DISCLAIMER

Final Technical Report

DE-EE0009956: Centipod WEC Design for PacWave

Recipient:	**Dehlsen Associates LLC**
Award Number:	DE-EE0009956
Project Title:	Centipod WEC Design for PacWave
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Executive Summary

This project developed a Wave Energy Converter (WEC) system design that was ready for fabrication, deployment, and prototype testing at PacWave. The WEC design incorporated the International Electrotechnical Commission (IEC) Technical Specifications (TS) and Institute of Electrical and Electronics Engineers (IEEE) standards to ensure that designs are fully ready to utilize for future fabrication and open-water testing. Moreover, the project began the certification process with a certification provider, allowing for a seamless continuation into future work beyond project-end.

This scope was informally split into two phases:

1) a preliminary design phase where the conceptual development of the WEC system was established and solidified, leading to a Preliminary Design Review (PDR), and;
2) a final design phase where the WEC design was advanced through thorough engineering processes, leading to a Final Design Review (FDR) which confirmed standards compliance and PacWave deployment feasibility.

Project work has allowed Dehlsen Associates to complete a WEC design suitable for fabrication and testing at the PacWave South test site, and coordination with a certification body has put DA on track to acquire prototype certification of the LN6 WEC upon testing. Economic modelling conducted in parallel with the design efforts has strengthened the case for a viable business case for this WEC technology. Dehlsen Associates will therefore work in the coming years to conduct at-sea testing, unlocking the commercial potential of the technology developed over this project.

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NOTE:

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Long-term development of the Centipod Wave Energy Converter including the accomplishments discussed herein would not have been possible without the support and vision of many DOE project managers.

Contents

Definitions and Acronyms

Table 1 - Definitions

Term	Definition
AHV	Anchor Handling Vessel
Cap-Ex	Capital Expense
C1P6	Centipod 1P6 WEC (renamed Anacapa LN6)
DA	Dehlsen Associates
DLC	Design Load Cases
DEL	Damage Equivalent Load
DEA	Drag Embedment Anchors
FCR	Fixed Charge Rate (for LCOE calculation)
FDR	Final Design Review
FEED	Front-End Engineering Design
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
LCOE	Levelized Cost of Energy
LN6	Anacapa LumaNet 6m diameter WEC
LUMA	Linear Universal Modular Absorber
MPC	Model Predictive Control
NMPC	Non-linear Model Predictive Control
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
Op-Ex	Operational Expense
PacWave	PacWave South Test Site in Newport, OR, USA
PDR	Preliminary Design Review
PET	Poly-Ethylene Terephthalate
PNNL	Pacific Northwest National Laboratory
PTO	Power Take-Off
RL	Reinforcement Learning
SoF	Statement of Feasibility
SRD	System Requirements Document
TQ	Technology Qualification
TRL	Technology Readiness Level
TS	Technical Specification
VPMLG	Vernier Permanent Magnet Linear Generator
WEC	Wave Energy Converter
ULS	Ultimate Limit State

Introduction

Project Objective

The objectives of this project aligned with the FOA-0002415: Advancing Wave Energy Technologies through Open Water Testing at PacWave [1] goals for Topic Area 2, Advancing Wave Energy Converter (WEC) Designs for PacWave. Namely, by end-of-project Dehlsen Associates LLC (DA) aimed to have achieved:

1. Design of a WEC and associated mooring system capable of two years continuous performance testing, and station keeping at the PacWave-South test site [2].
2. Design of a WEC and ancillary systems in accordance with the International Electrotechnical Commission (IEC) and Institute of Electrical and Electronics Engineers (IEEE) standards.
3. Development of robust manufacturing, deployment, testing, and decommissioning plans for a future PacWave test. The plans clearly describe how PacWave testing will advance the proposed WEC system towards commercialization and how testing will comply with standards (e.g., IEC TS 62600-3, 62600-103, 62600-30, 62600-100).
4. Design of a system that has an annual average power rating greater 100 W when deployed in the PacWave resource.

Technology Background

Dehlsen Associates' (DA) LumaNet[1] (LN) class WEC is a point-absorber that combines novel subsystem solutions, the LUMA linear direct drive PTO, and the NetBuoy inflatable prime mover into a lightweight and reliable architecture. Thanks to the modular PTO design and inflatable prime mover, this technology can easily scale as the wave energy market matures. The LN6 configuration is shown in Figure 1.

LN6 WEC Specification

Parameter	Value
WEC Type	Two-body point absorber
Mooring Type	Taut vertical line
Diameter	6.00m
Freeboard	4.00m
Draft	16.75m
PTO Rated Force	80kN
PTO Rated Power	120kW (instantaneous)
Structural Mass	22.5 mT (w/o Reaction Body)
Deployment Depth	50-150m

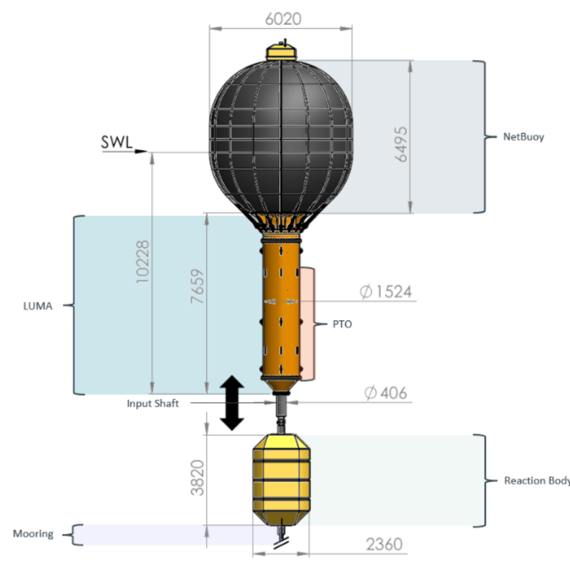


Figure 1 - LN6 WEC System

[1] Dehlsen Associates changed the name of their wave energy program from "Centipod" to "Anacapa" within the span of this project, the 6m diameter WEC name consequently also changed from "C1P6" to "LN6". Best efforts were made within this report to maintain consistency but the project name retains the original "Centipod" name.

LN6 leverages high TRL sub-systems to ensure device reliability and suitability for long-term deployment while advancing the boundaries of cost and performance. The primary WEC subsystems of LN6 are:

For wave capture, the TRL 7 NetBuoy leverages a robust membrane with low-cost materials and was tested by Tension Technologies International (TTI) at half-scale during a six-month at-sea demonstration in 2021. Following at-sea testing, TTI has worked with DA for the last three years on preparing the NetBuoy design for integration with the LN6 WEC

DA's TRL 6 LUMA PTO, a type of Vernier Permanent Magnet Linear Generator (VPMLG), was tested at 60kW scale at NREL's 2.5MW Dynamometer in 2021 and was further operationally validated in hardware tests at McCleer Power's facility in spring 2025.

The full WEC includes the following subsystems:

- Power take-off (PTO): The power take-off converts the mechanical energy from the wave energy capture device into electrical energy.
- Control system: The control system monitors and regulates the operation of the wave energy converter, including the power take-off.
- Wave-activated body: The wave-activated body is responsible for capturing the energy of ocean waves and converting it into mechanical energy.
- Reaction body: The reaction body provides a stable force reference for the wave energy converter.
- Mooring: The mooring physically constrains the wave energy converter to a specific location at-sea while providing load paths for forces transmitted between the converter and the seabed.

The following system hierarchy is defined for the system components:

ID	Subsystem
100	LUMA (linear universal modular absorber), comprised of:
101	Housing Tube
102	Linear Generator (PTO)
103	Electrical & Controls
200	NetBuoy (inflatable wave-activated body)
300	Reaction Body
400	Mooring

Scope Summary

This project developed a 120kW rated WEC system design ready for fabrication, deployment, and prototype testing at PacWave. This scope is split into two phases:

1) a preliminary design phase where the conceptual development of the WEC system was established and solidified, leading to a Preliminary Design Review (PDR), and;
2) a final design phase where the WEC design is advanced through thorough engineering processes, leading to a Final Design Review (FDR).

The following section breaks down all technical tasks within the project, omitting non-technical tasking such as reviews and report submissions (Tasks 1, 8, 15, and 16).

Summary by Task – Preliminary Design Phase

Task 2

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 2.0.0: Standards and Certification
>
> *Task Summary:* System engineering approach adopting standards and recommended practice to inform system design, risk mitigation and qualification tests, such as wave tank testing or power take-off subsystem testing, leading towards standards compliance and advancement of the WEC design within the certification pathway.

Task 2 Major Activities and Results

This project followed DNV-SE-0120 [3], Certification of wave energy converters and arrays to ensure proper technology qualification. Within this plan, technology qualification (TQ) process was conducted according to the outline flow chart shown in Figure 2.

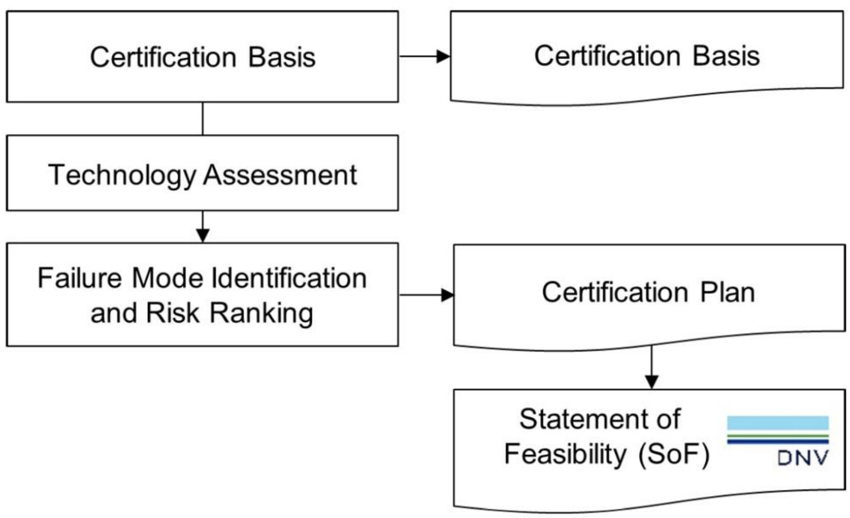


Figure 2 - DNV TQ Process according to DNV-SE-0120

The goal of this task was to adopt standards and recommended practice for the purposes of a well-considered system design and risk mitigation process. In pursuit of this, the DA team included IEC standards 62600-2, 62600-3, 62600-30, 62600-100, 62600-103 in the design process.

This task culminated in a Statement of Feasibility (SoF) from DNV, which can be found in Appendix 1 of this report.

Task 3

From the overarching Statement of Project Objectives (SOPO):

> **Task 3.0.0: Preliminary WEC Design**
>
> *Task Summary:* Develop a WEC design suitable for review fulfilling project goals and pass the Preliminary Design Review with a conceptual design for the fundamental systems of the PacWave-ready prototype.

Task 3 Major Activities and Results

The DA team outlined a conceptual baseline WEC design from which to start design refinement and technology qualification. The LN6 baseline defined is a two-body heaving point absorber as shown in Figure 3.

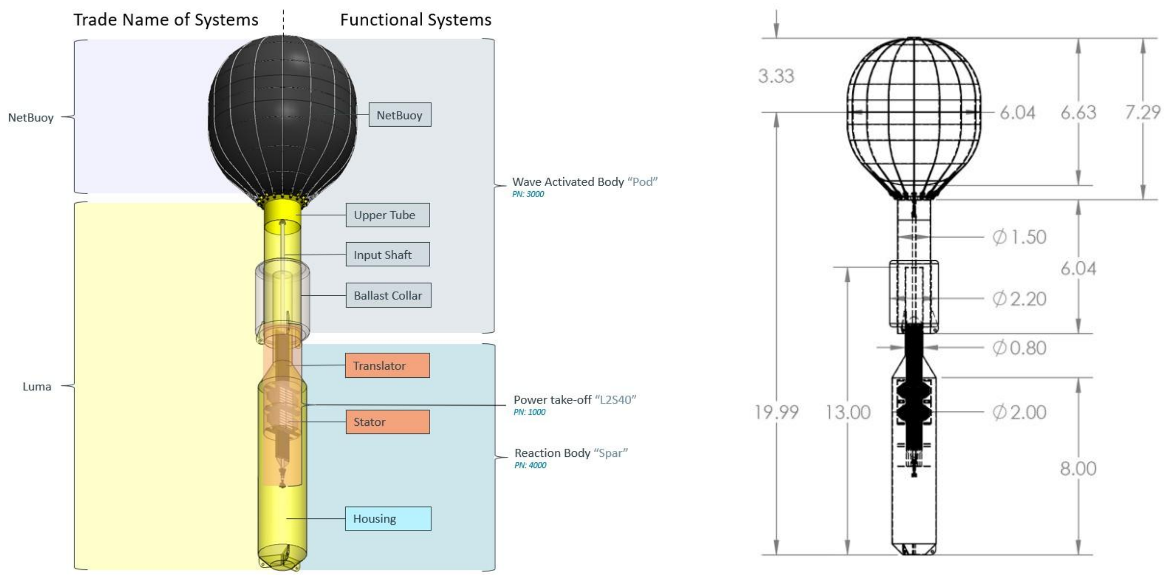


Figure 3 - WEC conceptual baseline (dimensions in meters)

The WEC was comprised of a single 6m diameter, surface piercing, wave activated body "pod", attached to a linear acting power take-off (PTO) within a housing "spar", a submerged, stable reference buoyancy, moored with pre-tensioned lines. The spar reaction platform is a vertical, tubular steel housing containing the power take-off system while providing buoyancy for the mooring system pretension.

WEC Configuration Concept

Configuration options were explored for the WEC concept, notably the choice of where the PTO should be housed, and how the connection between the two bodies should be accomplished.

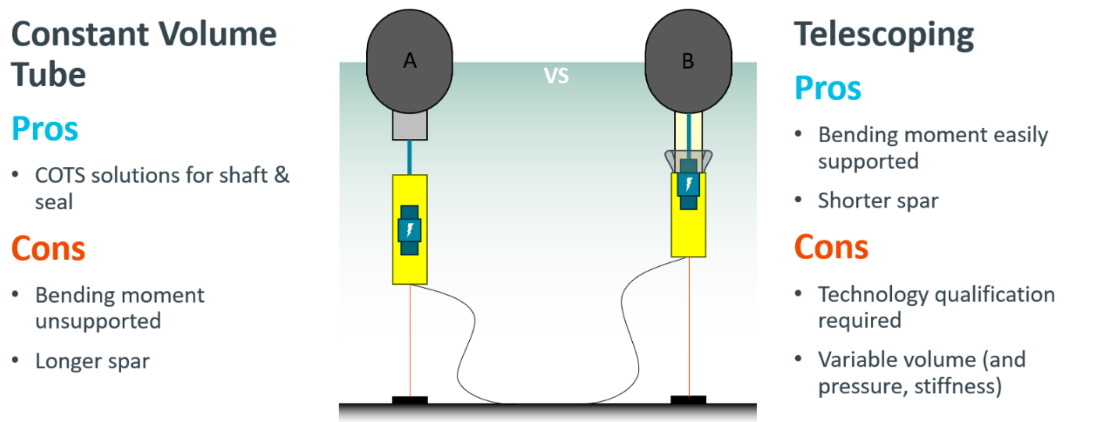


Figure 4 - Configuration trade step 1.

The first step of configuration trade-offs was whether the housing should be constant volume (CV) or a telescoping tube of variable volume. Due to mechanically prescribed constraints on control action and the additional technology qualification required, the telescoping option was deemed sub-optimal.

Control constraints: The telescoping tube would enclose a variable volume, and therefore linear oscillation would result in variable pressure. This would impart stiffness into the system that would favor a specific frequency range of mechanical response, preventing pure reactive control optimization.

Technology Qualification: Novel seal topologies would need to be explored and validated to accommodate the very large diameter concentric tube interface, allowing operation of the telescoping seal.

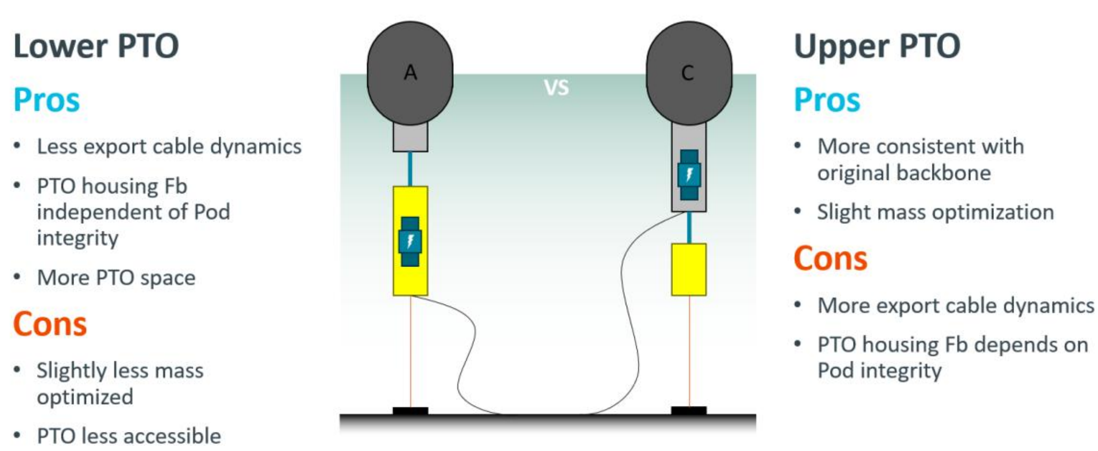


Figure 5 - Configuration trade step 2.

The second step of configuration trade-off considered whether to place the PTO in the upper or lower housing. Housing the PTO in the upper body was more mass-optimized. The upper PTO configuration allows the PTO and all associated mechanical structure to contribute to needed mass within the Pod to maintain the desired waterline, offsetting some ballast need. Bringing the PTO up also removes that mass from the reaction body, which needs minimal mass to provide a desired net buoyancy, and subsequent mooring pre-tension. The upper PTO choice therefore optimizes mass by adding mass where needed and subtracting where it is not. Furthermore, the upper PTO configuration maintains design flexibility to consider multiple-WEC clusters using a common reaction body[2] in future design scale-ups.

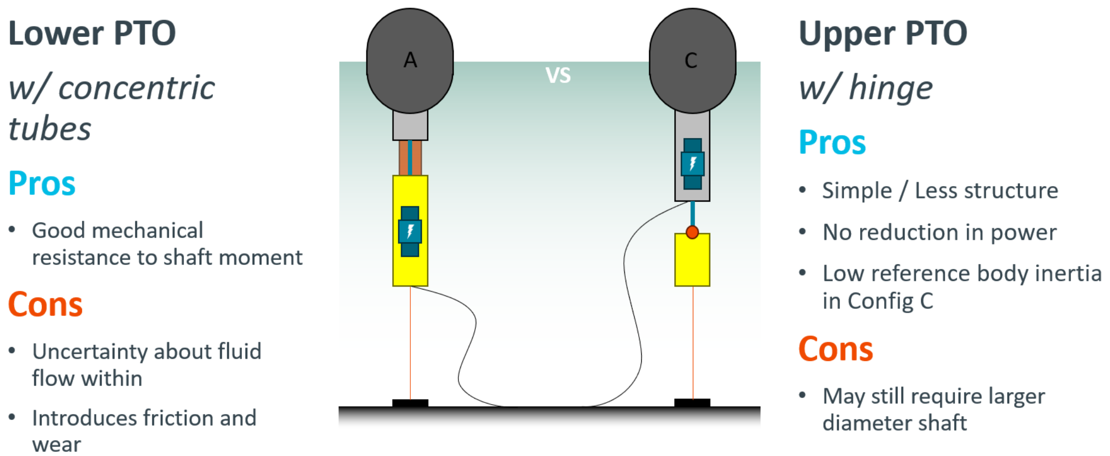


Figure 6 - Configuration trade step 3.

The third and final step of configuration trade-off answered the question of the mechanical linkage between the bodies. Between concentric large diameter tubes[3] and a simple, robust input shaft, the simple option was selected as it was capable of resisting the needed moments (see Task 10, Table 5 for an overview of relevant bending moments) while maintaining high-performance and reducing complexity.

Mooring Design Concept

Significant activity in the initial design configuration evaluation focused on the mooring system, with a need to define the preferred number of lines and attachment points prior to a concentrated mooring system design effort. Multiple mooring configurations were under consideration. The three options included: a three-line system that constrained the spar, a four-line system with three lines lightly constraining the pod with a single vertical tether vertically constraining the spar, and a four-line system where the three lines were instead connected at a clump mass below the vertical tether.

[2] **Note on nomenclature:** The Reaction Body has historically been called a "backbone" as referenced in Figure 5. This nomenclature stemmed from multi-point absorber WEC topologies explored under the Centipod program for many years by DA.

[3] **Note on nomenclature:** The system referred to as the "Spar" is the combination of the Reaction Body and PTO housing tube when mated as concentric tubes. The eventual configuration chosen does not include this combination and thus the "Spar" term was no longer used, being replaced by the separate systems: "Housing Tube" and Reaction Body"

Mooring Option: Three-line

A three-line system constrains the spar. The three lines which connect the reaction body to the sea floor are designed to be low-stretch, reducing heave displacementof the reaction body.

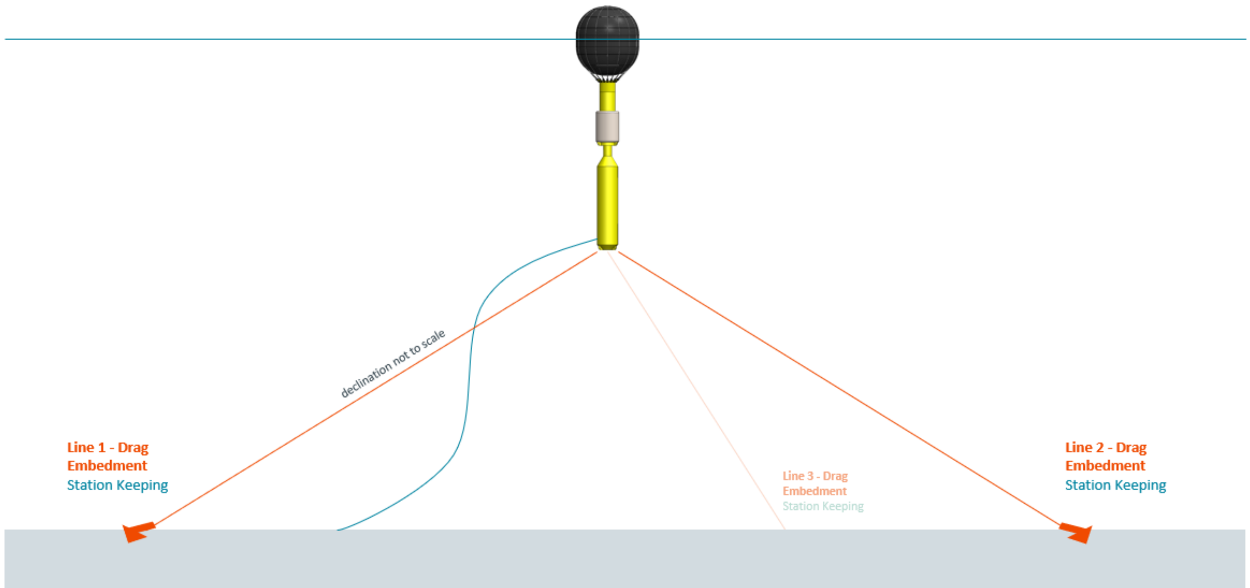


Figure 7 - Three-line mooring example

Mooring Option: Four-line

A four-line system constrains the pod as well as the reaction body. The four-line system includes one tether that is stiff and held to the seafloor by a mass preventing operational heave displacement of the reaction body, while the other three lines are attached to the pod having compliant properties, allowing for heave motion.

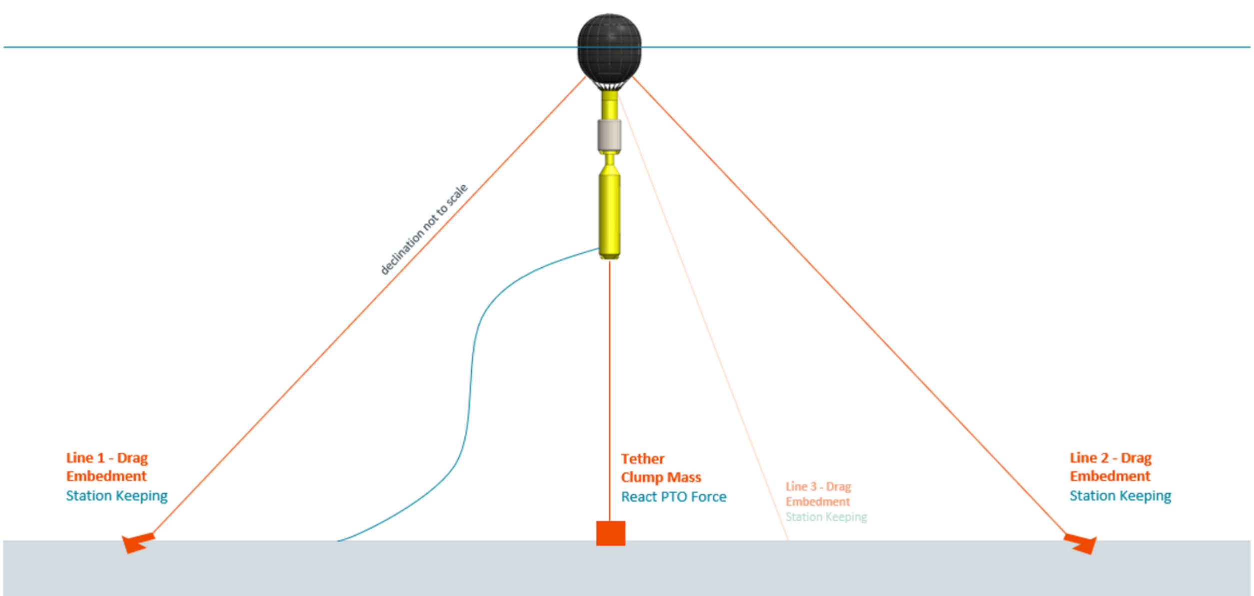


Figure 8 - Four-line mooring example

Mooring Option: Four-line (Admiralty-like)

A single taught tether connects the reaction body to a clump mass directly below the WEC, preventing vertical motion of the reaction body and providing a performance optimized PTO reference. The clump mass is sized to lift from the seabed in extreme events, providing an effect like a mechanical fuse, limiting ultimate loads. Three chain mooring lines connected to the clump mass run along the seabed and terminate in drag embedment anchors (DEAs), preventing lateral movement of the clump mass.

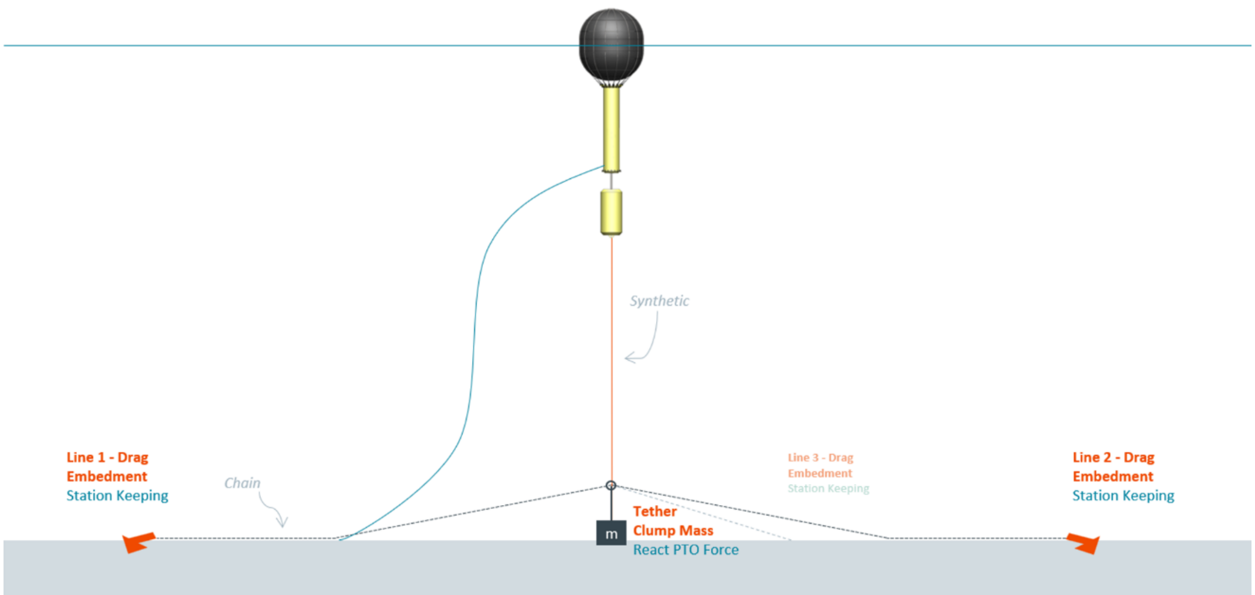


Figure 9 - Four-line mooring example (admiralty-like)

Anchors were selected based on site geotechnics with the preferred choice of high holding capacity drag embedment anchors, coupled with sufficient length and mass of chain to minimize uplift at the anchor on the pre-tensioned lines.

To select the final mooring design, thorough wave tank testing, and numerical model analyses were performed to compare the three-line, the four-line, and the admiralty option. It was found that the three-line solution did not provide sufficient vertical stiffness, which limited power production. The four-line option was initially designed to limit the device kinematics during extreme conditions; however, the design ultimately limited the behavior of PTO, would have been difficult to install, and was not necessary to reduce damage during extreme conditions. Additionally, reducing the number of vertical lines in the water column reduces the risk of entanglement for marine mammals. The best option was to employ a vertical tether. Once the vertical tether solution was selected, the admiralty-like mooring system was designed to achieve sufficient loads from the device. The results from tank testing at UNH and OSU were used to tune a control-coupled WEC-Sim [6] model to evaluate performance goals pertaining to the mooring design. Using a reduced set of operational sea states the vertical tether mooring stiffness was characterize versus mean power capture, as shown in Figure 10.

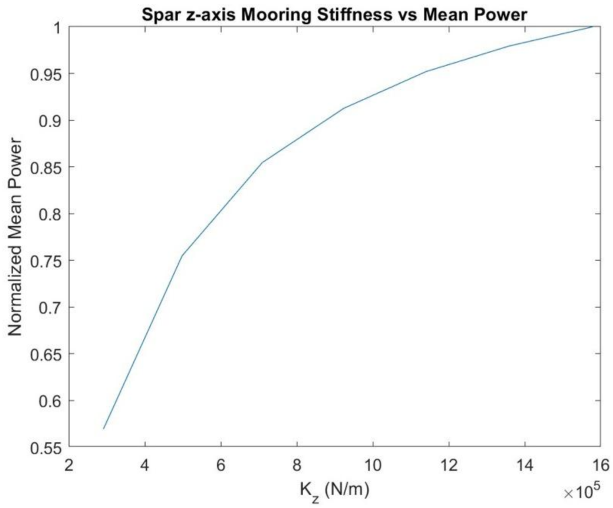


Figure 10 - Z-axis mooring stiffness versus mean power

Design Documentation

A suite of design documents was delivered prior to the PDR. A summary of the main design issues considered and outstanding at this point in the process, can be seen from the pre-PDR design issues table presented below.

Table 2 - Design Issues Table prior to PDR

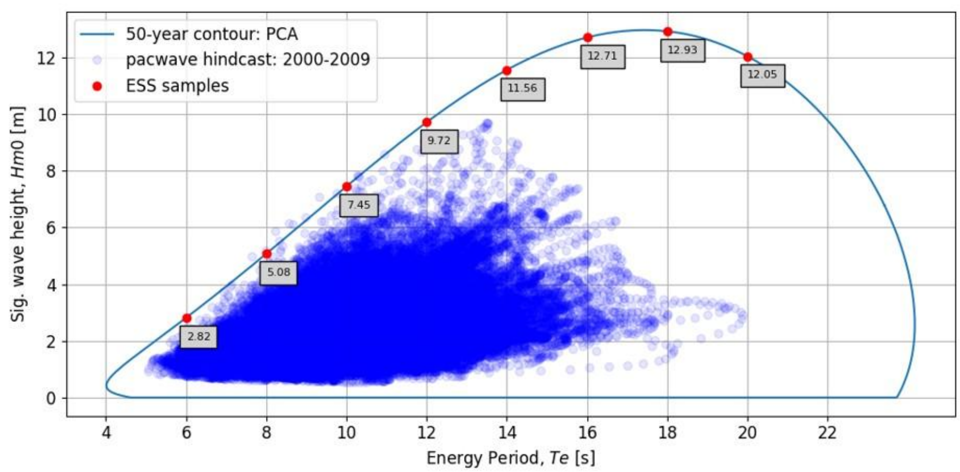
Design Issue	Description	Urgency 0-5	Impact 0-5	Priority	Impact
Vertical loads on anchors	There is a requirement for uplift in the mooring lines. VLA may be expensive or impractical.	3	4	12	Mooring system heave stiffness directly affects AEP
Tidal compensation	A degree of tidal compensation may be required in operating mode	3	2	6	Without tidal compensation, asymmetric stroke limits at tidal extents may negatively impact performance
Mooring system design	Reliance on mooring system to allow relative motion between the two bodies impacts engineering resource allocation	4	4	16	Competing design requirements for operation and survivability impacts engineering resourcing, bottlenecking design process. Resulting design impacts performance.
Control Optimization	Attention needed on controls optimization and/or co-design for improved power performance.	3	2	6	Suboptimal tuning of control system may limit AEP
Seal identification	Seals not yet identified for the PTO input shaft entry into the submerged housing	2	3	6	Delayed seal system requirements and sourcing may result in unrealistic requirements being carried far into the design process
Excessive bending moment in PTO shaft	Bending moments on the PTO input shaft cause deformation, reducing or preventing WEC functionality	3	4	12	Lack of structural support to transfer pitch DOF bending moments results in mechanical failure. Conversely excessive support structure increases cost and mechanical wear of sliding bearing components.
Structural parameters	Lack of coupling between the pre-processing tools makes design studies cumbersome leaving explorations of some parameters open and LCOE potential on the table	3	2	6	Lack of understanding of parameter sensitivity causes WEC design to result in sub-optimal LCOE
Excessive pitch response	Excessive pitch response due to mass distribution, mooring connection points, and pitch response frequency	2	2	4	Excessive pitch response impacts loads and/or performance
PTO performance	Prior to validation of modifications, PTO efficiency is projected based on numerical models	2	2	4	Inaccurate numerical model results could lead to false expectations of AEP

Design Load Cases

A design load case (DLC) document was drafted with the purpose of defining and describing the various design load cases that the LN6 wave energy converter is expected to encounter during its life cycle, and to specify the design criteria and requirements for each load case. The load case analysis was used to guide the design and engineering of the wave energy converter, and to ensure that it can withstand the various loads it will be subjected to.

Of particular note are the environmental conditions, which the WEC will be subjected to. This includes extreme wave events, as shown in Figure 11. The DA team used MHKiT [4], a set of Python-based tools developed by the national labs, to extract hindcast data for the PacWave site, and determine the 50-year wave contour. This contour was then used to select 8 sea states at equal interval across the wave period range to be used for evaluation of extreme wave events.

Similarly, extreme condition data was gathered for water level, current, and wind to define the environmental conditions modelled within the DLCs.



Extreme Sea States (ESS): From 50-year Contour								
Case	*ESS-01*	*ESS-02*	*ESS-03*	*ESS-04*	*ESS-05*	*ESS-06*	*ESS-07*	*ESS-08*
Te (s)	6.0	8.0	10.0	12.0	14.0	16.0	18.0	20.0
Hm0 (m)	2.82	5.08	7.45	9.72	11.56	12.71	12.93	12.05
EWH(m)	5.24	9.44	13.86	18.07	21.51	23.64	24.05	22.41

Figure 11 - 50-year wave contour with samples

Supplier Engagement

In parallel with the design effort, the DA team worked on preliminary supplier engagement. Interfacing with potential suppliers at the preliminary design stage allowed DA's engineers to build confidence in the feasibility of engineering solutions from the practical perspective of suppliers and fabricators. Primary effort was placed on engagement related to the key subsystems (the prime mover, and power take-off), but also extended to components such as seals, and bearings.

Task 4

From the overarching Statement of Project Objectives (SOPO):

> ### Task 4.0.0: Preliminary Installation Planning
>
> *Task Summary:* Develop plans for installation, operations, maintenance, and recovery of the WEC, resulting in evidence that the proposed WEC system is conceptually suitable and within pre-permitted allowances for deployment at PacWave.

Task 4 Major Activities and Results

The Installation and Operation planning task brought a rough concept of the IO&M Plan for LN6 at PacWave considering local vessel availability. This work was conducted in parallel with the WEC and mooring system design, allowing for instability considerations to flow back into the concept refinement activities. The installation concept, which was fully defined in the second stage of the project, yielded a basic process involving:

- Quay side assembly of the WEC;
- Loading WEC onto the deck of an Anchor Handling Vessel (AHV);
- Sequential installation of each of the three drag embedment anchors (DEA);
- Connection of WEC to tether, and;
- Overboarding via AHV stern roller

Task 5

From the overarching Statement of Project Objectives (SOPO):

> ### Task 5.0.0: Preliminary Simulation and Calculations
>
> *Task Summary:* Update numerical model suitable for usage in design assessment activities. Estimate the device performance at the PacWave test site.

Task 5 Major Activities and Results

The Preliminary Simulation and Calculation task aimed to update the WEC numerical model for usage in design assessment activities.

WEC-Sim

A baseline WEC-Sim model was developed in this project. The WEC-Sim model was configured and run, allowing for investigations into design parameters. Control formulation work was also completed and the non-linear model predictive controller (NMPC) was coupled with the model to give a more complete representation of the WEC response and performance. The model was completed and ready for tuning, using data from wave tank tests, prior to the preliminary design review.

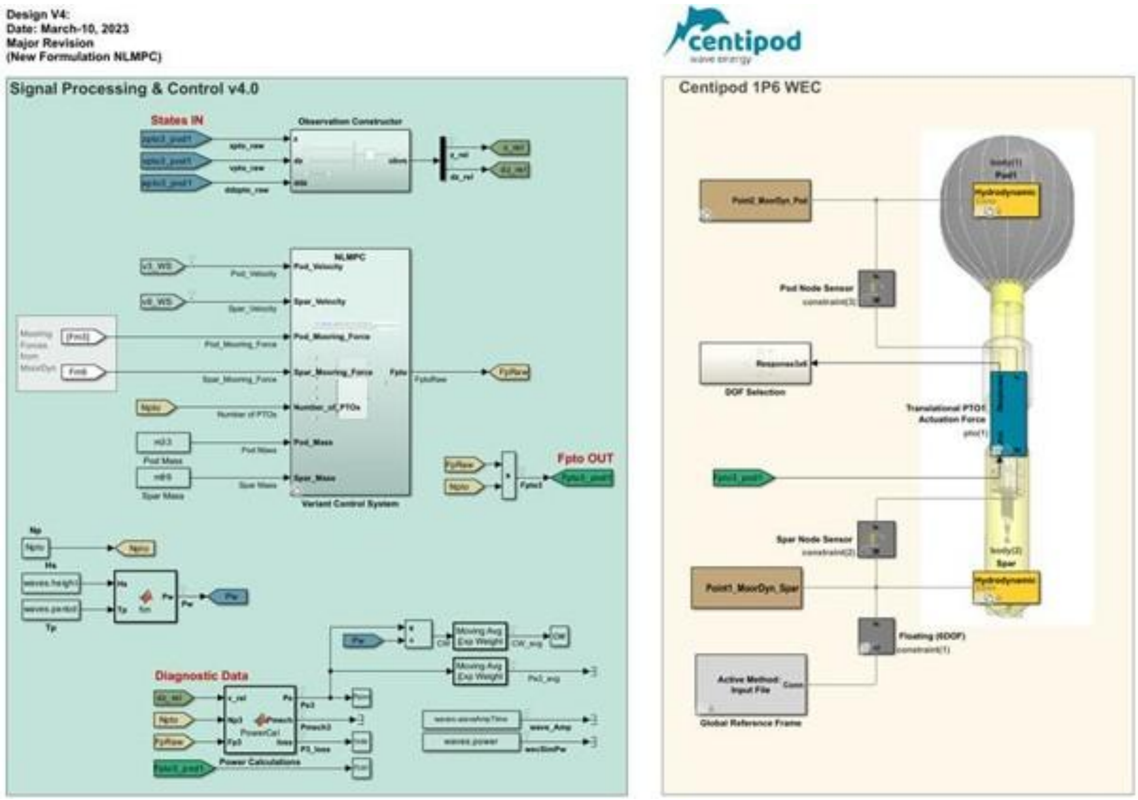


Figure 12 - WEC-Sim model in Simulink

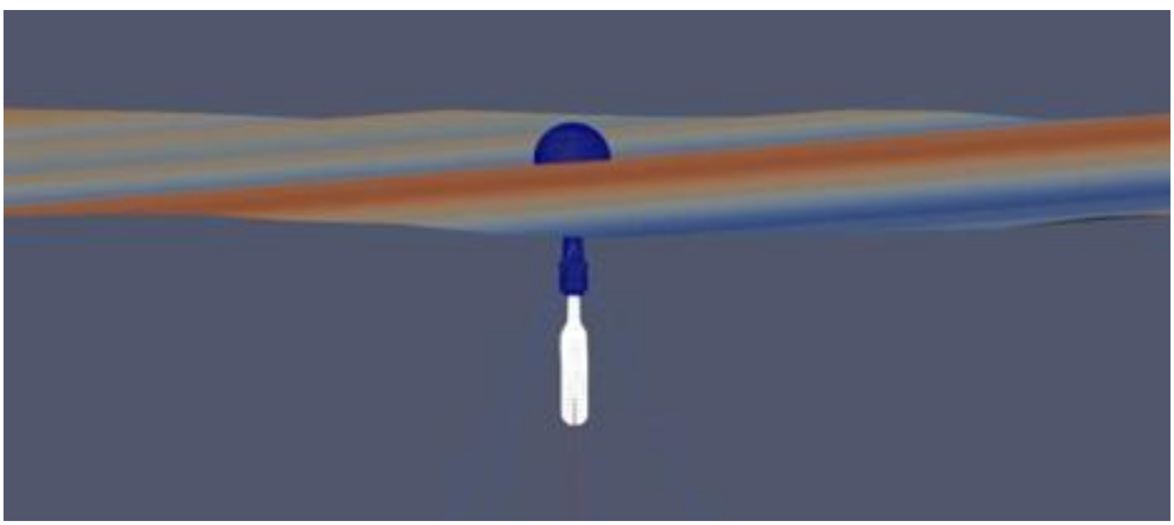


Figure 13 - WEC-Sim Model in Paraview

CFD

In parallel with WEC-Sim model development, DA worked with Sandia National Laboratory to develop a computational fluid dynamics (CFD) model of the WEC using OpenFOAM [9], an open-source, finitevolume based CFD package. The initial model set-up was completed prior to the preliminary design review but required more tuning of the model parameters following tank testing for useful results.

CFD model validation after tank testing showed good agreement in the heave (z motion) of the Pod and in the tether force. These two quantities were the most important to match, as the heave of the Pod strongly dominates the overall behavior of the system, and characterizing loads on the system (by which the primary mechanism of transfer is through the tether) was one of the key goals in performing high-fidelity CFD simulations of the device.

OrcaFlex

In addition to the WEC-Sim model, TTI set-up an OrcaFlex model in parallel, allowing for investigations into the mooring system. This gave the DA team a model-model verification opportunity to sanity check results of the other numerical models.

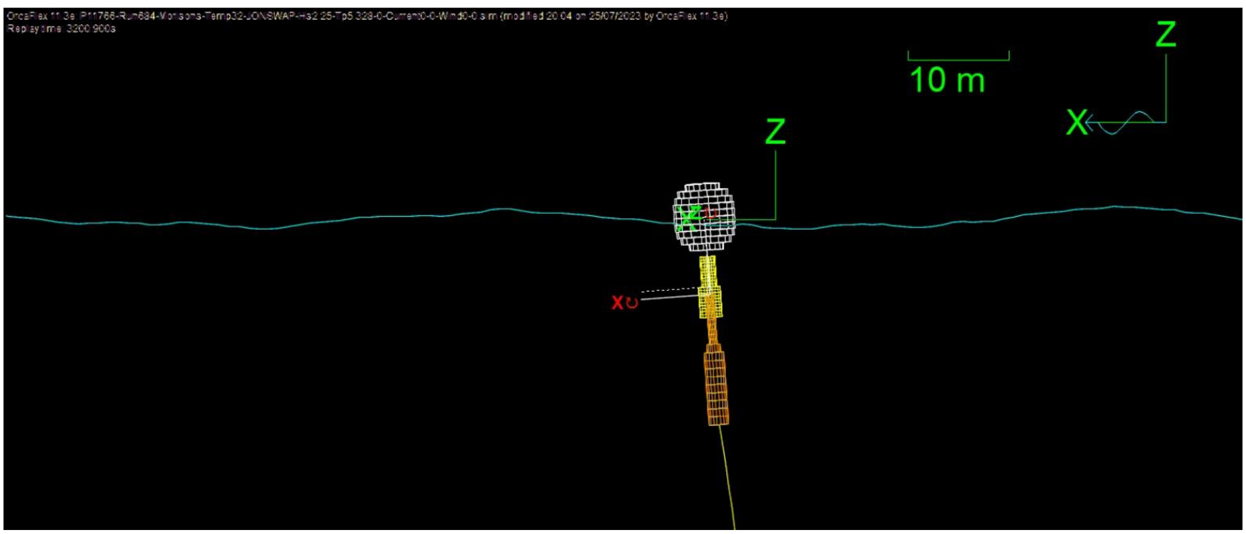


Figure 14 -OrcaFlex model of WEC

Task 6

From the overarching Statement of Project Objectives (SOPO):

> Task 6.0.0: Validation Planning
>
> *Task Summary:* Outline design tools required for loads assessment. Work with NREL to determine required experimental data for validation of mid and high-fidelity tools. Plan experimental testing.

Task 6 Major Activities and Results

Validation planning in the preliminary design phase focused primarily on the design and execution of wave tank testing of a 1:20 scale WEC model at the University of New Hampshire's (UNH) Jere A. Chase Ocean Engineering Laboratory (JACOEL).

Tank Testing

The DA team worked with NREL and UNH to complete the test plan, in the first project phase. The tests at UNH were used to validate numerical models (WEC-Sim, Orcaflex, OpenFOAM) for refinement of performance and load assessment, test two mooring configurations, and explore kinematics of the device in operational and larger sea states.

The general testing outline included measurement and analysis of the model's response to:

- Decay testing in still water
- Regular waves
- Irregular waves

The UNH Tank test focused on kinematics of the 1:20 scale model WEC, with the model motion tracked using video analysis in decay tests and wave cases. Additionally, the four-line mooring system (described in the Task 3 section above) was tested along with a configuration omitting the three Pod-attached lines to support the mooring design trade study. More detailed descriptions of these testing efforts are located in the Task 12 section below.

Task 7

From the overarching Statement of Project Objectives (SOPO):

> ### Task 7.0.0: Preliminary Commercial Viability
>
> *Task Summary:* Develop financial models for economic assessment of the WEC. Provide clarity on the long-term impacts that the proposed WEC system offers. Apply learning from conceptual design and modelling activities to refine and reduce uncertainty in the breakdown of expected system costs for the prototype.

Task 7 Major Activities and Results

Work on the Preliminary Commercial Viability task was undertaken in parallel with the preliminary design tasks to ensure a feasible course to economic viability for the WEC concept. Following the Preliminary Design Review, a commercialization plan was delivered to DOE with the subsequent Preliminary Commercialization Review.

The evaluation of economics was continually tracked in the preliminary design phase by using NREL's System Advisor (SAM) software tool [5] to calculate LCOE. With the SAM LCOE model, what-if and waterfall analysis allowed the team to explore pathways to market-competitive LCOE at larger deployment scales. A preliminary LCOE waterfall starts with initial commercial costs beyond First of a kind (FOAK) as a base. The waterfall then shows LCOE improvement from immediate enhancements like control co-design (CCD) work, as well as more speculative steps like FCR reduction that may come with decreased perceived risk when debt financing projects.

In parallel with LCOE estimates, economic proxies were used to sanity-check LCOE. Power to weight ratio (PWR) has historically been used as a proxy for LCOE in renewable energy. While it doesn't tell the whole story, this metric has value in understanding the relative technical and economic potential between devices when an objective LCOE comparison is absent. LN6 maintained a promising PWR throughout conceptual iterations, landing at a PWR of 5.88 at the conclusion of preliminary design work.

This effort set-up a fluid transition in the second project [phase where the LCOE model was expanded and finalized, as will be further described in the below section covering Task 13.

Summary by Task – Final Design Phase

Following the successful completion of the Preliminary Design Review and Preliminary Commercialization review, the Dehlsen Associates team continued work onward into a final design phase.

Task 9

From the overarching Statement of Project Objectives (SOPO):

> Task 9.0.0: Final Installation and Operational Planning
>
> *Task Summary:* With input from Preliminary Design Review, refine plans for installation, operations, maintenance, and recovery of the WEC, resulting in evidence that the proposed WEC system is conceptually suitable for deployment at PacWave.

Task 9 Major Activities and Results

At the start of the final design phase, the DA team began to refine preliminary installation and recovery plans and adapt for review feedback and conceptual design results. This entailed the development of an initial storyboard of the installation and recovery processes, identifying key safety risks, expected limitations and mitigation actions required for vessel availability at the site. Concurrently, the plan covered the mooring line installation and WEC installation and hookup. Moreover, the plan provided a clear understanding of the scope of work associated with each activity to be undertaken and to help to ensure a safe and efficient performance of the operation.

InterMoor Inc. (InterMoor) was contracted by Dehlsen Associates to develop the installation methodology for the LN6 WEC for PacWave. The resulting work includes the mooring preset of three mooring legs and the tow out or onboard delivery of the wave energy converter from Port of Toledo in Newport, Oregon to the PacWave South Test site.

The Installation Plan details the procedural steps for the mooring lines and WEC installation, and contains the procedural drawings.

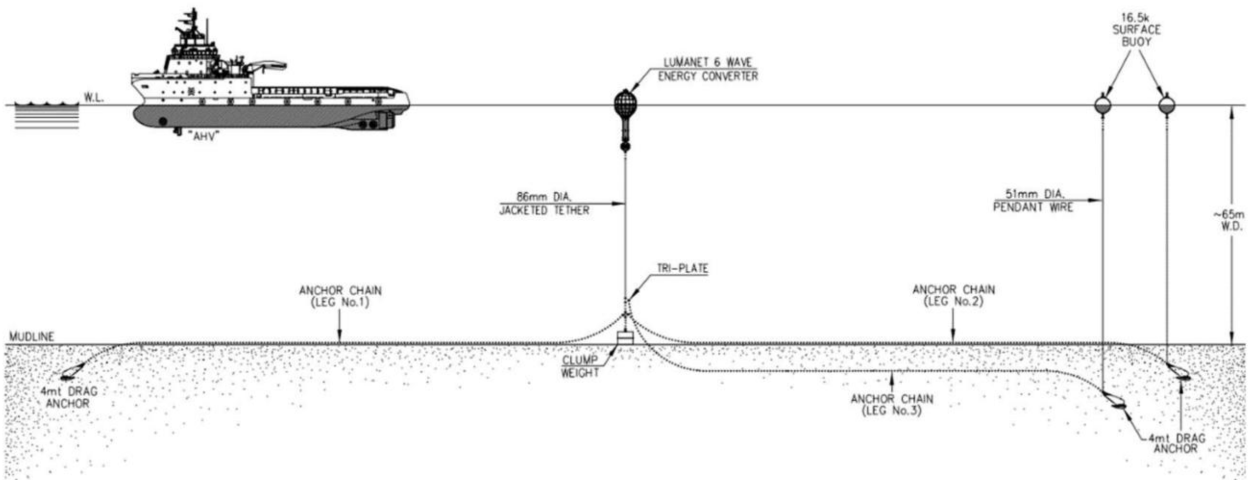


Figure 15 - Drawing from the Installation Plan showing the WEC after installation is complete.

Task 10

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 10.0.0: Final WEC Design

> *Task Summary:* Develop a WEC design suitable for review fulfilling project goals and pass the Final Design Review with a complete engineering design for the fundamental systems of the PacWave-ready prototype.

Task 10 Major Activities and Results

WEC design work continued into the second project phase, building on the completed Preliminary Design. In pursuit of a final design, the DA team advanced the WEC design through parameter refinement. In parallel, a documentation effort continued to supply DA's certification partner, DNV, with sufficient information for their Statement of Feasibility.

The basic WEC design properties were solidified in the first project phase, reaching a stable design as shown in Figure 1 under this portion of the project.

Loads and Design Studies

Design studies continued to be undertaken leading to the eventual full design report and documentation package for the Final Design Review. Meanwhile project partners continued work on updating the Front-End Engineering Design (FEED) studies conducted on other subsystems in the preliminary design phase. TTI's NetBuoy prime mover design was completed, and documentation was added to the review package.

The design review package included:

- CAD Design drawings;
- Load estimates at in the PacWave resource;
- Design loads calculations;

- Design weight calculation;
- Risk management plan and risk register;
- Final calculations of the metrics;
- Unresolved open design issues and resolution plans;
- Design, fabrication, and operation plan for 2yrs at PacWave;
- Demonstration of conformity to IEC and IEEE standards;

A summary of the product of this work is outlined in the subsections below.

CAD Drawings

Drawings were produced for the general WEC assembly and each subsystem to aid in the analysis and manufacturing consideration of the machine. These drawings included the design report provided for the Final Design Review.

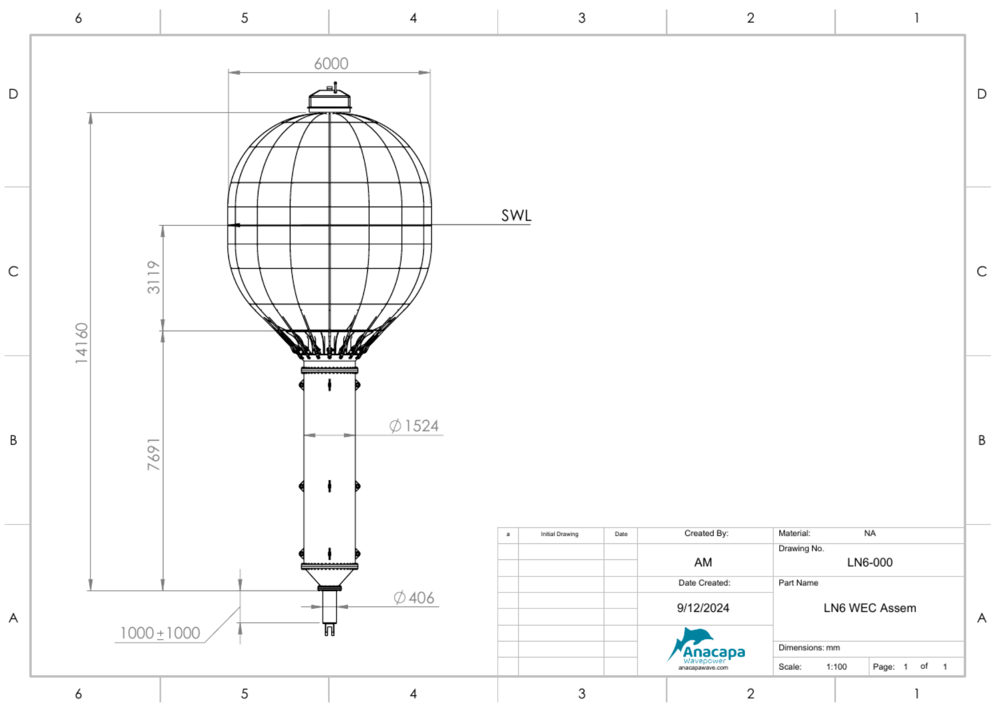


Figure 16 - General dimensions of WEC assembly for FDR

Design Weight Calculations

Final mass tables were produced for the WEC, freezing the mass, center of gravity, center of buoyancy, moments of inertia, and other hydrodynamic properties for consistency within the analysis effort.

Load Estimates

A general overview of characteristic load items resulting from 50-year return wave conditions can be found in the table below for reference. For more information on Extreme Sea State conditions, please refer to the design load case subsection under Task 3.

Table 3. Characteristic loads from ULS requirements

ULS #	Ultimate limit state description
1	Housing structure yielding (axial stress)
2	Housing structure yielding (bending stress)
3	PTO end stop yielding
4	NetBuoy elastomer rupture
5	Mooring line breaking load
6	Anchor max uplift exceedance

Safety factors were applied under guidance of IEC-TS-62600-2. To illustrate, an example for the Housing structure yielding (ULS 1 & 2) is broken down in Table 5. Partial safety factors of 1.35 for ultimate loads and 1.05 for steel were multiplied for a total safety factor of 1.42 [10].

Table 4 - Characteristic and Design Loads

Design Loads	Load Type	Load Sf	Material Sf	Load Correction
Housing ULS 2	Pitch (Nm)	1.35	1.05	1.42
Housing ULS 1	Heave (N)	1.35	1.05	1.42

This methodology was applied across the structure to evaluate against environmental conditions such as 50-yr return waves. System requirements stemming from these, and other, design loads flowed into the final design process.

Environmental Risk Register

An Environmental Risk Register (ERR) was drafted for LN6 at PacWave under the guidance of Pacific Northwest National Laboratory (PNNL). The ERR helped guide the final design process by providing a framework for recording environmental risk of the design.

Task 11

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 11.0.0: Final Simulation
>
> *Task Summary:* Update and validate numerical model suitable for usage in design assessment activities. Estimate the device performance at the PacWave test site using physical modelling data obtained from testing campaigns and numerical simulations validated against physical modelling data.

Task 11 Major Activities and Results

A numerical model of the WEC was designed and tested in MATLAB/Simulink using WEC-Sim toolbox as described in the preliminary simulation task. The Sim-Mechanics explorer view of LN6 WEC is presented in Figure 17. Legends are added in the explorer view for illustration and highlight various components of the LN6 WEC system, such as NetBuoy, reaction body, PTO shaft and mooring.

The mooring system was simulated using the MoorDyn-V2 [7] WEC-Sim add-on. The mooring system consists of a clump-mass, tether and tri-spread chains. A MoorDyn visualization subsystem is designed to enable mooring view in Sim-Mechanics explorer in Figure 18, which would otherwise require Paraview software, although the visualization is limited to the positions of the nodes in mooring configuration.

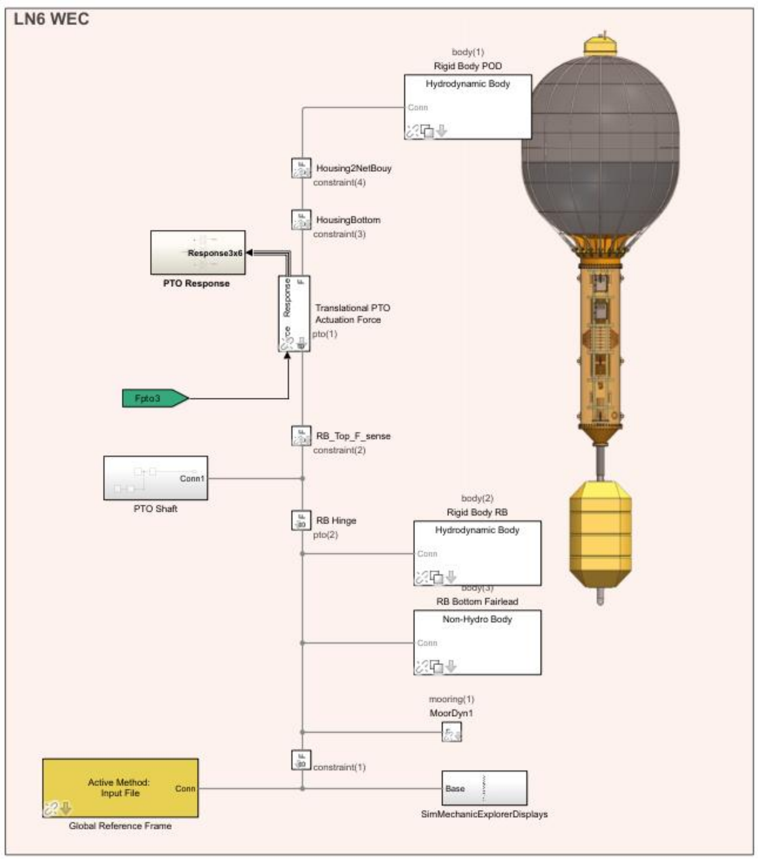


Figure 17 – WEC-Sim model of LN6 WEC device.

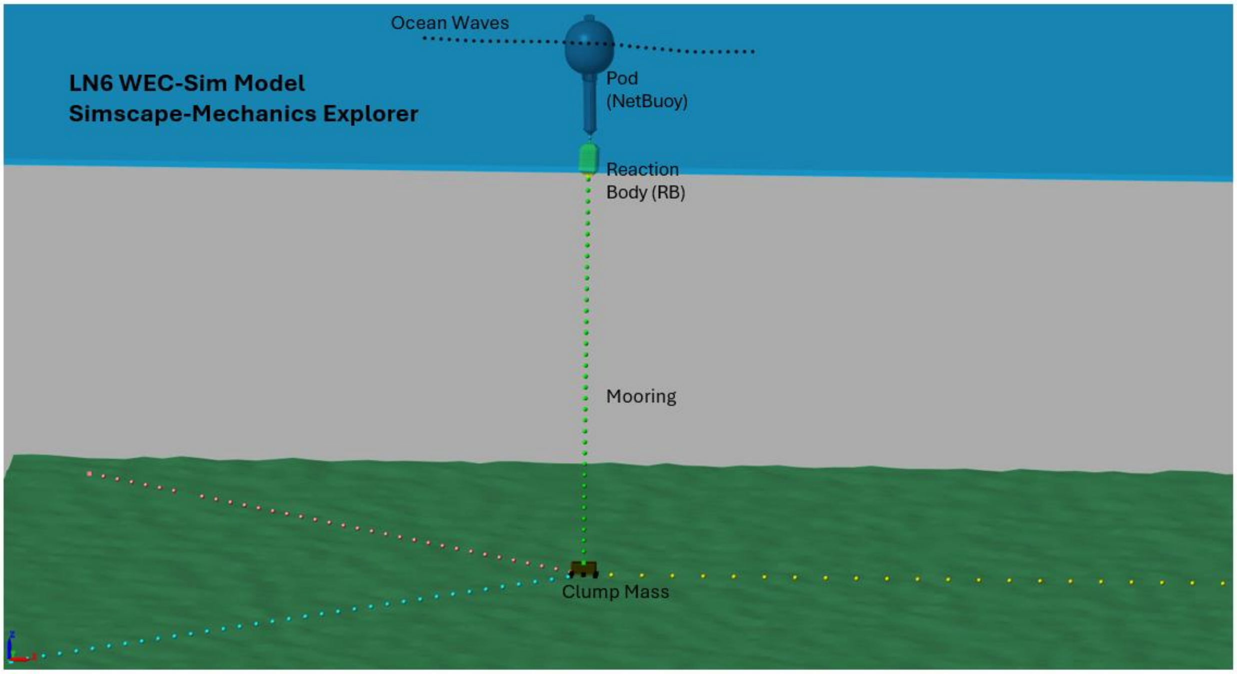


Figure 18 – WEC-Sim model of LN6 WEC device

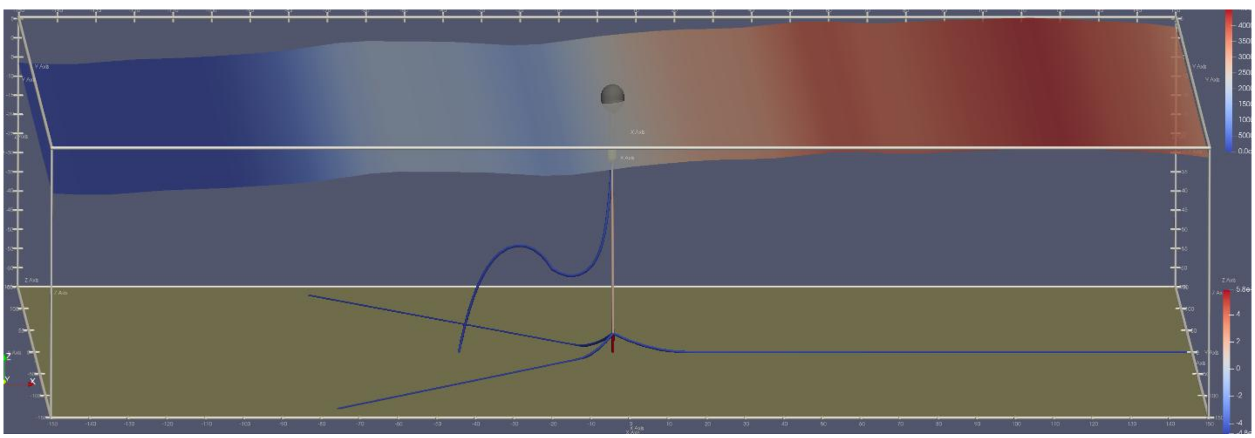


Figure 19 -Paraview animation of WEC-Sim model in extreme waves

Numerical model validation

The WEC-Sim numerical model of the LN6 device was validated against the Froude-scaled 40th scaled tank test model (Appendix 5, *40th Scale Numerical Model Validation – WEC-Sim*). The main goal of validation was to match the heave and pitch decay test of the wave-activated body (NetBuoy). An initial heave displacement of -2m was imparted on the WEC-Sim tank model of the LN6 and resultant heave decay responses are plotted in Figure 20 below. A good agreement is observed in the heave dynamics of the two models. A 17-degree initial pitch displacement decay test is presented in Figure 21, and after tuning hydro data of the WEC-Sim model, a similar agreement in the pitch decay tests of the two models was observed. The final validated model was used to design the control systems, evaluate power performance, and conduct load studies.

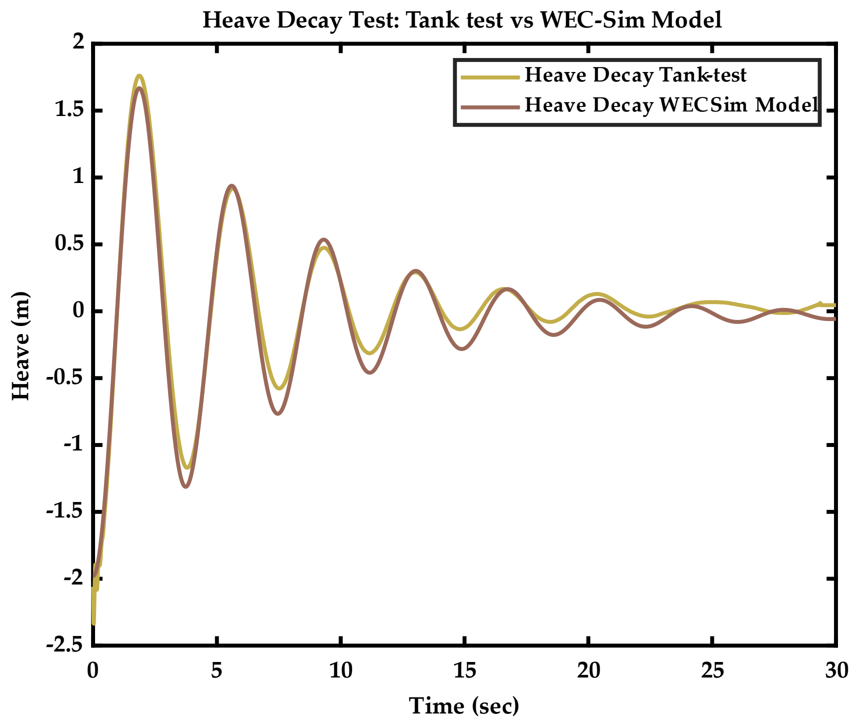


Figure 20 – Heave Decay Response Validation: Tank Test vs WEC-Sim Model

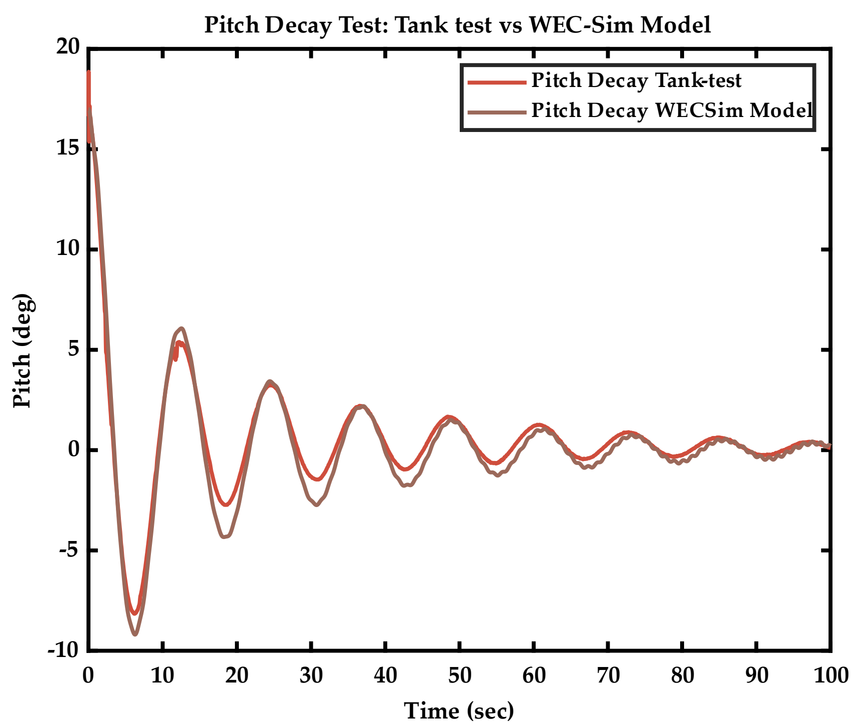


Figure 21 – Pitch Decay Response Validation: Tank Test vs WEC-Sim Model

Model validation efforts are fully laid out in Appendix 5, *40th Scale Numerical Model Validation – WEC-Sim*.

Task 12

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 12.0.0: Validation Exercises
>
> *Task Summary:* Complete model testing of the WEC in a wave tank and proceed with subsystem hardware testing. The objectives are: demonstrate and robustly measure the performance in the representative sea states; produce an extensive, traceable and calibrated data set which covers model setup, input waves and DAQ outputs - which will enable the validation of mid and high-fidelity numerical tools.

Task 12 Major Activities and Results

Validation exercises in the final design phase can be broken down into two major efforts: wave tank testing and power take-off (PTO) testing.

Tank Testing

The DA team completed testing of the 1:20th scale model of LN6 at University of New Hampshire's wave tank early in the design phase. The planned test cases were successfully completed within the 10 days of facility time booked. Following tank testing, the team began processing the data and compiled a test report covering the methodology.

Validation exercises stemming from the resulting datasets were completed with the help of the national labs. These reports were instrumental in building reliable numerical models for the design workflow. Key results from the validation exercise include replicating the natural period of the Model WEC with a 3% error and replicating the decay rate with an error of 0.54%, overall showing good agreement between tank model results and numerical model results.

Following the 1:20 scale testing at UNH another tank testing campaign was undertaken at Oregon State University's wave basin, allowing for experimental data of WEC dynamics in waves representative of the 50-year return contour at the PacWave site. Furthermore, this second wave tank test campaign used a model mooring system that closely matched the designed mooring system resulting from the design studies undertaken within the broader project. The data from this 1:40 scale test campaign was used to further validate the WEC-Sim model.

The major focus of tank testing at OSU was to observe, using Qualisys, how the admiralty mooring system operated and how the WEC body dynamics reacted to the Clump Weight, and the chain spread mooring system. The clump weight dynamics in extreme conditions were validated, and the chain and tether tensions were validated in WEC-Sim and MoorDyn.

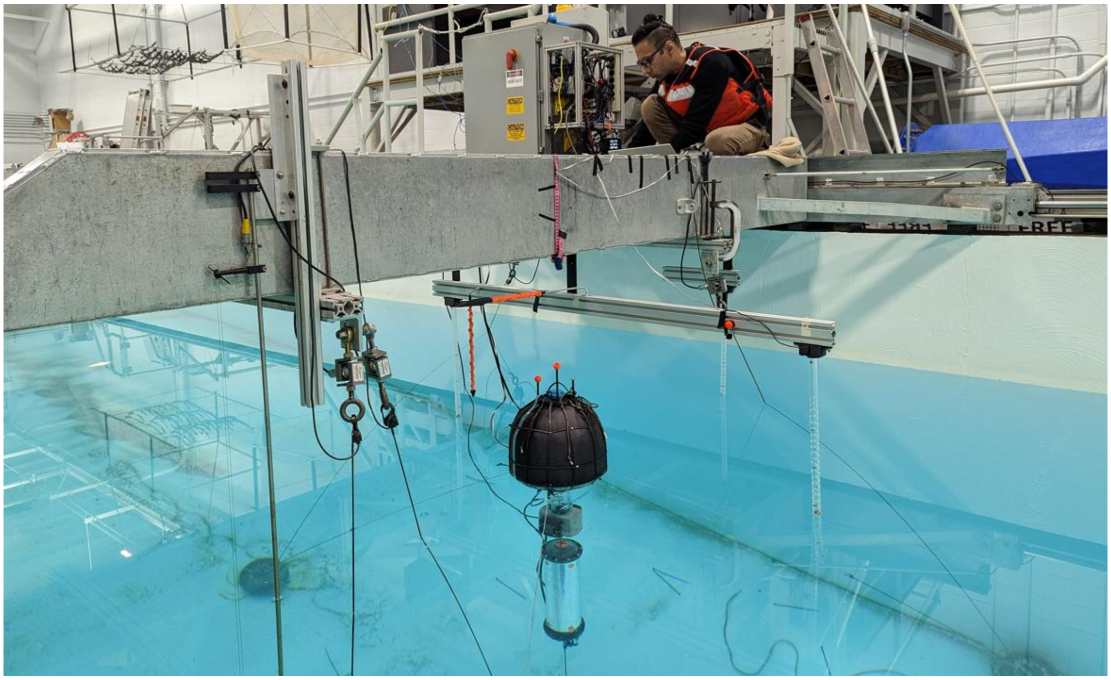


Figure 22 - Testing of 1:20 WEC model at UNH

PTO Testing

The second of the two primary validation exercises was a PTO Subsystem test conducted at project partner McCleer Power's facility in Jackson, Michigan. The objective of this subsystem test was to validate the performance of the PTO following design revisions and hardware updates, relating to translator structure electrical isolation and in-air-gap bearings.

Following testing of the PTO at NREL in 2021 under a prior project, analysis was conducted to identify the source of losses observed in the prototype machine. A time domain electromagnetic field solver was used to model the prototype PTO as-built in 3 dimensions, as opposed to the 2-dimensional model used for design. It was assumed that the source of high-velocity loss in the machine was due to previously unmodelled eddy currents, loops of electric current within the conductors that create a magnetic field reacting back to the original source. This would produce a result akin to increased mechanical damping in the machine's thrust direction.

To investigate this possibility, a machine model was produced in a numerical model that replicated the parameters of the physical PTO tested at NREL. The relationship between current (Iph), velocity (dz), and force produced was compared with the experimental results collected in testing.

As can be seen in Figure 23, the simulation matches experimental data, validating the model, granting confidence to subsequent model results.

With the model validated, an investigation into the source of losses was undertaken.

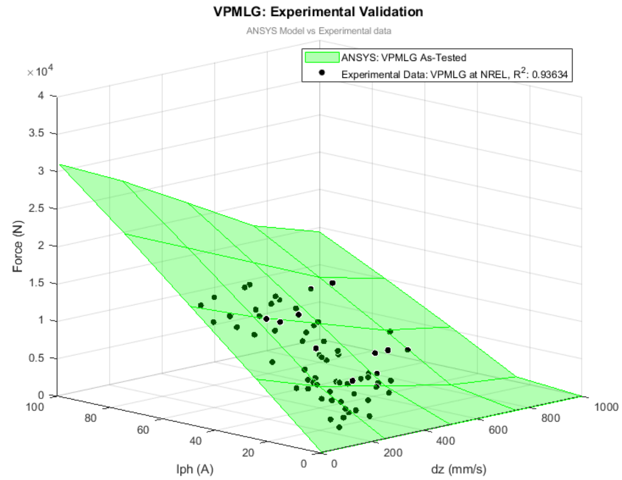


Figure 23 - Experimental validation of numerical model

Contrary to expectations, the vast majority of losses were coming from current circulating around whole system-sized structural elements, rather than smaller circulation within individual conductors (eddy currents). However, like eddy currents, the circulation found, linking the transverse structural elements to the longitudinal structural elements, resulted in the production of an unintended magnetic field reacting back to the original source. Because of the orientation of these elements, the induced current circulation was not noticed in the 2-dimensional cross-section model used for design, highlighting the value of 3-dimensional models in the design process where novel support structures are to be tested.

With this understood, the losses were be used to augment the machine performance results to calculate a projected efficiency map of the linear machine if a solution was implemented. The resulting performance of the machine was substantially improved with this correction.

This project therefore included work to experimentally validate this projection by implementing a design solution on the prototype machine and re-testing. The solution involved disassembling the structural elements of the translator and inserting dielectric material between the steel surfaces, preventing the problematic current circulation.

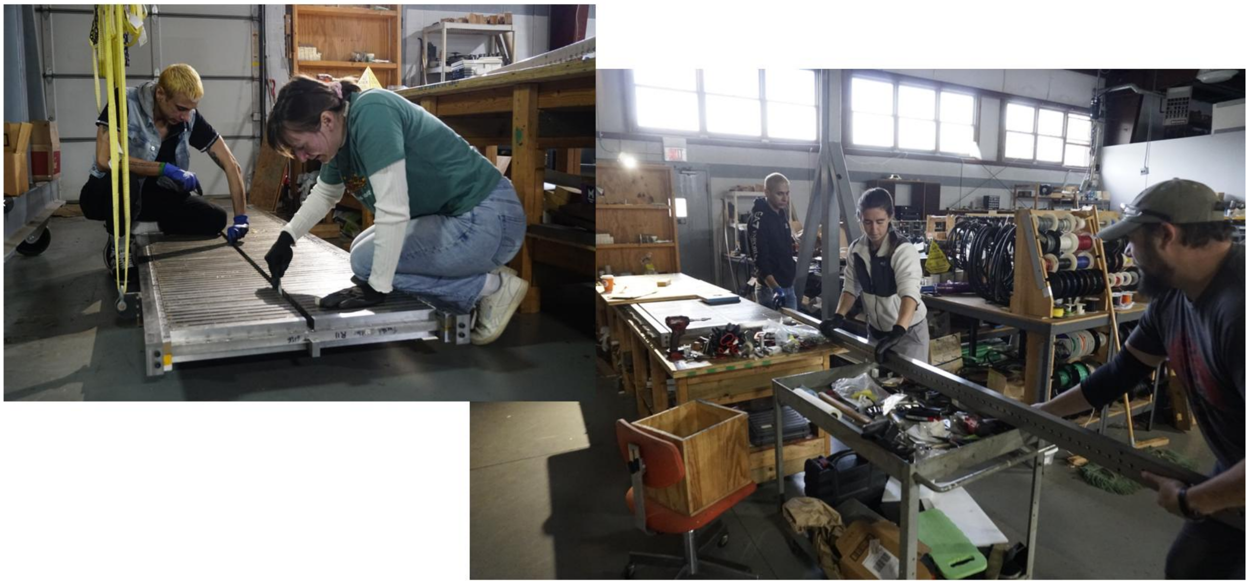


Figure 24 - Translator pole isolation retrofit work

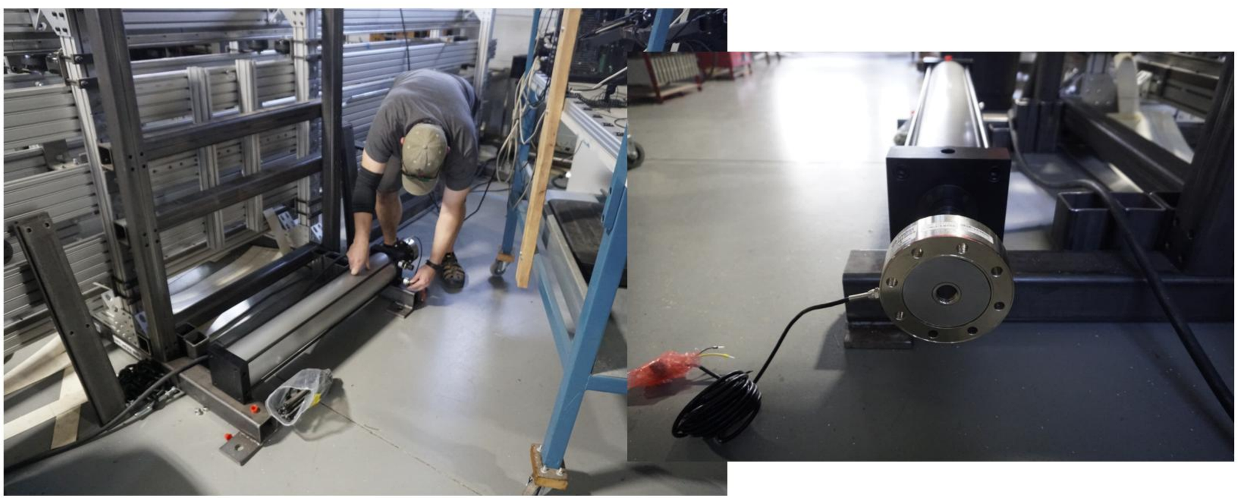


Figure 25 - Preparation of PTO frame and test actuator

Following electrical isolation retrofits, the translator was re-integrated into the machine. Test set-up, and performance of initial commissioning tests followed. Extensive work related to tuning of the mechanical elements such as shimming and placement of bearings in the air gap to allow for equal air gaps on either side of the stator without excessive play in the translator were then conducted, leading to test readiness.

Tests were accomplished by actuating the linear machine via an external pneumatic cylinder fitted with a load cell to record input force, in conjunction with a linear encoder, and an array of instrumentation within the PTO's power electronics cabinet monitoring voltage, current. The PTO was controlled to resist the pneumatic cylinder's input force in a similar manner to which it would operate by resisting excitation forces at-sea, thereby simulating operation in the laboratory and yielding a performance dataset across a variety of operating states.

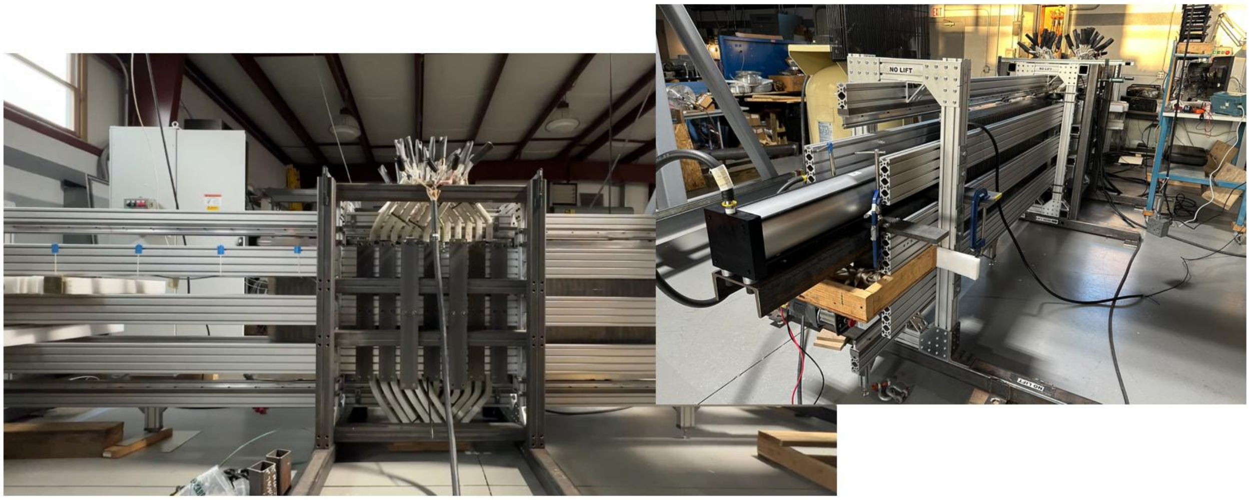


Figure 26 - Final test set-up of PTO

Key results from the test include the successful actuation of linear generator up to and beyond the design velocity limit of 1.5m/s, with input forces reaching 18kN. The force versus current relationship demonstrated by this test campaign was successful in demonstrating the electrical isolation design improvement, with conversion efficiencies increasing from those shown in the 2021 test campaign.

Task 13

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 13.0.0: Final Commercial Viability
>
> *Task Summary:* Finalize financial models for economic assessment of the WEC. Provide clarity on the long-term impacts that the proposed WEC system offers after design phase completed. Apply learning from final design and modelling activities to refine and reduce uncertainty in the breakdown of expected system costs for the prototype.

Task 13 Major Activities and Results

Commercial planning led to the commercialization plan and associated documentation package for the Final Commercialization Review. The final commercialization plan provided the following information:

- The intended market for the WEC device;
- The anticipated size of the target market;
- How the device will be deployed commercially (e.g., individually or in arrays);
- How this project advanced the technology towards commercial viability;
- The device target dimensions, power rating, and other relevant characteristics of the device;
- WEC design/system certification lessons learned.

LCOE formed the cornerstone of the team's decision-making process for design choices. Therefore, all numerical modelling and design work tied into the final LCOE with the financial and performance inputs of the LCOE model continuously being updated. Moreover, supplier engagement and manufacturability assessments were undergone in separate project tasks to provide additional incremental data to the model.

Through the commercialization viability task, DA has set a path for the LumaNet class of WECs to the target of $0.15/kWh by 2030.

All LCOE projections above have the benefit of pilot array installation costs, as absorbing the mobilization of a vessel for a single WEC install provides an unfavorable starting point. This pilot array is a small 8 WEC, 1MW rated array, beyond the PacWave prototype test targeted in this project. Other common assumptions are a 25yr design life, 5yr planned maintenance interval, and a target project IRR of 8%, giving the waterfall a common foundation.

Given first of a kind (FOAK) costing of LN6 WEC CapEx and AEP estimated from a numerically modelled power matrix, an initial LCOE starting point was calculated. By making mooring design optimizations, 16% of CapEx can be removed. These optimizations would involve reducing drag embedment anchor sizes while maintaining a safety factor of 1.9 during ultimate limit states, and 1.4 during accident limit states. The minimum safety factor necessary for DEAs is 1.5 for the intact condition. Reducing chain lengths from 150m to 130m, which maintains safety factor of 7, when a minimum of 2.2 is necessary.

A further 26% of CapEx can be removed through WEC cost optimization. This would come from moving from one-off NetBuoy costs to costing projected by TTI's cost tool [8], using standard modular buoyancy offerings for the reaction body, and other minor cost reduction.

This brings the optimized LN6 pilot array LCOE well within the realm of viability under favorable market conditions, such as the UK's Contracts for Difference (CfD) mechanism, a competitive bid process with a maximum strike price of $0.52/kWh [11]. To further unlock projects, DA needs a path to LCOE suitable for utility scale arrays. This is achieved through scale evolution towards a large prime mover. A 12m diameter WEC, "LN12", is capable of sufficient uplift in AEP to cover further anticipated cost and bring LCOE down to $0.15/kWh.

Task 14

From the overarching Statement of Project Objectives (SOPO):

> SOPO Task 14.0.0: Manufacturing Planning
>
> *Task Summary:* Develop manufacturing plan and estimate system fabrication, deployment, operations, maintenance, and decommissioning costs for a 2-year deployment at PacWave.

Task 14 Major Activities and Results

To ensure feasible economic modelling, DA had continual discussions with suppliers throughout the project.

DA was able to leverage existing relationships with many suppliers, including those used for sub-system prototype fabrication. An effort was made during the LUMA PTO prototype fabrication to use suppliers capable of volume production. This focus led the DA team to work closely with Potencia Industrial, a manufacturer of special application high efficiency electrical motors and generators. Potencia had previously collaborated with DA management on the production of Zond and Clipper Windpower's generators, lending confidence in their ability to produce the LUMA PTO at volume.

Elsewhere in the Anacapa supply chain, potential suppliers of seals, bearings and laser cladding have been communicated with forming initial lanes of communication and understanding of needs.

In many cases, formal quotes, or informal estimates were produced for the various components and systems making up the overall WEC CapEx, granting credibility to the design and business case. Moreover, these quotes were used as the basis of device costs in this project's LCOE modelling efforts.

Accomplishments

DA's LumaNet (LN) class WEC is a point-absorber that combines novel subsystem solutions, the LUMA linear direct drive PTO, and the NetBuoy inflatable prime mover into a lightweight and reliable architecture. Thanks to the modular PTO design and inflatable prime mover, this technology can easily scale as the wave energy market matures. The LN6 (6m diameter) WEC design is complete and ready for design finalization and fabrication. Scale models of the LN6 have been tested in the wave tanks at the University of New Hampshire (2023, 1:20 scale) and Oregon State University (2024, 1:40 scale), validating mid and high-fidelity models of the WEC. Data from tank testing were also used to validate mooring models in MoorDyn and OrcaFlex under a wide range of wave conditions. Additionally, these data were used for validation of a CFD model of LN6 developed by Sandia National Laboratories. With validated numerical models, the DA team was able to design LN6 to meet ultimate and fatigue loads associated with PacWave.

By the completion of this project, Dehlsen Associates proved a credible path to reaching below $150/MWh by 2030. DA believes this work has set the course for economic viability in a number of ways:

1. *Cost*: Prototype subsystems within the WEC have been built by suppliers capable of volume production, giving DA a solid cost basis for production and a head start on supply chain development.

2. *Power*: The WEC has been developed with optimal control development driving system design. This led to the LUMA PTO system, which couples optimal control strategies with optimized hardware cost, a feature that maximizes AEP in the LN6 WEC and larger-scale devices. Using a power-to-weight ratio (PWR) proxy for LCOE, the LN6 WEC maintains a promising position with a mass of approximately 20mT and a nameplate rating of 120kW (PWR 5.33).

3. *Reliability*: The Anacapa WEC has been designed with minimal maintenance as the objective. The WEC contains few moving parts, most of which have already been tested on a representative scale. This allows limited planned maintenance that can preempt unplanned outages.

4. *Ease of Transport*: DA designed the LN6 to be container-shippable to avoid costly logistics. The entire WEC can be packed within a standard 40-ft shipping container and transported on a flatbed truck, train, or container ship to the destination. With a full structural mass on the order of 20 tons, the WEC can be unloaded, assembled, lifted, and staged with equipment available at most port facilities.

5. *Scalability*: The product philosophy is predicated on the idea of minimizing non-recurring engineering by consolidating DA's core technology into a single adaptable unit: the linear universal modular absorber (LUMA). LUMA includes all necessary subsystems to convert linear mechanical inputs into electricity by coupling the unit with a prime mover. For LumaNet (LN), the prime mover is the Tension Technology International (TTI) NetBuoy. The DA team anticipates LN to allow larger scale prime movers with only modest design adaptations to the LUMA system. The goal of the LN6 WEC is to serve as an initial commercial product for intermediate projects while setting a foundation for expedited scale-up into large utility array units.

Lessons Learned

This project highlighted several important lessons for the future development and testing of wave energy converter (WEC) systems. First, the effort emphasized the difficulty of navigating pre-certification activities and aligning internal technology qualification processes with certification body expectations. Limited team size and time resources amplified this challenge. A closer review of certification body documentation requirements prior to project initiation could have streamlined this process by enabling internal documentation to be aligned from the outset, rather than retrofitted to external frameworks.

Finally, anchoring design activities to a specific test center and scale without secured funding for fabrication and deployment proved sub-optimal. The intended test center and scale are not feasible under private funding alone, creating a development gap and necessitating modifications toward a lower-capital-expenditure prototype path. This underscored the risks of a stage-gate approach that ends abruptly without a clear path to follow-on development work, thereby undermining the value of prior work. Future projects would benefit from more flexible planning, designed to deliver meaningful outcomes even in the absence of follow-on funding.

Together, these lessons underscore the importance of flexible project design, realistic planning for prototype development pathways, stable and predictable funding, and early engagement with certification frameworks to support the efficient advancement of marine energy technologies.

Conclusions

Project work has allowed Dehlsen Associates to complete a WEC design suitable for fabrication and testing at the PacWave South test site, and coordination with a certification body has put DA on track to acquire prototype certification of the LN6 WEC upon testing. Economic modelling conducted in parallel with the design efforts has strengthened the case for a viable business case for this WEC technology. Dehlsen Associates will therefore work in the coming years to conduct at-sea testing, unlocking the commercial potential of the technology developed over this project.

References

[1] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, FOA-0002415: Advancing Wave Energy Technologies through Open Water Testing at PacWave. Washington, DC, USA: U.S. Dept. of Energy, 2020.

[2] Oregon State University and U.S. Department of Energy, PacWave South Test Site. Corvallis, OR, USA, 2023. [Online]. Available: https://pacwaveenergy.org/south-test-site/

[3] DNV, "DNV-SE-0120: Certification of Wave Energy Converters and Arrays," Service Specification, Det Norske Veritas, Høvik, Norway, Mar. 2023.

[4] K. Klise, R. Pauly, K. M. Ruehl, S. Olson, T. Shippert, Z. Morrell, et al., MHKiT (Marine and Hydrokinetic Toolkit) – Python [Computer software], Jan. 2020. [Online]. Available: https://doi.org/10.5281/zenodo.3924683

[5] National Renewable Energy Laboratory. 2022. System Advisor Model Version 2022.11.21 (SAM 2022.11.21). Golden, CO. Accessed September 8, 2023. sam.nrel.gov.

[6] K. Ruehl, A. Keester, D. Forbush, J. Grasberger, S. Husain, J. Leon, D. Ogden, and M. A. Shabara, *WEC-Sim v6.1* [Software], Zenodo, Sept. 16, 2024. doi:10.5281/zenodo.13770349

[7] M. Hall, MoorDyn V2: New Capabilities in Mooring System Components and Load Cases, Preprint, National Renewable Energy Laboratory, Golden, CO, USA, 2020

[8] NetBuoy Design Tool. Accessed September 15, 2024. https://www.netbuoy.co.uk/design-tool

[9] OpenCFD Ltd. www.openfoam.com, 2025.

[10] IEC, IEC TS 62600-2 Technical Specification, 2 ed., Geneva: IEC, 2019, pp. 45-46.

[11] Department for Energy Security and Net Zero, Contracts for Difference (CfD) Allocation Round 7: administrative strike prices methodology note, Guidance, U.K., 23 July 2025.

Appendix

1) DNV Statement of Feasibility

Appendix 1:

DNV Statement of Feasibility

STATEMENT OF FEASIBILITY

Statement No.:	Issued:	Valid until:
SOF-DNV-SE-0422-12493-0	2025-09-17	2028-09-17

Issued for:

Technology Qualification

of

Anacapa Wavepower LumaNet 6 (LN6)

Specified in Annex 1

Issued to:

Dehlsen Associates LLC

805 845-7575

101 E. Victoria St., Suite F

According to:

DNV-SE-0120:2023-03, Certification of wave energy converters and arrays

Based on the documents:

CR-F-DNV-SE-0120-12493-0	Certification Report, dated 2025-09-17
CP-F-DNV-SE-0120-12493-0	Certification Plan, dated 2025-09-17

DNV has verified the Certification Basis, Technology Assessment, Failure Mode Identification and Selection of Qualification Methods and evaluated the main challenges of the technology as reported in the Certification Report. The technology is feasible and thereby suited for further development and certification according to DNV-SE-0120 applying the Certification Plan.

Changes of the technology are to be approved by DNV.

Hellerup, 2025-09-17

For DNV Renewables Certification

Bente Vestergaard

Service Line Leader for Type Certification

DAkkS Deutsche Akkreditierungsstelle D-ZE-22290-01-00

By DAkkS according DIN EN IEC/ISO 17065 accredited Certification Body for products. The accreditation is valid for the fields of certification listed in the certificate.

London, 2025-09-17

For DNV Renewables Certification

Claudio Bittencourt Ferreira

Project Manager