CWPT Open Water Demonstration

DE-EE0008097.0000
Budget Period 1

Updated ACE metric with Supporting Calculations:

May 2019

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

CONTENTS

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

FIGURES

TABLES

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

VARIABLES & DEFINITIONS

FURTHER CONVENTIONS

CalWave is using the following convention for the positioning and orientation of the global coordinate system. This convention is equal to the most common convention used in Naval Architecture and specifically in wave energy conversion related research & development:

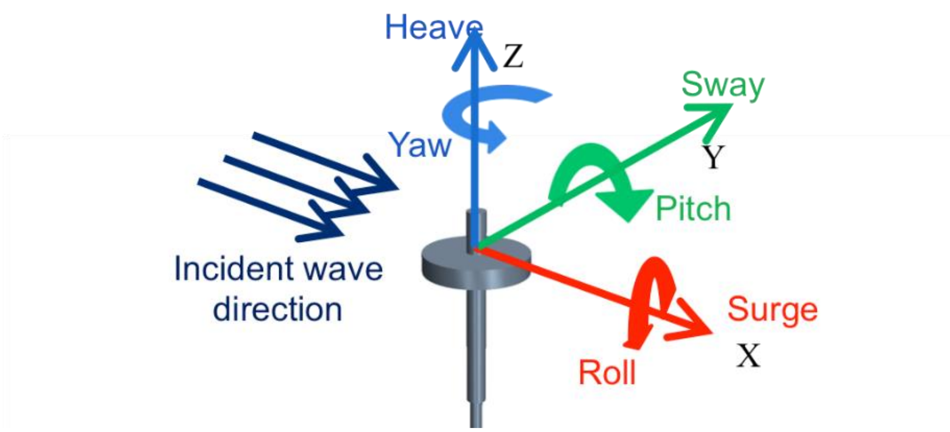

Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

ABBREVIATIONS

MBL – Minimum Breaking Load (Mooring Line Property)
PTO – Power Take-Off
WEP – Wave Energy Prize
MPC – Model Predictive Control
COG – Center of Gravity
COB – Center of Buoyancy
MOI – Moment of Inertia
AM – Added Hydrodynamic Mass
AD – Added Hydrodynamic Damping
DOF – Degrees of Freedom

1. INTRODUCTION

When comparing the economic attractiveness of power generating technologies, levelized cost of energy (LCOE) is a common metric frequently used in the power generation sector. LCOE is the ultimate expression of the ratio between effort (cost) and benefit (energy generated). Unfortunately, LCOE is difficult to use for lower Technology Readiness Levels (TRLs), because the data necessary is either not available or unreliable.

The objective of this project is to advance the Technology Readiness Level of the Wave Energy Converter (WEC) developed by CalWave Power Technologies Inc., (CalWave) through advanced numerical simulations, dynamic hardware bench-tests, and ultimately an open water demonstration deployment of a scaled Wave Energy Converter (WEC) while continuing to exceed DOE's target ACE threshold of 3 meters/M$. The goal of this report is to estimate the mass of the full scale WEC that is represented by the 1:5 demo WEC. The novel metrics ACE is being used which is calculated as:

$$ACE = \frac{ACCW\ [m]}{CCE\ [\$]}$$

with the *average climate capture width* (ACCW) and *characteristic capital expenditure* (CCE) where ACCW is defined as

$$ACCW_j = \frac{\sum_{i=1}^{n} \Xi_{ij} \langle AP(i) \rangle\ [kW]}{\langle C_P(j) \rangle\ [\frac{kW}{m}]}$$

with the average power absorbed AP and average annual wave energy flux CP and

CCE is defined as

$$CCE = RST \cdot A_{surf} \cdot \varrho \cdot MMC = m_{tot} \cdot MMC$$

where:

- RST representative structural thickness [m]
- A_{surf} is the total structural surface area [m^2]
- ρ is the material density [kg/m^3]
- MMC is the manufactured material cost [US$/kg]
- m_{tot} is the total mass.

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

Based on DOE's US Wave energy prize, six irregular wave cases were defined which are directly used to calculate ACE. The following Table 1 lists the six wave states including characteristic wave parameter. These wave cases were used to determine the device performance in absorbing power from waves, independently of the method (wave tank testing, numerical simulation, PTO hardware in the loop bench testing).

Table 1: Irregular Wave Cases (IWS) for ACE Assessment

Irregular Wave Cases (IWS) for ACE Assessment						
Label	**Dir [Deg]**	**Tp [s]**	**Te [s]**	**Hs [m]**	**Gamma**	**Spread**
IWS 1	10	7.290	6.260	2.340	1	Inf.
IWS 2	0	9.839	8.449	2.640	1	Inf.
IWS 3	-70	11.538	9.909	5.360	1	Inf.
IWS 4	-10	12.701	10.905	2.060	1	Inf.
IWS 5	0	15.250	13.223	5.840	1	Inf.
IWS 6	0	16.502	14.167	3.260	1	Inf.

2. ACCW Supporting Calculations

2.1 Numerical Simulation Derived ACCW

2.1.1 General Numerical Simulation Remarks

Based on CalWave's demonstration scale design a mid-fidelity simulation was set up in Simulink. The WECSim environment was used with major changes and tweaks regarding hydrodynamic models (derived from scaled wave tank testing), customized PTO units with Simscape toolboxes, mooring tether simulations and pulley dynamics via a novel Simulink 2018b cable and pulley feature.

For both, parametric hydrodynamic models using ANSYS Aqwa derived BEM solutions in addition to CFD derived viscous force models, as well as for up-scaled hydrodynamic models from wave-tank system identification, the ACE relevant IWS cases were run.

Performance optimization in the simulation was achieved by iterating on device geometry control parameters, PTO parameters, and absorber body multi-DOF controller parameters. Due to the improved optimization capability when running numerical simulation performance results were expected to be higher compared to wave tank testing. Additionally, wave cases such as IWS5 and IWS6 which were treated as survival cases during wave tank testing were optimized in the bounds of allowable forces and displacements in the numerical simulation.

It is important to mention, that the numerical simulation included an accurate model of the PTO drivetrains including inertial masses of PTO sub-components as well as mechanics of fairleads and pulleys.

Additionally, the global device controller optimizing power performance which was used in the final ACE relevant IWS computations was additionally improved to include all DOFs of the absorber body.

→ For more information and documentation of simulation results please also refer to the "*Updated Performance Predictions from Numerical Simulations*" report

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

2.2 Wave Tank Testing Derived ACCW & 3RD Party Validation

In coherence with the methodology used during the DOE's US Wave Energy Prize for ACE calculation, during BP1 of CalWave's open water demonstration, ACCW was determined from scaled wave tank testing. Wave tank testing was conducted at the W^2 wave basin at Orono, Maine. The campaign in November 2018 lasted for 10 testing days. Each run had a unique RunID that will be referred to in the summary of the ACE relevant performance results which is aligned to the IDs used in the wave tank testing report for more detailed post processing plots. A total of **121** runs were performed and recorded with a total runtime of approximately **45** hours of recoded data.

2.2.1 Wave Tank Testing IWS Post-processing

For ACE calculations the mechanical power was calculated for each individual PTO unit as Force x Velocity. Control and data signals were acquired at 25 KHz and 1kHz respectively, and post processed at 100 Hz. For baseline performance evaluation all 6 irregular wave cases were tested and WEC device control / PTO parameters were adjusted in between repeats to map performance.
IWS cases were ran for at least 300 x Tp and random irregular wave seeds

For WEC performance tests, **the IEC TC114 Part 103** standards were followed, requiring a minimum of 250 waves in each performance spectrum

➔ Thus, total runtime was based on dominant wave period Tp
➔ Repetition of (shorter) wave signals leads to an improved signal to noise ratio; detecting level of nonlinearities, quantifying noise, and removes the need for FFT windowing (rectangular window), no spectrum leakage
➔ Most often the first repeat was discarded but used to get the device into steady state, two more periods are used for actual post processing for any wave case

Before final runs for performance evaluation with relatively long run times (IEC standards were applied, see wave case calibration chapter) were conducted, multiple larger control parameter sweeps were conducted. As the controller was not based upon a simple PTO spring/damper model any longer, but rather on a multi-parameter controller, the optimization of control parameters sometimes even led to multiple settings leading to equal power capture performance.

For all performance evaluation cases the PTO, as well as absorber characteristics for the specific repeats were assessed in terms of feasibility and compliance with design specifications and limitations. This ensures that derived performance characteristics are viable for a demonstration scale implementation without violating device design criteria.

2.2.2 NREL 3rd Party Post Processing Validation

To ensure correct post processing of wave tank test data, post processing scripts and raw data files were submitted for review to NREL in January 2019. NREL reviewed and confirmed the correctness of post-processing scripts and executed the scripts with minor improvements which led to same performance results as CalWave derived.

The minor improvements and comments NREL listed regarding the post processing were documented and can be found in Appendix A

2.2.3 ACCW Calculation using Wave Tank Testing IWS Results

Figure 2 lists a summary of the final ACE relevant irregular wave cases (IWS) runs with each repeat during experimental testing at the W2 basin at the University of Maine during November 2018. The table lists experiment IDs, information about the incident wave spectrum, general device configuration parameters, PTO configuration parameters, performance measured in power as well as capture width ratio (CWR) for the different repeats.

Maine November 18 Post Processing - Irregular Wave Cases - Performance Ove

IWS #	Run ID	Repeat	Av. Device Power Cons.	Av. Device Power Prod.	Net Device av. Power	Wave Power [W]	CWR
IWS1	Run74	2	-2.63	5.73	3.10	4.91	63.19%
IWS2	Run75	3	-3.43	8.91	5.48	7.84	69.84%
IWS3	Run102	3	-3.86	7.26	2.21	42.95	5.15%
IWS4	Run73	3	-4.57	7.12	2.54	6.54	38.91%
IWS5	Run101	3	-3.93	7.38	4.32	58.59	7.37%
IWS6	Run77	3	-4.51	8.16	4.64	19.57	23.73%

Figure 2: Overview of power performance in Irregular Wave Cases (IWS) runs from experiments conducted.

Subsequently, ACCW is derived as shown in Figure 3:

Wave	Tp (s)	Hs (m)	Upscaled Power (kW)	Adjusted Weighting Each Climate: Alaska	Washington	Northern Oregon	Oregon	Northern California	Southern California	Hawaii
IWS 1	1.63	0.117	242.388	24.3%	13.7%	15.5%	17.5%	20.7%	15.2%	32.8%
IWS 2	2.20	0.132	427.900	33.2%	27.7%	30.7%	26.8%	23.0%	27.0%	24.5%
IWS 3	2.58	0.268	172.667	7.5%	4.1%	5.6%	5.8%	1.2%	1.4%	0.1%
IWS 4	2.84	0.103	198.820	20.0%	33.8%	34.4%	29.5%	46.6%	39.1%	13.3%
IWS 5	3.41	0.292	337.157	2.4%	2.2%	3.7%	3.4%	1.6%	1.0%	0.0%
IWS 6	3.69	0.163	362.819	1.2%	4.5%	4.2%	5.4%	6.4%	9.5%	1.3%
				88.6%	86.0%	94.1%	88.4%	99.5%	93.2%	72.0%
<CP> (kW/m) =				35.5	32.7	39.3	37.9	31.5	31.2	16.8
AACW(j) (m) =				7.4964	7.6379	6.9901	6.7762	8.6326	8.6658	12.8376
ACCW (m) =	**8.4338**									

Figure 3: ACCW calculation for tank test derived full scale device performance in ACE relevant IWS Cases.

→ For more information and documentation of detailed post-processing procedures please also refer the *Wave Tank Testing* Reports

2.3 PTO Bench Test Derived ACCW

TO gain a better understanding of the impact of PTO dynamic characteristics and efficiencies on the ACE metrics, CalWave ran all ACE relevant IWS cases using a hardware-in-the-loop simulation/experiment scheme. A single PTO unit was constructed on the PTO bench at UC Berkeley Civil Engineering laboratory and integrated into the simulation of the remaining three PTO units and the global dynamics of the absorber body including hydrodynamics. A tweaked WECsim/Simulink environment was used to couple the physical signals of the PTO operating/and being controlled at the bench with the rest of the simulation.

The hardware-in-the-loop simulations were iterative, meaning that for the remaining three PTO models in the simulation experimental bench test system identified models were used.

As for wave tank testing, following **the IEC TC114 Part 103** standards a minimum simulation time of 250 waves for each IWS case was adopted with multiple runs reducing uncertainty in statistical parameters.

→ For more information and documentation please also refer to *the PTO Bench Test* Report

3. CCE Supporting Calculations

The following chapter summarizes the supporting calculations and computations which were performed to derive a preliminary full scale CCE estimate to support ACE calculations. Based on the envisioned sizing of the device for fully energetic climates (e.g. PacWave, Oregon) the device structural analysis for CCE calculation is closely related to the definition and selection of design load cases.

As structural calculations directly use expected wave loads derived either from mid-fidelity/BEM simulations or, in the case of extreme waves, from CFD simulations, the analysis is sensitive to the design load case selection.

3.1 Full Scale WEC Layout and Design Load Cases

In the following, considered design load cases (DLCs) are summarized that are used to determine ultimate limit strength (ULS) of the structural parts considered for the CCE analysis. The two critical cases are the largest operational (Custom Wave State 1 – CWS1) and the largest survival case (eXtreme Wave State - XWS) sea states.

Table 2: Design load cases used to determine CCE

Design Wave States picked from PacWave Test Site as a full-scale climate reference		
Description	**Value**	**Unit**
Water Depth	60	m
Hull MOI	upscaled from demonstration scale	kgm^2
Hull buoyancy	upscaled from demonstration scale	m^3

The 50-year return wave state was derived from the PacWave extreme return wave contour as shown in Figure 4:

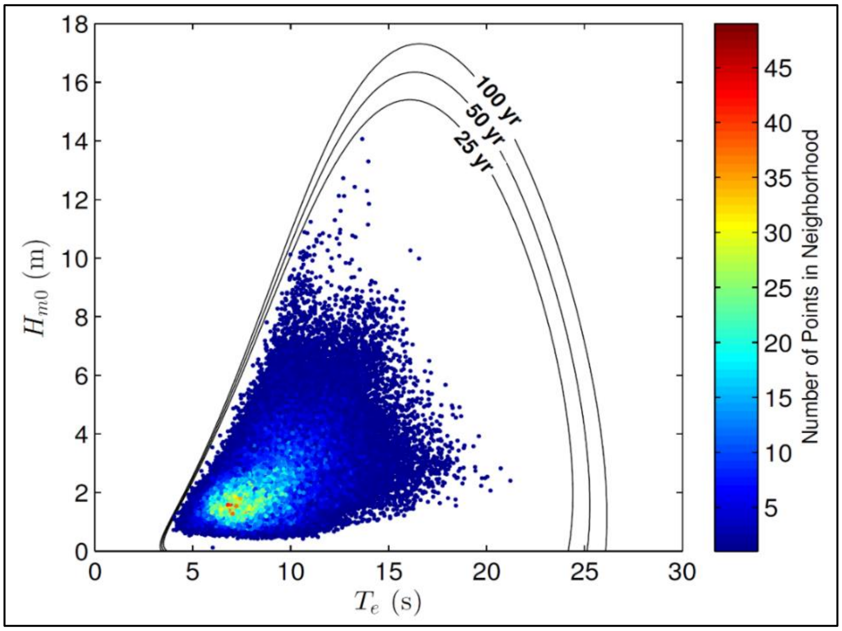

Figure 4: PacWave 100-year contour for NDBC 46050

The analyzed hull contains of three structures with different functions:

1) Tubular pressure vessel that houses equipment: An inner shell acting as a pressure vessel to provide a desired buoyancy and to host equipment in a dry environment
2) Outer shell acting as the main structure responsible for the dynamic wave structure interaction that leads to load and energy transfer from the waves utilized for power extraction. The outer shell hydrodynamic response only considers dynamic, not hydrostatic load (as hydrostatic pressure on the inside of the hull wall is the same as outside of the wall (neglectable difference from the sheet thickness)
3) Load Management Mechanism hatch / Geometry Control hatch

The gap between the inner, air-filled structure and the outer hull is passively filled with water via relatively small perforations in the outer hull. These passively filled water entrapment chambers lead to multiple desired effects such as stability on the surface during deployment, maintenance, and towing operations, a shift in the center of gravity while being submerged and operational; as well as an increase in total oscillating mass which is beneficial for control purposes.

3.2 Shell Pressure Calculation

Loads for the ultimate limit state (ULS) analysis will be separated in load pressures caused by the static water column and dynamic pressure from wave excitation/diffraction and device motion (radiation). The water pressure is calculated by DNVGL-ST-0119 section *4.9.3 Sea pressures for the ultimate limit state* taking the static and dynamic water line of the 50-year return wave into account.

For the dynamic pressure, CFD results are obtained and loads are separated between dynamic loads solely acting on the outer hull and water pressure loads from the DNV approach only acting on the inner shell.

Design pressures used for structural analysis are thus calculated according to the following guidelines:

Standard — DNVGL-ST-0119. Edition July 2018, Floating wind turbine structures

— Ultimate limit states (ULS) corresponding to the maximum load-carrying resistance.

4.9.3 Sea pressures for the ultimate limit state

4.9.3.1 The design sea pressure acting on slender floating wind turbine units in operating conditions in deep waters may, if not more refined analyses are performed, be taken as:

$$p_{d,ULS} = p_s \cdot \gamma_{f,G,Q} + p_e \cdot \gamma_{f,E}$$

in which:

p_s = $\rho\, g_0\, (T_E - z_b)$ (kN/m^2) ≥ 0

p_e = $\rho\, g_0\, (D_D - z_b)$ (kN/m^2) for $z_b \geq T_E$

= $0.5\rho\, g_0\, He^{-kz}\cos\theta$ for $z_b < T_E$

T_E = extreme operational draught (m) measured vertically from the moulded baseline (BL) to the assigned load waterline. The operational draught should be varied considering all relevant effects such as set-down, storm surge, tide, trim/heel angle and heave effects.

D_D = vertical distance (m) from the moulded baseline to the wave crest. Relative heave motions shall be considered.

z_b = vertical distance (m) from the moulded base line to the load point

p_s = static sea pressure

p_e = dynamic (environmental) sea pressure.

H = trough-to-crest wave height

θ = $kx - \omega t = k(x - ct)$

x = distance of propagation

c = wave celerity

ω = $2\pi/T$= angular wave frequency

k = $2\pi/\lambda$ = wave number, infinite water depth

z = $(T_E - z_b)$ = distance from mean free surface (defined as positive)

λ = wave length

4.9.5 Superimposition of responses

4.9.5.1 The simultaneity of the responses resulting from the local and global analysis models, including various sea and tank pressures, may normally be accounted for by linear superposition of the responses for logical load combinations.

4.9.5.2 When evaluating responses by superimposing stresses resulting from several different models, consideration shall be given to the following:

— loads applied in global and local models
— relevant combination of tank and sea pressures
— it should be ensured that responses from design loads are not included more than once.

4.9.5.3 Further information regarding superimposition of loads from local and global models can be found inDNVGL-RP-C103 Sec.4.

Moreover, the applied load at 20m submergence survival depth is estimated from a ratio of hydrostatic load, an increment dynamic load (10%), and a safety factor of 1.35.

Table 3: Load factors for ULS and ALS. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2013-06/OS-J103.pdf

Load factor set	*Limit state*	*Load categories* *G*	*Q*	*E – Safety class: Low*	*Normal*	*High*	*D*
(a)	ULS	1.25	1.25		0.7 (*)		1.0
(b)	ULS	1.0	1.0	1.20	1.35	1.55	1.0
(c)	ULS for abnormal wind load cases	1.0	1.0		1.1		1.0
(d)	ALS	1.0	1.0	0.9	1.0	1.15	1.0

Load categories are:
G = permanent load
Q = variable functional load, normally relevant only for design against ship impacts and for local design of platforms
E = environmental load
D = deformation load.
For description of load categories, see Sec.4.
(*) When environmental loads are to be combined with functional loads from ship impacts, the environmental load factor shall be increased from 0.7 to 1.0 to reflect that ship impacts are correlated with the wave conditions.

Based on the presented methods the actual pressure calculations are derived as shown in Table 4

Table 4: Pressure calculation.

CFD derived pressures for the extreme wave case (XWS) were interpolated in Mathworks Matlab to a fine grid to subsequently be used in the structural finite element analysis for rigidity assessment. Figure 5 to Figure 7 shows the interpolated pressure grid for a half section of the absorber body:

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

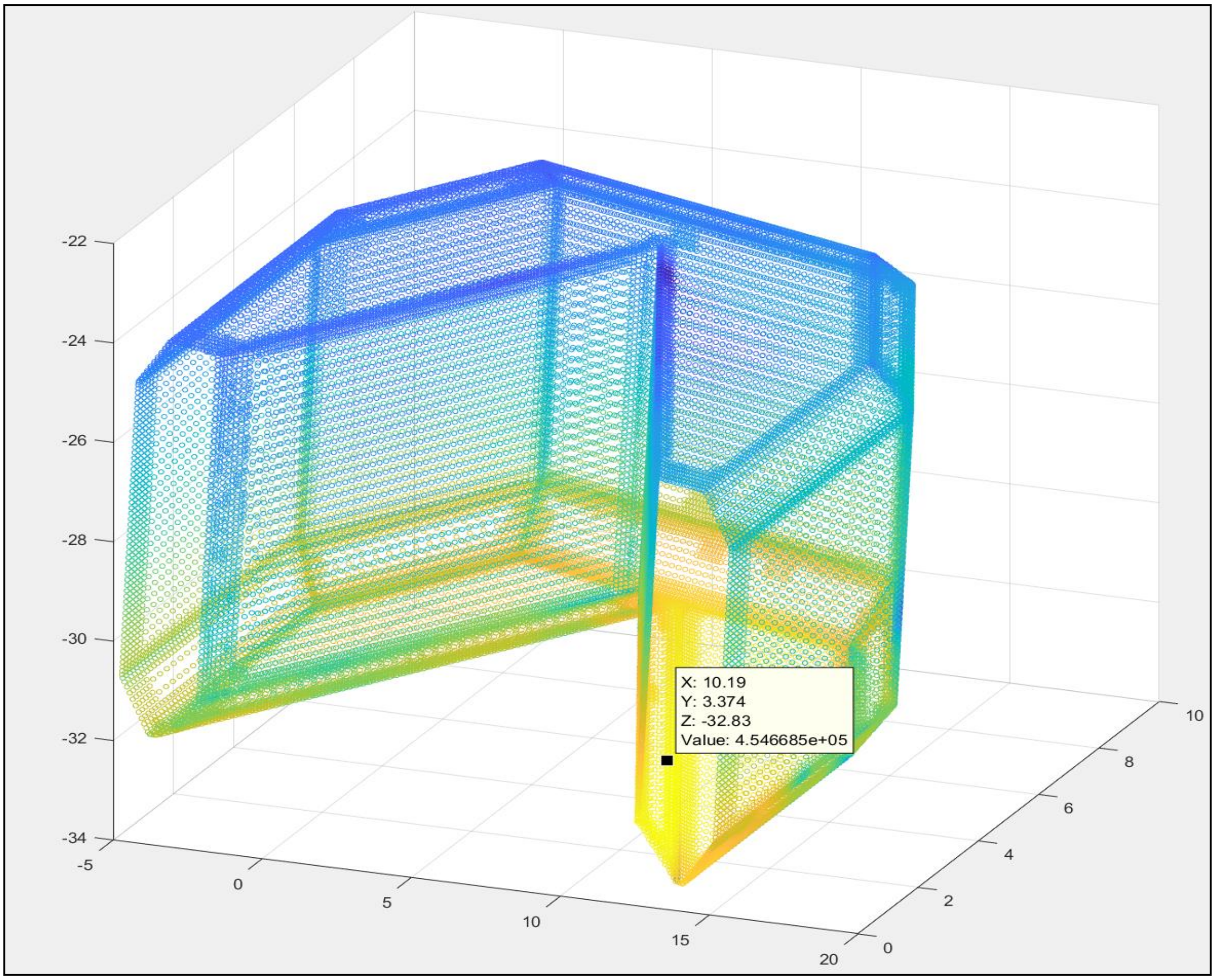

Figure 5: CFD pressure map on half section of full-scale hull in survival conditions.

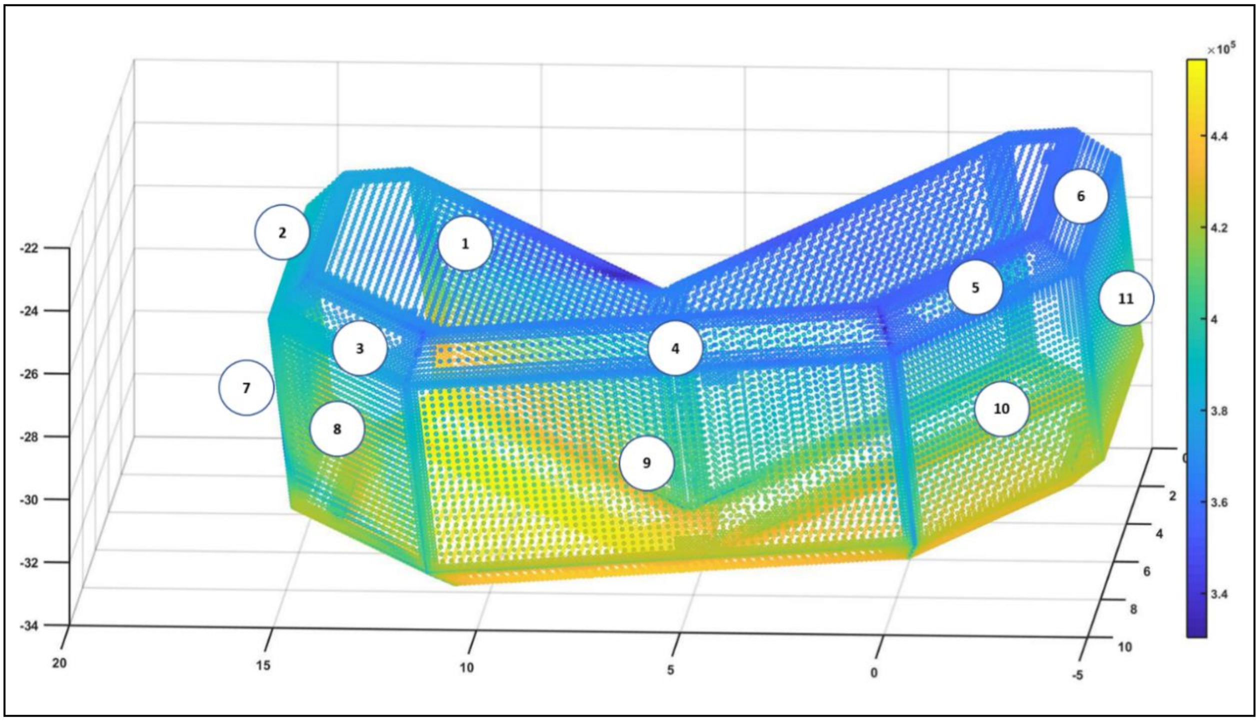

Figure 6: CFD result panel sectioning.

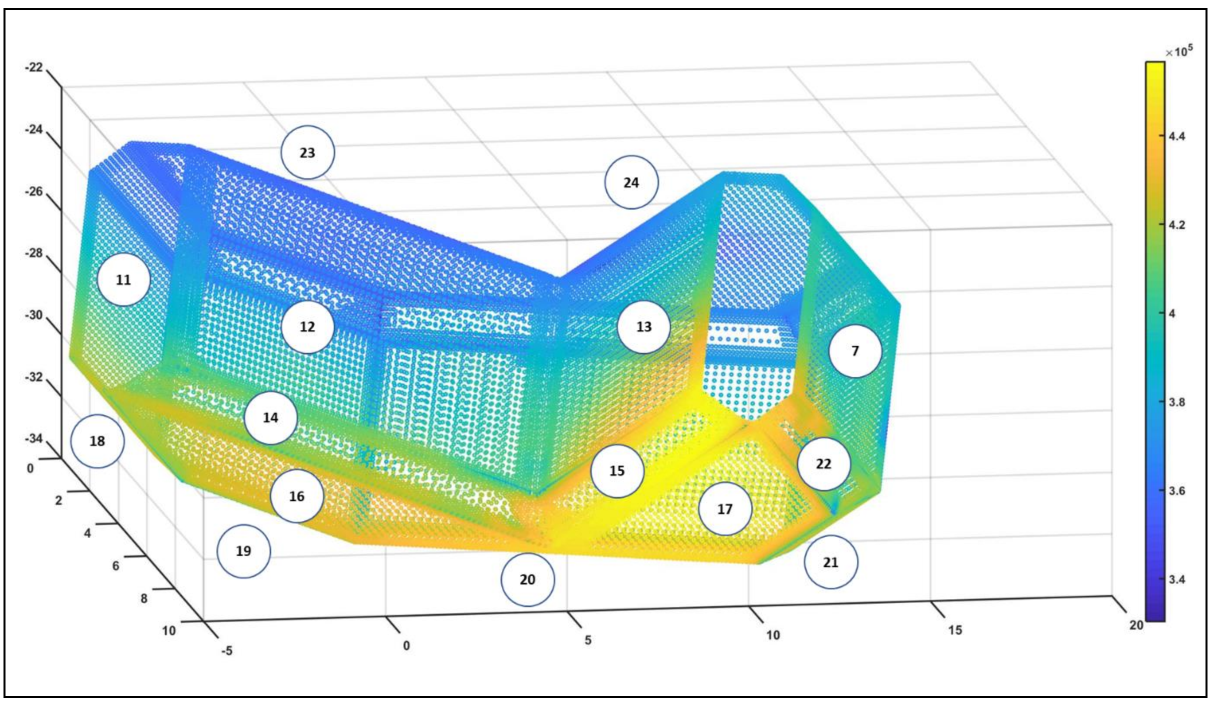

Figure 7: CFD result panel sectioning.

The above pressures assigned to the discrete CAD panels were then used in the global FEA analysis.

3.3 Design Loads for Load Management Mechanism Design

Contrary to the deep submerged survival case in which the load management mechanism is fully opened, the device will experience the largest loads on the hatch during the design load case (CWS1 as defined above). For this operational case with a much smaller wave period and wave height compared to the extreme case, loads were derived from a regular BEM solver (Ansys AQWA). Loads were used to assess the required rigidity of the load management mechanism and ultimately to derive a weight estimate for the load management mechanism structure:

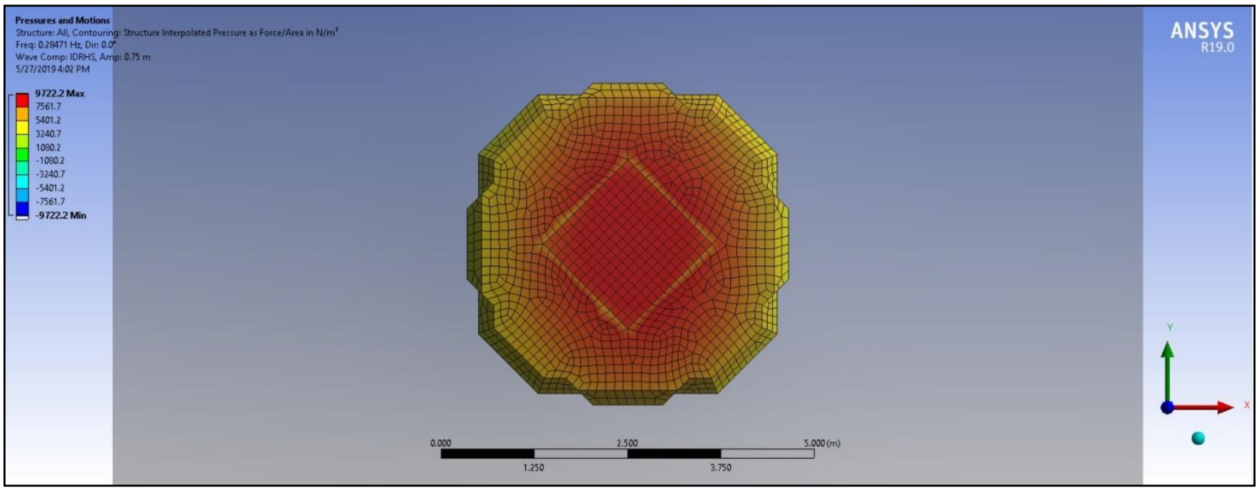

Figure 8: BEM pressure result at operating case – top view at wave phase with largest pressure on the hatch.

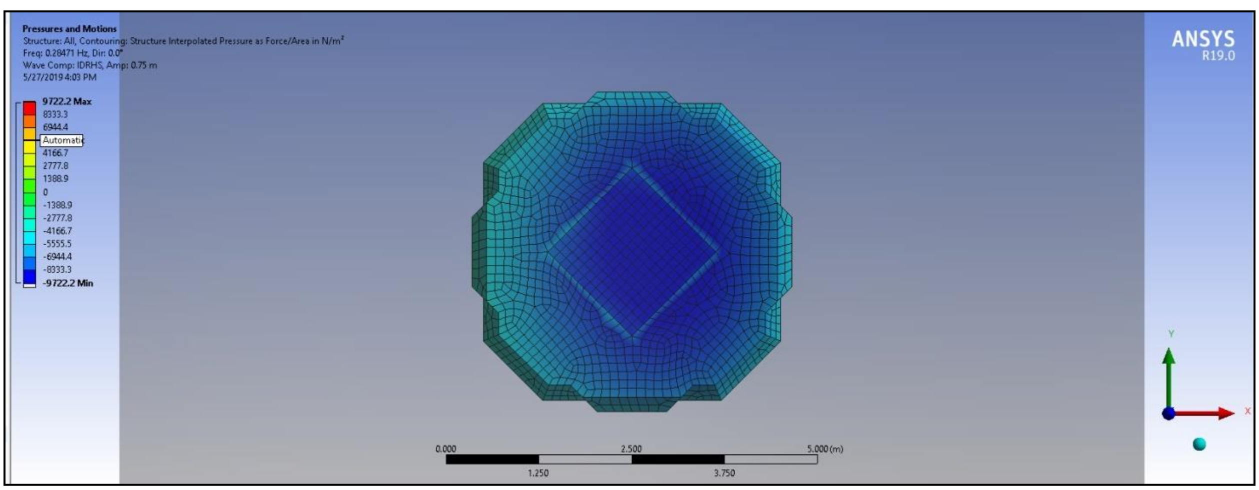

Figure 9: BEM pressure result at operating case – top view at wave phase with lowest pressure on the hatch.

The BEM solution allowed to extract the pressure acting solely on the hatch part of the absorber body and to be integrated into design loads used for the FEA analysis.

3.4 Structural Analysis and Structural Mass

In the following section the mass of the three main structural parts is determined to be used in the CCE calculation for ACE. The parts are designed using the Solidworks and a finite element analysis (FEA) is conducted to determine if the structural rigidity is sufficient to meet the requirements of a ULS analysis.

The first (pressure hull) and second parts (outer tubes) have to be analyzed in a combined analysis as the largest DLC occurs in a structurally coupled condition where static and dynamic pressure loads on the hull are combined and a worst-case constructive superposition is assumed.

Several iterations of stiffener and shell thickness have been conducted and the following results represent the structural arrangement that met the ULS requirements.

3.4.1 Structural Analysis Setup for Ultimate Limit Strength Analysis

In order to conduct the ULS structural analysis the derived design loads were used and a meshed CAD model for FEA was setup us as described in the following:

In the first step, the global FEA analysis setup is described where inertia relive was used as well as the pressure loads from the previous sections are applied on the respective panel groups as indicated in Table 5 below:

Table 5: Pressure groups, maximum group pressure and indicator color.

Group	Color
0	Red
1	Yellow
2	Orange
3	Brown
4	Green
5	Blue

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

3.5 Results of Structural Mass Analysis and CCE derivation

In the following the resulting CCE is calculated with the manufactured material cost (MMC) in [US$/kg] where

- **CCE_1: MMC = 3000$/tonne**
  Source: Funding Opportunity Announcement (FOA) Number: DE-FOA-0001663

- **CCE_2: MMC = 6000$/tonne**
  Source: Offshore wind lattice jacket, https://www.ceoe.udel.edu/File%20Library/Research/Wind%20Power/Publication%20PDFs/Industrializing-Offshore-Wind-Power-Final-2017.pdf

- **CCE_3: MMC = 2500$/tonne**
  Source: Offshore wind bucket construction, https://www.ceoe.udel.edu/File%20Library/Research/Wind%20Power/Publication%20PDFs/Industrializing-Offshore-Wind-Power-Final-2017.pdf

Table 6: CCE calculation.

Item #	Item	Mass [metric T]	CCE_1 [$]	CCE_2 [$]	CCE_3 [$]
1	Absorber Hull	257.6			
2	Hatch 1&2	23.4			
	Total Mass	**281.00**	**843000**	**1690000**	**700000**

4. ACE Summary

In coherence with the methodology used during the DOE's US Wave Energy Prize for ACE calculation during BP1 of CalWave's open water demonstration, ACCW was determined from scaled wave tank testing. Next to this methodology, ACE calculations were additionally performed using numerical simulation-based performance estimates for the six IWS cases. As a third alternative, and to increase the level of detail for realistic operation, ACE is calculated from hardware in the loop experiments in which CalWave's scaled PTO drivetrain for the demonstration scale deployment is used.

The following tables summarize the ACE calculations using

a) the ACCW calculation using IWS device performance estimates from the three different methodologies and
b) CCE estimates based on full scale device structural analysis using CFD and FEA tools

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy

2.1 Wave Tank Testing based ACCW

In the following the results for the ACCW calculation from tank testing are provided.

Table 7: ACE based on wave tank testing

ACE Calculation based on CalWave Wave Tank Testing (Maine - November 2018)										
Wave #	Tp	Hs	P (Tank)	Adjusted Weighting Each Climate						
ID	(s)	(m)	(kW)	Alaska	Washington	Northern Oregon	Oregon	Northern California	Southern California	Hawaii
IWS 1	7.29	2.34	241.39	24.30%	13.70%	15.50%	17.50%	20.70%	15.20%	32.80%
IWS 2	9.84	2.64	437.90	33.20%	27.70%	30.70%	26.80%	23.00%	27.00%	24.50%
IWS 3	11.54	5.36	172.67	7.50%	4.10%	5.60%	5.80%	1.20%	1.40%	0.10%
IWS 4	12.70	2.06	199.82	20.00%	33.80%	34.40%	29.50%	46.60%	39.10%	13.30%
IWS 5	15.25	5.84	327.16	2.40%	2.20%	3.70%	3.40%	1.60%	1.00%	0.00%
IWS 6	16.50	3.26	364.82	1.20%	4.50%	4.20%	5.40%	6.40%	9.50%	1.30%
Acc. weight				88.60%	86.00%	94.10%	88.40%	99.50%	93.20%	72.00%
<CP> (kW/m) =				35.5	32.7	39.3	37.9	31.5	31.2	16.8
AACW(j) (m) =				7.583	7.725	7.066	6.844	8.713	8.763	12.973
ACCW (m) =		8.5237								

2.2 Numerical Simulation based ACCW

In the following the results for the ACCW calculation from numerical simulations are provided.

Table 8: ACE based on numerical simulations.

ACE Calculation based on CalWave Wave Tank Testing (Maine - November 2018)										
Wave #	Tp	Hs	P (Tank)	Adjusted Weighting Each Climate						
ID	(s)	(m)	(kW)	Alaska	Washington	Northern Oregon	Oregon	Northern California	Southern California	Hawaii
IWS 1	7.29	2.34	315.39	24.30%	13.70%	15.50%	17.50%	20.70%	15.20%	32.80%
IWS 2	9.84	2.64	484.560	33.20%	27.70%	30.70%	26.80%	23.00%	27.00%	24.50%
IWS 3	11.54	5.36	709.580	7.50%	4.10%	5.60%	5.80%	1.20%	1.40%	0.10%
IWS 4	12.70	2.06	319.55	20.00%	33.80%	34.40%	29.50%	46.60%	39.10%	13.30%
IWS 5	15.25	5.84	337.140	2.40%	2.20%	3.70%	3.40%	1.60%	1.00%	0.00%
IWS 6	16.50	3.26	416.750	1.20%	4.50%	4.20%	5.40%	6.40%	9.50%	1.30%
Acc. weight				88.60%	86.00%	94.10%	88.40%	99.50%	93.20%	72.00%
<CP> (kW/m) =				35.5	32.7	39.3	37.9	31.5	31.2	16.8
AACW(j) (m) =				10.3587	10.4191	9.6001	9.3521	11.6262	11.4298	16.1186
ACCW (m) =		11.2721								

2.3 Hardware-In-the-Loop based ACCW

In the following the results for the ACCW calculation from hardware in the loop bench testing are provided.

Table 9: ACE based on hardware in the loop bench testing.

ACE Calculation based on CalWave Wave Tank Testing (Maine - November 2018)										
Wave #	**Tp**	**Hs**	**P (Tank)**	**Adjusted Weighting Each Climate**						
ID	**(s)**	**(m)**	**(kW)**	**Alaska**	**Washington**	**Northern Oregon**	**Oregon**	**Northern California**	**Southern California**	**Hawaii**
IWS 1	7.29	2.34	241.39	24.30%	13.70%	15.50%	17.50%	20.70%	15.20%	32.80%
IWS 2	9.84	2.64	437.90	33.20%	27.70%	30.70%	26.80%	23.00%	27.00%	24.50%
IWS 3	11.54	5.36	172.67	7.50%	4.10%	5.60%	5.80%	1.20%	1.40%	0.10%
IWS 4	12.70	2.06	199.82	20.00%	33.80%	34.40%	29.50%	46.60%	39.10%	13.30%
IWS 5	15.25	5.84	327.16	2.40%	2.20%	3.70%	3.40%	1.60%	1.00%	0.00%
IWS 6	16.50	3.26	364.82	1.20%	4.50%	4.20%	5.40%	6.40%	9.50%	1.30%
Acc. weight				88.60%	86.00%	94.10%	88.40%	99.50%	93.20%	72.00%
<CP> (kW/m) =				35.5	32.7	39.3	37.9	31.5	31.2	16.8
AACW(j) (m) =				TBD	TBD	TBD	TBD	TBD	TBD	TBD
ACCW (m) =	TBD									

2.4 ACE Summary Table

In the following the results for the ACE for the considered input parameters of the MMC and ACCW calculation is provided.

Table 10: ACE calculation based on MMC and ACCW variables.

		MMC ($/mt)		
		6000	3000	2500
ACCW (m)	8.524	5.056	10.111	12.133
	11.272	6.686	13.371	16.046
	TBD	TBD	TBD	TBD

1387 Scenic Ave, Berkeley, California, 94708 - +1 510-508-9897 - team@CalWave.energy