Holistic Control Embedded PTO Development

DE-EE0008632.0000

Budget Period 1

Task 1.2 Target Metrics Identification and Benchmarking

Target Performance Metrics Definitions Catalogue

June 2019

1387 Scenic Ave, Berkeley, California, 94708 - +1 510 - 717 – 6254 team@CalWave.org

CONTENTS

FIGURES

VARIABLES & DEFINITION

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:

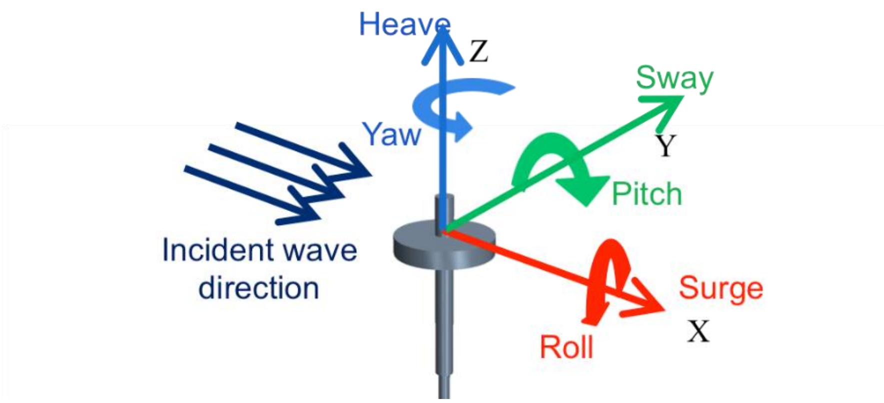

Figure 1: Global Coordinate System Position and Orientation used throughout this report. Picture / Scheme by WECSim - Theory section (https://wec-sim.github.io/WEC-Sim/theory.html)

GLOSSARY

PAR	Peak to Average Ratio
PCC	Power Conversion Chain
PTO	Power Take-Off
WEC	Wave Energy Converter

1 Introduction

This report was generated during Budged Period 1 of the DOE-EERE 'Marine and Hydrokinetic Technology Development and Advancement' grant with project number DE-EE0008632.0000. This project aims to advance the Technology Readiness Level (TRL) of CalWave's commercial scale Power Take-Off (PTO) subsystem through further increasing the level of coupling in physical PTO and concurrent controls design. This is achieved by incorporating a systematic holistic controls design into the TRL advancement of the PTO subsystem development, where the TRL advancement of the PTO is inherently coupled to the development of the WEC absorber body's hydrodynamic tuning approach (HyTune) in addition to the control method applied to the PTO itself.

This report falls under Task 1.2 - Target Metrics Identification and Benchmarking. The report can be used as a catalogue describing metrices summarizing most important performance figures for the PTO sub-system. As PTO and device performance figures are closely coupled, metrices listed in this report furthermore embrace total device characteristics.

Metrics definitions in Chapter 2 – Metrics Identification and Definitions include equations for calculating and precise definitions of input parameter/data/information. Metrics are clustered according to scope: **Individual PTO**, **Power Conversion Chain** (PCC, infrastructure shared among all PTOs), and **Device** (all PTOs in coordination with the WEC hydrodynamic response). Importance and impact on the PTO and overall device design are outlined. The desired direction for improvement (↑ when performance improvement increases the metric value, respectively ↓ for lower metrics value is desirable) is provided for each metric.

Finally, Chapter 3 – Metrics Evaluation includes evaluation of the most important performance metrics at three stages: 4.1 State of the Art from literature, 4.2 CalWave Internal estimates at project start, and 4.3 CalWave target values to be achieved over the course of the project. Section 4.4 is a brief plan for when and how metrics will be re-evaluated and compared to the target values provided in 4.3.

1387 Scenic Ave, Berkeley, California, 94708 - +1 510 - 717 – 6254 team@CalWave.org

2 Metrics Identification and Definitions

The metrics definitions listed in this chapter are organized by physical signal types and sub-component group. Usually statistical metric calculations do not change depending on what physical property (e.g. power, force, velocity etc.) is assessed. If not otherwise stated, metrics are defined regarding a single CalWave device unit and the metric unit system is used.

2.1 Individual PTO Sub-System Metrics

The following metrics target to summarize efficiency figures related to a single, physical PTO unit. Due to the XWave's topology including four individual PTO units with shared sub-components/auxiliaries these metrics are separated from the power conversion chain metrics in Chapter 2.2.

1. **$PPAR_{PTO,Gen}$: Peak to Average Ratio of the individual PTO power during power generation cycles ↓**: This metric describes the capability of the individual PTO and/or device control capability to reduce peak power to mean power during the generation/power absorption cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PTO,Gen} = \max\left[\frac{\max\left(P_{PTO,i}(P_{PTO,i} > 0)\right)}{mean\ (P_{PTO,i}(P_{PTO,i} > 0))}\right]$$

$P_{PTO,i}$ Instantaneous power of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metrics. PTO power absorption is defined as positive power; PTO power consumption is defined as negative power.

Baseline targets to improve can be found in literature stating ratios 15:1 [Quo16] up to 30:1 for annual average energy production (AAEP) compared to rated power [Yih18]. The upper threshold of 41:1 is based on physically tested PTO setups that have reported instantaneous absorbed power peak to average ratios up to 41:1 [Quo16]. Design target for instantaneous peak to average power ratio for both generation as well as consumption cycle is set to not exceed a ratio of 30:1.

2. **$PP2M_{PTO,Con}$: Peak to Average Ratio of the individual PTO power during power consumption cycle ↓**: This metric describes the capability of PTO and/or device control

means to reduce peak power to mean power during the consumption cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PTO,Con} = max\left[\frac{\max\left(P_{PTO,i}(P_{PTO,i}) < 0\right)}{mean\ (P_{PTO,i}(P_{PTO,i}) < 0)}\right]$$

$P_{PTO,i}$ Instantaneous power of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metrics. PTO power absorption is defined as positive power; PTO power consumption is defined as negative power.

3. **$PPAR_{PTO}$: Peak to Average Ratio of the individual PTO power during all cycles ↓**: This metric describes the capability of PTO and/or device control means to reduce peak power to mean power during any cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PTO,Con} = max\left[\frac{\max\left(P_{PTO,i}\right)}{mean\ (P_{PTO,i})}\right]$$

$P_{PTO,i}$ Instantaneous power of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metric. Whereas the mean of the PTO power is expected to be positive (net positive output), power peaks can occur either during generation or actuation of the PTO.

4. **$FPAR_{PTO,Gen}$: Peak to Average Ratio of the individual PTO force during power generation cycle ↓**: This metric describes the capability of PTO and/or device control means to reduce peak force to mean force during the power generation cycle.

$$FPAR_{PTO,Gen} = \frac{\max\left(F_{PTO,i}(P_{PTO,i} > 0)\right)}{mean\ (F_{PTO,i}(P_{PTO,i} > 0)}$$

$F_{PTO,i}$ Force of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metric. As PTO units are constantly providing a pre-tension due to the positive buoyancy of the absorber body, forces are always positive. Negative forces are explicitly avoided via minimum line tension control to prevent slack events in the taut mooring.

The maximum instantaneous peak value is used for the calculation of this metric. This differs from existing approaches where the statistical value among all forces exceeding the 95% threshold is used.

1387 Scenic Ave, Berkeley, California, 94708 - +1 510 - 717 – 6254 team@CalWave.org

Previous wave tank experiments and simulations conducted by CalWave have shown that Peak to average force ratios can reach up to 10:1 for severe sea states. Design target ratio for the proposed project is a reduction to 5:1 instantaneous ratio for severe sea states.

5. **$FPAR_{PTO,Con}$: Peak to Average Ratio of the individual PTO force during power consumption cycle ↓**: This metric describes the capability of PTO and/or device control means to reduce peak force to mean force during the power consumption cycle.

$$FPAR_{PTO,Con} = \frac{\max\left(F_{PTO,i}(P_{PTO,i} < 0)\right)}{mean\ (F_{PTO,i}(P_{PTO,i} < 0))}$$

$F_{PTO,i}$ Force of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metric. As PTO units are constantly providing a pre-tension due to the positive buoyancy of the absorber body, forces are always positive. Negative forces are explicitly avoided via minimum line tension control to prevent slack events in the taut mooring.

The maximum instantaneous peak value is used for the calculation of this metrics. This differs from existing approaches where the statistical value among all forces exceeding the 95% threshold is used.

6. **$FPAR_{PTO}$: Peak to Average Ratio of the individual PTO force ↓**: This metrics describes the capability of PTO and/or device control means to reduce peak force to mean force, without differentiating between power or consumption cycle.

$$FPAR_{PTO} = \frac{\max\left(F_{PTO,i}\right)}{mean\ (F_{PTO,i})}$$

$F_{PTO,i}$ Force of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metric. As PTO units are constantly providing a pre-tension due to the positive buoyancy of the absorber body, forces are always positive. Negative forces are explicitly avoided via minimum line tension control to prevent slack events in the taut mooring.

The maximum instantaneous peak value is used for the calculation of this metrics. This differs from existing approaches where the statistical value among all forces exceeding the 95% threshold is used.

7. **$xPAR_{PTO}$: Peak to Average Ratio of the individual PTO displacement** ↓: This metrics describes the ratio between the peak displacement to mean displacement during all operations of the PTO unit:

$$xPAR_{PTO} = \frac{\max\left(abs(x_{PTO,i})\right)}{mean\left(abs(x_{PTO,i})\right)}$$

$x_{PTO,i}$ Displacement of PTO i

Note that the largest value among all PTOs is used as the upper limit of this metric. The ratio is a measure of how much of the total PTO stroke is effectively used. Small ratios indicate a good usage of the designed/available PTO stroke. Although this metric is a performance metric, the impact on LCOE will depend on the marginal cost of additional PTO stroke.

8. **Individual PTO Quadrant Controllability - :** Capability of the PTO and/or controls for full four quadrant control including active and re-active parts. This metric is a binary ("pass/fail") evaluation criteria. The four-quadrant control capability relates to the ability of the PTO system to extract energy from the system and actuate the system in all four combinations of force and velocity directions. Note that this requirement does not necessarily demand that the electric machine must have the four-quadrant control capability.

9. **Phase Margin - PM - :** Phase margin of the closed loop controller for an individual PTO must stay positive. Thus, the phase at the zero-crossing magnitude frequency of the PTO's frequency response must stay below 180° to achieve close-loop stability.
10. **Gain Margin - GM - :** The gain margin of the closed loop control must stay positive and

$$PM = Phase(Gain = 0db) + 180°$$

in a reasonable range for a robust controller.

$$GM = 0 - Gain(Phase = -180°)$$

11. **PTO Bandwidth** ↑: The PTO bandwidth describes the capability of the PTO and/or controls to achieve required force tracking in a range of operational frequencies. The design target is attenuation of -3 dB for frequencies that are 2 times of the highest operating frequency. Hence, the bandwidth of the PTO controlling the device is defined on the high frequency side by the commonly used half-power point at which the power of the PTO force signal has dropped to half of its maximum (i.e. passband value which correlates to the -3dB margin). On the low frequency side such a cutoff frequency is not defined.

2.2 Power Conversion Chain Metrics

The following metrics target to summarize efficiency figures related to the common/shared infrastructure used by all four individual PTO units. Due to the XWave's topology including four individual PTO units with shared subcomponents/auxiliaries these metrics are separated from the individual PTO metrics in Chapter 2.1. Hence, forces and/or displacement related metrics are not defined for the power conversion chain metrics like they are for the individual physical PTO units. Power metrics dominate the characteristics of a well-designed PCC.

1. **$PPAR_{PCC,Gen}$: Peak to Average Power Ratio of the PCC during power generation cycles ↓**: The peak power to mean power on the shared infrastructure such as the voltage bus or a common mechanical rotating shaft is evaluated during the generation/power absorption cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PCC,Gen} = \frac{\max\left(P_{PCC}(P_{PCC} > 0)\right)}{mean\left(P_{PCC}(P_{PCC} > 0)\right)}$$

P_{PCC} Instantaneous power on the shared PCC

PTO power absorption is defined as positive power; PTO power consumption is defined as negative power.

Baseline targets to improve can be found in literature stating ratios 15:1 [Quo16] up to 30:1 for annual average energy production (AAEP) compared to rated power [Yih18]. The upper threshold of 41:1 is based on physically tested PTO setups that have reported instantaneous absorbed power peak to average ratios up to 41:1 [Quo16]. Design target for instantaneous peak to average power ratio for both generation as well as consumption cycle is set to not exceed a ratio of 30:1.

2. **$PPAR_{PCC,Con}$: Peak to Average Ratio of the PCC during power consumption cycles ↓**: The peak power to mean power on the shared infrastructure such as the electric bus or a common mechanical rotating shaft is evaluated during the consumption/actuation cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PCC,Con} = \frac{\max\left(P_{PCC}(P_{PCC} < 0)\right)}{mean\left(P_{PCC}(P_{PCC} < 0)\right)}$$

P_{PCC} Instantaneous power on the shared PCC

PTO power absorption is defined as positive power; PTO power consumption is defined as negative power.

3. **$PPAR_{PCC}$: Peak to Average Ratio of the PCC** ↓: The peak power to mean power on the shared infrastructure such as the electric bus or a common mechanical rotating shaft is evaluated during any cycle for different timescales (e.g. second to second, minute to minute, sea state to sea state).

$$PPAR_{PCC} = \frac{\max\,(P_{PCC})}{mean\,(P_{PCC})}$$

P_{PCC} Instantaneous power on the shared PCC

PTO power absorption is defined as positive power; PTO power consumption is defined as negative power.

2.3 Device Metrics

Metrics and wording labeled with * are directly taken from [WPTO18].

1. **LCOE - Levelized Cost of Energy*** ↓: LCOE is the total system cost per energy output based on annual average values, lifetime of the technology, and financing assumptions. It is a standard cost metric used to evaluate all electricity producing technologies in a market. It can be used for utility scale, or distributed markets, with the competitive thresholds varying based on market conditions. LCOE is a single metric for a complete system, where the system value is supported by underlying cost and performance information

$$LCOE = \frac{ICC \times FCR + OPEX}{AEP}$$

LCOE	Levelized cost of energy ($/MWh)
ICC	Initial capital cost per installed capacity ($/MW)
AEP	Annual energy production per installed capacity (MWh/MW/year=hours/year); AEP = CFx365x24
FCR	Fixed charge rate is the annual return, represented as a fraction of installed capital costs, needed to meet investor revenue requirements, FCR=10.8% in DOE guidance
OPEX	Operations and maintenance costs, including all routine maintenance, operations, and monitoring activity (i.e., non-depreciable) ($/MW/year)
CF	Capacity factor averaged over typical year (%). Note: must be consistent with the estimated ICC

Extensive information is needed to calculate LCOE, and estimates can only improve at higher TRLs. LCOE depends on the resource, and therefore tracking or comparing values should use a consistent and technology suitable resource (a joint probability distribution of sea states for wave, and a probability distribution of velocities for tidal). LCOE depends on the FCR, and per DOE guidance FCR is set to 10.8% in this project.

2. **CF_{Device} – (Device) Capacity Factor** ↑: The capacity factor describes the average electrical power generated by the WEC device divided by the device rated peak power.

$$\boldsymbol{CF} = \frac{mean(P_{Device})}{\max(P_{Device})}$$

Average electrical power	Average electrical power exported [kW]
Rated peak power	Rated export power [kW]

The average electrical power is dependent on the resource (site) selected. When comparing values, a consistent resource should be used.

3. **CWR – Capture Width Ratio* ↑:** Hydrodynamic absorber conversion efficiency as a function of significant wave height Hs and dominant wave period Tp.

$$\boldsymbol{CWR} = \frac{CW}{B} = \frac{P}{J \times B}$$

CW	Capture width, CW = P/J [m]
P	(mechanical) absorbed wave power [kW]
J	Wave resource power per meter of wave crest [kW/m]
B	Characteristic width of the device [m]

Note that although CWR does includes neither the individual PTO nor total PCC conversion efficiency, this hydrodynamic efficiency is affected by the PTO's dynamic characteristics.

4. **W2W - Wave2Wire Efficiency ↑:** This is the total efficiency of the device to convert energy in the incident ocean wave into electricity at shore, and thus includes: hydrodynamic conversion efficiency via CWR, mechanical and electrical PTO conversion efficiency via η_{PCC}, and transmission efficiency via the devices subsea cable connection/hub. W2W is a function of significant wave height Hs and dominant wave period Tp:

$$\boldsymbol{W2W} = CWR \times \eta_{\mathrm{PCC}} \times \eta_{\mathrm{Transmission}}$$

CWR	Capture Width Ratio
η_{PCC}	PCC efficiency from mechanical input to electric output
$\eta_{Transm.}$	Transmission efficiency to shore or hub

Due to the nature of the PTO design influencing the device behavior and thus hydrodynamic absorption efficiency (and conversely, the device behavior influencing the PTO efficiency) it is critical to merge both allegedly separated efficiencies into one metric. A high PTO efficiency alone might be achievable but can, potentially, have a negative effect on the device performance. On the other hand, optimizing solely hydrodynamic efficiency can lead to a required PTO behavior only achievable via low efficient PTO operations. The tight coupling of PTO performance and WEC performance is the nexus of this project.

A combined average power conversion efficiency of approximately 25% serves as a baseline. Note that for this combined conversion efficiency, device effectiveness in absorbing wave power was calculated using an averaging approach as described in [Dal18]. LCOE of a commercial scale WEC in $/kWh including cost per installed capacity in $/kW.

4 Metrics Evaluation

State of the art metrics values from literature are organized and sorted into the most important, identified metrics from Chapter 2 – Metrics Identification and Evaluation. This document will provide the benchmark against which final reporting will be validated.

4.1 Individual PTO Sub-System Metrics

1. **$PPAR_{PTO,Gen}$: Peak to Average Ratio of the individual PTO power during generation and consumption cycles ↓:**
   Baseline state of the art values to improve upon can be found in literature stating ratios 15:1 [Quo16] up to 30:1 for annual average energy production compared to rated power [Yih18]. For instantaneous absorbed power measured peak to average ratios on built PTO setups of up to 58.6 [Ted], 41:1 [Quo16], or a range of 30:1 to 73:1 [Hen16] have been reported and thus set the upper threshold. Other sources such as [Han13] or [Ted10] document an improvement of the ratio using appropriate controls down to 13:1 which aligns with CalWave targets for ratios for an individual PTO unit.

   CalWave's internal baseline of the $PPAR_{PTO}$ ratio is derived from simulations with the simplest low-level PTO controller (e.g. no peak shaving/capping). The ratio is derived as a function of significant wave height and dominant wave period as shown in Figure 2.

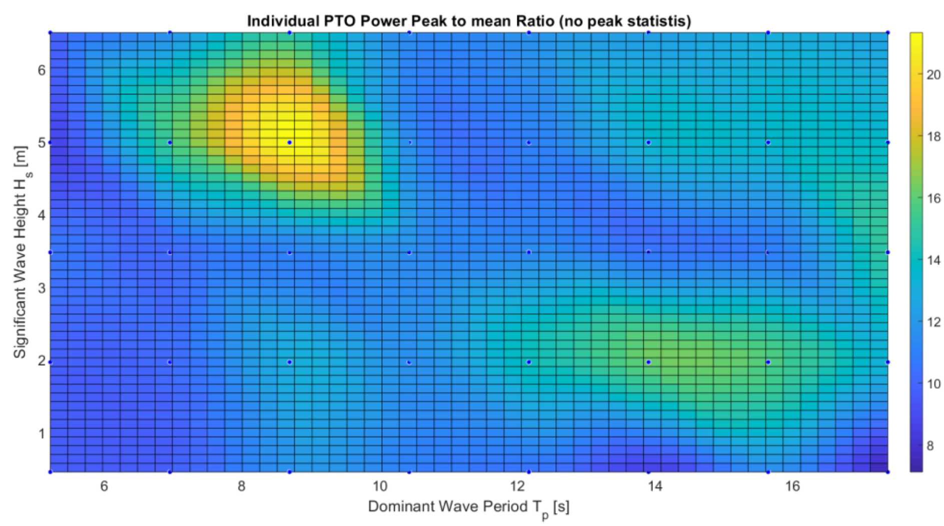

Figure 2: CalWave Internal Baseline: $PPAR_{PTO}$ ratio during the generation cycle. The absolute peak values recorded throughout the simulations were used for these ratios.

   Note, that a) all wave state were simulated as Brettschneider wave spectra and b) that the largest value among all PTOs is used as the upper limit of this metrics. Whereas the mean of the PTO power is expected to be positive (net positive output), power peaks can occur either during generation or actuation of the PTO.

If rather than the absolute peak value the mean of the top 95% values are used the distributions changes and is shown as shown in Figure 3. Note that the color scale in Figure 3 is the same as Figure 2, allowing direct comparison at a given Hs-Tp point.

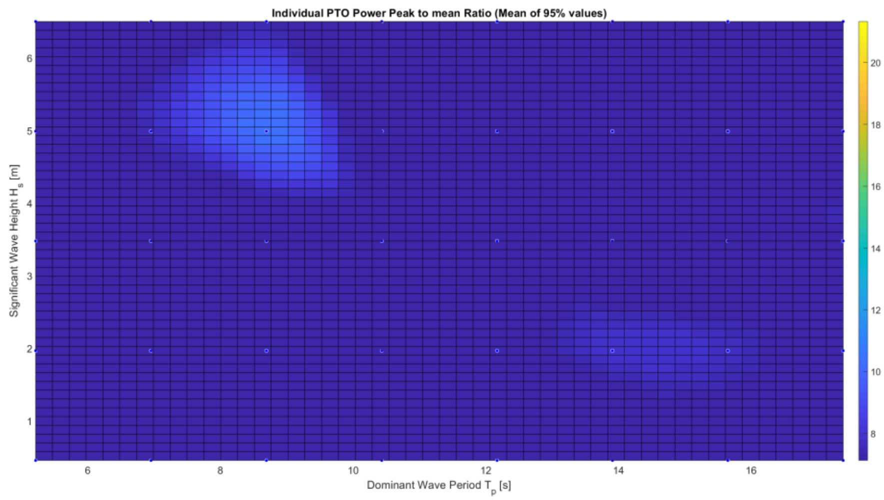

Figure 3: CalWave Internal Baseline: peak to average power ratio during the power generation cycle. The mean of all values exceeding 95% of the absolute peak were used for this figure.

Similar, the peak to average ratios for the consumption cycle can be assessed:

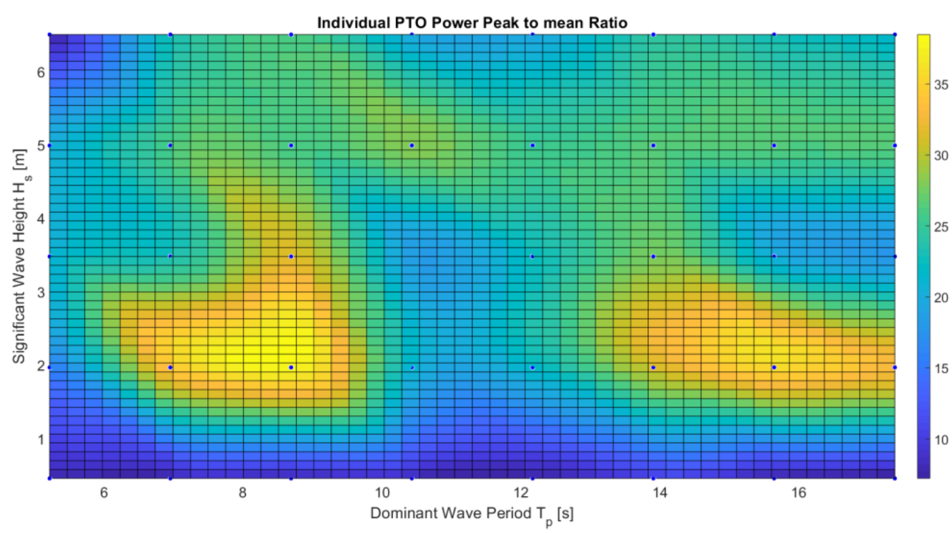

Figure 4: CalWave Internal Baseline: peak to average power ratio during consumption cycle. The absolute peak values occurred during the consumption cycle throughout the simulations were used for these ratios

And using a statistical peak value as the mean of the top 95% values:

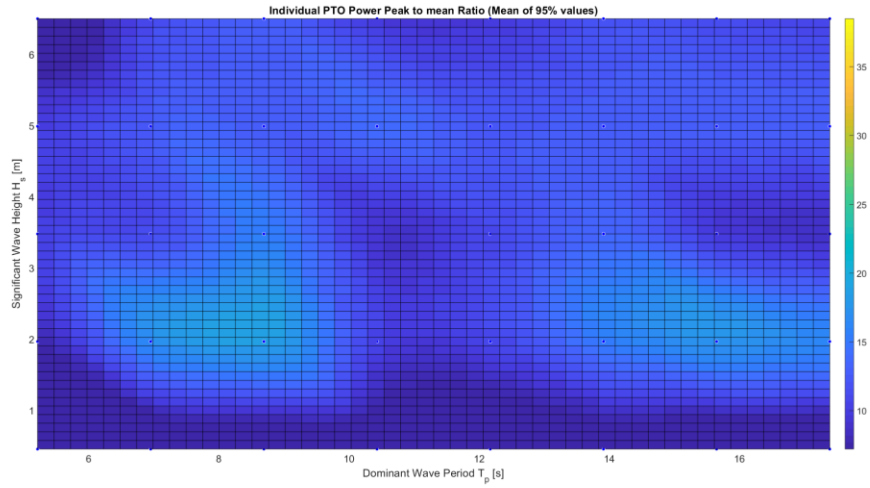

Figure 5: CalWave Internal Baseline: peak to average power ratio during consumption cycle. The mean of all values exceeding 95% of the absolute peak were used for this figure.

CalWave targets power Peak to Average Ratios of less than 10:1 for both, consumption as well as generation cycle when using the mean of all peak values exceeding the 95% percentile (statistical peak to average formulation).

2. **$FPAR_{PTO,Gen}$: Peak to Average Ratio of the individual PTO force during all cycles↓**: Previous tank experiments and simulations conducted by CalWave have shown that peak to average force ratios can reach up to 10:1 for severe sea states. Design target ratio for the proposed project is a reduction to 5:1 instantaneous ratio for severe sea states.

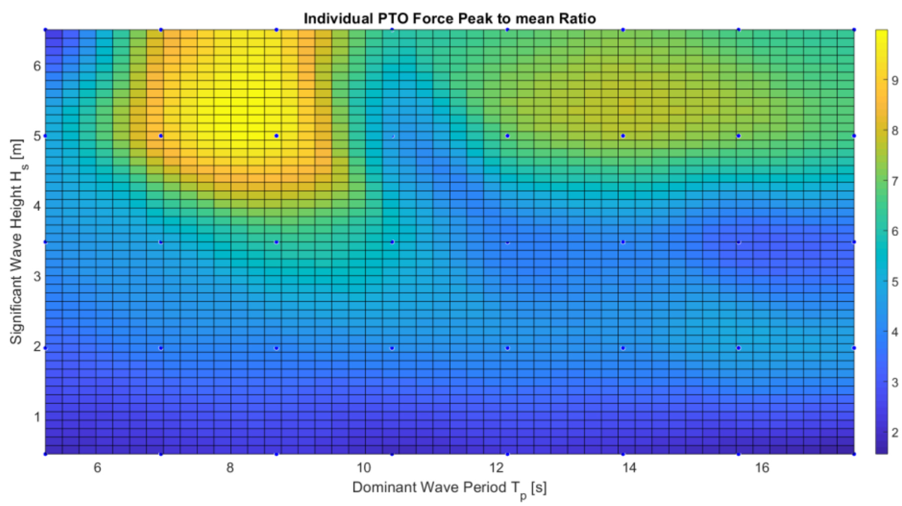

Figure 6: CalWave internal baseline: peak to average force ratio during all cycles (generation or consumption). No statistical peak calculation was applied.

3. **xPAR$_{PTO}$: Peak to Average Ratio of the individual PTO displacement ↓:**
CalWave's internal baseline derived from mid-fidelity, PTO agnostic simulations is shown in Figure 7.

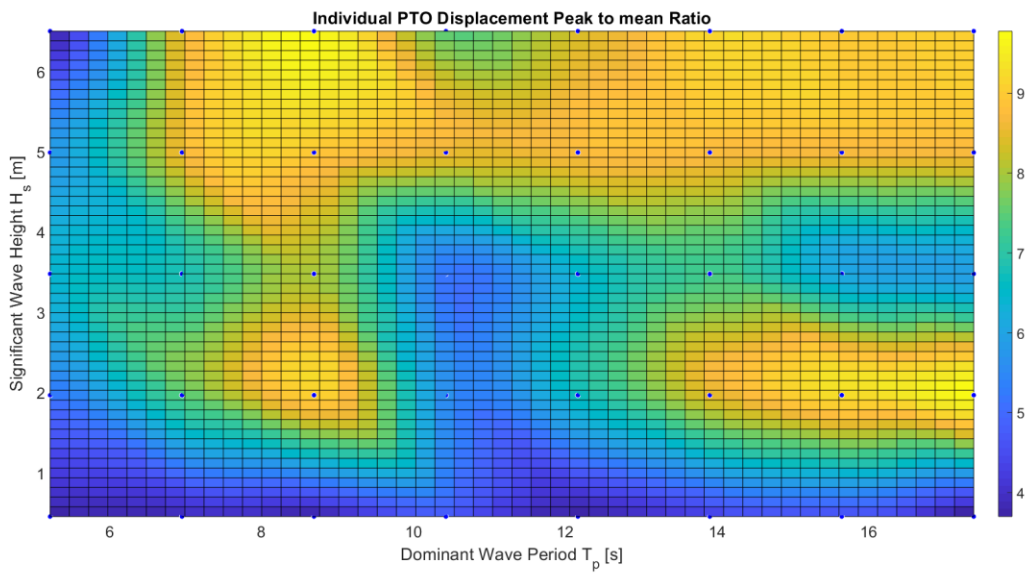

Figure 7: CalWave internal baseline: peak to average displacement ratio during all cycles (generation or consumption). No statistical peak calculation was applied.

CalWave targets displacement peak to average ratios across the given pallet of wave states of less than 7.

4. **PTO Bandwidth ↑:**
CalWave was not able to find explicit literature for wave power conversion systems assessing PTO bandwidth properties. In most literature assessing device properties the PTO capability is assumed to be infinite in terms of PTO bandwidth and excitation capability which, obviously, is not practical.

Calwave targets an attenuation of roughly -3 dB for frequencies around 0.4 Hz (T=2.5 seconds). No target is set for the low frequency side.

4.2 Power Conversion Chain Metrics

1. **PP2AR$_{PCC}$: Peak to Average Ratio of the PCC Power ↓:**
Most of the peak to average metrics found in literature are for devices using a single PTO architecture. Thus, literature values listed in the Individual PTO Sub-System Metrics section for peak to average ratios of individual PTO units also apply for the Power Conversion chain assessment.

Hence, peak to average power ratios in the range of 30:1 up to 73:1 are commonly reported.

Again, CalWave's internal baseline can be plotted as a function of the significant wave height and dominant wave period:

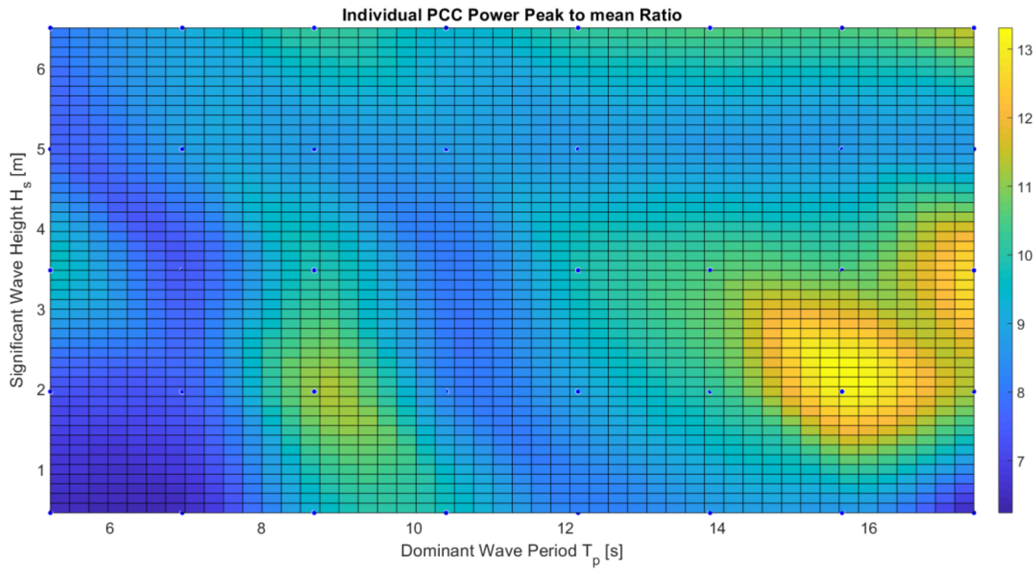

Figure 8: CalWave internal baseline: Peak to average PCC Power ratio during all cycles (generation or consumption). No statistical peak calculation was applied.

The distribution of the PCC power without explicit control strategies to cap or shave the power peaks already show the advantage of using a four-PTO setup with shared PCC infrastructure. The baseline Peak to Average Ratios are already lower than what is commonly states in literature.

CalWave targets a PCC peak to average power ratio of less than 10 for all the shown wave states which mean that especially for long period waves the ratios is targeted to be reduced.

4.3 Device Metrics

1. **LCOE - Levelized Cost of Energy ↓**:
   Due to the nascent stage of the ocean energy industry, the current baseline for LCOE for wave energy has a wide and unproven range, but a baseline LCOE of 0.22-0.67 $/kWh have been reported as estimates [DOE17]. Further sources report LCOE of 0.2 – 0.9 $/kWh as a function of energy density in the wave resource [San16].

   CalWave projected estimates for target LCOE in the context of a total installed capacity of 30MW and thus including economies of scale are in the order of $0.15/kWh. Due to the high uncertainty of additionally factors like CAPEX and installation costs the LCOE estimates inherently incorporate high uncertainty, too. Removing the OPEX estimates from the metrics leads to cost per installed capacity in $/kW which can serve as an additional metric. CalWave's estimate for this is in the order of 9,000 $/kW [WEC16].

2. **CF_{Device} – (Device) Capacity Factor ↑:**
The device's capacity factor is a resource dependent function once the power rating of the device is fixed. Ideally, for different resources the devices power rating is optimized based on the extractable energy over the entire year and the capacity factor is derived.

Assuming such an ideal design process upper limits of capacity factors of 20% up to 50% [San16] are stated in literature. Lower estimates for existing devices at various resources are, for example, derived in [Rus18] and range from 4.23% to 28.8% as shown in Figure Figure 9. Experimentally found capacity factors are stated in [Iba18] and indicate a value of 11%.

		Region			
WEC		Iceland	Azores Islands	Madeira Archipelago	Canary Islands
Wave Dragon	Cf	43.4	42	28.8	21.7
	CW	62.1	49.4	50.2	66.4
Pontoon Power Converter		9.45	5.58	4.23	3.48
		10.1	4.32	4.76	7.06
Sea Power		17.1	15.4	10.1	7.08
		13.7	10.2	10.2	12.1
OE		11.7	10.4	6.25	4.06
		8.51	5.48	5	5.5
Wave Star		13.8	12.5	7.57	4.84
		9.41	6.27	5.69	6.27
AWS		23.6	23.2	16.9	11
		9.68	10.3	11.1	11.5

Figure 9: Capacity factor and Capture Width of various WECS at different resources. Table taken from [Rus18]

CalWave targets annual average capacity factors for a device specifically designed for a given resource to exceed 50%.

3. **W2W - Wave2Wire Efficiency**
Whereas WEC device hydrodynamic efficiency is commonly used as a performance metrics in literature, the full wave to wire efficiency as a function of significant wave height and dominant wave period was not found in literature.

CalWave internal baseline for the wave to wire efficiency is plotted as a function of the significant wave height and dominant wave period in Figure 10. A PTO efficiency of 60% is assumed for this preliminary baseline value; more accurate estimates, as a function of significant wave height and dominant wave period, will be found in numerical modeling and bench testing.

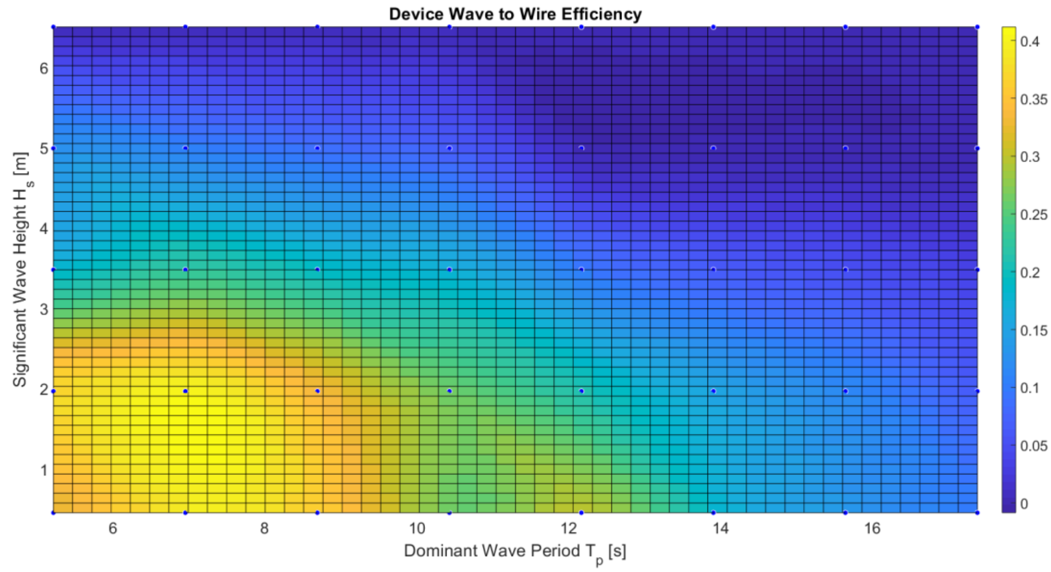

Figure 10: CalWave internal baseline: Wave to Wire efficiency as a function of significant wave height and dominant wave period.

4.4 Evaluation Plan

Calculation of all metrics defined in Chapter 3 are included in the standard post processing routine for the Simulink/Mid-Fidelity simulation. Metrics are ideally evaluated for a broad range of combination of significant wave heights and dominant wave periods to obtain interpolation surfaces for precise analysis. However, as this procedure can take long times, for assessment of specific PTO and PCC configuration mid-fidelity models might be used in combination with a set of target site specific wave cases (IWS cases from the Wave Energy Prize [DRE18]. The best estimate for each metric is thus updated continuously throughout the project as PTO and Control design and optimization proceeds.

The assessment of a general Hs-Tp table for a broad range of sea states (grid of roughly 40 design points) will be conducted at least once before the end of Budget Period 1 and can be used to assess the final PTO and controls design before entering BP2 including the built and experimental testing phase.

REFERENCES

[WPTO18] – Existing Ocean Energy Performance Metrics – WPTO & National Laboratories White Paper – May 16th 2018 - https://eere-exchange.energy.gov/FileContent.aspx?FileID=89a224a1-6062-4567-a52d-66ddca0aa158

[DRE18] - Driscoll et al – Wave Energy Prize Testing And Data Analysis Overview

[Iba18] Ibarra-Berastegi et al, Electricity production, capacity factor, and plant efficiency index at the Mutriku wave farm (2014–2016), Ocean Engineering 147:20-29, Jan. 2018, DOI: 10.1016/j.oceaneng.2017.10.018

[Hen16] J.C.C. Henriques et al: Peak/Power control of a grid/integrated oscillating water column wave energy converter; http://dx.doi.org/10.1016/j.energy.2016.04.098

[San16] Sandberg et al, Article Critical Factors Influencing Viability of Wave Energy Converters in Off-Grid Luxury Resorts and Small Utilities, Sustainability 2016, 8, 1274; doi:10.3390/su8121274

[Rus18] Eugen Rusu and Florin Onea, A review of the technologies for wave energy extraction, Clean Energy, 2018, Vol 2, No. 1, 10-19

[Ted] Tedeschi, E., Carraro, M., Molinas, M., and Mattavelli, P., 2011. “Effect of control strategies and power take-off efficiency on the power capture from sea waves,” IEEE Transactions on Energy Conversion, 26(4), pp. 1088–1098.

[Han13] Rico H. Hansen et al – Discrete Displacement Hydraulic Power Take-Off System for the Wavestar Wave Energy Converter, Energies 2013, 6, doi:10.3390/en6084001

[Ted10] E. Tedeschi and M. Molinas – Control Strategy of Wave Energy Converters Optimized Under Power Electronics Rating Constraints

[DOE17] U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Marine and Hydrokinetic [MHK] Technology: Background Information Marine and Hydrokinetics Distributed and Alternate Applications Forum November 2017, https://www.energy.gov/sites/prod/files/2017/12/f46/MHK%20Background%20Info.pdf;

[WEC16] Word Energy Council, World Energy Resources – Marine Energy 16; Table 4 page 26