Fig. 7. OWSC 2 – Survival function for DLC 1.1 (Site #2 SW England; Weibull tail distribution).

In particular, Site #2 (SW England) leads consistently to the lower ULS estimates. The inter-class variations also appear to be more significant than the impact of the type of method used to derive the ULS estimates; as detailed in Table VI, the relative differences between the estimates obtained via the contour approach and those related to the full environmental characterisation are everywhere below 6.5%, which provides reassurance when using the (significantly less computational intense) contour approach.

Although similar, the relative differences between the methods are generally more significant when the Gumbel distribution is used, noting that this is also the distribution for which the higher ULS estimates are obtained. For structural assessments, the use of the Gumbel distribution is suggested in guidelines such as e.g. DNV Classification Note 30.6 *Structural Reliability Analysis of Marine Structures*, which is consistent with the more conservative nature of the results associated with this type of distribution.

For the assessment of a parked design situation, DLC 6.1 was initially considered using the contour approach. Additionally, and to analyse the robustness of the contour approach when using different contours, DLC 6.2 was also analysed. Following the DLC table presented in [8], the unfactored estimates of DLCs 6.1 and 6.2 should be comparable as the same characteristic value (50-year) is estimated in either DLC. The main difference is associated with the long-term environmental contours used to define the input environmental conditions (*ESS* H_{s1} for DLC 6.1 and *ESS* H_{s50} for DLC 6.2).

For the OWSC 2 case, in this design situation only the PTO force is relevant, as for a parked situation, the PTO is locked. The key results are summarised in Table VII, where it is clear that all estimates are similar with the exception of those related to DLC 6.1 using a Gumbel distribution. Noting that the same distribution for DLC 6.2 yields lower estimates, the results indicate that the quality of the statistical fits associated with the DLC 6.1 Gumbel case may be somewhat lower; further work may suggest a standard metric to assess the quality of the statistical fits, to mitigate the risk for situations where the type extreme value distribution artificially affects the ULS estimates (see also V). Finally, in Table VII it is clear DLC 6.2 estimates are everywhere lower than those associated with DLC 6.1, suggesting that as a conservative approach the latter may be used in a first design loop. However, it is noted that the relative differences are minor when the (less aggressive) Weibull tail distribution is used.

TABLE VII
OWSC 2 – DLC 6.X ULS PTO FORCE

F_{PTO} (ULS in MN)	DLC 6.1 (ULS in MN)		DLC 6.2 (ULS in MN)	
	Gumbel distribution	Weibull tail distribution	Gumbel distribution	Weibull tail distribution
Site #1 – France	6.45	4.87	4.99	4.74
Site #2 – SW England	4.73	3.60	3.56	3.39
Site #3 – Norway	6.35	4.79	4.85	4.64

TABLE VIII
PA3 – DLC 6.X ULS PTO FORCE

F_{PTO} (ULS in MN)	DLC 6.1 (ULS in MN)		DLC 6.2 (ULS in MN)	
	Gumbel distribution	Weibull tail distribution	Gumbel distribution	Weibull tail distribution
Site #1 – France	6.88	5.38	5.58	5.45
Site #2 – SW England	6.09	4.77	4.74	4.47
Site #3 – Norway	6.82	5.28	5.28	4.96

TABLE IX
PA 3 – DLC 1.1 ULS PTO FORCE

F_{PTO} (MN)	Contour approach		Full environmental characterisation	
	Gumbel distribution	Weibull tail distribution	Gumbel distribution	Weibull tail distribution
Site #1 – France	0.52	0.54	0.51	0.53
Site #2 – SW England	0.54	0.55	0.54	0.58
Site #3 – Norway	0.56	0.56	0.55	0.57

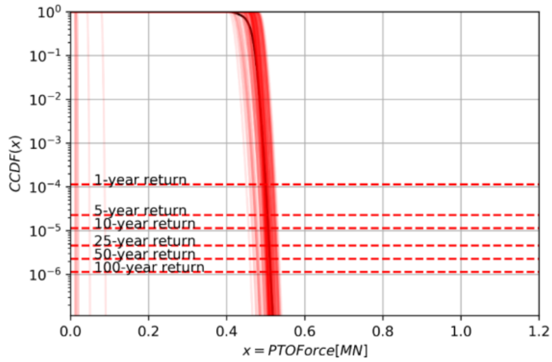


Fig. 8. PA 3 – Survival function for DLC 1.1 (Site #1 France; Gumbel distribution).

Similar observation and extreme load analysis results were observed for the remaining scenarios tested. For example, the extreme PTO load estimates related to the PA 3 WEC model are summarised in Table IX (DLC 1.1) and Table VIII (DLC 6.1 and 6.2). An example of a related survival function is also given in Fig. 8. For DLC 1.1, all estimates are approximately within 5% of each other. This provides some evidence of a WEC class effect, as well as reassurance that all methods to derive the ULS estimates are comparable. For DLCs 6.1 and 6.2, and as per the OWSC 2 case, it is clear that all estimates are similar with the exception of those related to DLC 6.1 using a Gumbel distribution. DLC 6.2 estimates are also generally lower than those associated with DLC 6.1.

B. *Fatigue Load Analysis*

As detailed in II. E. 2), marine environments typically present highly variable loads, and as such a WEC must withstand considerable fatigue loading during its design life. An assessment of the dominant fatigue loads is therefore of critical importance, in particular for key subsystems such as the PTO.

The WDRT [10] was used in the fatigue analysis assessment. The toolbox uses the Palmgren-Miner rule to predict the cumulative damage for variable loading. The Palmgren-Miner rule is based on the assumption that the cumulative damage of each load cycle is sequentially independent, allowing the calculation of the total DEL as a linear summation of the distributed load ranges. Initially, one-hour DELs for each sea state, S_{eq1h}, were estimated. Damage equivalent load were then derived for additional reference periods (10y, and 50y) to assess the evolution of the DELs with increasing life requirements.

TABLE X
OWSC 2 FLS F_{PTO} ESTIMATES

F_{PTO} (DEL in kN)	DLC 1.1			DLC 6.4		
	Site #1	Site #2	Site #3	Site #1	Site #2	Site #3
S_{eq1y}	33.26	23.46	37.40	33.58	29.39	35.62
S_{eq10y}	15.44	10.89	17.36	15.59	13.64	16.53
S_{eq50y}	9.03	6.37	10.15	9.12	7.98	9.67

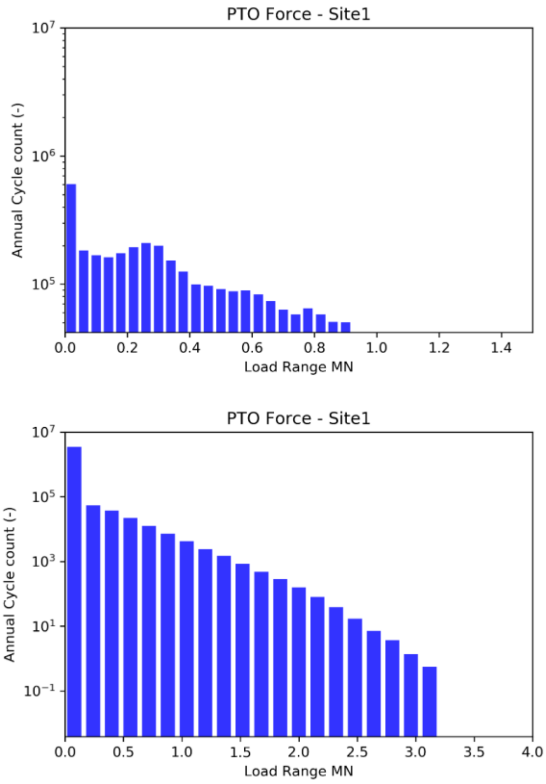


Fig. 9. OWSC 2 1y PTO load histogram (Site #1 France): DLC 1.1 (top); DLC 6.4 (bottom)

Representative results are summarised in Table X, where DEL estimates for the PTO force associated with the OWSC 2 WEC are summarised. All three target sites and three references periods (1y, 10y and 50y) are analysed. It is clear from Table X that the results are similar across the three sites, which provides an indication of a class effect and can in turn be related to the site selection process – see also [3].

Additionally, the DELs for DLC 1.1 and DLC 6.4 are also similar, indicating a similar damage estimate for a power production scenario and for a parked scenario (with the PTO locked and the prime mover mostly away from the wave-induced action). However, this result should not be considered as a general finding – thus some caution in extrapolating conclusions is recommended. This is clear when assessing the corresponding 1y load histograms (Fig. 9), as both the number of cycles and the load range(s) are DLC-specific (despite the similar contribution to an approximately similar equivalent load).

V. CONCLUSIONS AND POTENTIAL NEXT STEPS

A. *Summary of the Key Findings*

This paper summarises the technical specifications related to the definition of the PTO load environment used in the IMAGINE project. Multiple design situations were considered, involving e.g. operational and parked conditions. A range of WEC types and target sites were covered, in an effort to assess and maximise applicability of the PTO solution.

Fully coupled WEC-Sim models were created to obtain estimates of key metrics that allow the definition of the loading environment affecting the PTO. ULS and FLS metrics were derived, to characterise extreme and fatigue loading on the PTO (respectively).

The analysis led to both IMAGINE specific and (wave energy industry) generic findings. The former relate to the actual (absolute) PTO load estimates that have been obtained, and that may condition the EMG PTO development efforts under the IMAGINE project; the latter relate to wider implication to WEC and / or WEC subsystem design. For both categories, the key findings can be summarised as follows:

- Although there is considerable variation in the load estimates across the shortlist WEC types, ULS PTO load estimates are typically in the approximate range of 0.5 to 7MN, with the upper end being related to a parked design situation (DLC 6.x).
- For fatigue damage, parked scenarios also tend to yield higher DELs. The exception is OWSC 2, where the damage is approximately identical regardless of the design situation considered.
- As the PTO is locked in all parked situations, the finding that the higher ULS and FLS estimates are associated with DLC 6.x indicates that the PTO design (and its interface to the prime mover) may not be driven that a power production design situation. Load shedding strategies for such situations may be considered as part of the detailed control investigations, to be completed under WP5 *Control System Design and Implementation* of the IMAGINE project, led by NTNU.
- The contour approach yields similar results to those derived via the full environmental characterisation method, suggesting that a less computationally intensive approach may not compromise the value of the ULS estimate. This generic finding may be particularly useful for initial, concept design level investigations, to potentially allow a wider range of DLCs to be considered from an early stage.
- The use of different types of extreme value distributions has an impact on the ULS estimates. More aggressive distributions (e.g. Gumbel) will typically lead to more conservative ULS estimates. However, no standard metric to quantify the quality of fit is recommended in applicable guidelines. In future work, it is recommended that a metric is defined and communicated when presenting ULS estimates.
- Overall, the FLS estimates indicate that the estimated DELs depend on the type of WEC and on the DLC, but not on the target site if these are in the same WEC class. This finding provides some indication of the potential to extrapolate DEL estimates across sites within a certain WEC class using data from a single representative site.

B. Potential Next Steps

The following actions are suggested as potential next steps. Some of proposed actions are beyond the scope of the IMAGINE project, and may be therefore be considered in follow-up activities.

- As the IMAGINE project progresses and further information becomes available from other work packages, an iterative design stage will follow with respective updates to the WEC models and the simulation of additional DLCs (if required). The iterative design process will consider advanced control system options proposed in WP5 ('*Control System Design and Implementation*'), development of the EMG design in WP3 ('*EMG Prototype Design and Fabrication*') and links to the HWIL simulations in WP4 ('*HWIL Test Bench Design and Fabrication*'). The metrics presented in this paper may be used to assist in the iterative design process, allowing comparisons between the multiple updates to the PTO design.
- The EMG testing in IMAGINE's WP6 will make use of a novel HWIL test bench, to emulate the interaction of the EMG with different WEC concepts in representative environments. Where applicable and within the experimental constraints, it is recommended that some of the results presented are replicated, contributing to their validation. It is noted that the WEC models have been created in a format that allows their use in a real-time testing environment.
- The activities described in this paper focus mostly on the design of the EMG PTO. Other load sources and the interfaces between the PTO and the main structure of the WECs (potential *hot spots* for stress concentration) may be addressed at a more detailed design stage.
- When transitioning from concept to detailed design, a wider list of DLCs may be considered. In some cases, machine and / or controller specific decisions that are beyond the scope of the IMAGINE project need to be taken, and these may often benefit from testing in a real-time environment (either numerically or experimentally).

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APPENDIX A SUMMARY OF THE SITE CONDITIONS

TABLE XI

DEFINITION OF ENVIRONMENTAL CONDITION METRICS FOR SITE #1: FRANCE (45N, 2.5W)

Environmental conditions metric	NSS	ESS			
		ESS H_{s1}		*ESS* H_{s50}	
Target values	H_s (m) [0.75 : 0.5 : 5.75] T_p (s) [4 : 1 : 16] [Start_Value : Step : End_Value]	H_s (m)	T_p (s)	H_s (m)	T_p (s)
		2.64	6.64	3.45	6.64
		3.54	7.75	4.44	7.75
		4.60	8.86	5.73	8.86
		5.87	9.96	7.39	9.96
		7.32	11.07	9.45	11.07
		8.83	12.18	11.76	12.18
		10.17	13.28	13.77	13.28
		11.00	14.39	14.76	14.39
		11.09	15.50	14.57	15.50
		10.42	16.61	13.52	16.61
		9.09	17.71	11.91	17.71
Notes	143 sea states covering 96% of occurrences.	Sea states for 1- and 50- year return periods presented.			

TABLE XII

DEFINITION OF ENVIRONMENTAL CONDITION METRICS FOR SITE #2: SW ENGLAND (49.8N, 5W)

Environmental conditions metric	NSS	ESS			
		ESS H_{s1}		*ESS* H_{s50}	
Target values	H_s (m) [0.25 : 0.5 : 5.25] T_p (s) [5 : 1 : 16] Where applicable: [Start_Value : Step : End_Value]	H_s (m)	T_p (s)	H_s (m)	T_p (s)
		3.63	6.64	3.93	6.64
		4.34	7.75	5.25	7.75
		5.03	8.86	6.08	8.86
		5.70	9.96	6.91	9.96
		6.33	11.07	7.72	11.07
		6.90	12.18	8.49	12.18
		7.37	13.28	9.20	13.28
		7.70	14.39	9.80	14.39
		7.80	15.50	10.21	15.50
		7.56	16.61	10.34	16.61
		6.71	17.71	9.98	17.71
Notes	132 sea states covering 96% of occurrences	Sea states for 1- and 50- year return periods presented.			

TABLE XIII

DEFINITION OF ENVIRONMENTAL CONDITION METRICS FOR SITE #3: NORWAY (62.5N, 5.5E)

Environmental conditions metric	NSS	ESS			
		ESS H_{s1}		*ESS* H_{s50}	
Target values	H_s (m) [0.75 : 0.5 : 6.25] T_p (s) [5 : 1 : 16] Where applicable: [Start_Value : Step : End_Value]	H_s (m)	T_p (s)	H_s (m)	T_p (s)
		3.61	6.64	3.93	6.64
		4.84	7.75	5.35	7.75
		6.15	8.86	6.97	8.86
		7.47	9.96	8.74	9.96
		8.70	11.07	10.59	11.07
		9.68	12.18	12.47	12.18
		10.22	13.28	13.69	13.28
		10.14	14.39	13.62	14.39
		9.30	15.50	12.58	15.50
		7.68	16.61	10.72	16.61
		5.24	17.71	8.25	17.71
Notes	144 sea states covering 96% of occurrences	Sea states for 1- and 50- year return periods presented.			