CalWave Design for PacWave

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Abstract

CalWave Inc. (CalWave) is developing a wave energy converter (WEC) technology that can generate electricity from ocean waves. CalWave's design offers a unique approach to wave energy conversion that operates fully submerged and can actively adjust the wave excitation. This capability gives the architecture enhanced survivability in ocean storms without adding significant costs. Prior to this project, CalWave had completed a demonstration of a fully functional WEC system in an open ocean demonstration at nominal 1:5 scale under FOA 1663.

The goal of this project was the detailed design, following relevant standards and industry best-practices, of a variant of the xWave WEC technology that can safely and efficiently operate at the DOE's PacWave-South test site for a targeted deployment of up two years. The WEC design and associated review processes proceeded in two distinct project phases: a 'Preliminary' and a 'Final' design phase.

The first phase of the project consisted of the systematic design of the WEC's key features with regards to appropriate IEC standards. The work resulted in a preliminary design of the xWave hull including structural and Power Take-Off (PTO) load estimates, as well as performance estimates for all ocean conditions the WEC would operate in at PacWave South. Following the first open-water demonstration of CalWave's small-scale "x1" device under FOA 1663, lessons learned were fed directly into a comprehensive review of the xWave design in the second design phase of this FOA project.

CalWave's work was supported by Sandia National Lab (SNL) and the National Renewable Energy Lab (NREL) on the holistic WEC design, and detailed feedback from specialized partners on hull design, mooring and anchoring specification, and electrical grid interconnection. Optimization of the WEC system was performed using a novel numerical optimization tool developed by Sandia and optimization trends were confirmed via an experimental model scale tank test campaign. Performance estimates for PacWave and a detailed xWave design including integration of all relevant system components were concluded. The mooring design was also concluded in the Final design phase using the most up to date sea floor characterization (CPT) data.

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1. INTRODUCTION AND TECHNICAL OBJECTIVES

This report was generated as part of the closeout reporting of the DOE-EERE 'Water Power Technologies Office 2019 Research Funding Opportunity' with project number DE-EE0008951. The objective of this project was to advance the detailed design, following relevant standards and industry best-practices, of an xWave variant of the *xWave* WEC for operation at the PacWave-South test site. Design and review were planned to proceed in two distinct project phases, summarized in Section 2 below.

Using a structured systems engineering approach, CalWave has developed a submerged pressure differential type Wave Energy Converter (WEC) architecture called xWave. The xWave architecture manifests as a single absorber oriented horizontally below the water surface. As waves pass over the submerged absorber, a pressure differential is created above and underneath, exciting the absorber in multiple degrees of freedom to oscillate in resonance. Energy is efficiently extracted using multiple independently controllable power take-off units. By changing the absorber's submergence depth using smart load management controllers, the pressure differential can be altered to effectively control wave excitation loads and shift hydrodynamic device properties. CalWave's device overcomes challenges that have faced the wave energy industry by integrating novel features such as advanced load management mechanisms via submergence depth control.

CalWave's xWave WEC design addresses the fundamental challenge in wave energy conversion: the large differential between wave energy flux during typical conditions and rare but powerful storm conditions and extreme events which contribute little to annual energy production but dramatically increase structural costs and thus hinder cost competitive electricity production.

The first phase of the project consisted of the systematic design of the WEC's key features with regard to appropriate International Electrotechnical Commission (IEC) Technical Specifications (TS), including 62600-2 and 62600-10. The outcome guided the design of the *xWave* hull including structural and Power Take-Off (PTO) load estimates, as well as performance estimates at PacWave. Following the first open-water demonstration of CalWave's small-scale "*x1*" device, lessons learned were fed directly into a comprehensive review of the *xWave* design in the following 'Final Design Phase' of the project.

CalWave collaborated with Sandia National Lab (SNL) and the National Renewable Energy Lab (NREL) on the holistic WEC design, and detailed feedback from specialized partners on hull design, mooring and anchoring specification, and electrical grid interconnection.

The outcome of the preliminary design phase including a preliminary WEC CAD design, estimates for power performance at PacWave South and correlating mechanical and electrical loads, and project metrics including LCOE, peak-to-average mechanical power, and capture width ratio for the intended commercial deployment resource labeled 'PacIsland' as well the PacWave-South resource, design weight estimate, first IO&M concepts, and a summary of unresolved open design issues. A preliminary design presentation was held including the DOE project team and reviewers from the National Laboratories.

Throughout the detailed design process, CalWave utilized various approaches for efficiency and power performance improvement and ultimately optimized the system within volume and load constraints. Design changes that were made to the preliminary hull and PTO design/integration that stem out of the optimization efforts were validated via tank testing at the Deep Ocean Basin (DOB) at the University of

Cork, Ireland. The tank testing results also validated CalWave's hydrodynamic models and moreover, the optimization trends.

Parallel to the mechanical design of the WEC and the PTO integration, the control and holistic operating strategy including submergence depth control was optimized. This included a very large number of iterations on designs and re-simulations/evaluations with respect to cost estimates and power performance, safety factors, and IO&M implications.

The detailed design of the absorber hull concluded at the end of the final design phase and housed all required auxiliary and power electronic equipment as well as the PTO drivetrains. Throughout all design efforts the IEC technical specifications, specifically the IEC TS 62600-2 (Design Requirements), 62600-10 (Mooring system design), 62600-103 (Early-stage development of WECs), and 62600-101 (Wave Resource Assessment) were considered. Design load case scenarios were evaluated using all methods available to CalWave: Experimental (wave tank) testing, validated CFD modeling in collaboration with NREL, and experimental impedance model based mid-fidelity simulation.

Along with the technical specification and design standard integration, CalWave planned the IEC accredited testing to be conducted at PacWave South with NREL. Test planning and instrumentation preparation were discussed and documented to allow accredited testing according to IEC TS 62600-3 (Mechanical Loads), IEC TS 62600-30 (Electrical Power Quality), IEC TS 62600-40 (Acoustic Characterization), and IEC TS 62600-100 (Electrical Power Performance). While this was strictly speaking not part of this project award, applying IEC standards to the design ultimately comes along with instrumentation planning into the WEC design.

2. Project Summary

This section provides a comprehensive summary of the work performed during the single budget period of the FOA 2080 project. The project comprised of 3 overarching main tasks, namely 0. Project and Risk Management; 1. Preliminary WEC design; and 2. Final WEC Design.

As there was only a single Budget Period, no GnG review existed. However, a Preliminary design review meeting with the DOE team and subject matter expert reviewers/national laboratory members was conducted and feedback was received.

Project and Risk Management

The Project and Risk Management task ran throughout the entire FOA project, spanning over both, the preliminary as well as the final design phase.

CalWave applied best practices in project organization using project management tasking tools and planning tools throughout the duration of the project. A project management plan was created at the start of the FOA 2080 project and updated throughout to manage not only project partners, all running and planned tasks, the global schedule, FOA budget, and reporting requirements.

The risk management plan and risk register include risks that could be encountered during a potential device manufacturing, deployment, and testing project. Partner review of identified risks and mitigation strategies is critical to ensuring risks are adequately addressed in every phase of the design.

Throughout the FOA2080 project, CalWave applied and utilized the NREL MHK Risk Management Framework and collaborated with expert partners in their respective fields to identify and assess potential threats and hazards related to the design development and testing.

During the preliminary design phase an initial Risk Register was created and populated with the highest system level risks. Risk review meetings were conducted on a frequent basis, both CalWave team internal and with relevant partners, to identify risks and mitigation strategies. As part of the Risk Management Framework the Risk Register and existing health and safety procedures were reviewed alongside the development of IO&M planning in order to ensure safe installation and operation of the constructed WEC when it is deployed at the PacWave test site.

After each IO&M meeting the Risk Register was updated and reviewed prior to the subsequent risk review meeting. Comments and responses from the dialog between CalWave and partners were captured and maintained to ensure they are adequately addressed and incorporated into the Risk Register.

This process continued in the Final Design Phase of the project and led to a much more propagated and reviewed risk register and revised risk management plan.

Preliminary Design Phase

Phase 1 of the project focused on the preliminary WEC design and included multiple Subtasks. Work conducted and deliverables derived are outlined in the following:

During the preliminary design phase CalWave collected and reviewed IEC and IEEE technical specifications and standards. A large list of specifications and standards applicable to the project and design was derived and subsequently evaluated in terms of priority and applicability for the deployment at PacWave. Project tasks were connected to the identified specifications and standards to ensure that design of the xWave system aligns with standards and best practices.

For initial sizing as well as load derivations, existing mid-fidelity models for the xWave system were used. CalWave compared existing models of PTO and mechanical system modeling tools with the existing data collected of the x1 in field operation A preliminary CAD design of the xWave WEC hull was completed including the hull structure and winch type PTO integration. Weight estimates and inertia properties were derived based on structural load requirements. Shape and construction of the WEC absorber were discussed with external fabricators for feedback going into the final design phase.

A preliminary electrical system was drafted with focus on the electrical system architecture. Power electronics, energy storage, and device umbilical were sized based on estimates of the xWave performance at PacWave South. A target SCADA platform was selected that aligned closely with the SCADA system and architecture that CalWave utilized during the x1 deployment. Multiple iterations on the low-level control strategy as well as the general xWave operation at PacWave depth adjustment approach were conducted.

During the preliminary design phase CalWave engaged with and discussed more detailed scope of work for the preliminary design phase. A database of potential vessel providers in the vicinity of PacWave was created and towing routes from fabricators were laid out. Additional site resource characterization specific to the PacWave site was conducted and design load cases relevant for the installation and maintenance activities were added to CalWave's DLC list. CalWave staff also traveled to Oregon and met with PacWave and grid operator staff and surveyed the local area to determine optimal locations for onshore services and laydown areas.

At the end of the preliminary design phase, CalWave provided a design report that included a thorough summary of the derived WEC system design. Load and power performance metrics, LCOE, peak-to-average mechanical power, capture width ratio, IO&M concept and mooring design were included. The preliminary risk management plan and risk register as well as CalWave's plans to incorporate the IEC 62600 and IEEE design specifications and standards for grid interconnection were included.

Preliminary Design Review

A preliminary design review took place in Spring 2021. CalWave shared with DOE and multiple reviewers from National Labs a thorough presentation on the activities and the preliminary xWave design derived during the first phase of the project. Comprehensive feedback was collected from the reviewers and responses and clarifications were provided by CalWave in follow up calls. Recommendations and feedback were sorted into the respective sub-tasks of the Final WEC design phase.

Final Design Phase

Subsequent to the Preliminary WEC design phase and the completed Preliminary Design Review meeting with DOE and reviewers, the Final WEC Design Phase commenced. Following the preliminary design review, the initial mid-fidelity simulation model was updated and used to confirm device and PTO operational requirements in all operational sea states at PacWave South. This analysis followed IEC guidelines to identify and define design load case (DLC) conditions that included not only fully operational conditions, but furthermore a large set of faults or abnormal conditions and scenarios that were modeled. Design driving characteristic loads were derived and safety factors according to IEC 62600-2 guidelines applied to obtain design loads.

A high fidelity CFD model was built in collaboration with NREL. This model was used to assess the device operational characteristics in sea states that cannot be accurately modeled using simplified Boundary Element Method wave theory. Extreme return waves as well as additional scenarios such as surface breaching and wave slamming scenarios were assessed. CFD results were compared and aligned with wave tank testing results.

Next to time domain models, CalWave developed in collaboration with Sandia National Labs a representative optimization model in the WecOptTool environment. The model included drivetrain and even specific nonlinear control characteristics, while optimization variables such as geometric shape parameters and mooring layout parameters were included as optimization variables. Due to the high computational requirements for a large set of optimization variables, the derived models were scaled up to AWS cloud computing tools which allowed to run hundreds of thousands of optimizations runs. Results were used in an iterative manner to obtain optimal device geometric aspect ratios and mooring arrangement in combination with control and PTO parameters and components.

A 1:25 scaled xWave prototype was constructed based on the optimization results and used in wave tank testing experiments at the Deep Ocean Basin at Cork, Ireland. System identification tests (SID) and performance tests were conducted to a) derive updated hydrodynamic models and intrinsic impedance models for the updated geometry and b) validate kinematic and dynamic design loads derived from numerical tools to conclude the design requirements for component selection and as a design input into the absorber detailed structural and mooring/anchor design.

A detailed CAD model of the WEC hull including PTO and systems integration was developed. Load rainfall diagrams for PTO and hydrodynamic loads were used to acknowledge design requirements against fatigue for a 20-year lifetime of the WEC. Interfaces between the PTO and the hull were defined and additional mounts and support structures were designed for integration of the existing PTO design. The final WEC electrical system concluded, aligning with PacWave interconnection requirements. Component selection of power electronics concluded and single line diagrams as well as detailed electrical diagrams were prepared. CalWave ensured that the potential umbilical options were suited for integration into the MacArtney connector, a requirement to connect to the static PacWave subsea cable.

Throughout the entire final design phase, CalWave applied IEC 62600 technical specifications to the design. Three of the desktop design rooted IEC technical specifications were explicitly applied to the design process, namely:

- TS 62600-2, “Design requirements for marine energy systems”, which defines the Design Load Cases (DLCs) or operational states meant to capture the system requirements in the various conditions that was used during the simulation task.

- TS 62600-10, “Assessment of mooring systems for marine energy converters (MECs)” defines mooring components and their required safety factors based on device and site parameters. The mooring system technical specifications were applied to the anchor and mooring design and CalWave ensured that such specifications were applied by third parties involved in the design.

- IEC 62600-103, "Guidelines for the early-stage development of wave energy converters - Best practices and recommended procedures for the testing of pre-prototype devices" were applied during the wave tank test planning and the actual execution of the testing.

  Furthermore, IEEE 1547-2018 "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources [DER] with Associated Electric Power Systems Interfaces" standard was applied to ensure the electrical design followed PacWave South requirements.

Along with the detailed design of the WEC and mooring/anchor system, CalWave derived an IO&M plan that includes xWave WEC transportation, staging at the test site pier-side, lifting & towing operations, potential local vessels and vessel operators, anchor deployment steps, and WEC deployment steps.

Furthermore, safety aspects were discussed for operations which will further be aligned with WPTO's best practice guidelines from Environmental Health and Safety (EHS) to minimize risks for all operations involved in the IO&M of the WEC. The IO&M planning also embraced a description of how the WEC will be operated at PacWave, how data collection and alignment with accredited test data sampling is planned, and a summary of tests planned for accredited testing in collaboration with PacWave, NREL, and PNNL.

Based on DLC results from numerical models and wave tank testing a final anchor specification document was derived including design targets for mooring loads and angles. Application of the IEC 62600-10 was discussed in detail with the anchor design partner and safety factors that align with the technical specification were applied. The detailed mooring design utilized Cone Penetration Testing (CPT) data that was sampled via OSU and PacWave in Summer/Fall 2023.

CalWave engaged with multiple potential fabricators to discuss a manufacturing plan and derive rough order of magnitude (ROM) cost estimates. Drawings from the work with a third-party naval architect were used to discuss further improvements of the WEC absorber design for production and feedback was incorporated.

A final design report was assembled that included a description of the xWave WEC designed for PacWave South. Additionally, the final commercialization planning task included all efforts to plan for a potential market entry with the exact size and rating of the developed xWave WEC under this award. Building upon the preliminary commercialization plan, the final commercialization plan included an update on CalWave's tangible commercialization efforts and work. Furthermore, target markets were more precisely defined and financing tools were identified and discussed. A marketing plan was added to the final commercialization plan and impact metrics (e.g. alignment with Sustainable Development Goals) discussed.

3. Challenges and Lessons Learned

CalWave successfully concluded a final detailed design of the xWave unit for a planned two-year deployment at PacWave South. The design of a highly energy production efficient, yet safely operating and cost efficient WEC unit requires an immense effort: Design of subsystems can only progress individually to a certain extent until subsystem interdependencies (e.g. PTO and absorber integration, auxiliary system integration) requires iterative alignment between designs.

The following summarizes high level challenges and lessons learned from this award. Many of these challenges and lessons learned are not specific to CalWave's technology design and can be applied to other projects and WEC device architectures.

PacWave South Test Site Alignment and Development

This award started in the Spring of 2020 with the preliminary WEC design phase which lasted for about one year and concluded in a preliminary design in the Spring of 2021. During the preliminary design phase many of the PacWave specifics such as grid interconnection/umbilical connection as well as sea floor geotechnical information was only partially given. Going into the detailed design phase, CalWave had to iterate on anchor solutions once more detailed CPT data for the test site became available.

IEC (RE) Certification/Accreditation

Historically, certification bodies (CB) such as DNV-GL, or ABS have developed their own certification processes and ruleset of technical specifications and standards. While certification according to specific CB's guidelines was the norm for the wind energy industry, the industry also pivoted towards an IEC based system, ultimately also pushing such certification bodies towards offering services to certify according to the IEC established standards.

It is certainly a worthwhile effort to strive for a harmonization of certification efforts as this comes along with multiple benefits. Harmonization promotes greater clarity for end-users and industry stakeholders including equipment manufacturers, power producers, insurance companies, test laboratories and certifying bodies by converging on using the same ruleset for development, testing, and evaluation of components and entire systems. This should also lead to industry-wide cost reduction.

In practice however, certification according to the IEC-RE system for Marine Energy Converters (MECs) in general, and WECs in particular is currently rather challenging given the status of technical specifications, and accredited testing laboratories. To CalWave's knowledge only a single CB has so far accredited a tidal developer according to a single IEC 62600 technical specification (-4). No accredited testing for power performance, power quality, or mechanical loads have ever been successfully concluded nor have testing reports been used by a certification body.

Challenges were also encountered in applying the IEC 62600 technical specifications during the design process as language was occasionally unclear or included recommendations that were disagreed with. This is somewhat to be expected as the technical specifications are in earlier releases of the lifecycle to becoming established standards. Feedback for the IEC working groups has been collected throughout the project and has been provided to IEC 62600 convenors. Interpretation of guidelines that have a tangible impact on WEC/mooring design inevitably leads to more design discussions and iterations, ultimately leading to increased workload and time required for decision making. This highlights the importance of WEC developers as end users to marine energy technical specifications and standards getting involved in the specification development process.

Application of Sandia's WecOptTool

CalWave made extensive use of Sandia National Laboratory's WecOptTool. The tool is the first optimization environment approach to couple hydrodynamic, WEC intrinsic, as well as PTO impedances in a multi-port impedance matching approach. This allows to evaluate both comprehensive and complex optimization challenges that are non-intuitive (e.g. how does the radiation dampening of a specific absorber body shape influence the PTO component selection).

Due to the complexity of the optimization problem, them wecOptTool is not a simple black box that can be applied rapidly to any type of WEC. The setup of an optimization problem cannot be made generic regarding the kinematics and dynamics of a WEC architecture and hence, a customized tool setup was required that included a multi-DOF model of the xWave. The complexity of the implementation of such a model depends heavily on the targeted optimization parameter.

The optimization of WEC characteristics is made only if PTO characteristics are (partially) known or iterated within realistic bounds. If the bounds are removed and/or no suitable PTO impedance description is used, the optimization problem is often ill conditioned and will not converge/lead to any realistic solutions. Hence, application of the WecOptTool must already come along with some constraints regarding practical PTO approaches and or sizing, rating, loss models, to be productive.

Overall, the tool is a unique and very helpful addition to the modeling and optimization environment supported by the National Labs. However, blind application for optimization without economic evaluation of optimization trends must be avoided.

The optimization results and trends in the wecOptTool was thoroughly compared to time domain models and performances and also validated by CalWave with different absorber shapes in a dedicated tank test campaign, which further increased the confidence of CalWave's xWave implementation into the wecOptTool.

Offshore Operations planning years in advance

CalWave invested a large amount of time in scoping potential offshore operations partner and vessel operators to derive, de-risk, and cost out offshore operations for the xWave deployment at PacWave South. While all discussions CalWave had with potential vessel operators for tow, deployment and recovery of the unit were immensely helpful to shape the operations planning and flush out technical details, it certainly is challenging obtaining reliable cost estimates for operations that are years out. With CalWave's planned deployment of the xWave unit at PacWave South in 2026, cost estimates are rather difficult to obtain or were rather vague. This not only makes the evaluation of certain equipment design with respect to operations difficult, but also prohibits accurate budget estimation and planning for the actual deployment as well as increases the uncertainty of LCOE estimates.

This challenge isn't unique to CalWave but highlights again that project plans need to be handled flexibly, especially when getting closer to the actual deployment operations of a WEC.

4. NEXT STEPS

Based on the successful detailed design of the xWave technology conducted under this award and the encouraging results on WEC behavior and performance derived from wave tank testing and numerical simulations, CalWave will move forward with the actual drivetrain testing and ultimately the build of the xWave demonstrator for deployment at PacWave South under FOA 1837 (PTO Testing) and FOA 2415 (xWave system build and PacWave deployment) respectively:

1) **FOA 1837 - PTO Control Co-Design**
   CalWave has derived a fully co-optimized PTO design that aligns with the xWave system developed under the FOA 2080 award as well as the Holistic Control strategies (submergence depth control and PTO/drivetrain control). Currently, CalWave is in the process of staging equipment and hardware for an at-scale PTO test rig that will allow the complete evaluation of performance characteristics of the drivetrain designed for the xWave system for PacWave South. System identification and hardware-in-the-loop approaches will be used to derive even more accurate numerical models and confirm the high performance of the xWave system.

2) **FOA 2415 – CalWave xWave at PacWave**
   CalWave has concluded the first Budget Period 1 of the FOA 2415 award which included comprehensive PacWave preparation activities. As the next steps, CalWave will start the equipment and hardware procurement as well as the fabrication of the Absorber body for the xWave WEC. Consecutively, under this FOA 2415, CalWave will deploy, operate, and decommission the designed xWave system at PacWave South with a targeted deployment duration of 2 years. The xWave system will be grid connection via the PacWave subsea cable to the local utility grid and this project will push the xWave technology towards high TRL levels.

Beyond the above two FOA projects, CalWave has started to plan the continued evolution of the xWave system towards MW class device designs.