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Any findings, opinions, and conclusions or recommendations expressed in this report are those of the author(s) and do not necessarily reflect the views of the Department of Energy,

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List of Acronyms

ABS	American Bureau of Shipping
AIM	Active Interface Module
ALM	Active Line Module
CDIP	Coastal Data Information Program
CO	Carbon Monoxide
CO2	Carbon Dioxide
CONOPS	Concept of Operations
COTS	Commercial Off-the-Shelf
CPwr	Columbia Power Technologies, Inc.
CRT	Cast Resin Transformer
DAA	Development Accompanying Assessment
DAQ	Data Acquisition
DC	Direct Current
DLC	Design Load Case
DNV	Det Norse Veritas
DOE	U.S. Department of Energy
DOF	Degree of Freedom
EA	Environmental Assessment
FMECA	Failure Modes and Effects Criticality Analysis
FRP	Fibre Reinforced Plastic
GL-RA	Germanischer-Lloyd Renewables Advisory
GL-RC	Germanischer-Lloyd Renewables Certification
GPS	Global Positioning Service
HECO	Hawaiian Electric Company
HINMREC	Hawaii National Marine Renewable Energy Center
Hm0	Average Wave Height
HMI	Human Machine Interface
HMSC	Hatfield Marine Science Center
HSC	High Speed Craft
LandRAY	Test Article for Project DE-EE0006399
LL	Lower Level
M2G	Motion-to-Grid
MCBH	Marine Corps Base Hawaii
MBP	Molluscan-Broodstock Program
ML	Middle Level

MNm	Mega Newton-meter
MoMo	Motor Modules
NAVFAC	Naval Facilities Engineering Command
NEXWC	Naval Engineering and Expeditionary Warfare Center
NREL	National Renewable Energy Laboratory
O&M	Operating & Maintenance
O2	Oxygen
PE	Power Electronics
PLC	Programmable Logic Controller
Project	This Project DE-EE0005930
PTO	Power Take Off
RAID	Redundant Array of Independent Disks
RCW	Relative Capture Width
S1	StingRAY Project
SCADA	System Control and Data Acquisition
SOF	Statement of Feasibility
SPM	Single-Point Mooring
SQL	Structured Query Language
SST	Sound and Sea Technologies
StingRAY	WEC used in Project N39430-14C-1485
TA	Technology Assessment
Te	Energy Period
UL	Upper Level
UPS	Uninterrupted Power Supply
WEC	Wave Energy Converter
WETS	Wave Energy Test Site

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1 EXECUTIVE SUMMARY

1.1 Significant results

This funding opportunity and Project were well-timed with Columbia Power Technologies' (CPwr) commercial development and technology demonstration needs. In early 2012, CPwr had determined that further cost and performance optimization was necessary in order to commercialize its StingRAY wave energy converter (WEC). CPwr's progress toward commercialization, and the requisite technology development path, were focused on transitioning toward a commercial-scale demonstration. This path required significant investment to be successful, and the justification for this investment required improved annual energy production (AEP) and lower capital costs.

Engineering solutions were developed to address these technical and cost challenges, incorporated into a proposal to the US Department of Energy (DOE), and then adapted to form the technical content and statement of project objectives of the resulting Project (DE-EE0005930). Through Project cost-sharing and technical collaboration between DOE and CPwr, and technical collaboration with Oregon State University (OSU), National Renewable Energy Lab (NREL) and other Project partners, we have demonstrated experimentally that these conceptual improvements have merit and made significant progress towards a certified WEC system design at a selected and contracted deployment site at the Wave Energy Test Site (WETS) at the Marine Corps Base in Oahu, HI (MCBH). The WEC design solutions and corresponding validations include:

1.1.1 Removal of rotary end stops has been experimentally validated at 33rd scale and confirmed to enable:

- unlimited float motion in extreme seas, which will improve availability by >5% and allow for greater float range of motion in all expected sea states, both of which increase AEP
- a float recovery process that passively restores the forward float to its normal operating condition by supervisory control and data acquisition (SCADA) remote command, once a storm has diminished
- removal of expensive end stops requirements, resulting in component cost reductions of over $1,000,000 per WEC.
- elimination of fore and aft float-to-end-stop collisions during larger waves, which had resulted in cost-prohibitive design requirements on the drive shafts and float structure

1.1.2 Experimental demonstration of the 33rd scale single point mooring (SPM) design and concept that confirmed the StingRAY commercial-scale WEC will:

- passively self-orient to the predominant wave heading--without external power, due to wave forces alone—allowing sweep (drift) from up to 90 degrees, with respect to the nominal no-load heading, into alignment with the mean wave-direction, increasing AEP up to 5% above a fixed heading mooring design
- reduce the amount of mooring hardware (anchors and lines) deployed, lowering mooring capital costs
- reduce the mooring footprint and amount of gear in the water, lowering the probability of negative interactions with marine fauna

1.1.3 Improved hydrodynamic shape and ballast design

- modeled WEC performance of the Project WEC design increased from 83% to 108% above the baseline WEC, depending on the wave site evaluated, with an expected improvement of 86% at WETS.

1.2 WEC loads, design and certification

WEC loads were evaluated as part of the certification process by CPwr and DNV GL Renewables Advisory (DNV-GL RA) and reviewed by DNV GL Renewables Certification (DNV-GL RC). These loads were the foundation for the WEC structural design work and certification activities, including design evaluations, design basis review, risk analysis, risk register compilation and receipt of the Statement of Feasibility (SOF). The full-scale detailed design for the Project StingRAY was developed up to the interface point with the WETS infrastructure. The interfaces between the WEC and the WETS infrastructure is scoped to and funded by a separate Navy contract.

1.3 SCADA Hardware design, programming and build

To reduce risk during the WETS StingRAY deployment, the SCADA system for LandRAY (DE-EE0006399), a land-based power-take-off (PTO) test, was designed, programmed and built. This provided a robust and proven platform, on which the StingRAY SCADA system was further developed. The SCADA has been installed for the LandRAY PTO test, currently in-progress.

1.4 Selection of build site, test sites and operations plans

Deployment locations and construction sites were evaluated and selected with priority directed toward meeting commercialization strategies and objectives, project success and cost reduction. Essential to these decisions are wave climate, existing electric-grid-connection, bathymetry, testing fees, O&M contract fees and permitting requirements; all of which have varying degrees of impact on the intended one-year or longer testing plan. Decisions and results of this logistical investigation confirmed that:

- WETS, located at MCBH, Kaneohe Bay, Oahu, Hawaii, will be the WEC test site location
- Vigor Industrial in Portland Oregon will be the major assembly site for the WEC
- a submersible barge will be leased and a tug hired to transit the WEC from Portland to Oahu, followed by deployment of the WEC at WETS
- Sea Engineering in Honolulu, HI, has been selected as the marine operations crew supporting WEC operations and maintenance (O&M)

Columbia Power wishes to thank the US Department of Energy for its collaboration, oversight and financial assistance, which has materially contributed to the success of this critical project.

2 INTRODUCTION

This Project aims to satisfy objectives of the DOE's Water Power Program by completing a system detailed design (SDD) and other important activities in the first phase of a utility-scale grid-connected ocean wave energy demonstration. According to the DOE, water power resource energy production can provide 15% of present U.S. electricity consumption by 2030. Wave energy has the potential to match or exceed that currently provided by conventional hydroelectricity. However, a practical cost-effective demonstration of this technology, at sufficient scale, in the open-ocean for an extended period of time, is required to attract the necessary private capital to develop commercial wave energy farms. Public funding of this and future project phases is critical to attracting additional private capital and enables Columbia Power to transition this technology from laboratory- and intermediate-scale tests to a full-scale open-ocean demonstration.

Current critical-path efforts to drive the StingRAY towards commercialization include:

- completion the StingRAY v3.2 final design, along with issuance of a Statement of Feasibility as a part of this Project
- advancement of the StingRAY WEC to a next generation v3.3 design to leverage the learning and knowledge recently gained

- achieving TRL6 for PTO through validation testing of a large-scale prototype at the National Wind Technology Center with the 5MW dynamometer.
- conducting a structural optimization project to reduce hull structural risk and manufacturing costs
- optimizing the WEC for cost-effective installation, operations and maintenance activities
- planning for a large-scale WEC test from 2017-18 at the US Navy's WETS facility

The StingRAY WEC is intended for utility-scale energy market. CPwr's target customers will purchase and operate the WECs in grid-connected, offshore wave farms. Offshore wave energy farms offer one of the best, new domestic opportunities for clean, predictable, abundant and reliable, utility-scale power generation. CPwr's goal is to produce a WEC that will provide cost-competitive, reliable energy generation with a survivable, low-impact system. These qualities are keys to successful market acceptance, product commercialization and meeting the DOE's goals.

The StingRAY WEC is designed to reliably and cost-effectively produce electricity, with perhaps unique ability to deliver 100% availability in extreme sea states. It has a tri-member fiber-reinforced plastic (FRP) hull and two high-torque, low-speed, direct-drive, rotary, permanent-magnet-generators (PMG). Simple in its operation, the StingRAY v3.2 device (Fig. 1), which is the subject of this Project, has three moving bodies: two floats and a central body. The central body (nacelle/spars) is coupled to the forward and aft floats through drive shafts, along the nacelle's central longitudinal axis.

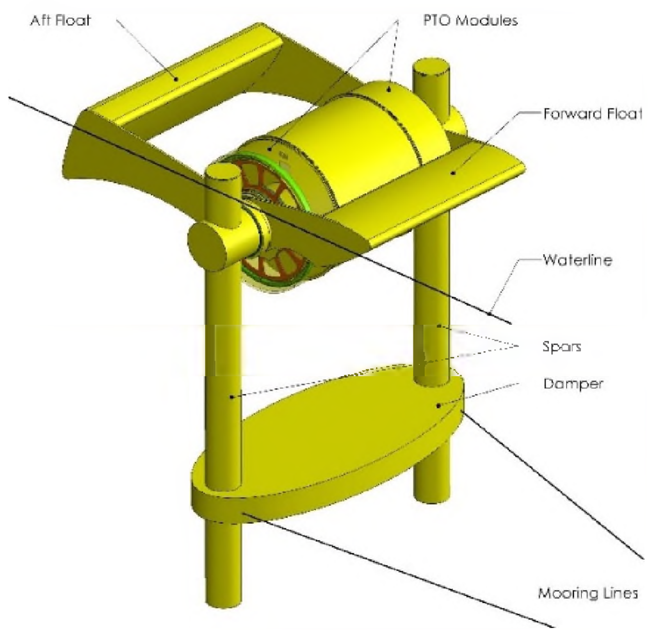

Figure 1 - StingRAY v3.2 WEC

The StingRAY's hybrid design significantly increases energy capture, availability and survivability, relative to point absorbers or attenuators. This hybrid approach is unique in the wave power industry and results in a design that is well-suited to meet expected customer requirements. The device will be deployed offshore, where the energy is greatest, with the least amount of visual and stakeholder impact (Fig. 2). The SPM system represents a relatively small profile in the water column relative to other offshore systems, minimizing its environmental impact.

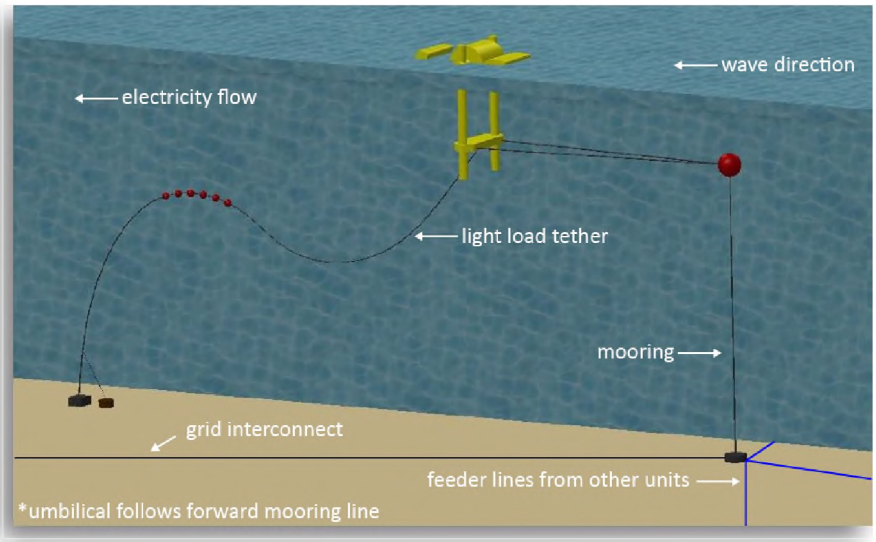

Figure 2 - Example deployed StingRAY WEC

3 BACKGROUND

CPwr has ten employees in its offices in Corvallis, OR and Charlottesville, VA, in addition to an international team of researchers, component developers and supply chain partners. In 2005, CPwr was founded by the principals of Greenlight Energy, Inc. (Greenlight) to commercialize a WEC technology, then being developed at OSU. CPwr is one of five independently owned and operated renewable energy companies founded by members of the Greenlight team; three of the five companies have since been acquired: Greenlight Energy Resources by BP in 2006, Axio Solar by SunEdison in 2011, and Heliosage by Coronal in 2015.

Under the oversight of the DOE and Navy, CPwr has conducted over 10,000 hours of in-water testing, with tens of thousands of hours of modeling, design and engineering.

Through a sound engineering path, CPwr has developed its proprietary WEC design with extensive use of internally- and externally-generated numerical models. Emphasis has been placed on experimental validation of numerical performance models, at the smallest appropriate scale and in the safest and most controlled environment available. This approach has allowed for cost efficiency and credible results, systematically reducing the risks involved with scaled testing in advance of commercial deployment.

The first six years of product development drove a number of significant techno-economic design improvements (Fig. 3).

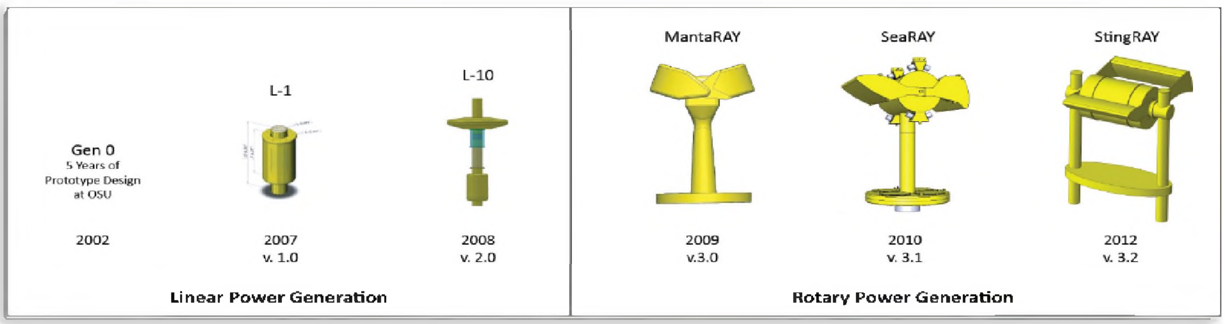

Figure 3 - Generational Advancement of Columbia Power WEC.

The linear motion of the first (v1.0) and second (v2.0) generation designs was replaced by rotary motion (v3.0 MantaRAY) to enable heave- and surge energy capture and a more cost-effective PTO. Additionally, a balance between hydrodynamic optimization and manufacturability resulted in a shape (v3.1 SeaRAY), which could be readily scaled up by CPwr's manufacturing partner and strategic investor, Ershigs Inc. The SeaRAY design delivered a dramatic improvement in both projected performance and survivability, providing a more-assured path toward commercialization. After the SeaRAY sea trials, CPwr devised a number of innovations described below that decreased structural costs and increased power production, including production through a wider range of sea states. These improvements were experimentally validated in in 2012. The net result of these innovations is the StingRAY (v3.2).

CPwr has tested scaled PTOs at the Wallace Energy Systems & Renewables Facility at OSU, in addition to linear (v1.0, v2.0) and rotary (v3.x) WEC prototypes in 2D and 3D wave tank experiments at OSU's OH Hinsdale Wave Research Laboratory (HWRL) and in open-water sea trials in Newport, OR and Puget Sound, WA.

Table 1 - Testing schedule

Year	Version	Scale	Units	Location
2007	1.0	1:10	1	Sea
2007/8	1.0/2.0	1:10	1	PTO Test Bed
2008	2.0	1:10	1	Sea
2008	3.0	1:50	1	Tank
2009	3.0	1:33	1	Tank
2010	3.0	1:15	1	Tank
2010	3.1	1:33	3 & 5	Tank
2011	3.1	1:4.5	1	Sea
2012	3.2	1:33	1	Tank

Following the linear and rotary test bed investigation of direct-drive PTO topologies and the 2007/8 v1.0 and v2.0 sea trials, projected LCOE and reliability considerations necessitated a departure from the v2.0

design and the creation of a new concept design using DDR PMGs. CPwr conducted extensive numerical modeling to investigate six major WEC body configurations able to incorporate the DDR PMG. Optimizations were then performed on shape, center of gravity (CG), inertia, mooring and damping to derive the v3.0 design. The v3.0 design allowed improved performance, allowing 100% active PTO material utilization at all times. The v3.x designs provided the key to unlocking the full potential of cost-effective wave energy conversion by harnessing the ocean's slow speed and high torque and allowing effective balance between the opposing challenges of ensuring survivability and lowering LCOE.

The 1:15 scale 2010 2D tank testing in full-scale equivalent signficant wave heights of 14.85m, with single wave events reaching 29.0m, demonstrated the inherent survivability traits. Post-test, over 350 discrete float shapes were then hydrodynamicly modelled, leading to the v3.1 prototype. The v3.1 design delivered an easier-to-manufacture hull geometry and included a large-diameter nacelle, which allowed for an increased generator diameter and provided an estimated 230% increase in energy production. The v3.1 design was tested in a 3D tank and sea trials.

In addition to producing electricity 84% of the time, CPwr gained significant experience in areas including: permitting, insurance, health & safety, marine operations, environmental monitoring, corrosion and bio-fouling management, and risk and significant-event management.

4 RESULTS AND DISCUSSION

4.1 Task 1.0 Wave Tank Testing and Assess Results

A 1:33 scale v3.2 prototype was designed, built and tested at Oregon State Universities, O.H. Hinsdale Tsunami wave basin. Testing included fifteen days of in-tank testing to collect detailed experimental data sets used to evaluate energy absorption, mooring loads and offshore behavior. Post processing was performed on wave, WEC and mooring data. Test conditions were numerically duplicated and modeled to evaluate actual vs. numerical-modeled mooring loads and performance. A final numerical model was developed using these data sets to improve its accuracy. Results from the testing were used to influence the final WEC and mooring design.

4.1.1 Test summary

A 1:33 scale model of the v3.2 prototype WEC was designed, built and tested by CPwr in a directional wave tank. The WEC mooring load-displacement responses were prescribed using a programmable mooring controller that was jointly developed by CPwr, OSU and NREL to accurately simulate scale equivalent forces expected from the mooring. Froude scaling is used in all aspects of this scaled experiment, as inertial and gravitational forces dominate. A detailed test plan was devised to examine the WEC response over a range of representative wave conditions (regular waves and directionally spread real seas), as well as effects of modifications to the WEC (e.g. ballast changes) and modifications to the incident wave field (e.g. changes to significant wave height or directional spreading). A numerical model of the as-built prototype WEC was developed using ANSYS AQWA and the test conditions reproduced numerically.

To summarize the primary findings of the regular wave tank testing and model validation:

- WEC performance, characterized by relative capture width (RCW), is greatest in shorter wave periods, dropping off considerably by 9 and 11 s for the aft and fore RCWs respectively.
- The numerical model identified the period of peak response quite accurately, but tended to over predict aft RCW and under predict fore RCW; the total power predictions were reasonably accurate.
- The pitch response of the fore float is much greater than that of the aft float or the central body (i.e. spar), and all three have resonant peaks at different frequencies.
- WEC performance was observed to decrease significantly with increasing regular wave height.

- The model predictions are considered to be generally acceptable.

To summarize the primary findings of the operational real seas wave tank testing and model validation, with default test conditions:

- WEC performance is quite high for $T_e < 8$ s but declines significantly with increasing T_e, and more moderately with increasing H_{m0}.
- The numerical model tended to over-predict aft RCW and under-predict fore RCW; the total power predictions were reasonably accurate. The errors for the fore PTO range from -28 to +6 % with an arithmetic mean of -14 %, while the errors for the aft PTO range from +11 to +37 %, with an arithmetic mean of +21 %. For this metric, normalization of fore- and aft performance is based on total performance.
- Spectral RCWs correlate strongly with RCWs obtained from regular wave testing.
- Extreme (99.8 percentile) relative pitching speeds are roughly two to three times the typical (70th percentile) speeds.
- The WEC was observed to have good seakeeping ability in these default operational seas.
- The model predictions are considered to be generally acceptable.

To summarize the primary findings of the operational real-seas wave tank testing and model validation, with modified incident-wave test conditions:

- WEC performance is sensitive to spectral shape, in that increased spectral peakedness concentrates wave energy in particular frequency bands, from which the WEC is either better or worse able to take advantage. The effect on performance was observed to be in the range of 5 to 15 %.
- WEC performance was seen to be sensitive to directional spreading. The decline in performance for spread seas was on the order of 5 to 20 % for the conditions tested.
- WEC performance was seen to be generally insensitive to initial wave heading, as the intended weathervaning capability proved successful.
- The WEC was observed to have good seakeeping ability in these operational sea states.
- The model predictions are considered to be generally acceptable.

To summarize the primary findings of the operational real-seas wave tank testing and model validation, with modified WEC configurations:

- WEC performance is marginally better for 'in-water' arms, as compared to 'out-of-water' arms.
- The model predictions for generator damping changes were generally acceptable.
- Modifications to damper tank position had a fairly small effect, with the greatest effect being on the aft performance; these performance changes were fairly-accurately predicted by the simulations.
- Ballast modifications had a large effect on performance, with total performance declining by up to 30 %. Performance predictions by the numerical model for the ballast modification cases were less than satisfactory.
- Both fore- and aft performance declined dramatically with the fore float in the aft position. The predictions of the numerical model for these cases were reasonably accurate.

To summarize the primary findings of the extreme-seas wave tank testing and model validation:

- The numerical model failed in all cases. The motions of the bodies were far more extreme than observed in the tank, to the point that the simulated response was considered entirely unrealistic.
- The 33rd scale test buoy was constrained to applying linear damping only. Consequently, generator torque in excess of 20 MNm was observed in the largest seas tested (H_{m0} of 14.3 m at full scale). Unlike the test buoy, the full-scale generator design torque is reduced to 1.5MNm for optimized

cost of energy, and non-linear controls keep torque limited to 1.5 MNm. Even with these unrealistically high torques from the test article, the fore float was observed to overtop the nacelle. It is expected, and 33rd scale confirmed that, at full scale, the fore float will overtop. The minimum conditions that will result in overtopping are estimated and used in the WEC's design and energy production estimates.

- The seakeeping ability of the WEC in extreme seas, even in seas that were initially beam-on, was observed to be excellent, as measured by pitch, roll and yaw.
- With the fore float in the aft position, the speed and torque of both fore- and aft generators are greatly reduced (on the order of 20 to 40 % with overdamping).
- The ballast modifications tested had a significant effect on generator speed and torque, and accelerations of the nacelle, stator and rotor. However, there was no ballast configuration tested that resulted in results more favorable (with regards to reducing speed, torque and acceleration) than fore-in-aft position.
- Fore-in-aft position is seen as having strong potential as a survival mechanism.
- The soft-latching fore float return mechanism was tested and found to function as expected in seas with $H_{m0} \geq 2.5$ m. It is hypothesized that a modified technique (not tested) will extend this capability to less energetic seas.

To summarize the primary findings of the mooring analysis in wave tank testing and model validation:

- The mean and oscillatory components of fore mooring tension increase with increasing wave height and decrease with increasing wave period.
- In operational real seas, the maximum fore mooring tension was observed to be 25 to 100 % greater than the mean tension. In extreme seas the maximum tension was observed to be up to 1,100 % greater than the mean tension.
- In extreme seas, the mean fore mooring tension for cases where the spar was ballasted down was reduced by roughly 40 % from that observed in the default ballasting case.
- The aft line tension was observed to increase with weathervaning angle, and with wave height, as expected.
- The AQWA numerical model greatly under-predicted both mean and maximum mooring tensions, as well as the WEC excursion due to wave drift. The experimental data will be used to validate other models that are potentially better suited to the task.

4.2 Task 2.0 Environmental Forces and Associated Load Analysis

The WEC system is subject to the environmental conditions found at the deployment site and the forces associated with those conditions. These environmentally-induced loads are associated with wave, wind current conditions for WETS, located at MCBH. The analytical modeling approach looks at normal operating conditions, as well as extreme conditions, with the objective to provide an assessment of loads on the structure, which then provide input for structural design. Extreme conditions for wave, wind and current are based on the 50 year return period at the WETS. The load assessment approach was developed by CPwr with guidance from DNV-GL RA and DNV-GL RC. Loads were evaluated by CPwr and, independently, by DNV GL RA. Loads were provided to Ershigs Inc. to support structural design.

4.2.1 Load assessment methodology

The WEC will be deployed at the deep-water Berth B of WETS, at a depth of 80 m. Site specific frequency-directional spectral wave data spanning 34 years of hourly records, obtained by a phase-averaged wave propagation model run by Hawaii National Marine Renewable Energy Center (HINMREC), form the basis of operational-seas characterization. The vast majority (98%) of individual sea states observed in the modeled data set have an Hm0 between 0.8 and 3.6 m, and a Te between 5.6 and 13.3 s. As wave propagation models tend to under-predict extreme wave conditions, Hm0 associated with R-year return seas is derived from the 13-year dataset measured at nearby wave buoy CDIP 098. The 50-year return Hm0 is estimated as 7.57 m, with an associated Te between 10.6 and 11.3 s.

The design load methodology requires that loads are assessed computationally using fully-coupled time-domain numerical simulations, accounting for all load contributions simultaneously. All relevant non-linearities (e.g. mooring lines, PTO) are considered. Comprehensive design load cases (DLCs) are specified, covering all relevant design conditions (e.g. normal, idling, extreme, fault).

Design loads were assessed and developed by CPwr using ANSYS AQWA. The model validation was instrumental in guiding the loads model development. DLCs cover a range of conditions, including fault cases and extreme seas. The WEC, which consists of three rigid bodies connected by one degree of freedom (DOF) pitching joints, was modeled as seven bodies to allow for loads to be extracted at critical interfaces. Body loads, joint loads, and body accelerations were output in local (i.e. body fixed) coordinate systems, in six DOFs. As the loads were provided in local coordinate systems, and the only relative motion permitted by the PTO constraints is pitch, the only relevant position data is the absolute pitch of each body. Additionally, PTO force and mooring loads were output. Design pressures were also provided, based upon the extreme draft observed in simulation. The outputs of this assessment were provided to Ershigs in support of 0100 Hull structural design (presented in subsection 4.3.1). Additionally, loads were provided as appropriate for various subsystem designs.

Independently of the CPwr loads assessment, a third party (DNV-GL RA) was contracted to undertake a loads assessment. DNV-GL RA developed a WEC model using WaveDyn, their commercial numerical simulation tool similar to ANSYS AQWA; DNV-GL RA also performed model validation using the 33rd scale tank test data discussed in section 4.1. The outputs of this assessment were used by DNV-GL RA for structural analysis of select hull components (see subsection 4.3.1). CPwr compared peak-loads output by the CPwr and DNV-GL RA assessments and found general agreement.

4.3 Task 3.0 Complete Full Scale Design

The WEC system design is organized into major subsystems 0100 – 0800, and Project design details are discussed in subsections 4.3.1-4.3.8.

4.3.1 Hull structure – 0100

The Hull Structure is composed of the main bodies of the WEC: nacelle, spars, damper, forward float, aft float, and ballast. In addition to the global system requirements, the Hull Structure is designed to satisfy the following design requirements:

- Convert wave motion into relative pitch between bodies
- Provide watertight barrier
- Provide separate modules for the generators and the control equipment
- Remain corrosion- and biofouling-free
- Allow docking of vessels and human access to all internal areas

A first-pass structural design was performed by Ershigs. The purpose of this effort was to establish a workable composite scantling specification for each body. Stiffening is accomplished with bulkheads or hat stiffeners laid over a structural foam core. The method of the design was described in the report:

> "The best guidance on the design of composites for commercial marine usage we are aware of is published as a ruleset by the American Bureau of Shipping (ABS), as part of the High Speed Craft (HSC) code. The sections involving calculation of design hydrostatic pressure, and material allowable properties were utilized, while the structural loadings were obtained from the previous StingRay AQWA study and post-processing effort. The structural

> computations published in the HSC code are very typical of those utilized for ships and other offshore structures, and produce reasonable figures in this application, but the strength methods and allowable design factors are published specifically for use with composites. As part of this design process, a hydrostatic pressure based upon the size/depth of the structure and the design wave-height of 7.58m (24.8 ft). This produces a skin pressure which is, in most cases, higher than the values resulting from the AQWA simulation. An industry acceptable design will utilize the higher of either the ABS derived pressures, or the AQWA simulation results. The final engineering design will be conducted using DNV rules. The ABS rule set, which will produce is roughly equivalent, if not slightly more conservative results, was close at hand, familiar, and appropriate for a preliminary analysis.
>
> Each structure was also analyzed for resistance to structural loads, as determined by AQWA. A required skin thickness to achieve adequate bending and shear resistance to those loads was determined. In general, the stresses from skin pressure, which produce local bending stresses were superimposed upon the global loading to result in increased skin thickness over what would be required to resist each load in isolation. No credit was taken for spaces which might ultimately be filled with concrete, foam, or other self-supporting material. It may be possible in the final design to reduce or eliminate stiffening members in such compartments."

The most efficient manufacturing method for FRP is to be made on mandrels. Because of this, all major bodies do not have concave contours. Also, when possible, the bodies do not have any complex shapes and are preferably cylindrical. After the bodies are constructed they will be pressure tested to ensure that there are no leaks through fitting, hatches, FRP bonds, etc.

The following is a description of each system related to the Hull Structure:

4.3.1.1 0110 Forward Float Assembly

The forward float assembly is a wave-activated body. The relative motion between the float and the nacelle drives the starboard generator. The forward float assembly is composed of a float, a drive arm, and an idler arm. The overall width of the forward float is 14.0 meters.

4.3.1.1.1 0111 Forward Float

The forward float's leading edge is shaped to capture head-on waves in the most efficient way possible. This leading edge has gone through many shape optimizations to its current design of the angle of attack, draft, and distance from the PTO origin. The trailing edge is shaped to rotate about the nacelle while moving the least amount of water, creating the most efficient motion. The forward float has a hull thickness of 0.788 inches with transverse stiffeners and bulkheads. The float body is attached to a drive and idler arm on the starboard and port sides respectively. The float has an airtight chamber that houses seawater ballast, foam and ballast compartmenting components.

4.3.1.1.2 0112 Forward Drive Arm

The forward drive arm is attached to the starboard side of the forward float and the starboard PTO shaft. The drive arm transmits the full drive loads (vertical and bending moments) as well as the lateral loads. The drive arm is 0.60 meters wide and has an FRP thickness of 0.854 inches with a structural foam core.

4.3.1.1.3 0113 Forward Idler arm

The forward idler arm is attached to the port side of the forward float and the port idler bearing. The idler arm transmits all loads in all degrees of freedom except for drive torque. Even though the idler arm transmits fewer loads than the drive arm, they both have the same cross section. The idler arm is 0.60 meters wide and has an FRP thickness of 0.854 inches with a structural foam core.

4.3.1.2 0120 Aft Float Assembly

The aft float assembly is a wave-activated body. The relative motion between the float and the nacelle drives the port generator. The aft float assembly is composed of a float, a drive arm, and an idler arm. The overall width of the aft float is 16.8 meters.

4.3.1.2.1 0121 Aft Float

The aft float's leading edge is shaped to capture waves from under the nacelle in the most efficient way possible. This leading edge has gone through many shape optimizations to its current design of the angle of attack, draft, and radius from the PTO origin. The trailing edge is shaped to rotate about the nacelle while moving the least amount of water, creating the most efficient motion. The aft float has a hull thickness of 0.854 inches with transverse stiffeners and bulkheads. The float body is attached to a drive and idler arm on the port and starboard sides respectively. The float has an airtight chamber that houses seawater ballast, foam and ballast compartmenting components.

4.3.1.2.2 0122 Aft Drive Arm

The aft drive arm is attached to the port side of the forward float and the port PTO shaft. The drive arm transmits the full drive loads (vertical and bending moments) as well as the lateral loads. The drive arm is 0.60 meters wide and has an FRP thickness of 0.802 inches with a structural foam core.

4.3.1.2.3 0123 Aft Idler arm

The aft idler arm is attached to the starboard side of the aft float and the starboard idler bearing. The idler arm transmits all loads, except for drive torque. Even though the idler arm transmits fewer loads than the drive arm, they both have the same cross section. The idler arm is 0.60 meters wide and has an FRP thickness of 0.802 inches with a structural foam core.

4.3.1.3 0130 Nacelle

The nacelle is an assembly of components that make up the cylindrical body on the top of the WEC. The upper level (UL) of the nacelle contains the control room with all power electronic (PE) equipment, energy storage, auxiliary system controls and SCADA. The middle level (ML) of the nacelle contains the entrance to the PTO module, ladders up to the UL, transformer, entrances to the nacelle tube via the spars and entrance to the lower nacelle via the nacelle tube. The PTO modules are the only part of the nacelle that has a lower level (LL). The LL contains bilge pumps, cooling pumps, bilge tanks, cooling expansion tanks, cooling system components and greasing components.

Integration of various systems, as mentioned above, into the nacelle during WEC assembly will occur while the nacelle is in a vertical position (normal while deployed). The nacelle will be shifted to a horizontal position during integration with the spars, which are described in Section 4.3.1.4, and maintained in that orientation until deployment. Special design consideration for personnel access to and operation of certain sub-systems, e.g. bilge pumps, while in horizontal orientation in dry dock, dock-side or pre-deployment will be necessary. Access to the nacelle while deployed will occur in vertical orientation.

4.3.1.3.1 0131 Nacelle Tube

The nacelle tube is the structural member that rigidly connects the spars to the nacelle. The use of two spars creates a requirement for a component that supports the nacelle. The nacelle tube is also used as a passageway for human access from the spars into the generator modules or the control room. There is space in the center of the nacelle tube in which large heavy components can be placed to maintain a low center of gravity; the transformer is stored here. The FRP is 4 inches thick.

4.3.1.3.2 0132 Lower Nacelle

The lower nacelle is an FRP housing that maintains the shape of the overall nacelle and helps support the PTO modules and the control room. The FRP is 1.072 inches thick with transvers and circumferential stiffeners.

4.3.1.3.3 0133 PTO Hull - Starboard

The starboard PTO hull is the outer housing for the starboard generator module. This hull component is made out of 1.072" thick FRP with two circumferential stiffeners. There is an emergency escape hatch out the top and an access hatch out the inboard wall, aft of the nacelle tube.

4.3.1.3.4 0134 PTO Hull - Port

See PTO Hull Starboard. The only difference between the two systems is their access hatch location; every other feature is identical.

4.3.1.3.5 0135 Control Room

The control room is a modular system that houses all of the control systems needed for the WEC (0300, 0400, 0540, etc.). Special consideration in the hull design is made for this component because the internal space needs to be maximized. The design and operational procedures insure that the space is a regulatory-compliant, safe working-environment for personnel, while in dock or at sea. For emergencies, there is an escape hatch out the top and two access hatches out the floor, aft of the nacelle tube.

4.3.1.4 0140 Spar Assembly

There are two spar assemblies, one starboard and one port.

4.3.1.4.1 0141 Spar - Starboard

The starboard spar rigidly connects the nacelle tube to the damper. This hull component is made out of 2.910 inch thick FRP. There is a passageway from the spar platform to the nacelle tube. There is both hard- and water-ballast in the bottom of the spar, and foam everywhere else. A cable routing tube will span from the platform to the mooring connection location. For the starboard spar, this tube will house the umbilical cable connection, data from the mooring load cells, strain gauge data and pressure sensor data.

4.3.1.4.2 0142 Spar - Port

The port spar rigidly connects the nacelle tube to the damper. This hull component is made out of 2.910 inch thick FRP. There is a passageway from the spar platform to the nacelle tube. There is both hard- and water-ballast in the bottom of the spar and foam everywhere else. A cable routing tube will span from the platform to the mooring connection location. For the port spar, this tube will house data from the mooring load cells, strain gauge data and pressure sensor data. Alongside the cable routing tube will be inlet and outlet ballast piping for the seawater ballast in the damper.

4.3.1.4.3 0143 Spar Platform - Starboard

The starboard spar platform will be the secondary use platform. This platform will house auxiliary systems, outfit and furnishings, burn resistors, surveillance cameras, hatch for human entrance into WEC, and solar panels.

4.3.1.4.4 0144 Spar Platform - Port

The port spar platform will be the primary use platform. This platform will house auxiliary systems, outfit and furnishings, seawater ballast inlet and outlet valves, hatch for human entrance into WEC, and auxiliary power connections to service vessels.

4.3.1.5 0150 Damper

The damper is a structure that rigidly connects the starboard and port spars. This hull component is made out of 1.612-inch-thick FRP with transvers stiffeners and bulkheads. There is hard ballast and seawater ballast in the damper. Seawater ballast inlet and outlet pipes connect from inside the damper where the seawater is located to the pipes in the port spar.

4.3.1.6 0160 Ballast

Ballast is used to achieve a desired draft, center of gravity and moment of inertia of the three main bodies of the WEC. For the nacelle-spar-damper body, the ballast is placed as low as possible in the WEC to achieve the lowest center of gravity for optimal performance.

4.3.1.6.1 0161 Hard Ballast

The hard ballast volume in the first-pass design is conceptually composed of steel spheres that pack together and fill 74% of the volume. Seawater fills in the remaining 26% for a combined density of 6038.5 kg/m^3 (7800*.74+1025*.26). The preliminary design includes 556,000 kg of hard ballast.

4.3.1.6.2 0162 Sea Water Ballast

Seawater ballast is used in the floats and the damper to ballast and trim the bodies and to achieve an overall mass and draft. Seawater is used because it is readily available during deployment. The volume of water was chosen to match the displaced mass needed to maintain the nominal draft height during the worst-case biofouling state. There is also some additional seawater ballast for trimming the WEC during commissioning. All seawater ballast must be placed below the nominal water line. In the event of a leak in the ballast chamber, this prevents the water from escaping and allows the chamber to remain filled.

4.3.1.6.3 0163 Foam

Foam is used to fill all voids where other components or human access are not located. Filling as many voids as possible prevents sufficient seawater to sink the WEC. Closed cell 3 lb/ft^3 foam is used for ballast foam (non-structural) and closed cell 5 lb/ft^3 foam is used for structural foam in stiffeners, bulkheads and the float arms.

4.3.1.6.4 0164 Ballast Compartmenting

Ballast compartmenting is the hardware and components that store and move the ballast material. These components include: baffles, pipes, tanks, valves, fittings, etc.

4.3.1.7 0170 Final FRP Assembly

The final FRP assembly is all of the layups and fittings used to interface between different hull components.

4.3.2 Power Take Off - 0200

The Power Take Off system is designed, built and tested under representative loads for risk reduction and performance evaluation under a separately funded project, "Build and Test of a Novel, Commercial-Scale Wave Energy Direct-Drive Rotary Power Take-Off Under Realistic Open-Ocean Conditions" (DE-EE0006399).

4.3.3 Electric Plant – 0300

The 0300 Electric Plant includes all equipment from the connection to the stator cables to the umbilical grid connection. The 0300 Electric Plant is composed of the Siemens Motion-to-Grid (M2G) system equipment, which controls the two generators and provides power to the grid. The StingRAY electric plant design is based on similar architecture as the LandRAY M2G system used to test the PTO of project DE-EE0006399. The StingRAY electric plant includes connection for two independent generators, power to the WEC station power system, and redundant active line module (ALM) + active interface module (AIM) grid connection. The StingRAY design also includes a larger appropriately-sized energy storage system, a marine transformer suitable for the interface with Hawaiian Electric Company (HECO) at WETS, and enclosures suitable for the environmental conditions specified in 0640 Marinization & Corrosion. A list of the major system components is included in Table 2 – Electric Plant system major component list

Table 2 – Electric Plant system major component list

0300	Electric Plant
0310	Motor Drives
0320	Drive Control
0330	Energy Storage
0340	Grid-Tie Inverter
0350	Transformer
0360	Transformer Umbilical Connection
0370	Emergency Resistor
0380	Switch Gear and Electric Buses
0390	Enclosures and Mounting

The Siemens S120 motor modules (MoMo) connect the groups of stator segments via automated breakers and provide power to a 720V DC bus. The 720V DC bus connects motor modules, energy storage, emergency resistor and ALM & AIM. The energy storage system provides power smoothing capability and braking resistors protects the DC link from overvoltage in the case of a fault. Two equally-rated ALMs, one for either side port and starboard, provide power to the grid via the main breakers to the medium voltage marine cast resin transformer (CRT).

The commissioning of the two generators and M2G systems will occur during dockside testing of the PTO systems. The commissioning of the segmented generators and M2G system will be performed by Siemens. The testing will verify that all systems are fully operational prior to completing the WEC final assembly. The final commissioning is performed once the WEC is deployed and connected to the grid. The testing is made possible by using all four quadrants of operation. For dockside testing, some stator segment groups are motored, while others are generating. This unique segmented machine design allows for a multitude of operational configurations and allows for testing of individual stator segments or groups of stator segments independently.

During normal operation the M2G synchronizes the segments of the generators to operate as two independent PTOs--port and starboard--on either side of the nacelle. The amount of power generated by the PTOs is controlled by the M2G system. Damping commands are provided to the M2G by the SCADA System. A portion of the power generated will be provided to 0540 Station Power for WEC on-board systems. WEC on-board systems include the M2G auxiliary loads, SCADA, bilge pumps, cooling system pumps, emergency systems, climate control, aids to navigation, and lighting & receptacles. In the case of a loss-of-grid fault, the M2G switches to ‘Islanding’ mode, in which the two PTOs operate with reduced damping at a reduced power level equal to WEC on-board loads.

4.3.4 Supervisory Control and Data Acquisition – 0400

The 0400 SCADA system serves as the central nervous system of the StingRAY device. It provides many critical functions during the calibration, commissioning, tow operations, deployment and recovery, and trial data collection stages of the StingRAY project (S1). The SCADA system is connected to the M2G, cooling system, and communications network allowing it to issue commands and collect data from these systems. The SCADA system allows operators to access real-time data, capture WEC operational and performance data, and implement PTO control strategies. The 0400 SCADA system is organized by the following subsystem designations.

Table 3 – SCADA subsystem designations

0400	SCADA
0410	Sensor Network
0420	I/O Modules
0430	Control Hardware
0435	Control Logic
0440	Human Machine Interface (HMI)
0450	Communications
0460	Data Server
0470	Software
0475	MATLAB® Data Interface
0480	Alarms, Diagnostics & Fault Recovery
0490	Enclosures
0495	Cabling

4.3.4.1 System Functionality

The roles of the S1 SCADA system are organized into the five major functional categories; Generator & Cooling Control, Human Machine Interface (HMI), Data Collection, Alarming, and Communication.

4.3.4.1.1 Generator & Cooling Control

The control function of SCADA provides safe control and oversight of the two PTOs, which are comprised of direct-drive generators and their supporting M2G equipment, as well as the cooling systems. Operators are able to adjust all control parameters through the SCADA system to achieve desired test configurations.

4.3.4.1.2 Human Machine Interface

The HMI is a secure operator interface for visualization of the SCADA system, providing operators a real-time view of StingRAY operational and performance data. All time-series plots, commands, and alarms will be accessible through the HMI. The HMI is also the means for operators to control and operate the StingRAY PTOs, as well the utility to start and stop data recording manually or automatically.

4.3.4.1.3 Data Collection

The SCADA is responsible for collecting a vast array of high-resolution data coming from the sensor network. Data collection is critical to the StingRAY testing, and allows for further analysis of the overall system response and performance. All data will be stored to disk as calibrated time-series-trial data in SI units within a formatted structured query language (SQL) database. SQL databases are an industry standard approach for collecting large, relational data sets.

4.3.4.1.4 Alarming

Automated alarming allows the SCADA system to rapidly respond to fault or alarm conditions and to execute appropriate actions. When alarm conditions are encountered, operators are immediately notified, and an automated response or shutdown request can be issued for any critical conditions.

4.3.4.1.5 Communications

The communication network provides a high-speed data connection between the S1 device and operators and engineers. Several diverse and redundant communication links make up the communications network, providing high availability in all conditions. All connections to the S1 SCADA system require an authorized password before a connection can be established. Predefined user authorization levels will allow for different levels of functionality.

4.3.4.2 Instrumentation

The sensor network is composed of a wide array of instrumentation that will be used to collect time-series data during StingRAY operations and trials. Sensors were chosen for operation in an ocean environment, including water resistance and materials selection. The list of onboard instrumentation is extensive, but will include: PTO position encoders, torque-rod load-cells, rail-wheel load-pins, bearing lubrication level, bearing temperature, seal leak detector, sump water level, inertial measurement units, ballast and external water levels, temperature and humidity within enclosed spaces, station power voltage and current, stator airgap measurement, stator displacements, seal gap measurements, bilge pump status, structural strain gauges, wave conditions, wind speed and direction, GPS position, WEC heading, vibration measurements, mooring tensions, M2G voltages and currents, stator temperatures, and cooling water level, pressure, flow, and temperature.

4.3.5 Auxiliary Systems - 0500

The auxiliary systems include all system which support the WEC and PTO power production. The auxiliary systems design documents are listed in Table 4. The vital systems covered by this design work are described in the following sections.

Table 4 – Auxiliary Systems

0500	Auxiliary Systems
0510	Ballast Control
0520	Safety & Emergency Systems
0530	Climate Control
0540	Station Power
0550	Aids to Navigation
0560	Cooling System
0570	Bilge System

4.3.5.1 0510 Ballast Control

The Ballast Control system is the hardware needed to house and control the ballast. The Ballast Control system is designed to allow for both fill and purge of seawater ballast tanks, provide passive ballast system for reducing reserve buoyancy of fore float when in fore-in-aft position and to provide ballast configuration to allow for tow from Honolulu Harbor to the deployment site

In the operational configuration, the WEC is floating and moored, with the spar-nacelle-damper structure in a vertical orientation and the fore and aft floats in the fore and aft positions, respectively. A key feature of the WEC is the ability of either or both floats to rotate independently about their shared axis of rotation without any risk of collision with any part of the WEC system. If in normal operations a large wave lifts the fore float up to and beyond the vertical orientation, it is free to continue rotating to a 'fore-in-aft' position with no risk of collision with either the nacelle or the aft float. While the direct-drive generator can be used as a motor, the system is not capable of applying sufficient torque to overcome the reserve buoyancy of the float. As such, a passive ballast design ballasts-down the float sufficiently, to allow motoring to return the float to the forward position.

For local towing operations (e.g. from Honolulu Harbor to the WETS deployment site), the WEC will transition to a towing configuration in which the spar-nacelle-damper structure is floating in an approximately horizontal orientation; the fore float may either be in front of the nacelle, or to the aft nested in between the nacelle and the aft float. During commissioning and post-biofouling, the seawater ballast tanks will be filled, trimmed, and/or emptied to achieve the required draft. All seawater ballast filling will be performed above water by a service vessel. The service vessel will either pump seawater into ballast tanks or use compressed are to purge the tanks. All ballast control connections will be on the port side of the WEC. The spar-nacelle-damper connections will be located on the spar platform and the float connections will be on top of each float.

4.3.5.2 0520 Safety & Emergency Systems

The Safety & Emergency system is a standalone system designed for high availability. It will identify and report on all unsafe conditions that affect personnel and device safety. Separate from the SCADA system, the Safety & Emergency system has its own dedicated power supply, sensor network, and communications link. The system will continuously monitor S1 for smoke/fire, CO2, CO, O2 levels, flooding, equipment failures, manually activated alarms, access interlock openings, mooring attachment loss, and watch-circle-breach events. Data from the Safety & Emergency system will be shared with the SCADA system for collection purposes.

Table 5 – Safety & Emergency Systems

0520	Safety & Emergency Systems
0521	Fire Protection
0522	Flooding alarms
0523	Air Quality Monitoring
0524	Access Interlocks
0525	System E-stop Monitoring
0526	Safety Controller
0527	Safety Communications

In addition to the global system requirements for the Safety & Emergency systems, the system is designed to continuously monitor all safety parameters to detect emergency events, immediately, reporting these to specified personnel, maintain a high availability (less than one failure in 100,000 years) and to report status and events to SCADA for display and data collection

The Safety & Emergency system will be powered primarily by the main station power system. In the event that this is unavailable, there is also a dedicated Safety & Emergency 24V battery backup power supply which is supplemented by a topside solar panel array. This will ensure high-supply-power availability to the Safety & Emergency system under all conditions. In the case of an S1 emergency event, the Safety & Emergency system will immediately notify specified personnel. The Safety & Emergency Systems has its own dedicated communication link to maximize availability.

4.3.5.3 0530 Climate Control System

The current concept design is based on using commercial-off-the-shelf (COTS) equipment. The main components of the climate control system are a chilled-water air conditioner for the dry control room, and the air dryer for PTO module. The PTO cooling system and submerged surface area of the PTO module provide ample cooling to keep ambient temperatures within the operating range. The thermal effect of solar energy on the nacelle is also considered for the control room, since the top of the control room is above the water line. The climate control system will have designated modes of operation based on operations of the WEC. Categories of operation for the climate control system shall include pre-commissioning trials, commissioning, and decommissioning, normal operation, maintenance and repair, transport, and transitional deployment. All controls for the climate control system will be available remotely via the 0400 SCADA system control and communications. While the WEC is deployed, service personnel will enter the WEC for maintenance, repair and inspections. The climate control system will work in conjunction with service equipment installed by personnel, to ventilate the spaces to maintain air quality within specifications. Climate control systems is designed operations during maintenance and repair when hatches and doors are open, and spaces being occupied by service personnel.

4.3.5.4 0540 Station Power System

The Station Power system is an electrical distribution system for all WEC equipment, which can receive power from the 0300 Electric Plant, 0545 solar power, and uninterruptable power supply (UPS) battery to supply power to the three categories of loads. The system include cabling, conduits, distribution switchgear and breakers with interface control to SCADA. WEC station loads are divided into three categories; non-critical, transitional, and critical loads. The Station Power requirement is to provide power to all WEC system loads, receive power from the Electric Plant and/or solar power, provide uninterruptable power supply power from batteries to critical loads, provide safe insolation in the case of a fault of any station power circuit, and interface with service vessel and dockside power, as needed for operations.

4.3.5.5 0560 Cooling System

The 0560 Cooling System provides cooling water to both generators and the 0530 Climate Control system. Each stator segment of the generator has its own independent cooling loop as part the generator cooling system distribution. The cooling system provides PTO closed-loop cooling water distribution to all stator segments, closed-loop cooling water to the climate control system, and interfaces with SCADA system which controls stator segment pump flow. The cooling system concept design uses hull-mounted grid coolers for the fresh-water-to-salt-water heat exchangers. The three grid coolers are connected to port and starboard generator cooling distribution and the climate control for the dry control room. The PTO cooling loops use redundant variable-speed pumps, controlled by the SCADA to maintain stator temperatures at the desired level. Flow to the climate control system is determined by the fresh-water-cooling heat exchanger for the air conditioner.

4.3.5.6 0570 Bilge System

The Bilge System is a network of pumps and plumbing that keep the WEC free of internal water. The Bilge System is designed keep all internal WEC spaces free of water during tow and normal operations. It also provides levels of protection for depending on the severity of the leak, as well as maintains functioning pumps during power outage and flooding. Pre-commissioning trials test the Bilge System prior to the WEC commissioning. Once all components of the Bilge System are installed in the WEC and tested, the system is ready for WEC commissioning. At the deployment site the WEC is down-righted and installed. Upon completion of commissioning, the bilge will be set into normal operation. The reverse shall be true for decommissioning. During normal operations the Bilge System components will be automatically activated to remove water from bilges. The Bilge System will interface with the SCADA for monitoring status, diagnostics, and control. The bilge equipment is responsible for removing water from all compartments of the buoy. Normal bilge operations will transfer normal amounts of water from bilge tanks to overboard.

4.3.6 Outfit and Furnishings - 0600

Section 0600 covers all outfit and furnishings for the StingRAY WEC. Some design scope of the outfit and furnishings are completed by the WETS design interface. The following sections address general system designs of the StingRAY WEC. The outfit and furnishings design documents are listed in Table 6.

Table 6 – Outfit and Furnishing Design Sections

0600	Outfit & Furnishings
0620	Hull Fittings
0630	Hull Penetrations
0640	Compartmental Marinization & Corrosion
0650	Workspace, lighting & Receptacles

4.3.6.1 0620 Hull Fittings

Hull fittings for the WEC include all hull-to-system equipment attachment points, pick points, hand rails, ladders, walkways, etc., which are all marine-rated. Inside the nacelle and spar tubes, this fitment will allow for personnel access and egress. For topside access of the WEC, reasonable design effort will be made to prevent vandalism, occupancy, access or accidental damage. The gap between the forward float and the nacelle creates a potential safety risk. During the FMECA, it was determined that webbing should be used to mitigate the risk.

4.3.6.2 0630 Hull Penetrations

Hull penetrations include all hatches and cable penetrations. These are all marine and waterproof depth rated as necessary. For internal access of the WEC, the hatch will be locked with appropriate warning signs when approved personnel are no present. The hull penetration design regulates the hull interface design requirements to ensure the hull is properly finished for waterproofing. A quality control and verification process is included to reduce the risk of leakage during deployment.

4.3.6.3 0640 Marinization & Corrosion (Internal)

The marinization of all components internal to the WEC is a critical design aspect. The watertight compartments in the WEC will be environmentally controlled, to meet the DNV certification standards for componentry. The standards include, material selection, cathodic protection, coatings and processes, for withstanding the temperatures, humidity, and vibrations of the location. Process, assembly procedures and other design modification are controlled to reduce risk of failure or degradation. The compartmental design requirements for air handling and dehumidifying equipment are also defined as part of the environmental specifications requirements.

4.3.6.4 0645 Marinization & Corrosion (External)

This section specifies the means to protect external components from the effects of a marine environment. An example of external protection is a coating on the surface of the hull to protect against biofouling. A study was conducted on a biofouling coating performed by a student at Oregon State University. Plates were deployed June 14, 2012. There are two coatings used, one is a standard gel coat and the other is PCT 900. One set of plates (one with each coating) was deployed near the surface of a tank fed continuously with filtered seawater at Hatfield Marine Science Center (HMSC) in Newport, OR. Three more pairs were deployed from the Molluscan Broodstock Program (MBP) dock at HMSC, at depths of 0ft (just submerged) 6ft, and 12ft. Initially clean white surfaces, all plates showed heavy fouling. Results from these tests will guide the coating to be used for StingRAY. Recently shared experience from US Navy on prior deployments at the WETS deployment site in Hawaii suggests that biofouling will be insignificant and this requires confirmation; once confirmed standard gelcoat type treatment will be used on the hull.

4.3.6.5 0650 Workspace, Lighting & Receptacles

The workspace, lighting and receptacle design is optimized for service personnel on the WEC. The design includes lighting electrical distribution and placement, switch placement, outlet placement, and design feedback to equipment locations, platforms, and work areas, which are designed to allow safe operating conditions for service personnel to accomplish service, operation, and maintenance tasks for all WEC systems.

4.3.7 Mooring - 0700

The purpose of the Mooring system is to keep the WEC on station in a defined watch area, while allowing the WEC to passively orient (weathervane) into the waves.

A schematic of the mooring system is presented in Figure 4, with subsystems labeled:

- 0710 Single Point – Converting the existing three-point mooring such that it acts like a SPM
- 0720 Bridle – Constrains the WEC to weathervane about the single-point attachment

- 0730 Tether – Return WEC to default position in calm seas
- 0740 Accessories – Mooring load cells (not pictured)
- 0780 Existing WETS mooring – 3-point mooring provides anchoring and restoring force for single-point and tether
- 0810 Umbilical Cable – Conduct electrical power and fiber optic signals to primary subsea cable (not a part of the Mooring system)

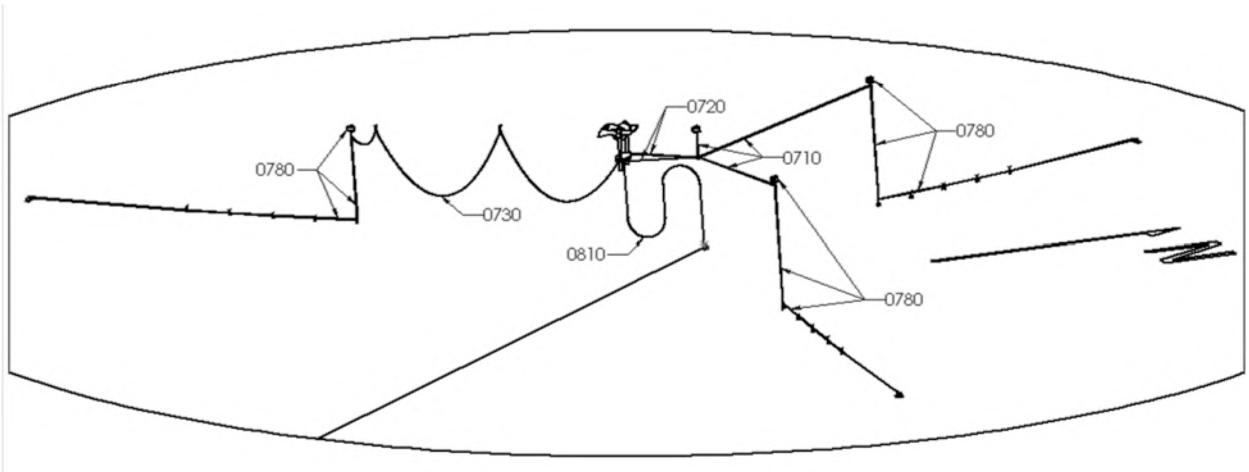

Figure 4 – Schematic of mooring system during normal operations.

Each three-point mooring leg includes a 9 metric ton Bruce FFTS Mk4 anchor, 700 feet of 2.75-inch chain, five (4.5-ton) concrete sinkers and a 75-kip reserve buoyancy surface buoy (MB-340. The chain sections are equipped with zinc anodes to inhibit corrosion.

The SPM configuration adapts the existing three-point infrastructure to allow for WECs, such as the StingRAY, to weathervane effectively. The SPM consists of a pair of hawsers connecting two of the existing three-point legs (the north and east legs) to a sinker suspended below a surface buoy, which is located at the center of the berth, making the WETS mooring act like a SPM.

The bridle consists of two 50 m mooring hawsers extending from the SPM sinker to the WEC attachment points on the damper. As the two hawsers are attached on the vertical face of the damper and towards the port and starboard sides, the bridal provides yaw control.

The tether extends from the tow plate beneath the buoy of the southeast mooring leg to a mooring attachment aft of the damper. This line needs to allow for large excursions in the case of storms incident from the north or east, and provides system pretension in null conditions.

The accessories subsystem consists of mooring load cells installed between the bridal hawsers and the damper, and between the tether and the damper. Structural bypass of the load cells is incorporated in the present design, in case of failure.

Sound and Sea Technologies (SST) was contracted by the Navy to design the three-point mooring systems (0780) for the two deep-water berths at WETS, including Berth B where the CPwr WEC will be installed. SST was also contracted by the Navy to design a SPM configuration (0710), as well as the bridle (0720), tether (0730) and load cell (0740) subsystems. Note that the target single-point mooring response is based upon previous design work performed for CPwr in collaboration with InterMoor. InterMoor designed a

SPM system for CPwr in a greenfield stand-alone configuration (i.e. not incorporated into an existing three-point mooring system).

Note that some elements of tether and load cell component specifications are conditional upon mooring integration design work to be completed under a separately-funded Navy contract.

4.3.8 Electrical Collection - 0800

The scope of the StingRAY Electrical Collection (0800) design covered the umbilical cable (0810) and design interfaces. The primary function of the umbilical is to provide electrical transmission from the WEC to the seafloor transmission cable junction. WETS will provide a subsea trunk cable to the mooring sites. The marine cables are brought ashore within a shore armored section to a bunker, where the marine cable transitions to above-ground ducted power cables. Electrical ratings for the WETS umbilical connection are shown in Table 7.

Table 7 – Electrical Properties from WEC

Parameter	Value	Unit
Maximum power	500	kW
Voltage	11.5	kV
Current	25	A

The umbilical cable also includes fiber optic communications which exist the cable inside the medium voltage umbilical connection at the top of the spar and then are routed out via conduit to the communications fiber optic to Ethernet converter box. The umbilical cable at the waterproof medium transformer connection interface at the spar. The umbilical cable is routed from the spar platform down to the center of the bottom of the damper, where it exits the hull with strain reliefs. From the center of the damper, the cable forms a lazy-S towards the center of the single-point mooring, where it is routed to the subsea junction at the ocean floor. The umbilical cable will be designed for a life of five years, meeting the WETS requirements for subsea cable interface and design to withstand hydrodynamic loading.

4.4 Task 4.0 SCADA Hardware Build and Programming for PTO

In support of LandRAY (Project DE-EE0006399), the SCADA system was designed, built and tested to support control and data acquisition during the direct-drive generator test. Some designs developed in this task are used in support of the WEC's SCADA system design (Task 4.3.4).

4.4.1 SCADA Design

The purpose of the LandRAY SCADA system design is to provide safe control of the generator, user interface, and data collection, to allow for the analysis of PTO performance. The goal of the design process was to identify appropriate hardware, software, and other design aspects in order to provide a reliable, scalable, and cost-effective system.

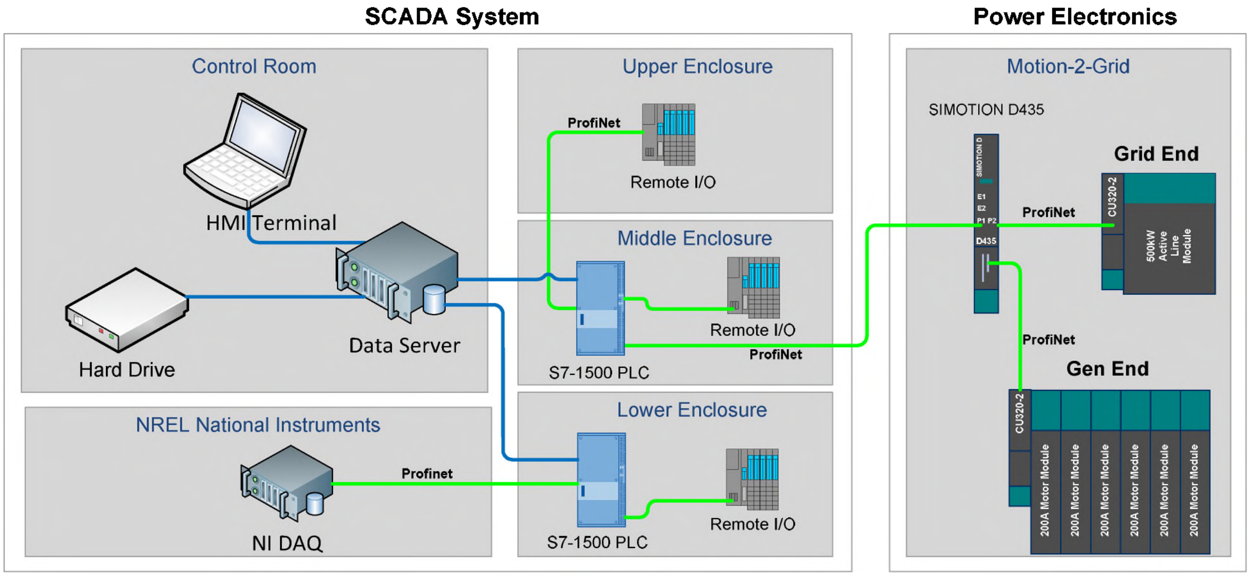

Figure 5 – LandRAY SCADA layout and interconnect diagram

The SCADA system serves as the central nervous system of the LandRAY test article. It provides critical functions during all stages of testing including commissioning, calibration, and data collection during trials. It is interconnected between the M2G system, NREL data acquisition (DAQ) system, and the cooling system. The LandRAY SCADA design will become the basis of the StingRAY design, so flexibility is essential. The SCADA system allows the operator to access the data stream, implement control strategies, and capture data necessary for analysis of the WEC response.

All design functions of the LandRAY SCADA system are organized into the five major functional categories.

- Generator & Cooling Control
- Human Machine Interface
- Data Collection
- Alarming
- Safety Systems

Figure 5 – LandRAY SCADA layout and interconnect diagrams shows the SCADA system overview, including the major building blocks: data server, PLC, I/O modules, and interface with the Simotion D435 controller. The PTO power electronics is also shown to illustrate how data and control parameters will be shared. Each component in this overview has been identified within the detailed design

4.4.2 SCADA Build

The SCADA system is comprised of Commercial Off-The-Shelf (COTS) components and custom assemblies.

Concept Systems was commissioned to produce the SCADA server and remote I/O cabinets according to the LandRAY design specification. Build drawings for the LandRAY SCADA system include locations where all hardware is mounted within their respective enclosures. Additionally, a SCADA conduit and cable plan assigns wire type, label, grounding, shielding, and routing for all required SCADA wiring.

The sensor network is composed of a wide array of instrumentation used to collect time-series data during LandRAY trials. Sensors were specifically chosen for future operation with a marine environment in mind, including both water resistance and materials selection. The sensor network is a compilation of equipment provided by NREL, CPwr, and its contractors. Generally, sensors are connected to the PLC via a 4-20 mA analog signal. This is the preferred standard for long cable lengths or high-electromagnetic-noise environments as it provides significantly greater noise immunity than 0-5V, 0-10V or -10V/+10V methods. Much of the externally-connected sensor data is also provided by a high-speed time-deterministic ProfiNet connection.

The sensors are located throughout the LandRAY test fixture. The SCADA system is separated into three enclosures; upper, middle, and lower, to facilitate shorter wire lengths to sensors located in close proximity.

4.4.3 SCADA Programming

Programming for the LandRAY SCADA system includes the HMI, control logic for the PTO and cooling system, and data handling and storage. CPwr provided all SCADA system functional programming requirements for the LandRAY project to Concept Systems, who was responsible for their implementation.

4.4.3.1 Human Machine Interface

The HMI provides the visualization for the SCADA system, providing operators a real-time view of LandRAY operational and performance data. All time-series plots, commands, and alarms will be accessible through the HMI. The HMI will have the utility to start record data manually and automatically.

4.4.3.2 Control Logic

The control system manages the PTO and cooling system, and the control hardware is programmed to perform the desired algorithms for their control. The control logic also interfaces with the NREL Dyno controller and provides alarm functionality to alert operators when parameters are outside of operational set points.

Control of the PTO is accomplished by the Siemens M2G equipment via a series of nested controllers to maximizing flexibility. The CU320 controllers at the lowest level are responsible for controlling the front-end ALM and MoMo. The Simotion DS435 is a powerful motion controller that provides control oversight of the CU320s. The Simotion controller is capable of calculating and providing basic-to-intermediate PTO control commands for the system. It also communicates and shares data bi-directionally with the PLC via a ProfiNet link. Simotion will serve as the backup controller in the event of PLC or communication failure. The PLC is a powerful controller and provides primary control functionality of the LandRAY system.

4.4.3.3 Data Handling and Storage

The LandRAY data server acts as the primary data collection method for all trials. This includes data from the PLC and NREL 5 MW dynamometer; a common data server for a majority of the data, convenient for post processing. The data server also serves as the primary PLC programming device and HMI terminal.

Data server specifications were established by identifying the system speed, reliability, storage, and connectivity requirements. The industrial server is based on a 19” rack mount chassis from SuperMicro. It utilizes Microsoft SQL Server 2012 and is capable of reliably storing up to 2 TB RAID protected storage. Software is essential for the proper development and operation of the LandRAY SCADA system. A high performance and flexible database is required to store all LandRAY data in a structured format. This includes trial parameter data, preview data, and time-series trial data.

CPwr’s primary data analysis tool is MATLAB. All performance and operational data will be stored in a Microsoft SQL database. In order to access and process trial data from the database, a convenient method of transferring data to MATLAB is required. The MATLAB Database Toolbox will be utilized, which allows MATLAB to establish a connection to an SQL database and import data through query calls.

4.5 Task 5.0 Certification of Design and Statement of Feasibility

For offshore marine systems, the design certification activities for a new WEC technology, do not include a "Classification," but are intended to provide a level of confidence for authorities, underwriters, investors, and other stakeholders. These activities confirm that the technology or equipment has been designed to operate safely within an acceptable level of risk and that it complies with relevant standards and guidelines.

The certification process is determined in large part by the selected certification society. Originally, Germanischer Lloyd Renewables Certification (GL RC) was commissioned to conduct the certification, which included a Development Accompanying Assessment (DAA). During the Project, GL merged with Det Norsk Veritas (DNV), forming DNV-GL, and the succeeding renewable energy certification group DNV GL RC. Consequently, a new certification process from DNV GL RC was required. The incorporation of the hybrid process has redefined the certification plan and now includes a Statement of Feasibility (SOF).

Certification activities include a "Design Basis Review" and SOF.

4.5.1 Design Basis Review

Definitions for function, safety and environment were reviewed and the design baseline was assessed for the WETS deployment site. The StingRAY Design Basis was originally reviewed by GL RC, who affirmed that all elements of the Design Basis were found to be in compliance with the applied standards and guidelines.

Certification activity continued under DNV GL RC following the process defined in DNV-OSS-312 [1] and included the definition of the Certification Basis, the Technology Assessment (TA), the Failure Mode Identification and Risk Ranking, Selection of Qualification Methods, and the definition of Certification Plan.

The Certification Basis defines the expectations of the technology in the absence of relevant codes and procedures, and includes technology specifications, functional requirements and reliability targets. Qualification Methods were selected that adequately address the identified failure modes of concern with respect to reduction of uncertainties and documentation of sufficient margins to failure.

4.5.2 Statement of Feasibility (SOF)

Issuance of the Statement of Feasibility is a significant milestone in the certification process, confirming that, in the independent opinion of DNV GL, the StingRAY S1 is considered technically feasible according to the agreed targets. It can be concluded that the technology is suited for further development and certification, according to the principles outlined in DNV-OSS-312 and relevant standards.

4.6 Task 6.0 Site Selection, Shipping, CONOPS and Logistics Planning

4.6.1 Subtask 6.1 Fabrication-site preparations

4.6.1.1 Fabrication-site requirements, preferences and considerations

Identifying a fabrication site that meets all preferred conditions is unlikely. The site used for S1 fabrication and assembly should consider, or include, a combination of preferences that allow for a safe and low cost assembly.

4.6.1.2 Sites considered

CPwr has investigated shipyard opportunities in Honolulu, Hawaii; Seattle, WA; Vancouver, WA; and Portland, Oregon. At each of the four locations, CPwr observed and reviewed site capabilities with shipyard management. A summary of those investigations is in Table 7. Of the sites considered, Portland, Oregon meets the CPwr requirements best.

Table 8 – Assembly Site Comparison

Assembly Site consideration	Portland, OR	Seattle, WA	Vancouver, WA	Honolulu, HI
Waterway	3	4	3	2
Transit to wave site	2	2	2	5
Dry-dock	5	5	2	2
Assembly bay	3	3	2	1
Equipment	5	4	4	2
Labor	4	3	4	2
FRP labor	4	3	4	2
Electric, water, air	4	4	4	2
Engineering Accessibility	4	2	4	1

Table Considerations (ranked 1-lowest through 5-highest)

Consideration descriptions

- ***Waterway*** - Access to waterway with greater than 12m depth through to open-ocean for offshore transit to deployment site
- ***Transit to wave site*** - A low risk, cost efficient and technically sound method of transiting (barging) S1 from the proposed fabrication/assembly site to deployment site
- ***Dry–dock*** - A dry-dock or floating dry-dock large enough to test S1 in horizontal orientation, and ideally deep enough to test in the vertical orientation
- ***Assembly bay*** - Covered and walled assembly bay with reinforced concrete and level floors for PTO testing and fabricating FRP, or allowance to install temporary structure that provides same
- ***Equipment*** - Equipment (e.g. cranes, heavy lift trucks, fork lifts, etc.) that can perform all steps of the S1 fabrication and assembly plan. Some assemblies have combined masses in excess of 100 mT and the site must have sufficiently rated equipment to safely execute all assembly tasks
- ***Labor*** - Cost-effective skilled labor available to perform typical shipyard work, or alternatively ready-for-hire local labor with similar skillsets
- ***FRP labor*** - Contract labor available to fabricate FRP hull, or allowances to bring in external resources to do the same
- ***Electric, water, air*** - Electrical distribution with sufficient power to test PTO and electric plant. Pneumatic supply for air tools, water supply for cooling and cleaning
- ***Engineering Accessibility*** - Accessible site that is reasonably close to CPower offices in Corvallis, Oregon. Fabrication and assembly of a prototype with designs, shapes and masses that are somewhat unordinary, as compared to conventional ocean systems, will frequently require CPower engineering resources for design guidance, engineering change orders, technical briefings, inspections and consultations during the build phase that will last up to one year. Due to this high frequency requirement of on-site engineering, travel times of four hours or less from Corvallis to site will help reduce assembly delays.

4.6.2 Subtask 6.2 Site selection and survey

The WETS site was selected for the deployment location. This decision was significantly biased by the capability to test the WEC in a grid-connected demonstration, a high priority for WEC commercialization. Additionally, the WETS site has little or no fees associated with testing – providing for significant savings over other alternatives for a one-year demonstration. The wave climate provides for a good compromise of favorable sea states when considering WEC demonstration requirements, O&M access, prototype survival and development of power matrices.

4.6.3 Subtask 6.3 Deployment, Maintenance and Decommissioning CONOPS

Once the StingRAY WEC is placed at the pier, all WEC operations will be described in detailed operating procedures, providing introductory details, system description, operating conditions and procedures that apply to all operations from dockside through to WEC recovery.

4.6.4 Subtask 6.4 Deployment, Decommissioning, Maintenance Planning

Maintenance services, including periodic inspections, will be accomplished through sub contract with Sea Engineering, located in Honolulu Hawaii. On-site interviews with Sea Engineering management and a guided tour of their vessels and capabilities have led CPwr to the conclusion that their equipment, vessels, crew and divers are well-suited for the types of planned and unplanned maintenance expected.

Deployment will take place in two stages. The first stage is a barge transit from Portland, Oregon to Oahu, Hawaii. This transit was investigated under four different scenarios for cost and risk assessment. This investigation included consideration of an open-water WEC tow that was dropped due to high fuel costs and high risk. The best cost scenario includes the use of a submersible barge that is used for both transit and deployment, and then used for cargo services and revenue on its return trip to the mainland (a requirement because barges are typically leased and must be returned).

In the deployment with submersible barge scenario, the WEC is towed directly to the WETS mooring upon arrival to Oahu. Once on-site, the barge and WEC are moored at the WETS mooring while final deployment preparations are completed; the WEC is then deployed from the submersible barge.

The decommissioning plan is to relocate and redeploy the WEC for an extended demonstration period. If re-purpose is not possible, the WEC will be disassembled, some equipment cannibalized for use on the next WEC, some sold off as scrap and the remainder recycled as pulverized FRP, which will be used in extrusion manufactured plastics.

4.7 Task 7.0 Permitting

WETS site permitting, document submissions and interaction with permitting entities will be accomplished through correspondence with NEXWC and NAVFAC PACIFIC of the department of Navy. Permitting responsibilities have been investigated through reviews of WETS permit documentation and frequent open dialogue with NEXWC. Early engagement with NEXWC during the Environmental Assessment ensured that the StingRAY WEC was part of the WETS WEC design envelope. CPwr will have primarily responsibility for the NEPA process and for Coast Guard interaction regarding Private Aids to Navigation (PATON). CPwr will work directly with NEXWC to provide them with WEC design, Mooring adaption design and operational documentation and instruction. NEXWC will have primary responsibility for all agency dialogue for the remainder of the required permitting activity as outlined in the StingRAY Permit Register (Appendix 9.1).

4.8 Task 8.0 Dissemination of results

Columbia Power has collaborated with and shared results throughout the Project performance period. Specifically, this includes the following details.

- 2014 DOE Water Power Peer Review, presentation and poster display
- Numerous domestic and international conferences, sharing of MHK relevant lessons learned, highlighting the v3.2 WEC design, single-point mooring and certification [GMREC VI, VII; OREC VIII, IX, X; DOE WPP Peer Review; ICOE 2014; OSU Marine Energy Forum; Renewable UK Wave & Tidal]

- CPwr, OSU and NREL collaboration on development, design and build of a programmable mooring controller (PMC) used during Task 1.0 Tank testing
- Sharing of wave tank test results with OSU, NREL and Sandia
- Development of SPM and StingRAY WEC designs that were provided to NEXWC and SST. These designs were then used by SST for three-point mooring design and an adaptation of Columbia Power's SPM design into a WETS SPM design that is available to all qualified future developers testing at WETS

5 ACCOMPLISHMENTS

5.1 33rd scale tank testing:

Many key uncertainties were eliminated during the 33rd scale testing. This allowed for design progression with confidence that, at at a minimum, the following assumptions were tested and experimentally validated.

5.1.1 Designed built and tested 33rd scale buoy

Columbia Power worked with Ershigs and Intermoor to design a 33rd scale WEC with SPM that was essential for proving cost-savings measures and energy increase. Additional conceptual assumptions about WEC operation in differing sea states, wave spreading and wave headings were observed, some of which demonstrated unexpected behavior or resolved uncertain behavior, but all discussed in this section are confirmed and significant accomplishments.

5.1.2 Single point mooring (SPM) validation

Tank testing demonstrated that the WEC is capable of moving in the yaw direction to weathervane such that its heading is within 10 degrees of the oncoming waves. This was validated in 10 degree increments with respect to the oncoming waves up to a 90 degree WEC offset,. This capability essentially eliminates variable energy production caused by sensitivity to the oncoming waves and increases AEP by >5%.

5.1.3 Validation of survival mode with no end-stops requirements

Designing and testing a 33rd scaled system without end-stops confirmed that a significant reduction in CAPEX was possible. The cost savings of end-stoprevmoval (~$1M) and reduction of impact loads at the end-stops (~10x), resulted in reduced structural requirements on floats, float arms, main bearings and further CAPEX reduction in the end regions of the nacelle.

5.1.4 WEC energy performance and torque validation

Both CPwr's use of AQWA and DNV GL RA's use of WaveDyn numerical models were compared to 33rd scale tank tests for comparisons of WEC body position, speed and acceleration, as well as drive-shaft torque and drive-shaft angular-position, -speed and -acceleration. These comparisons allowed for an understanding of model variance and for exploration of viscous drag effects on the numerical model, thereby improving overall correlation at 33rd scale. However, this is unlikely to be used to modify full-scale drag, because viscous drag effects become less significant at full-scale. Modeled energy production accuracy is considered acceptable across the full spectrum of simulated sea states. CPwr has established higher confidence in our numerical modeling of AEP and RCW over the full spectrum of wave conditions.

5.1.5 Programmable mooring controller development and collaboration

InterMoor developed load-displacement curves for the mooring lines using OrcaFlex; these load displacement curves were used to program the PMC for tank testing. During testing, the filtered average of those curves was well represented in the experiment by the PMC; however the PMC created significant load peaks above and below the mean, which exceeded numerical estimates. These extremes appear to be caused by slow response from the PMC; it is expected that for scaled testing a revised PMC can be used, which has a better representation of both short- and long-term load-displacement control. At a high level, this first PMC experiment by CPwr, OSU and NREL has demonstrated a viable technology that can be extended to development of an accurate-scaled mooring system, which is needed by industry if more-accurate mooring-experiments are to be accomplished.

5.2 Designed full-scale WEC for WETS testing

Columbia Power worked with Ershigs, DNV GL RA, Siemens, Concept Systems and InterMoor to design the full-scale StingRAY WEC. Designs developed in this Project will be used in the WETS project and on future WEC projects beyond WETS.

5.3 Statement of feasibility, certification pathway

DNV GL RC issued a SOF to CPwr for the StingRAY WEC. This was a significant effort, requiring the development of DLCs and communication of met-ocean data, WEC design data, WEC O&M plans, and tank-test data review and analysis, all culminating in a comprehensive risk identification and mitigation process. In the future, the detailed plans will be established that take the WEC through the certification pathway:

1) evaluation of field-proven status
2) design review
3) survey during construction
4) verification of open-ocean testing of the completed WEC product
5) review of manufacturer's construction, operating & maintenance documentation
6) issuance of a Prototype Certificate.

5.4 Site selection for build and test, preliminary planning decisions

Selecting WETS at MCBH as the test site and Portland, Oregon for most manufacturing and assembly allowed the creation of design requirements and continuation of StingRAY design work. Significant weight is given to this decision process due to its direct impact on CPwr's commercialization success, including timeline budget and achievement of Project goals.

5.5 Concepts of operation, assembly and transit

Identification and gathering of information to understand and optimize the numerous site options, shipping methods, procedural concepts, operational concepts, and costs of facilities, resources and equipment, with sufficient detail to guide the manufacturing, transportation, and logistics of a full-scale WEC, was an essential and material undertaking for the CPwr team. Achieving this level of understanding and planning, in addition to supply chain identification, is a significant accomplishment for CPwr.

5.6 Detailed outline of build and test plans

The shipyard identification and selection process included the development of a comprehensive planning documentation, which described and illustrated the WEC-assembly and sequencing processes. Identification of these processes through industry proxy, assuring their relevance to CPwr, and incorporating them into CPwr plans contributed to a comprehensive WEC testing strategy.

5.7 Comprehensive understanding of permit requirements and responsibilities

Through prior experience of a "greenfield" permitting process for the intermediate-scale WEC deployment (SeaRAY) in Puget Sound, CPwr understands that permitting requirements can be a considerable burden.

For this Project, CPwr participated in the early environmental assessment (EA) effort conducted by NEXWC, in order to assure that the StingRAY was incorporated into the EA envelope. Later CPwr effort included a comprehensive review of WETS interface-requirements, examination of NEXWC-supplied permitting details and clarifying communication with NEXWC regarding permitting requirements and responsibilities. Through this effort and prior experience, CPwr has established and completed a Permit Register identifying expectations of the permitting process, and primary responsibility for relevant permits, which is due to initiate in the next few months.

6 CONCLUSIONS

6.1 Necessary but not final step

The Project scope was well-aligned with CPwr's technology pathway. It contains the properly-focused, critical-path tasks necessary for developing a baseline WEC system. The accomplishments, in this Report, materially contribute to the likelihood of success of the WETS WEC deployment. Parallel effort has also identified incremental improvements to the WEC, which represent AEP increase and costs decreases, in addition to Project-validated improvements. With the baseline, full-design completed as part of the Project, the design platform has been set for further refinement.

6.2 Provided base understanding for new innovation

This Project advanced CPwr's v3.2 design from a concept for WEC improvements to a detailed design, with tank test data supporting the original concepts. This level of detail allowed for a 3rd-party SOF along with a reasonably mature and accurate assessment of WEC CAPEX and AEP.

6.3 Confirmed core belief in hybrid point absorber

This is the third generation of the CPwr direct-drive-rotary technology. Each succeeding generation, and the resulting performance and cost improvements--along with new insights, knowledge and data gained during the Project—has confirmed for CPwr that the current pursuit of a hybrid point absorber provides a promising and robust pathway to achieving a competitive LCOE.

6.4 WETS is a near ideal test site

WETS is well-suited for the initial open-water-demonstrations of full-size WEC due to the following attributes:

- appropriate wave climate
- existing subsea cable and electric-grid-connection
- pre-installed mooring system with appropriate SPM WEC-mooring interface
- favorable bathymetry
- no testing fees
- no fees for in-water WEC inspections and environmental monitoring
- completed EA with StingRAY included in EA WEC design envelope
- permitting requirements defined and primarily handled by WETS
- third-party validation of WEC energy production

A significant drawback, however, is the distance from the US mainland, along with the associate costs and limited availability of fabrication, assembly and operational resources.

6.5 DOE Participation is key

DOE collaboration, oversight and funding is critical for technology-development risk mitigation and creates an appropriate environment for development of promising WEC designs and attraction of the private funds necessary to fund pre-commercial WEC demonstration.

7 RECOMMENDATIONS

7.1 Scaled PTO accuracy

CPwr's experience, within this Project and four prior tests, have underscored a strong requirement for an accurate, low-weight, 4-quadrant controllable PTO for prototype tank-testing. The quality of scaled-test data has a direct impact on the results expected from projects and their goals and objectives. However, there are no known PTOs available at a size, rating or accuracy that are appropriate for scaled testing. As such, technology developers, looking to tank-test prototypes, are required to internally develop a PTO capable of meeting challenging specifications, present due to scaling restrictions. This one-off approach is expensive and causes redundant effort for WEC technology developers. A DOE- or lab-focused solution that addresses the problem would benefit the MHK industry.

7.2 Programmable Mooring controller

WEC wave-tank experiments need accurate reproduction of the scaled mooring loads. This is extremely difficult to create with off-the-shelf solutions (e.g., the fishing tackle) used by industry to date. An advanced, next-generation PMC will address the problem in like manner with the PTO issue discussed above and would likewise benefit the MHK industry.

7.3 Need for broader understanding of certification process

Following completion of the SOF, it became more apparent how the certification process transitions through a technology's development and growth. A comprehensive and advance understanding of the process would provide time and cost savings for pre-TRL-7 technology developers.

7.4 Need for alignment of DOE and certification body requirements

The WEC certification process is fundamentally integral to the system design process. This is true of DOE-sponsored WEC system and major sub-system development projects. Aligning DOE expectations and requirements with major certifying agency requirements would allow for improved project costs and resource efficiency, in addition to more-industry-consistent risk-management processes and would thereby benefit the MHK industry and reduce overall DOE costs as well..

8 BIBLIOGRAPHY

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9 APPENDICES

9.1 APPENDIX: StingRAY Permit Register

Document title	StingRAY Permit Register
File name	APP 9.1 DE-EE0005930 M7 Permit Register UD v1.0 06-16-2016