C·POWER

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1 EXECUTIVE SUMMARY

The goal of Project DE-EE0008954 “Optimization, Design, and Commercialization Planning of Next-Generation StingRAY H3 Wave Energy Converter” (Project), which was successfully achieved, was to develop a standards-compliant, fabrication-ready design of Columbia Power Technologies’ (C·Power) next-generation wave energy converter (WEC), the StingRAY H3p. The H3p is a design iteration of C·Power’s StingRAY WEC and is intended for electrical power generation suitable for micro-grids or remote loads. The H3p was designed for grid-connection and at least two years of continuous testing and operation at the proposed PacWave-South (PWS) test site.

The original intent of the Project was to design the WEC explicitly for utility-scale electricity generation. A modeling study performed early in the Project indicated that a larger WEC minimized estimated LCOE and was optimally sized for long-term commercial development. However, due to the high costs and logistical challenges of such a large device, concerns arose that a WEC optimally sized for utility-scale was not a rational next step in the technology development path. To limit C·Power and stakeholder financial and operational risks and increase the likelihood of keeping project costs for the anticipated build and deployment in-line with future funding opportunities, a decision was made in conjunction with DOE to focus the design effort on a smaller prototype WEC, which is referred to as H3p. The commercialization plan developed in-Project and described below, identified offshore market opportunities for the H3p, further justifying the decision. The StingRAY product line is intended to serve a full range of power needs, from remote offshore loads up to utility-scale applications.

The Project metrics target values established in the Statement of Project Objectives (SOPO) assumed the original, optimally sized utility-scale WEC, as described above. To maintain the measurement of Project success against the SOPO metrics, the metrics estimates developed in this Project are based on the larger StingRAY WEC, which is referred to as the H3u. To be clear, the H3p is the full-scale system designed within this Project. For comparison to the original SOPO metrics, the H3p design was scaled up to the H3u. The H3p WEC was deemed to be similar enough in size to the H3u that its deployment would validate performance and load models, and present similar logistical challenges. The inherent scalability of the StingRAY design enabled this approach and the opportunity to make reasonably accurate estimates for the H3u.

A design basis was developed to establish key system requirements, targets, and operational limits. The H3p was designed for grid-connection and at least two years of continuous testing and operation at the PWS test site. Metocean conditions at PWS were characterized, and design load cases were developed. Safety levels were defined for the hull structure, mooring, and other systems. The H3p targets operability in a broad range of conditions, including extreme seas and loss of grid.

A hydrodynamic modeling study was performed to establish the primary characteristics of the H3p WEC, including hull dimensions, ballast mass, and generator torque limit. Parameterized cost and mass estimates were developed, and model results were assessed for performance, leading to the identification of configurations that had favorable cost-to-performance ratios. More than 700 unique WEC configurations were modelled (more than 25,000 simulations) to estimate performance, including a wide range of WEC displacements (860 to 4600 mt). Baseline cost estimates were based on previous work and were scaled for other sizes and power levels in a manner similar to that described below.

The study indicated that a large WEC minimized estimated LCOE and was optimally sized for long-term commercial development. However, due to the high costs and logistical challenges of such a large device, concerns arose that a WEC of this size was not a rational next step in the technology development path. To limit C·Power and stakeholder financial and operational risks and increase the likelihood of keeping project costs for the anticipated build and deployment in-line with future funding opportunities, smaller WECs were considered. With DOE concurrence, C·Power decided to design a smaller prototype WEC within this

Project, while maintaining long-term focus on a larger commercial WEC, allowing for Project technology development goals to be met while reducing near-term technical and economic risk to manageable levels.

A commercialization plan was developed to ensure the StingRAY design aligns with C·Power's market strategy. The ultimate market for StingRAY is utility-scale electricity generation, however, utility-scale wave farms for wholesale markets are a number of years from implementation. The Project-targeted H3p is specifically intended to service non-terrestrial loads of near-term markets (e.g., diesel genset replacement, at-sea vessel charging, etc.) and will be well-placed for terrestrial applications when those become available. C·Power's market study suggests that the H3p system will have a near-term addressable market value of approximately $6 Bn, and that the total StingRAY addressable market opportunity (i.e., H3p, H3u, and subsequent models) will be approximately $120 Bn in 2030. This Project represents a key step to delivering the initial prototype for a later validation project and subsequent near-term market development and is a practical and concrete step towards future development of the larger utility-scale H3u.

Systems designs began with the development of detailed engineering design requirements, and led to a final design that aligns with Project objectives and is ready to take into a fabrication stage. C·Power engaged outside expertise for design support on critical systems, including Cardinal Engineering for hull structure; Supplier 1 (a large multinational corporation) for generator and electric plant; National Renewable Energy Laboratory for mooring; and Blue Frontier Engineering for the dynamic umbilical cable.

Preliminary plans were developed for manufacturing, and installation, operation, and maintenance of the StingRAY H3p. The H3p will be fabricated and assembled at a shipyard on the Columbia River, and then towed under its own buoyancy down the Columbia and then south along the coast to PWS. The mooring and umbilical systems will be pre-installed, simplifying the necessary operations during WEC installation. Once installed the WEC will remain on location under continuous operation for at least two years. Inspection and maintenance operations are planned to occur quarterly, and remote monitoring will be ongoing to reduce the need for onsite visits.

A Risk Management Plan was developed, specifying a process of identification, analysis, and mitigation of risks. Failure Modes Effects and Criticality Analysis (FMECA) was conducted iteratively to systematically identify all potential failure modes and their effects on the system, and to analyze the criticality of each risk based on the likelihood of the event and the severity of the impact. Engineering actions to mitigate risk were developed and documented. The Risk Registers resulting from this process guided the design process by identifying and prioritizing critical risks and providing a road map for the Certification Plan described below. Engineering actions that were carried out within the Project were documented, and the effected risks reassessed. Other actions are meant to be carried out in later stages (e.g., during manufacturing or while deployed).

Technology Qualification was conducted, with support from DNV, in accordance with *DNV-SE-0120 Certification of Wave Energy Converters and Arrays*. A Certification Basis was developed that defines the expectations of the novel H3p WEC, including requirements, targets, and limits of operation. A Technology Assessment was performed, classifying the novelty of the systems and components, identifying applicable standards, and specifying the required level of DNV involvement in qualification and certification activities. Recommended actions to mitigate risks from the Risk Registers were consolidated into a Certification Plan, comprising a comprehensive set of actions to be carried out during certification of the H3p WEC. At the conclusion of the Technology Qualification process, DNV issued a Statement of Feasibility, affirming that the H3p WEC is conceptually feasible and suited for further development and qualification.

Tank testing was performed in the Directional Wave Basin of the Hinsdale Wave Research Laboratory, over a period of four weeks. The scale WEC model was designed and built, to the degree practical, as a 1:28 scale model of the H3p WEC. The model was an aluminum fabrication, with a PTO consisting of a dual stage belt-drive to a PMG motor. Test conditions included a diverse set of wave conditions, including operational and extreme seas, and modifications to WEC controls and ballasting. Overall, the numerical model predicted the performance and motion response trends observed in tank testing with reasonable

accuracy, in operational and extreme seas, giving confidence to the modeling efforts supporting Project design of the H3p.

Earlier in the Project, C·Power undertook a novel effort to use a 3D printed prototype for the tank test model. While the model's fabrication methodology hadn't been specified in the original Project planning, an opportunity was seen to develop a rapid, cost-effective method of delivering small-scale prototypes. Unfortunately, the prototype had significant leak paths and issues with maintaining engagement of the PTO belt drive. Fortunately, these issues were discovered during C·Power's pre-test efforts, rather than during tank testing. While C·Power believes there is merit in the 3D printed approach, we have learned within this Project that small-scale prototyping in composites presents significant issues due to the difficulty in manipulating composites post-manufacture. While less of an issue once in normal production, novel designs rarely do not require post-fabrication adjustments. In hindsight, it is clear that this was a case in which avoiding novel fabrication methods would have been the correct path.

Project metrics were based on the utility-scale H3u and include Levelized Cost of Energy (LCOE), Peak-to-Average Mechanical Power (PAMP), and Capture Width Ratio (CWR). Targets were established for two sites of interest, PWS and the European Marine Energy Center (EMEC), and the final H3u metrics estimates yielded mixed results. The final H3u CWR estimate for PWS exceeds the target, while for EMEC the final estimate does not. Final H3u PAMP estimates exceed the targets for both PWS and EMEC. Final H3u LCOE estimates fall short of the SOPO targets for both PWS and EMEC; performance and cost issues impacting final H3u LCOE estimates, and identified mitigating improvements, are described in the following paragraph.

Factors negatively impacting the final metrics estimates were identified, and the potential for improvement in the near-term was assessed. Three areas for potential improvement of cost and performance were considered achievable in the near-term and further explored, including performance gains from advanced controls; efficiency and cost improvements from co-development of generator and electric plant; and cost, mass, and performance improvements from implementation of C·Power's Localized Airgap Reduction System (LARS). Based upon these potential areas of performance and cost improvements, C·Power estimates that all targets can be met in the near-term, bringing the StingRAY H3p WEC to a state of cost-competitiveness for the near- and medium-term markets identified in the Commercialization Plan.

These near-term improvements, listed in order from highest priority, along with their estimated individual impact on LCOE are: efficiency and cost improvements from co-development of generator and electric plant (-25%); cost, mass, and performance improvements from implementation of C·Power's LARS (-17%); and performance gains from advanced controls (-3%).

In light of these potential gains and subsequent to this Project, C·Power has initiated a work package targeting the two highest priority improvements (i.e., co-development of generator and electric plant, and LARS), which will be the primary focus in 2024 for StingRAY development. The effort will be self-funded at least through Phase 1 (conceptual design), while C·Power actively pursues additional funding opportunities. C·Power intends to design, fabricate, and validate the performance of these systems with a comprehensive dynamometer test program. The development of advanced controls is also being planned, though at a lower priority. These improvements will yield significant benefits in terms of performance and cost-effectiveness and will bring the StingRAY WEC a long way towards cost-competitive commercial wave power generation.

The goal of this Project was successfully met: to develop a standards-compliant, fabrication-ready design of the StingRAY WEC, intended for grid-connected operation at PWS for at least two years, with electrical power generation suitable for remote loads or micro-grids. The H3p design delivers an innovative, high-performance, survivable, and reliable device that is acceptable to potential customers, regulators, and other stakeholders, while also demonstrating the StingRAY's path towards cost-competitive electricity generation. Risk was assessed and mitigated in-Project through tank testing, FMECA, and DNV-supported

Technology Qualification. The H3p design provides a strong platform for prototype demonstration and near-term markets, while the H3u concept points the way towards long-term utility-scale market share.

2 LIST(S) OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

Table 1 – Symbols, abbreviations, and acronyms.

6399	DE-EE0006399 - Build and Test of a Novel, Commercial-Scale Wave Energy Direct-Drive
8954	DE-EE0008954 - Optimization, Design, and Commercialization Planning of Next-Generation StingRAY H3 Wave Energy Converter
2D	Two-Dimensional
3D	Three-Dimensional
A	Amp
AC	Alternating Current
AEP	Annual Energy Production
AFE	Active Front End
AIS	Automatic Identification System
ALS	Accidental Limit State
ATS	Automatic Transfer Switch
BESC	Battery Energy Storage Converter
BESS	Battery Energy Storage System
BFE	Blue Frontier Engineering
BMS	Battery Management System
Bn	Billion
°C	Degrees Celsius
cg	Center of Gravity
C·Power	Columbia Power Technologies, Inc.
CapEx	Capital Expense
CB	Certification Basis
ConOps	Concept of Operations
cos	Cosine
COTS	Commercial Off-the-Shelf
CRT	Cast Resin Transformer
CWR	Capture Width Ratio
DAQ	Data Acquisition
DC	Direct Current
DDR	Direct Drive Rotary
DLC	Design Load Cases
DOE	Department of Energy
DOF	Degree(s) of Freedom
DWB	Directional Wave Basin
EDR	Engineering Design Requirements
EMEC	European Marine Energy Center
EMI	Electromagnetic Interference
ESS	Extreme Sea States

ESS	Energy Storage System
FCA	Fatigue Critical Area
FCR	Fixed Cost Rate
FEA	Finite Element Analysis
FLS	Fatigue Limit State
FMECA	Failure Mode, Effects and Criticality Analysis
FOA	Funding Opportunity Announcement
g	Gravitational Acceleration
GFCI	Ground-Fault Circuit Interrupter
GPM	Gallons per Minute
GPS	Global Positioning System
H2	StingRAY WEC (Previous generation)
H3	StingRAY WEC (Next generation)
H3p	Project Targeted H3 WEC
H3t	Tank Scale Model H3 WEC
H3u	Utility-Scale H3 WEC
Hm0	Significant Wave Height
HMI	Human Machine Interface
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
HWRL	Hinsdale Wave Research Laboratory
Hz	Hertz
I/O	Input/Output
ICC	Installed Capital Cost
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
I-FORM	Inverse First Order Reliability Method
IMU	Inertial Measurement Unit
IO&M	Installation, Operations, and Maintenance
IPxx	Ingress Protection Rating
JONSWAP	Joint North Sea Wave Project
kbps	Kilobits per Second
kg	Kilogram
km	Kilometer
kNm	Kilonewton-Meter
kV	Kilovolt
kVA	Kilovolt-Amps
kW	Kilowatt
kWh	Kilowatt-Hour
LARS	Localized Airgap Reduction System
LCOE	Levelized Cost of Energy

LED	Light Emitting Diode
LLPDE	Linear Low-Density Polyethylene
LV	Low Voltage
m	Meters
MB	Machine Bridge
min	Minute
mm	Millimeter
Mn	Million
MNm	Meganewton-Meter
MODAQ	Modular Ocean Data Acquisition
mt	Metric Ton
MW	Megawatt
NB	Network Bridge
NI	National Instruments
NPT	National Pipe Thread
NRE	Non-Recurring Engineering
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
OpEx	Operational Expenses
OSS	Operational Sea States
OV	Overvoltage
PAMP	Peak-to-Average Mechanical Power
PE	Power Electronics
PEX	Cross-Linked Polyethylene
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PLA	Polylactic Acid
PMG	Permanent Magnet Generator
PNNL	Pacific Northwest National Laboratory
PSF	Partial Safety Factor
PTO	Power Take-Off
PWM	Pulse Width Modulation
PWS	PacWave South
QC	Quality Control
r	Annual Failure Rate
R&D	Research and Design
rad	Radian
RCW	Relative Capture Width
RMP	Risk Management Plan
rms	Root-Mean-Square
ROV	Remotely Operated Vehicle

rpm	Revolutions per Minute
RR	Risk Registers
R-year	Event Return Rate, in Years
s	Seconds
SAM	System Advisory Model
SBV	Small Business Venture
SCADA	Supervisory Control and Data Acquisition
SI	International System of Units
SL	Safety Level (i.e., SL1, SL2, SL3)
SLS	Serviceability Limit State
SN	Stress Cycles to Failure Curve
SNL	Sandia National Laboratories
SOC	State of Charge
SOH	State of Health
SOPO	Statement of Project Objectives
Supplier 1	Large, Multinational Corporation Contracted to Design Generator and Electric Plant
t	Ton
TA	Technology Assessment
TCP/IP	Transmission Control Protocol/Internet Protocol
tdms	Technical Data Management Streaming (file format)
Te	Energy Period
TQ	Technology Qualification
TS	Technical Specification
UCMF	Utility Connection and Monitoring Facility
ULS	Ultimate Limit State
V&V	Verification and Validation
VAC	Volts Alternating Current
VDC	Volts Direct Current
VFD	Variable Frequency Drive
VSI	Voltage Source Inverter
WEC	Wave Energy Converter
θ_{Jmax}	Maximum Directionally Resolved Wave Power

3 INTRODUCTION

The goal of this Project was to develop a standards-compliant, fabrication-ready design of Columbia Power Technologies' (C·Power) next-generation wave energy converter (WEC), the StingRAY H3p. The H3p is a design iteration of C·Power's StingRAY WEC and is intended for electrical power generation suitable for micro-grids or remote loads. The H3p was designed for grid-connection and at least two years of continuous testing and operation at the proposed PacWave-South (PWS) test site.

The H3p design is intended to deliver an innovative, high-performance, survivable, and reliable device that is acceptable to potential customers, regulators, and other stakeholders, while also demonstrating the StingRAY's path towards cost-competitive electricity generation.

The project-targeted H3p is being developed for near-term market opportunities requiring roughly 50 to 250 kW annual average (e.g., diesel genset replacement, at-sea vessel charging). A larger H3u is planned for future development, which will be targeted towards utility scale power generation (e.g., 250 kW or more annual average). The Project metrics targets and estimations are based on the utility-scale H3u.

To deliver the Project goals, several objectives were achieved:

- Key system requirements (e.g., performance, reliability, cost, and safety level) were developed through consideration of relevant constraints (e.g., commercial viability, potential testing, and design standards).
- Hydrodynamic models were validated following a comprehensive scale-model experiment.
- Conceptual system designs were developed, building upon the Project team's previous work and experience, and advanced through preliminary and final design.
- Market commercialization plans were developed.
- Project and technical risks were identified, and mitigating actions taken and/or planned for future effort.
- A fabrication-ready design, along with associated deliverables, has been delivered.

The purpose of this report is to summarize the technical accomplishments achieved through Project efforts. The design basis guiding the H3p WEC development is summarized in Section 4. The commercialization plan is discussed in Section 5. WEC system designs are covered in Section 6. Project metrics estimates are discussed in Section 7. Risk mitigation is covered in Section 8. The tank test and subsequent model validation are covered in Section 9. Issues, resolutions, and lessons learned are discussed in Section 10. Project conclusions are summarized in Section 11 and references are listed in Section 12. Additional detailed reporting is provided as Appendices in Section 13.

Note that due to the proprietary nature of the next-generation H3p WEC design, no descriptive details regarding performance or cost are contained in this Unlimited Data *publication. Such details are restricted to the* Protected Data *Appendices. The* Protected Data *Final Design Report (DE-EE0008954 H3-FDR Final Design Report, Appendix 13.1) covers the same topics as this report, albeit at a higher level, while including performance and cost details excluded from this report.*

4 DESIGN BASIS

4.1 Design Objectives

Primary design objectives and requirements were established early in the Project and are documented in *DE-EE0008954 H3-DB-2.1 Objectives* (Appendix 13.1) and *DE-EE0008954 H3-DB-2.2 ConOps* (Appendix 13.3).

Select elements are highlighted in Table 2 below. System level requirements are derived from these global requirements.

Table 2 – Primary Objectives and Requirements

Descriptor	Requirement
Prototype objectives	The H3p design will deliver an innovative, high-performance, survivable, and reliable device that is acceptable to potential customers, regulators, and other stakeholders, while also demonstrating a path towards cost-competitive electricity generation. The prototype and its deployment will provide invaluable data and lessons learned to aid in future design and operations. As such, data collection is paramount and shall be prioritized in design and planning activities.
Deployment duration and location	H3p will be designed for grid-connection and at least two years of continuous testing and operation at PacWave South (PWS).
Safety philosophy	Safety is of utmost importance and incidents will be kept as low as reasonably possible through effective policy, communication, and preparation for all operations.
Risk management	Technical and project risks will be identified, analyzed, and mitigated throughout the design process, following the process detailed in the Risk Management Plan.
Standards conformance	The following standards will be followed to the degree determined to be practical: • *IEC TS 62600-2 Design Requirements for Marine Energy Systems* • *IEC TS 62600-10 Assessment of Mooring System for Marine Energy Converters* The following standards will be considered in the design to the degree determined to be practical: • *IEC TS 62600-30 Electrical Power Quality Requirements* • *IEC TS 62600-40 Acoustic Characterization of Marine Energy Converters* • *IEC TS 62600-100 Power Performance Assessment of Wave Energy Converters* • *IEEE 1547 Grid Interconnection Requirements* The above-listed standards normatively reference many other standards, generally IEC and ISO. Alternates may be considered for these 'secondary standards' provided the alternates are fit-for-purpose and provide similar confidence to the design.
Regulatory compliance	H3p design and operational planning should comply with all relevant regulations and permitting requirements. All necessary permits and authorizations will be facilitated by PWS and coordinated with C·Power.
Design load cases	Design load cases (DLCs) will be developed following *IEC TS 62600-2* and *IEC TS 62600-10* and will include extremes representative of a 50-year return period. Design environmental conditions will be established based on a characterization of PWS metocean conditions. The DLCs will consider all phases of the H3p life cycle.

Descriptor	Requirement
Design life and maintainability	H3p design life is a minimum of 5 years. Systems and components (a.k.a. elements) may have a design life that is less than 5 years, provided that a maintenance plan is developed to preserve the overall H3p design life. Where possible, elements should be designed for inspection, maintenance, and replacement and/or repair while H3p is on-station (in situ). Some elements may not be accessible in situ, and recovery of the H3p (to e.g., a dry dock) will be necessary.
Safety levels	H3p structural design targets a safety level of three (SL3), associated with a target failure rate of less than 10e-3 annually. The mooring system, and the safety and emergency system, target SL2 (a target failure rate of less than 10e-4 annually), based on significant consequences of failure.
Logistics	Design will strive for an operational plan that avoids the need to lift the WEC (e.g., onto a barge) for transport, and instead relies on short-distance towing of the H3p from point of assembly to the deployment site.
Availability	A minimum availability of 92.5% is targeted for the H3p prototype.
Efficiency	An aggregate efficiency of 67.5% is targeted, between total mechanical power and electrical power delivered out the umbilical.
Safe access	Provision of safe access for service vessels – and for trained crew on and within the WEC – will be established for inspection and maintenance purposes.
Limit risk of sinking	H3p water-tight compartmenting should limit risk of sinking from a single point of failure.
Operability over broad conditions	H3p should be able to generate power in as broad a range as is practical, including continued operation during storm seas (including extreme events).
Operability during grid loss	Generator will be controlled to provide power to all onboard systems in the case of loss of grid (a.k.a. *islanding* mode).

4.2 Concept of Operations

The H3p WEC Concept of Operations (ConOps) is described briefly below, with further details found in *DE-EE0008954 H3-DB-2.2 ConOps* (Appendix 13.3). The primary purpose of the H3p is to convert the energy in ocean waves into electrical energy. As a prototype, the H3p also serves to collect data (performance, loads, reliability, etc.) and provide invaluable operational experience.

The H3p comprises two bodies constrained to a single degree of freedom (DOF) of relative motion via a hinged power take-off (PTO) interface; the two bodies are referred to as the *central body* and the *float* (see Figure 1). The central body comprises nacelle, nacelle tube, pontoons, ballast tank, spars, and knee braces. The float assembly comprises float and float arms. The relative pitching motion between the nacelle and float actuates the rotary PTO which is the mechanism by which mechanically absorbed wave energy is converted into useful energy.

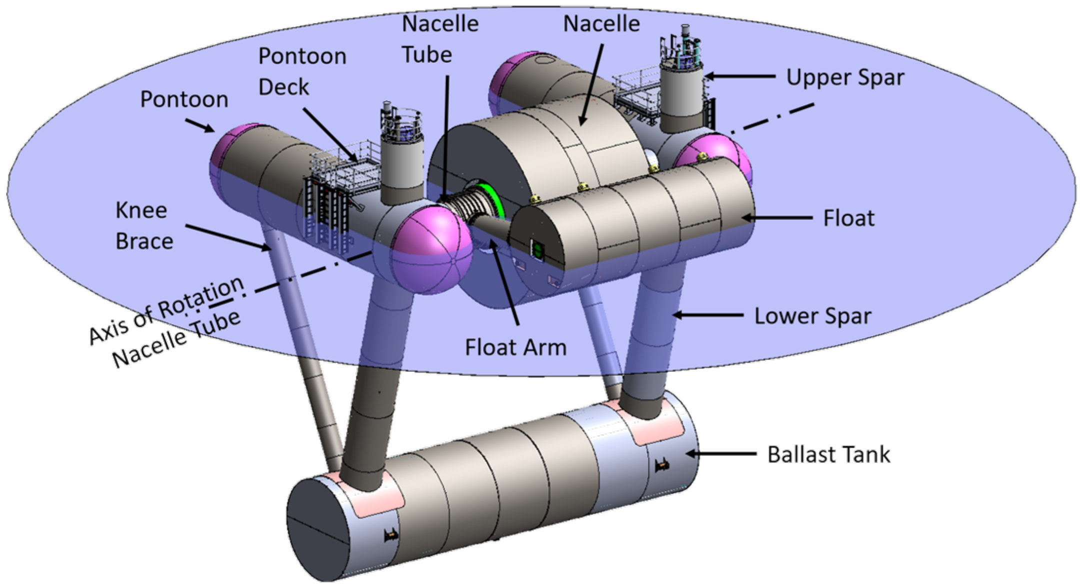

Figure 1 – Dual-member architecture of H3p WEC, in deployed operational orientation.

In its normal operating mode, the H3p floats and is compliantly moored. Wave action lifts (heave) and pushes (surge) the float; due to the PTO constraint, these motions result in rotation (pitch). Similarly, the central body is acted on by wave forces, resulting in a pitching motion. A sequence of images (see Figure 2) illustrate a typical cycle of pitch motions of the float and central body, due to heave and surge wave loads (images are taken from C·Power numerical model). Significant portions of the central body mass are concentrated in the nacelle and ballast tank, and the overall center of gravity is below and aft of the nacelle. With this off-axis center of gravity, heave, and surge wave forces on the nacelle lead to a pitching motion. Furthermore, the highly buoyant pontoons act as hydrostatic springs; as they are pushed into the water in response to wave action, a hydrostatic return force (and torque) is induced. The central body's mass and buoyancy constitute a mass-spring system that is exploited in pitch. The design of the float and central body lead to a separation of pitch response in phase and amplitude, which manifests as generator actuation and allows for energy conversion.

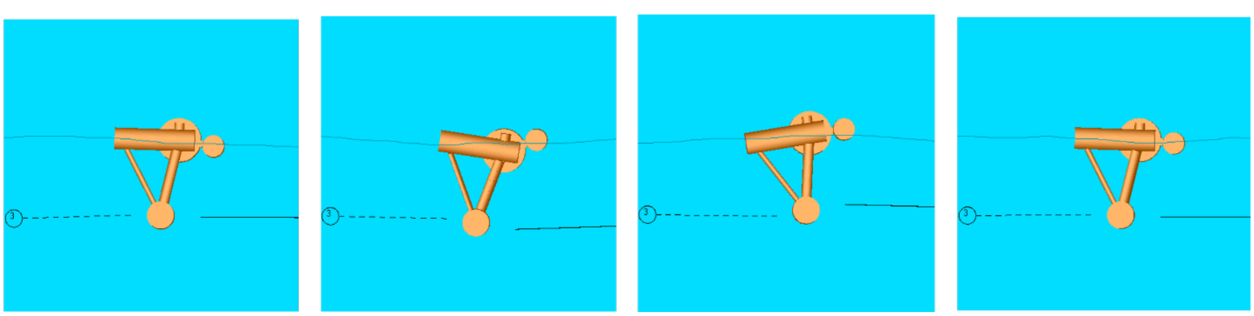

Figure 2 – Pitching motion of float and central body due to heave and surge wave loads, typical.

The starboard float arm drives a shaft which is connected to a direct-drive rotary permanent magnet generator (PMG) housed within the nacelle. The wave action leads to a bidirectional actuation of the PTO, with oscillations occurring on the wave timescale. Thus, electrical power is generated in pulses, dropping to zero twice with every oscillation. An electric plant housed within the nacelle serves as low-level control of the generator and conditions power as needed for grid quality.

The single-point mooring system keeps the floating WEC on-station, while allowing the WEC to passively weathervane to orient with the incident waves. An umbilical cable runs from the H3p to a seafloor junction box where a connection is made to a subsea cable that extends to a shore-based station and the local power grid.

The H3p is designed to operate in all anticipated wave conditions, including the extreme sea states driving the design. In extreme wave conditions, the float may be carried over the top of the nacelle (i.e., overtopping), taking a new mean position aft of the nacelle (i.e., between the pontoons). In this aft position (see Figure 3), the power generation is reduced, along with loading on the float and at the float-to-nacelle interfaces. When conditions allow, the float can be returned to its normal position.

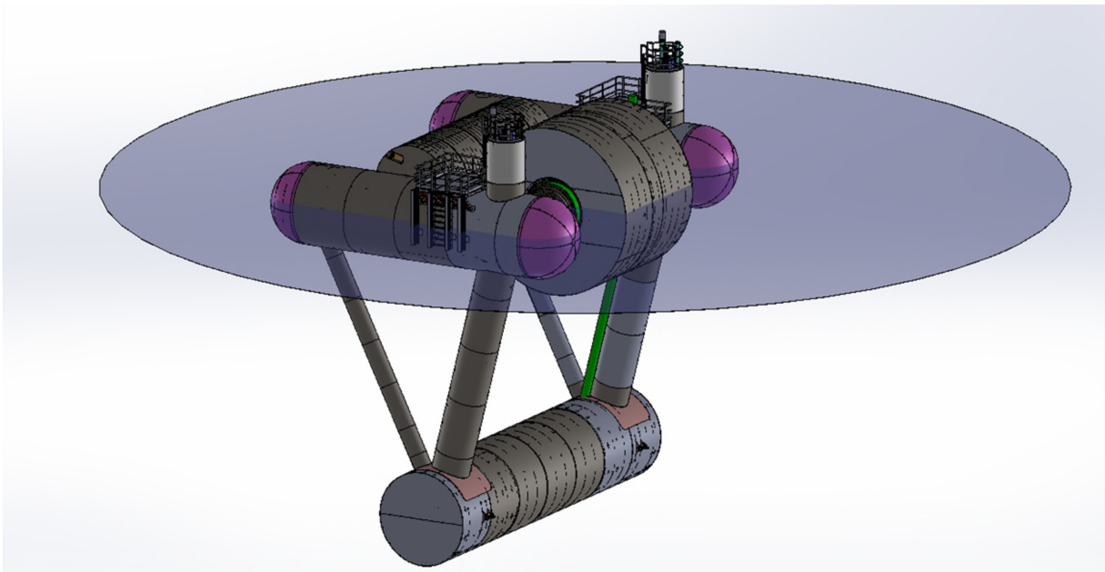

Figure 3 – H3p WEC with float overtopped.

The WEC can be towed in a shallow-draft configuration (see Figure 4). By removing the sea water variable ballast, the ballast tank becomes positively buoyant and floats to the surface. The WEC is towed from the ballast tank, with the float trailing; fittings on the ballast tank allow for the tow line attachment.

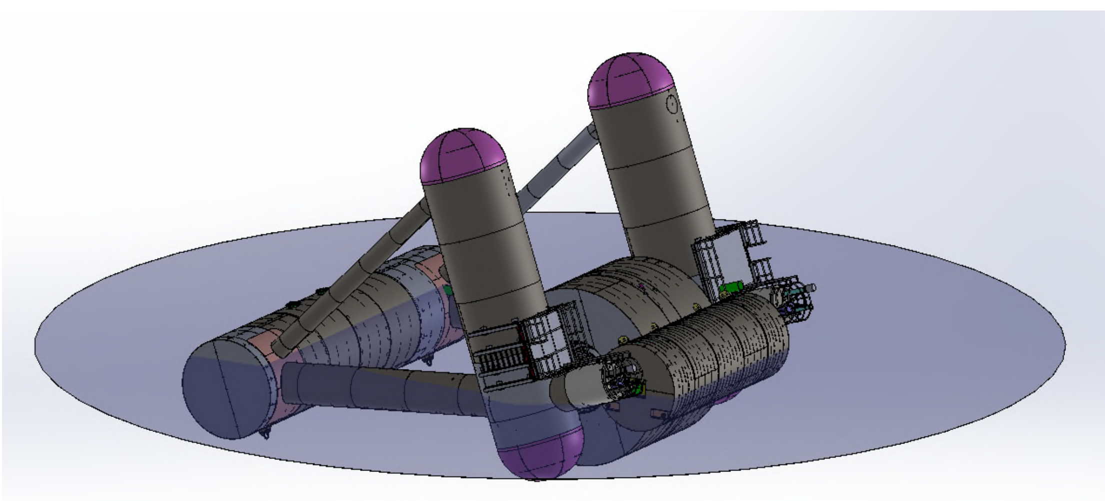

Figure 4 – WEC floating in towing orientation.

Safe access is provided for trained personnel to board and enter the WEC (see Figure 5). Pontoon landing platforms provide a place for service vessels to land, for trained personnel to board, and for equipment to be offloaded. Spar platforms provide safe access for personnel and equipment into the WEC interior via the upper spars, as well as space to mount equipment. Ladders within the upper spars give access to the nacelle tube, where a walkway connects the two spars and provides access into the port side of the nacelle (through watertight hatches).

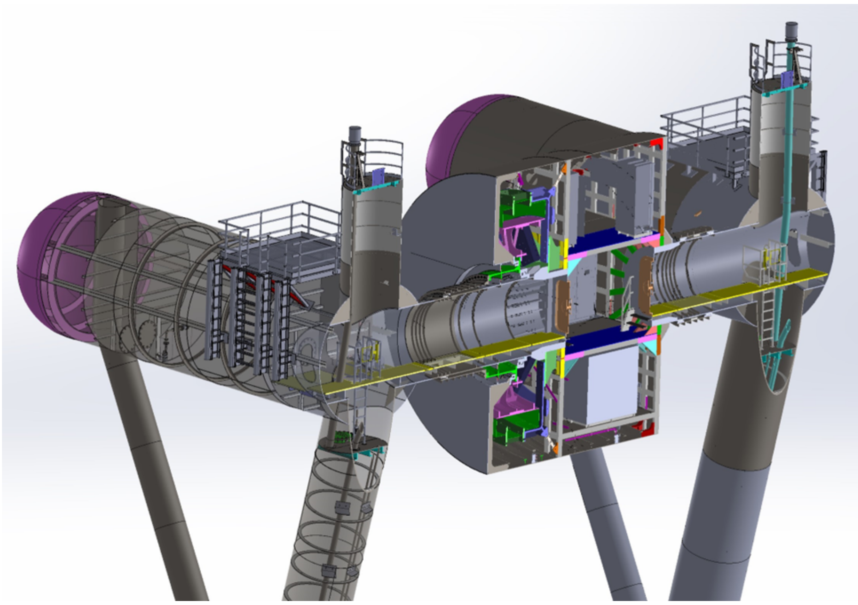

Figure 5 – Section/transparent view of nacelle and spar tube, showing access.

4.3 Site and Metocean Conditions

The H3p WEC was designed for deployment and testing at PWS. Site and metocean conditions are described briefly below, with additional details found in *DE-EE0008954 H3-DB-2.6 PWS Site Characterization* (Appendix 13.4). The European Marine Energy Center (EMEC) was identified as a secondary site of interest; site and metocean conditions for EMEC can be found in *DE-EE0008954 H3-DB-2.6.b EMEC Site Characterization* (Appendix 13.5).

PWS is an in-development, state-of-the-art, pre-permitted, accredited, grid-connected wave energy test facility funded by the US Department of Energy and developed by Oregon State University. The test site, which comprises four berths, is positioned 12 km offshore of the Port of Newport (see Figure 6) and encompasses nearly 7 sq. km. Bathymetry over the four test bays comprising PWS is depicted in Figure 7; depth ranges from 62 to 78 m. The sea floor is composed of medium to coarse sand, with fine sand to silt in the low areas.

PWS is currently under construction and is expected to be operational in 2025. PWS will provide subsea power and data cables from the test berths to shore, fitted with one half of the requisite dry-mate connector. From shore they are routed terrestrially to the shoreside Utility Connection and Monitoring Facility (UCMF), where a connection is made to a local utility grid.

The primary data source for PWS wave characterization is a 32-year, high-resolution hindcast created by Pacific Northwest National Laboratory (PNNL) and made available by National Renewable Energy Laboratory (NREL) [1]. The model was extensively validated for all IEC resource parameters against data from publicly available buoys. Sea state characterization was performed following the guidance of *IEC 62600-101 Wave Energy Resource Assessment and Characterization* [2].

A scatter table indicating the expected annual occurrence of sea states is given in Figure 8. Sea states are sorted by significant wave height (H_{m0}) and energy period (T_e), using bin widths of 0.5 m and 1 s, respectively. Sea states not expected to occur annually are indicated with light grey text, using a threshold of one hour annually (equivalent to an expected annual occurrence of 1/8766, or about 10 records out of 90,584). Mean values of H_{m0} and T_e are 2.33 m and 9.91 s, respectively.

Wave direction, as indicated by the maximum directionally resolved wave power (θ_{Jmax}), is generally from the west. A wave rose indicating expected annual occurrence for H_{m0}-θ_{Jmax} sea states is given in Figure 9. The mean wave direction is 278°, with 95% of seas incident from between 233 to 308° (a 75° range).

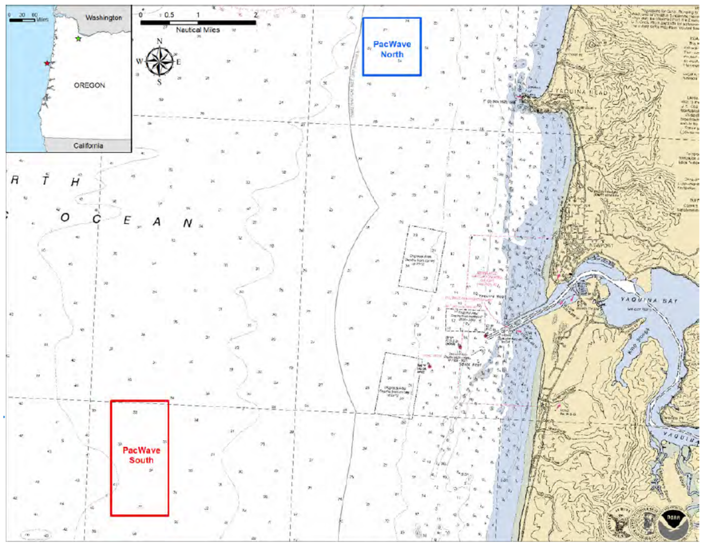

Figure 6 – PacWave South location.

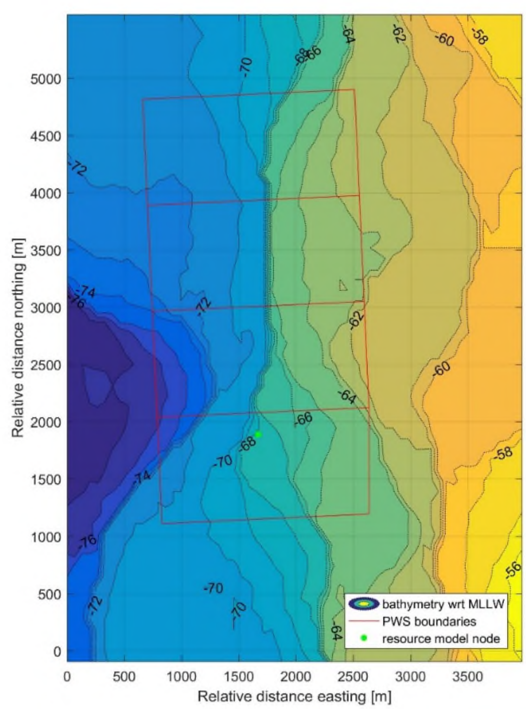

Figure 7 – PacWave South test berth bathymetry.

Sea state characteristics associated with 1-year, 5-year, and 50-year return seas were derived from the 31-year data set described above as a long-term measured record was not available. A modified Inverse First Order Reliability Method (I-FORM) developed by Sandia National Laboratories (SNL) was used to generate environmental contours in the H_{m0}-T_e plane [3].

Environmental contours for 1-year, 5-year, and 50-year return periods are shown in Figure 10, along with a density plot of the hourly sea state records. The maximum H_{m0} along the 50-year contour is 13.2 m, with an associated T_e of 16.5 s. However, any sea state along the contour may induce the most extreme loading, particularly one with a lower T_e.

Note that the extreme conditions assessed for EMEC exceeded those of PWS (maximum 50-year return H_{m0} of 15.2 and 13.2 m respectively), but a decision was made to base the H3p design on PWS conditions. While EMEC will continue to represent the alternate European market, the intention for H3p remains a 2-year deployment at PWS and the additional expense of designing for larger seas is not justified as deployment of the prototype at EMEC is very unlikely in the near-term.

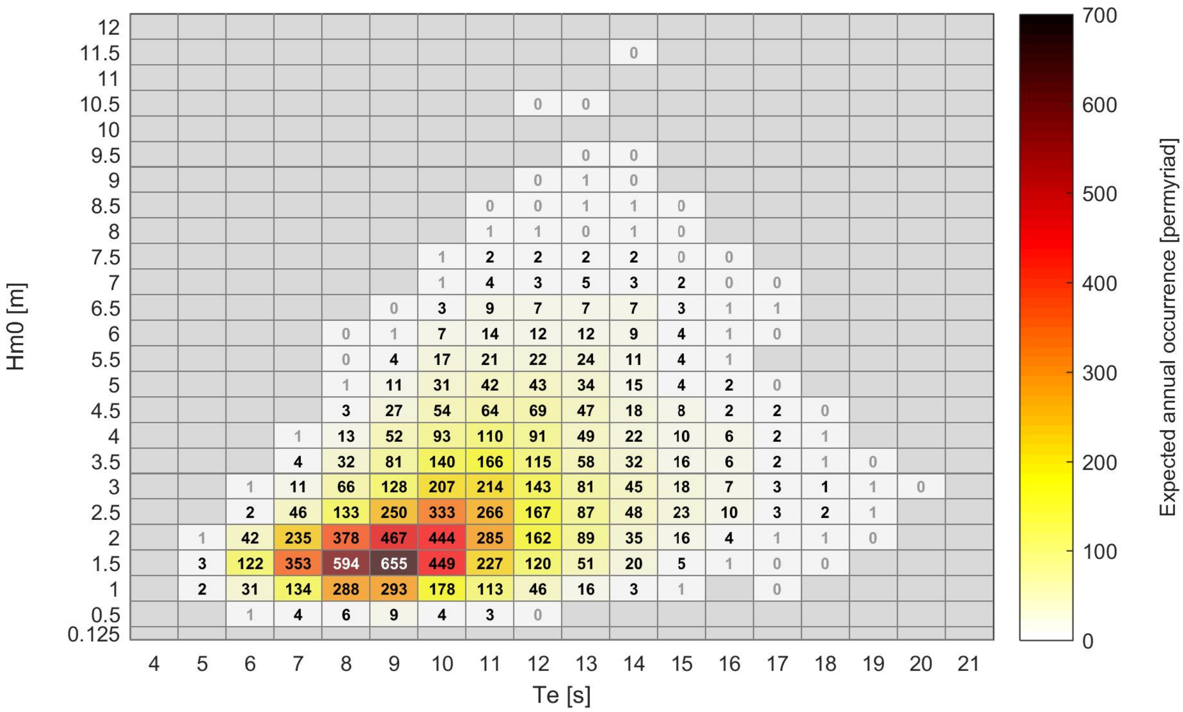

Figure 8 – Expected annual occurrence of H_{m0}-T_e sea states.

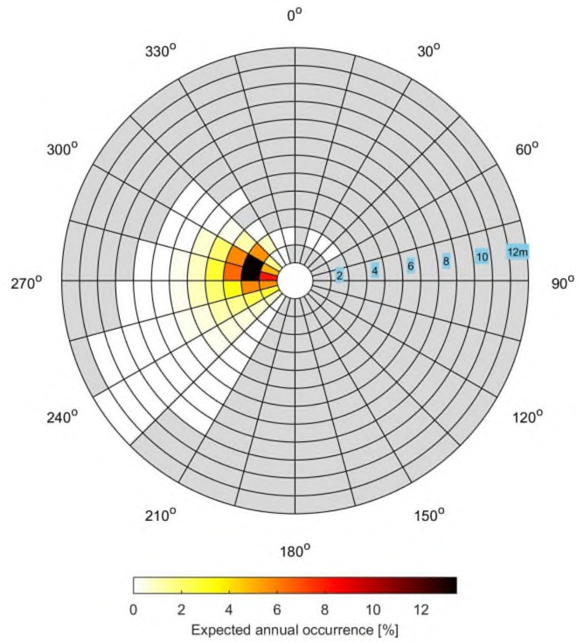

Figure 9 – Wave rose of expected annual occurrence of H_{m0}-θ_{Jmax} sea states.

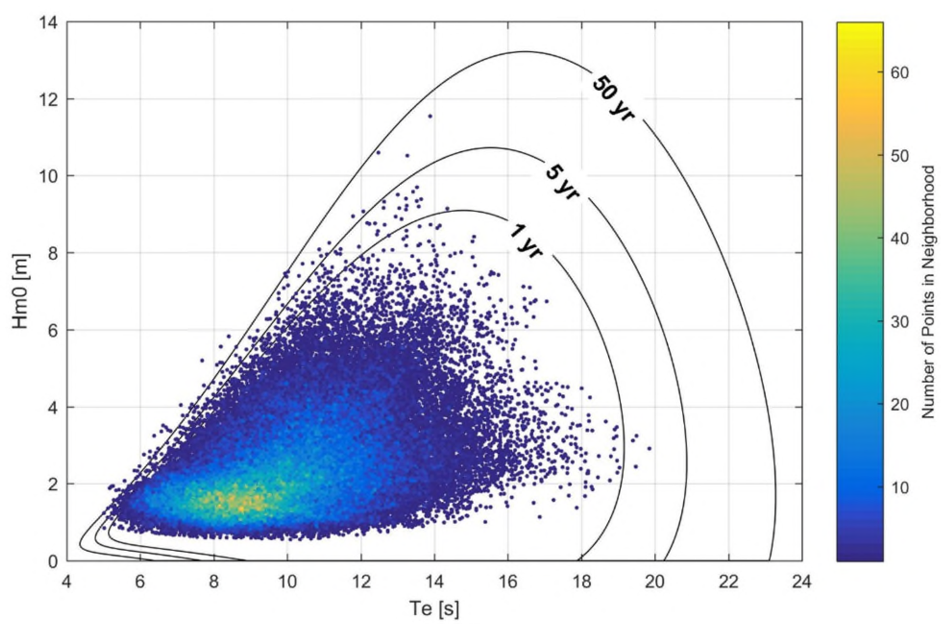

Figure 10 – Extreme H_{m0}-T_e plane environmental contours.

4.4 Design Load Cases

Specification of the design load cases (DLCs) was guided by *IEC 62600-2 Design requirements for marine energy systems* [4] and *IEC 62600-10 Assessment of mooring system for marine energy converters* [5]. Detailed description of the DLCs, and justification of their selection, is covered in *DE-EE0008954 H3-DB-2.7 Design Load Cases* (Appendix 13.6).

The DLC environmental conditions were derived from the characterization of PacWave-South (PWS) described above in section 4.3.

The operational sea states (OSS) are 24 sea states selected to represent the conditions that are reasonably expected on an annual basis. See Figure 11 for the PWS annual occurrence table with OSS indicated by blue circles. Analysis time for these sea states is 40 minutes, or 200 times the energy period, whichever is greater. Due to the relatively narrow range of incident wave directions, and the self-aligning nature of the single-point moored H3p WEC, OSS will generally be assumed to be head on. The OSS are assumed to have Pierson-Moskowitz spectral shape (equivalent to JONSWAP with a peak enhancement factor of 1), and cos-2s spreading indices for each OSS are based on the PWS characterization.

Extreme sea states (ESS) were specified for a return period of 50 years. The ESS were assessed using environmental contours (see Figure 10) and it is important to note that the limiting design load may come from anywhere along the contour (particularly at points with lower energy periods, due to the nature of H3p WEC response). A total of six discrete points along the contour were specified for ESS, including the point with the maximum significant wave height, and are indicated as red squares in Figure 11. The ESS are assumed to have a JONSWAP shape with a peak enhancement factor of 3.3, and a cos-2s spreading index of 12. An analysis period of three hours is specified for all ESS.

Currents are assumed to be secondary to waves in their effect on the WEC, however extreme currents may cause a misalignment between WEC and waves and are considered alongside wave conditions in select DLCs.

Wind is not expected to have a significant effect on loading, due to the low profile of the H3p, and is not generally considered in the DLCs. The mean sea level (MSL) at the site ranges from 62 to 78 m, and a MSL depth of 70 m is assumed for the WEC's deployed position.

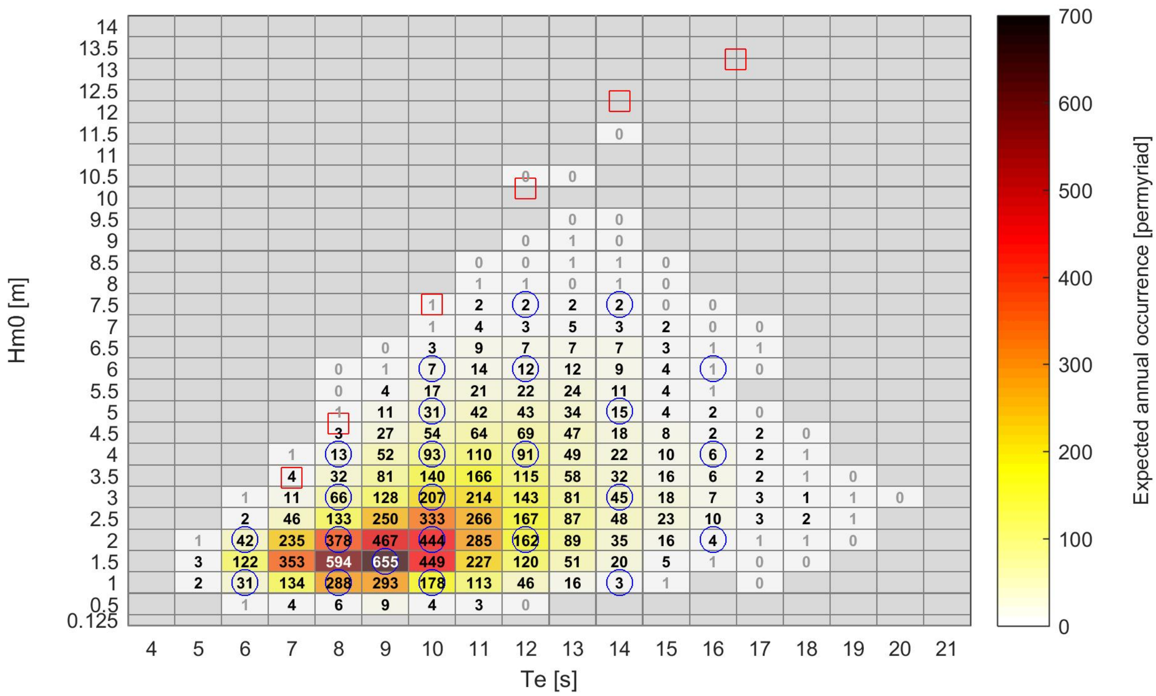

Figure 11 – Expected annual occurrence of H_{m0}-T_e sea states (OSS = blue circles, ESS = red squares).

The DLCs were assessed for design criticality, the critical DLCs were determined to be power production in OSS; power production in ESS; freewheeling (idling) in OSS; freewheeling (idling) in ESS; transport (towing); and damaged stability (flooded compartment, and single mooring line failure).

4.5 Safety Level and Partial Safety Factors

H3p structural design targets a safety level of three (SL3) due to low risk of human injury and minor environmental and economic consequences, associated with a target failure rate of less than 10e-3 annually, as specified in *IEC 62600-2 WEC Design* [4].

Note that *IEC 62600-2* [4] establishes specific design requirements only for SL2 (target failure rate of less than 10e-4 annually) but allows for other safety levels, stating:

> "The requirements in this document, including partial safety factors for loads and materials, have been derived to comply with the target probability of failure for safety level 2 (SL2). Other safety levels may be appropriate depending on project particulars."

With regards to SL3, *IEC 62600-2* [4] states:

> "When failure of a [WEC] does not imply risk of human injury and environmental impact and may only cause minor economic consequences, SL3 may be selected, subject to compliance with local regulations. Safety requirements for the [WEC], including partial safety factors, shall be agreed upon between the manufacturer and the customer."

Due to inherent risks associated with a large freely drifting body, and in accordance with *IEC TS 62600-10 Mooring Design* [5], SL2 is specified for the mooring system. Note that *IEC TS 62600-10* [5] may use different notation for this safety level; to be clear, the mooring system is designed for a target failure rate of less than 10e-4 annually. Due to lack of support in relevant standards for alternate safety levels, all other H3p systems target SL2.

Partial safety factors (PSFs) for structural design loads are specified for ultimate limit state (ULS) in combination with load and design categories; PSFs for fatigue limit state (FLS), serviceability limit state (SLS), and accidental limit state (ALS) are always unity for structural design. The ULS partial loads safety factors for structural design presented in Table 3 correspond to SL3 and have been reduced with respect to the SL2 PSFs presented in *IEC TS 62600-2* (except for 0.9≤PSF≤1.1, which were left unchanged). Modifications to structural PSFs (SL3) were guided by *DNV OS-J103 Design of Floating Wind Turbines* [6], which includes PSFs for low, normal, and high safety classes (equivalent to SL3, 2, and 1).

Table 3 – Partial safety factors for ULS structural design.

Load category	**Normal**	**Extreme**	**Abnormal**	**Transport**	**Favorable (all categories)**
Environmental	1.2	1.2	1.1	1.35	0.9
Operational	1.2	1.2	1.1	1.35	0.9
Gravity	1.2	1.2	1.1	1.2	0.9
Other inertial	1.2	1.2	1.1	1.2	0.9

Table 4 – Partial safety factors for mooring design.

Safety level	**ULS**	**ALS**
SL1m	2.2	1.25
SL2m	1.67	1.25

4.6 Concept Design

A hydrodynamic modeling study was performed to establish the primary characteristics of the H3p WEC, including hull dimensions, ballast mass, and generator torque limit. The hydrodynamic model was developed in ANSYS AQWA and permitted rapid implementation of modifications to dozens of design parameters (e.g., specific hull subcomponent dimensions, generator torque limit, ballasting, etc.). Parameterized cost and mass estimates were developed, and a set of sea states was selected to span the design resource. For each unique WEC configuration, the primary outputs of the modeling were metrics representative of performance and expense. The objective was to find configurations that have favorable cost to performance ratios.

Following a phased approach, more than 700 unique WEC configurations were modelled and assessed (more than 25,000 simulations). The initial phases evaluated the effect of single degree of freedom (DOF) studies, where only one parameter was modified at a time and the resultant WEC was modeled in a suite of sea states to assess the response. The following phases consisted of multiple DOF studies, using those parameters that the initial phases indicated had the strongest effect and clustering them in functional groups. As one example, a full factorial sweep of four key float-related parameters (float length, float diameter, float ballast, and float arm length) was conducted with three states each, resulting in 81 unique configurations; this particular study simulated each configuration in nine sea states and with three distinct generator damping settings resulting in over 2,000 individual simulations. The first two multi-DOF modeling studies focused first on the float, and then on the central body (i.e., pontoons, nacelle, ballast tank); after this there were two more multi-DOF studies in which the baseline configuration and parameter ranges were informed by the previous results. The final study swept through a range of WEC sizes (globally scaled from the optimized baseline). In addition to sea states and generator damping, a range of maximum generator torque levels were modeled for each WEC size (each size had individually suitable generator damping and torque ranges).

While most of the modeling was performed with WEC configurations displacing 1600 to 1900 mt, the results from this optimization exercise provide WEC configurations over a greater range (total displacements ranging from 860 to 4600 mt). Investigation over this large range allowed C·Power to assess the WEC scale appropriate to target for long-term commercial development and for the present prototype design development.

Select characteristic values are given in Table 5, where each column represents the optimal configuration at each of the seven basic scales investigated. Performance (capture width ratio) is plotted against estimated expenses (capital and operating) in Figure 12. Estimated LCOE is plotted against estimated expenses in Figure 13. These results indicate dramatic improvements in performance and LCOE with increasing WEC scale. While the performance gains continue to climb over the study scope, the LCOE improvements plateau at around the 2800 mt displacement size. Note that the scales are obfuscated in this "Unlimited Data" document but can be viewed in the "Protected Data" *Final Design Report* (Appendix 13.1).

The cost and performance estimates of the concept design study indicated that a very large WEC (~2800 mt displacement) minimized estimated LCOE and was optimally sized for long-term commercial development. However, due to the high costs and logistical challenges of such a large device, concerns arose that a WEC of this size was not a rational next step in the technology development path. To limit C·Power and stakeholder financial and operational risks and increase the likelihood of keeping project costs for the anticipated build and deployment in-line with future funding opportunities, smaller WECs were considered.

With DOE concurrence, C·Power decided to design a smaller prototype WEC within this Project, while maintaining long-term focus on a larger commercial WEC, allowing for Project technology development goals to be met while reducing near-term technical and economic risk to manageable levels.

The smaller project-targeted prototype (indicated by green in the table and figures below) is called H3p. The larger utility scale WEC (indicated by orange in the table and figures below) is called H3u.

Table 5 – Primary characteristics for concept design stage WECs.

Characteristic	Units	H3p	H3.b	H3.c	H3.d	H3u	H3.f	H3.g
Total displacement	mt	870	1200	1600	2100	2800	3600	4700
Draft	m	18	19	21	23	26	28	30
Beam width	m	21	22	24	26	28	31	33
PTO torque limit	MNm	1.5	2.2	3.1	4	7	10	13

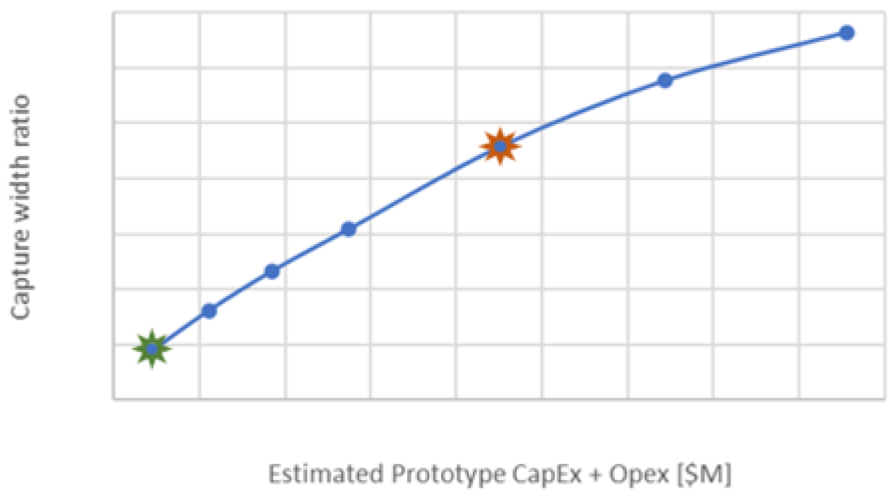

Figure 12 – Concept design stage results: performance versus cost.

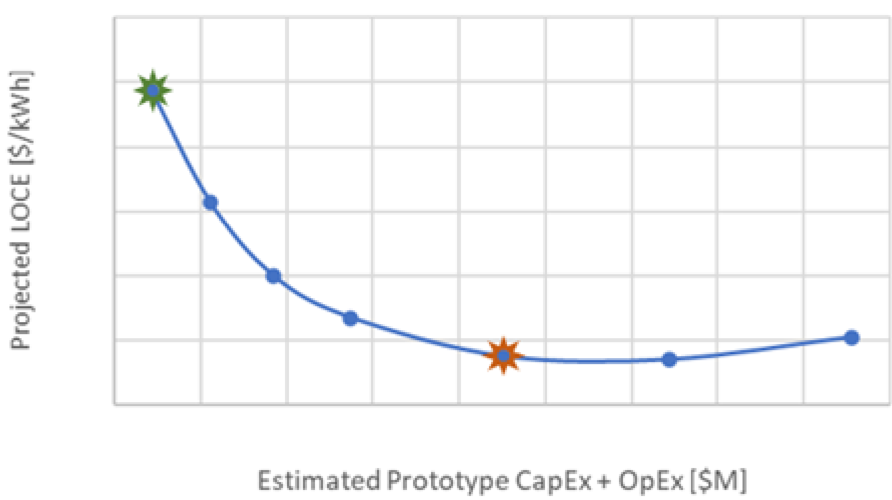

Figure 13 – Concept design stage results: levelized cost of energy versus cost.

5 COMMERCIALIZATION PLAN

C·Power's commercialization plan for the StingRAY H3p is outlined below. The Final Commercialization Plan is detailed in *H3-fCP-6.6 Final Commercialization Plan* (Appendix 13.7).

The ultimate market for StingRAY is utility-scale electricity generation. Like offshore wind farms, the individual power plants will be arranged in offshore wave farms that are connected to terrestrial grids, with the energy produced being sold into wholesale markets. The wave farms will be developed, owned, and operated by utilities and independent power producers. C-Power will be an equipment supplier.

However, utility-scale wave farms for wholesale markets are several years from implementation. Energy harvesting and conversion technologies, like the StingRAY, and their sub-components, like PTOs, have not matured enough to cost effectively compete with terrestrial resources, e.g., natural gas, onshore wind, or offshore wind, even with substantial financial support mechanisms. This Project is a key step towards maturing C-Power's design in pursuit of cost-competitiveness. However, it will take several design-build iterations to begin to approach subsidized competitiveness with the current resources.

For smaller remote and island grids and mini-grids in which diesel fuel is a primary energy source, wave energy technologies will rapidly approach competitiveness and represent a prime early market opportunity. These loads tend to range from tens of kWs to 10 MWs and are critical building blocks for achieving the scale and volume needed to eventually deliver cost-effective utility-scale ocean energy. The existing high-cost, or even absence, of reliable electricity supplies for these locations, which can be due to the logistics and product costs of diesel fuel, presents a major market opportunity for a maturing technology to build the scale, competitiveness, supply chain, customer base, and channel necessary for entry into utility-scale markets.

However, a significant obstacle here is infrastructure costs – most specifically export cables for grid-interconnection – that prevent development of smaller farms for island or coastal village-scale grids without significant financial support mechanisms. The costs of cable, along with time and resources required for engineering, permitting, and deployment, can easily outweigh the capital costs of the generation capacity itself. The difficulty and expense surrounding implementation of the cabling infrastructure at PacWave South is a relevant example of this issue. Cabling and other infrastructure costs will impede market development, at both village- and utility-scale, until more cost-effective solutions are developed. Alternative markets are needed.

The predominant near-term markets and applications are power for surface and seafloor operating equipment and at-sea vessel charging. Medium term use cases will target isolated small grids and loads, e.g., "village-scale" power or desalination for coastal locations. Longer term, the StingRAY product will be targeted towards wholesale terrestrial energy markets, which are highly competitive, i.e., a sub five cent per kWh LCOE is currently required to participate. C·Power's market strategy includes capacity progression from single systems providing from tens to hundreds of kW followed by arrays capable of MW-scale production. This progression is intended to match the techno-economic maturity of the StingRAY to the price sensitivity of the targeted market.

Lower power markets tend to be less sensitive to the cost of energy given the current high cost of fuel and associated logistics, which can easily range from $.40-.80/kWh. In the near-term, it's easier for the StingRAY to compete as an alternative or replacement in these markets versus $.03-.05/kWh required by wholesale markets. For offshore loads with these higher energy costs, especially from diesel fuel, the added high cost of export cables required for the terrestrial village-power sub-markets are avoided. As such, the cost-competitiveness of the StingRAY is increased, making these offshore diesel and natural-gas replacement markets the initial, primary target. As export cable costs fall, C·Power's market focus will expand to incorporate the village-power opportunities and eventually the ultra-competitive wholesale power markets.

The Project-targeted H3p is specifically intended to service non-terrestrial loads of near-term markets—diesel genset replacement, at-sea vessel charging, larger class remotely operated vehicles (ROVs), remote marine operating equipment (e.g., pumps), and others—and will be well-placed for terrestrial applications when those become available.

Single WECs or arrays of WECs will be utilized, depending on customer load. Production will initially follow a fabless strategy, leveraging partners' strengths and expertise for structural and component assembly. Sales will utilize distribution partners, if possible, to avoid overhead associated with direct sales to end use customers. This Project represents a key step to delivering the initial prototype for a later validation project and a practical and concrete step towards the future development of the larger utility-scale H3u.

While the larger, utility-scale H3u benefits from a more advantageous hydrodynamic interaction with the resource as well as from economy of scale, it is not feasible nor practical to target the utility-scale H3u StingRAY within this Project, and as explained above, the H3p StingRAY design that has resulted from this Project is directly applicable to a number of near-time market opportunities that are well served by its more modest production levels.

While the Project-targeted H3p StingRAY prototype is a smaller scale version of the expected utility-scale H3u StingRAY, the Project's techno-economic metrics and subsequent analysis are based on the latter. Primary design targets that were established for the Project-targeted H3p and utility-scale H3u StingRAY are provided in Table 6.

Table 6 – Primary design targets, in deployed operational configuration.

Description	Units	Project-targeted H3p	Utility-scale H3u
Displacement, ballasted	mt	950	2800
Freeboard	m	5.0	6.5
Draft	m	17.5	25.5
Beam width	m	20.5	28.1
Length, fore-to-aft	m	20.7	29.9
Max generator torque	kNm	1500	7000
Max generator power (electrical)	kW	750	2500

Long-term and for the utility-scale market, the world's oceans hold enough practically extractable energy to power over 200 Mn homes. C·Power's market study estimates a total StingRAY addressable market opportunity (i.e., H3p and H3u) of approximately $120 Bn in 2030. This opportunity is dominated by the expansion of the terrestrial grid market and the assumption that StingRAY can address 100% of the market opportunity available to offshore wind. For the StingRAY class of devices in the nearer-term (i.e., H3p), C·Power's market study suggests that the system will have an addressable market value of approximately $6 Bn.

The initial market opportunities are for powering offshore operating equipment, carbon-fuel replacement, e.g., diesel genset, and at-sea larger USV charging. These market opportunities will start in the 50 to 250 kW range of required generation capacity.

6 WEC DESIGN

6.1 WEC overview

The H3p is conceptually broken down into systems. These systems are further broken down into subsystems, components, and parts. The primary systems are each identified by a ‘hundred series’ number (e.g., 0100 Hull, 0200 PTO) and further breakdown is identified using numbers within each ‘hundred series’ (e.g., 0100 Hull > 0110 Float Assembly > 0112 Float Drive Arm). The primary systems (and select secondary systems) are listed in Table 7, along with their functions.

System designs began with the development of detailed Engineering Design Requirements (EDRs), followed by Preliminary then Final design efforts. C·Power contracted outside expertise for design support on critical systems. Description of system designs are given below, in section 6.2.

Table 7 – WEC systems and functions

ID		Element	Function
0100		Hull Structure	Wave activated bodies Watertight compartments & access Structural connectivity & load transfer Ballast containment, buoyancy, & stability Provide maintenance access
0200		PTO	Electromechanical energy conversion Constrain relative motion to 1 DOF (pitch) Torque transmission Maintain stator/rotor air gap
0300		Electric Plant	Low-level control of generator segments Power smoothing Condition power for grid quality
0400		SCADA	Collect performance, loads, and other data Issue PTO and auxiliary system commands Communication between WEC and shore Alarms, diagnostics, and fault recovery
0500		Auxiliary Systems	(see below)
	0510	Ballast Control	Facilitate ballast operations
	0520	Safety & Emergency	Automated condition monitoring and alarms
	0530	Climate Control	Regulate environmental conditions in designated spaces
	0540	Station Power	Power distribution to WEC systems
	0550	Aids to Navigation	Alert mariners of the WEC's presence in the open ocean
	0560	Cooling	Supply coolant to generator and climate control, reject excess heat
	0570	Bilge	Collect and remove water from within hull compartments
	0580	Surveillance	Monitor status of WEC/components, remote inspections
0600		Outfit & Furnishing	(see below)
	0610	Designation & Markings	Provide necessary safety and other information
	0620	Hull Fittings	Provide for routing of pipes and cables, and other features

ID		Element	Function
	0630	Hull Penetrations	Maintain water tightness while providing passages for e.g., plumbing and cabling
	0640	Marinization & Corrosion	Specify means to protect against marine environment Define environmental specifications for internal compartments
	0650	Workspace & Lighting	Provide light and power for inspection and maintenance
	0660	Emergency Equipment	Provide onboard emergency equipment
	0665	Lightning Protection	Protect systems and people in event of lightning strike
	0670	Stowage	Storing emergency equipment and maintenance supplies
0700		Mooring	Keep WEC on station Facilitate WEC orientation into incident waves
0800		Electrical Collection	Conduct electrical power and data between WEC and shore

6.2 System Designs

6.2.1 0100 Hull

Cardinal Engineering was contracted for Hull system design, as well as Ballast Control (C·Power System 0510) and Bilge (C·Power System 0570). The hull design is outlined below, with further details presented in the following documents:

- Hull Preliminary Design Report
  - *DE-EE0008954 H3 0100 Hull PDR* (Appendix 13.8)
- Hull Final Design Report
  - *DE-EE0008954 H3 0100 Hull FDR* (Appendix 13.9)
- Hull 2D Drawings
  - *DE-EE0008954 H3 0100 Hull 2D Drawings* (Appendix 13.10)
- Weight Calculations
  - *DE-EE0008954 H3 Weight Calcs for Hydrostatics* (Appendix 13.11)

Subsystems and functions are listed below in Table 8.

Table 8 – 0100 Hull subsystems.

ID	Element	Function
0110	Float Assembly	Wave activated body Watertight compartment Drive generator shaft
0120	Nacelle Assembly	Wave activated body Watertight compartment Housing PMG, electric plant, and other equipment
0130	Pontoons	Wave activated body Watertight compartment Hydrostatic reaction torque
0140	Spars	Structural connectivity (between ballast tank and nacelle tube) Watertight compartment, ballast containment Access to nacelle (upper spars)
0150	Kneebraces	Structural connectivity
0160	Ballast Tank	Watertight compartment Ballast containment

ID	Element	Function
		Inertial reaction
		Buoyancy (in towing configuration)
0170	Ballast	Lower center of gravity, stability
		Adjust draft, heel angle
		Transition between towing and operational orientations
0180	WEC Access	Provide for safe access by trained personnel

6.2.1.1 Loads Development and Structural Analysis

Design loads were developed collaboratively by C·Power and Cardinal Engineering. Hydrodynamic models were developed by C·Power and provided inputs for Finite Element Models (FEA) developed by Cardinal.

Loads were assessed computationally using fully coupled time-domain numerical simulations, accounting for all load contributions simultaneously (ANSYS AQWA-NAUT v16). All relevant loads were considered in the calculations, including hydrodynamic loading, inertial loading, and functional loading from PTO and mooring. The hydrodynamic loads included hydrostatic, Froude-Krylov, viscous drag, added mass, and drift forces.

The WEC was decomposed and modeled as 11 substructures, with substructures connected either rigidly or via single degree of freedom (DOF) hinged joint as appropriate. The decomposition allowed AQWA to output 11 separate sets of loading time series. Thus, for each DLC simulated there was a time series of hydrodynamic loading, acceleration, velocity, depth, and body-to-body constraint loads for each of the discrete substructures; generator torque; PTO friction and non-torque constraint loading; and mooring and umbilical attachment point loading. In extreme seas, some substructures occasionally left and re-entered the water. In these instances, a slamming pressure was estimated from concurrent hydrodynamic loads and wetted surface areas.

A total of 66 50-minute simulations were run for power production mode in extreme seas, and another 66 for the WEC idling in extreme seas. These simulations covered the six 50-year return sea states (i.e., ESS) identified in section 4.4, and both default float ballasting as well as the heavily ballasted float in an overtopped state. Simulations of identical conditions had unique sets of random phase angles for the spectral components; with multiple simulations of each set of conditions, more conservative design loads resulted. The seas were modeled with directional spreading, but with the mean direction head-on to the WEC (as the single-point mooring allows the WEC to align itself with the waves). Extreme seas simulations were run with 0.01 second time step (100 Hz), to fully capture the dynamics of the wave-induced loading. To keep files sizes manageable for structural analysis the resulting time series outputs were down-sampled by a factor of four (resulting in 25 Hz data sets).

A total of 24 simulations were run for power production in operational seas, and another 24 for the WEC idling in operational seas. A single simulation was run for each of the 24 OSS identified in section 4.4. Analysis time for these sea states was 40 minutes, or 200 times the energy period, whichever was greater. Similar to extreme seas, the operational seas were modeled with directional spreading. Operational seas simulations were run with 0.02 second time step (50 Hz), to capture the dynamics of the wave-induced loading. To keep files sizes manageable for structural analysis the resulting time series outputs were down-sampled by a factor of five (resulting in 10 Hz data sets).

Substructure accelerations and intra-body loads were used to aid in selecting the worst extreme seas cases for further analysis. A total of nine "worst cases" were selected from power production DLCs, and another nine from idling DLCs. Two particularly "extreme" operational seas were also selected at this stage.

Beam element FEA models were developed in NASTRAN for the central body and for the float assembly. Hydrodynamic loads were applied to the mass elements of each substructure. Mooring loads and PTO torques (PMG and bearings) were applied at appropriate locations, as were bearing constraint loads. The

bearing constraint loads were necessary as the central body and float assembly models were run independently. Counteracting inertial loads were calculated from the accelerations and applied to balance the models, such that they could be run as quasi-static. All time steps of the identified DLCs were simulated, yielding time-series of structural loading.

For each of the H3p substructures (e.g., nacelle, nacelle tube, upper spar, etc.), the maximum bending moment, shear, axial force and torque were determined across all the time steps. The maximum moments and loads were found across all the load cases and served to identify design load instances for further analysis and design. To assess hydrostatic loading, the maximum depth for each body was determined for each instance.

In addition to the primary loading developed using AQWA, Cardinal utilized DNV specifications to generate loads for impact loads (slamming), sloshing, tank loads, and tugboat loads.

A material PSF of 1.15 was specified. Used alongside the loads PSF of 1.2, a total safety factor of 1.38 was utilized (1.20 * 1.15 = 1.38). This safety factor was used to scale the allowable material limits, and the FEA models were run as-is (without applying PSFs to the loads).

Global sizing of structural elements (e.g., shells, scantlings, etc.) was performed using calculations from appropriate DNV specifications. FEA sub-models were then used to find areas of concern and designs were iterated to improve.

Sub-models were developed for each of the substructures using plate elements, which were then incorporated into the global beam element allowing for individualized hybrid plate/beam models for each substructure. As an example, the pontoon hybrid plate / beam model is shown in Figure 14, and again in Figure 15 with the shell removed to show more detail. For each of the design load instances identified for worst-case e.g., pontoon loading, the hybrid model with the plate element pontoon was run with all concurrent loads applied. Pressure loads were applied as well in these hybrid model simulations. These detailed sub-models were used to identify areas of concern and areas requiring additional design iterations.

A fatigue assessment was conducted, to ensure that the specified 5-year design life was met. The 24 OSS were grouped by significant wave height, and one sea state was selected to represent each group. Higher occurrence was balanced against energy periods with a greater WEC response to ensure a conservative approach. Only the power production DLC load cases were considered.

An FEA analysis approach similar to the extreme DLCs was undertaken, utilizing plate sub-models. Peak stresses due to each load case at various locations from the plate sub-models were used to identify fatigue critical areas. Time histories of the representative parameter of each load case (e.g., bending moment, acceleration) were normalized, and used to scale stress magnitude at each fatigue critical area (FCA) to create time histories of stress magnitudes. Rain flow counting was then used to calculate incremental fatigue damage from each cycle and each load case, at each fatigue critical area. Lifetime accumulated damage from each load case was summed at each FCA (total damage is scaled by 1.2 to account for corrosion). If total accumulated damage at any area exceeded 1.0 a fatigue crack was assumed to initiate within the 5-year lifetime.

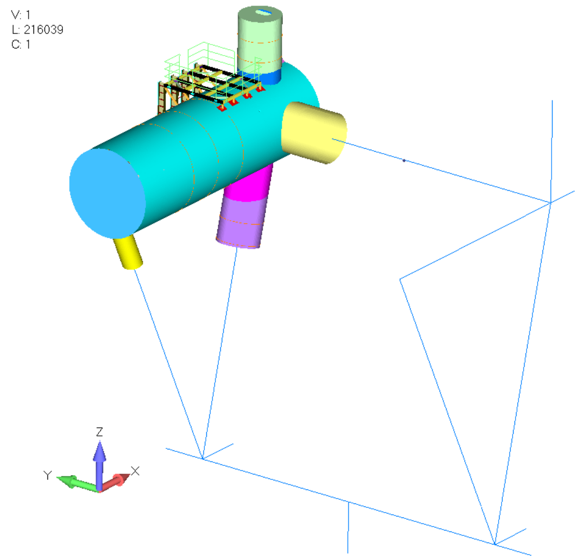

Figure 14 – Hybrid plate / beam element FEA model for pontoon.

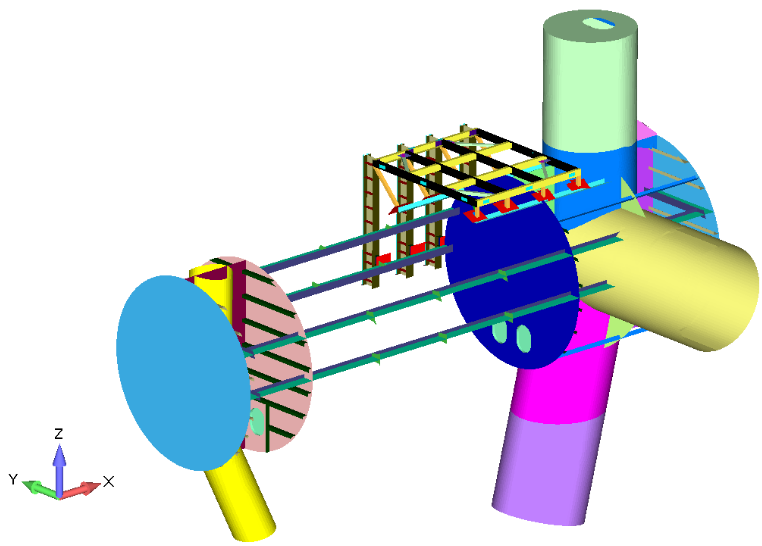

Figure 15 – Plate sub-model for pontoon, with shell removed to show detail.

6.2.1.2 Structural Design

The H3p hull structure is a steel fabrication utilizing NV-AH36 for plating, ASTM A500 GR B for tubes, and ASTM 529 for structural shapes. Detailed 2D drawings were developed by Cardinal, as was a 3D model. The 2D drawings include weld specifications. An illustrative example of the 2D drawing package is included as Figure 16.

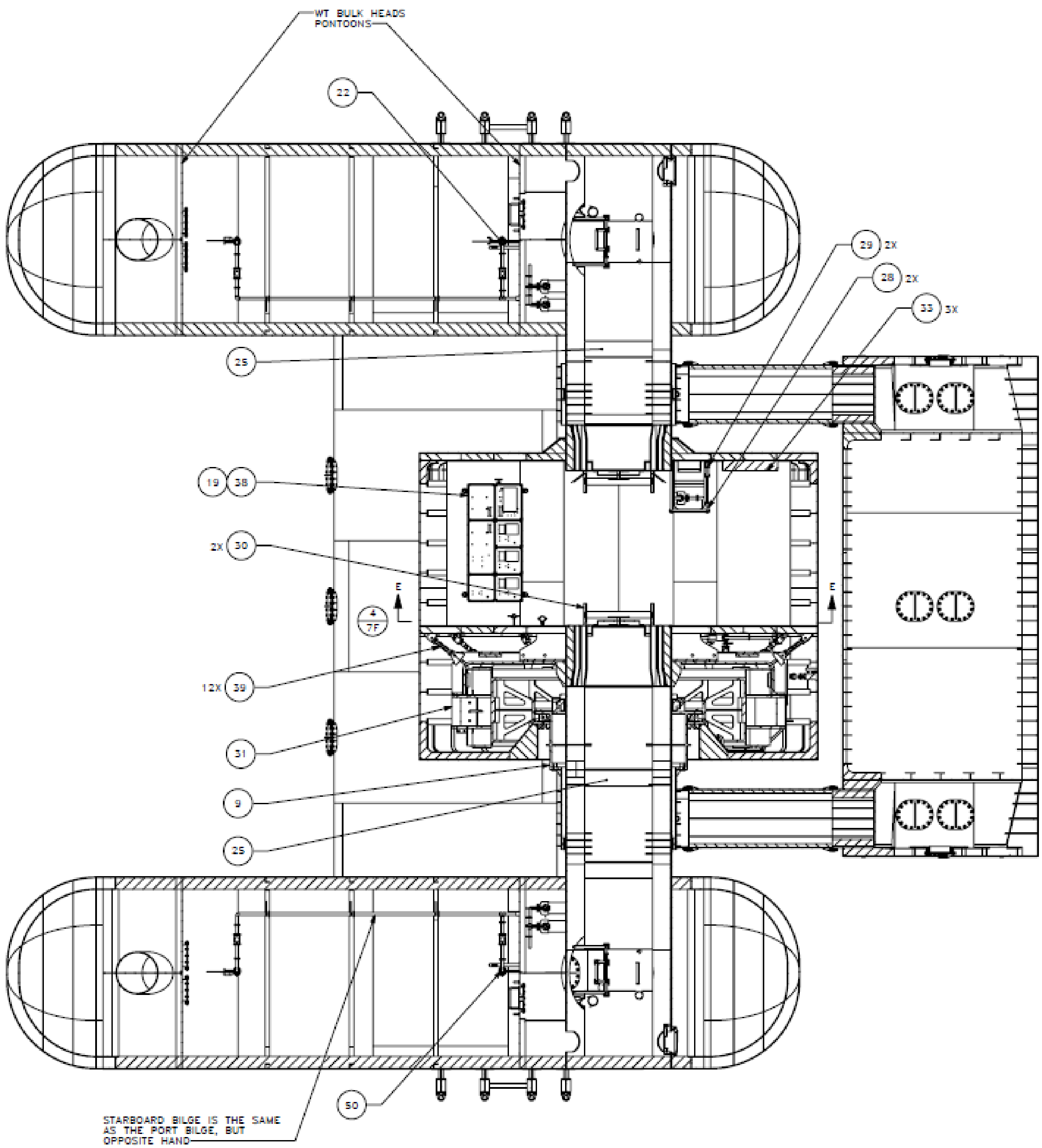

Figure 16 – H3p sectioned at waterline, illustrative example of 2D drawing package.

As discussed in the previous section, the structural design considered ultimate, fatigue, and buckling failures; global stresses and local stresses at joints; hydrodynamic loading including slamming and maximum pressures; mooring and PTO loads; and towing and tugboat loads.

Pontoon landing platforms provide a place for service vessels to land, for trained personnel to board, and for equipment to be offloaded. Spar platforms provide safe access for personnel and equipment into the WEC interior via the upper spars, as well as space to mount equipment. Ladders within the upper spars give access to the nacelle tube, where a walkway connects the two spars and provides access into the port side of the nacelle (through watertight hatches). The port side of the nacelle has three levels of platforms; the

middle level is accessed via the nacelle tube, and from there the upper and lower levels are accessed via ladders. A bulkhead separates the port and starboard nacelle sides, restricting access to the moving elements of the PTO. Platforms in the lower spars, accessed via ladders from the nacelle tube, provide space for bilge water collection and pumping. These platforms also serve as watertight bulkheads for the variable ballast held in the variable ballast tanks below. Access to the pontoons, if required, is through watertight hatches. See Figure 17 for an overview of WEC access features.

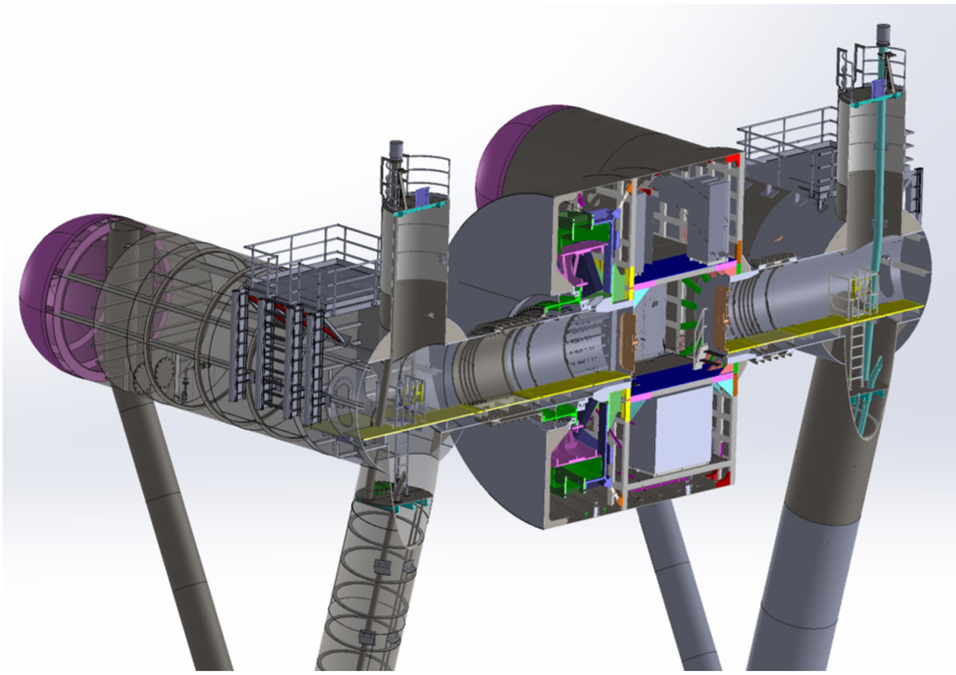

Figure 17 – Cut view of nacelle and spar tube, showing access.

The nacelle structure underwent significant design iteration. A major challenge is that it must carry all loads between the port and starboard sides, while also remaining sufficiently stiff to accommodate the PMG air gap tolerance. A significant amount of design effort was expended, in collaboration with the PMG design team, in detailing the nacelle/PMG interface such that the air gap tolerance was met. The rotor and stator interfaces are both at the nacelle tube and were kept as close to one another as possible to reduce relative deflection. The final design meets the air gap tolerance requirements but increases the weight of the structure significantly. Nacelle design features are indicated in Figure 18, and again in Figure 19 with PTO and equipment cabinets installed.

One area of investigation was if the nacelle tube should be continuous through the nacelle. It was determined that the nacelle tube did not carry a significant portion of the load through the port side of the nacelle, and so design iterations optimized for load transfer from the starboard nacelle tube to the central bulkhead, through the deck stiffeners to the port bulkhead, and finally to the port nacelle tube. A port-side conical transition (from bulkhead to nacelle tube) reduces stress at this joint.

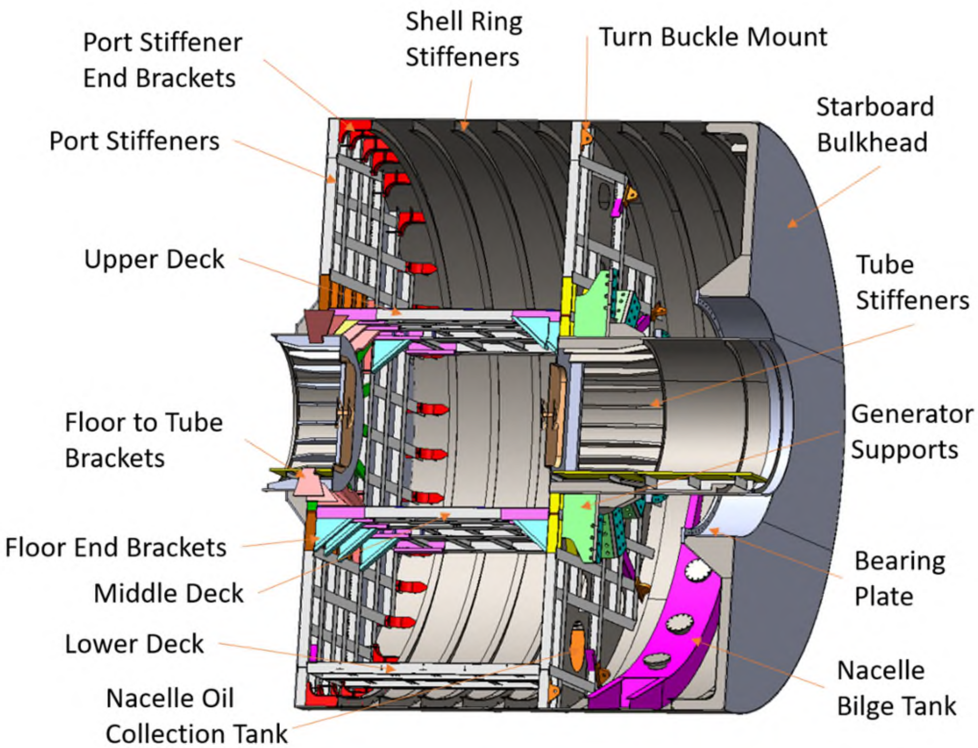

Figure 18 – Nacelle structural features.

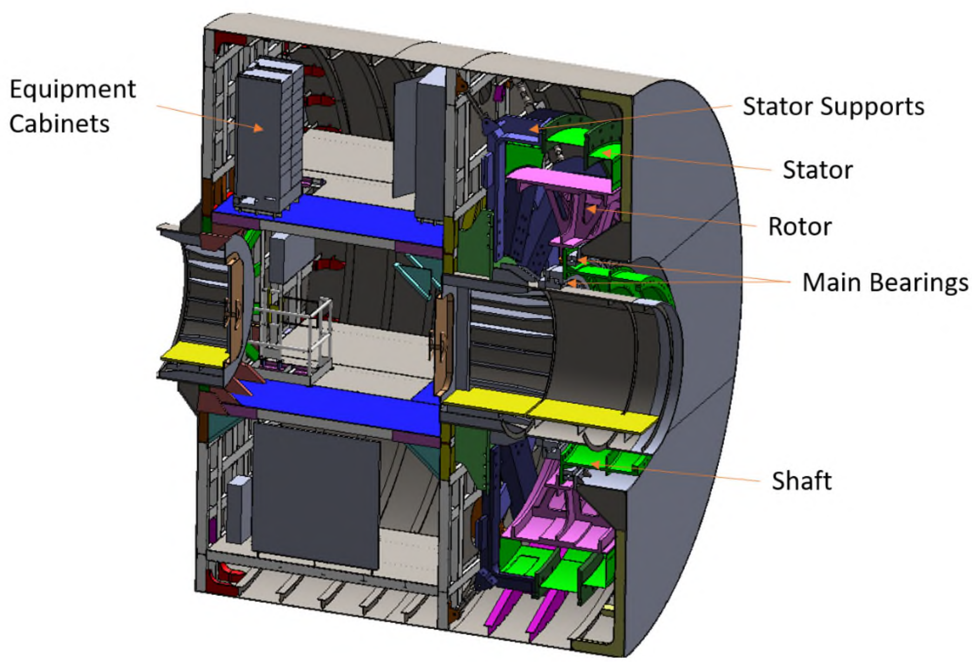

Figure 19 – Nacelle with PTO and equipment cabinets.

The float is compartmented (see Figure 20), allowing for partial flooding of the float. When flooded, the reserve buoyancy is greatly reduced and the PTO torque can then be used to motor the float under the nacelle, transitioning from one side to the other. This feature allows for the float to be returned to the normal operating position in the case of an extreme wave event sending the float over the top of the nacelle (i.e., overtopping). Overtopping is discussed in section 4.2, and illustrations of the float in normal and overtopped positions are provided as Figure 1 and Figure 3. A system of valves and vents was designed to flood the float when it is aft and upside down (after overtopping) and drain the float when it is forward.

The ballast tank is compartmented to accommodate both permanent and variable ballast (see Figure 21). The central compartments hold the permanent ballast, which consists of wet packed sand and fresh water. The permanent ballast mass is biased towards the port side, to balance overall system mass (which is biased starboard due to the PMG). A low cg is important for performance. Variable sea water ballast is held in the port and starboard compartments, which include the lower spars. Adjustments to variable ballast can be used to adjust draft and heel angle. Without variable ballast, the ballast tank is buoyant and the WEC floats in a horizontal towing orientation, and when variable ballast is added the ballast tank sinks and the WEC floats in its vertical operational orientation (see Figure 22). As discussed in section 6.3, additional permanent ballast was specified in final design to mitigate raising of cg due to mass increases in the nacelle.

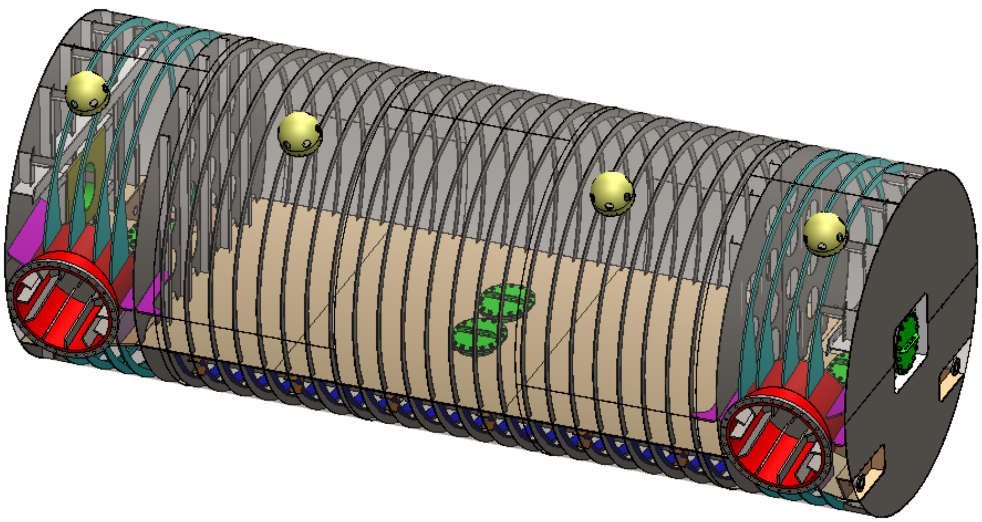

Figure 20 – Float structure; compartment above the horizontal bulkhead floods for return operations.

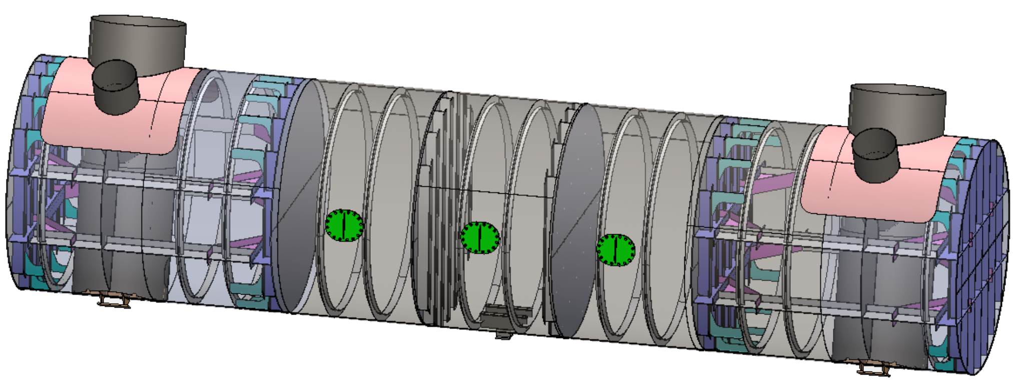

Figure 21 – Ballast tank structure.

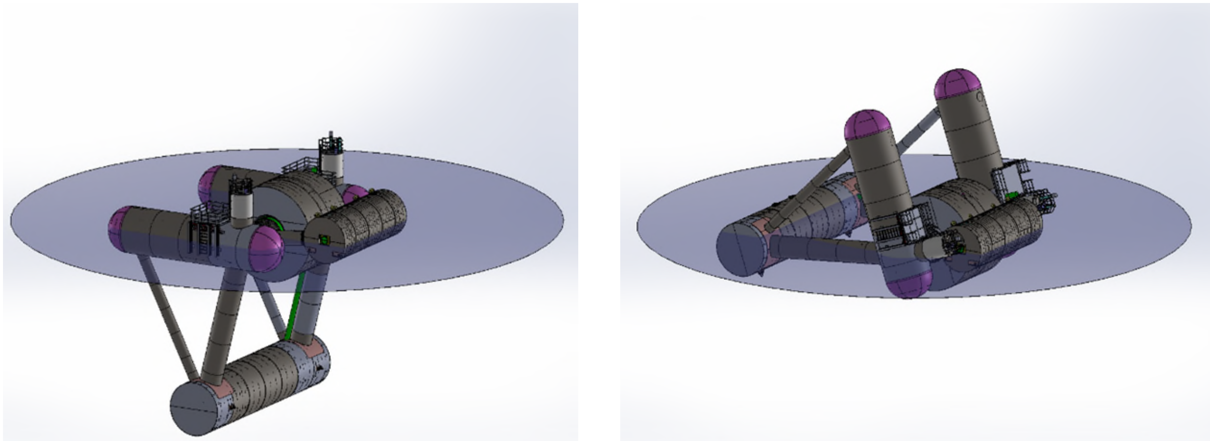

Figure 22 – H3p in operational (left) and towing (right) configuration.

The hull is subdivided into several compartments via watertight bulkheads and hatches. The compartments are designed such that the WEC remains buoyant and stable in the case of a failure resulting in the flooding of any single compartment. Hydrostatic analysis performed for flooded compartments (single) indicates that the H3p will remain floating and stable with a single flooded compartment. The worst-case scenario is a flooded nacelle; if the float is also flooded (due to an overtopping event), there is minimal freeboard remaining and the risk of sinking is not insignificant. As a result, a decision was made to reconfigure the float ballasting features from passive to manually actuated, such that the float will not flood when it overtops. Thus, the risk of sinking is greatly reduced, but personnel will need to be onsite to manually flood the float for a float return operation in the unlikely event of overtopping.

Corrosion protection is provided by coatings and sacrificial anodes. A coating system is specified for zones above, adjacent, and below the waterline. Aluminum sacrificial anodes are specified.

6.2.2 0200 Power Take-Off

The PTO is responsible for electromechanical energy conversion. It constrains relative motion between the central body and the float to a single DOF (pitch), while transmitting torque, and maintaining the PMG air gap. The PTO consists of the PMG and mechanical subsystems, which are shown in Figure 23, listed in Table 9, and discussed in the following subsections.

Table 9 – 0200 PTO subsystems.

ID	Element	Function
0210	PMG	Electromechanical energy conversion Provide generator torque Maintain stator/rotor air gap
0260	PTO Shaft	Transfer torque between float drive arm and generator input shaft
0270	PTO Bearings	Constrain float/nacelle relative motion to 1 DOF pitch Alignment of rotor
0280	PTO Shaft Seals	Maintain watertight integrity of nacelle where it is penetrated by a rotating shaft

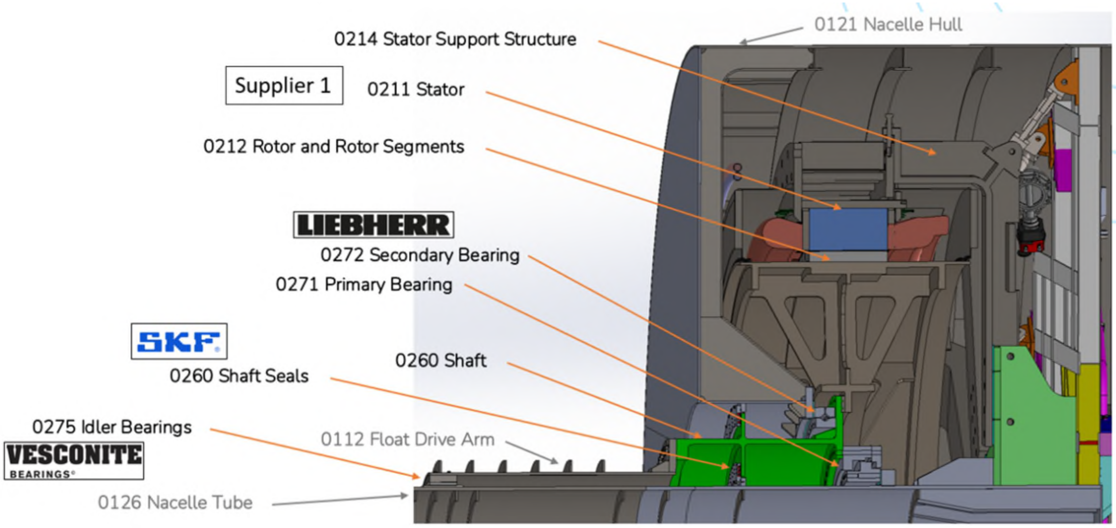

Figure 23 – PTO subsystems.

6.2.2.1 Generator

A large multinational corporation ("Supplier 1") was contracted for generator system design. The generator design, which included the structure to maintain the air gap under load, is outlined below. Further design details are presented in the following documents:

- PMG Final Design Report
  - *DE-EE0008954 H3 0210 PMG FDR* (Appendix 13.12)
- PMG Datasheet and Characteristic Curves
  - *DE-EE0008954 H3 0210 PMG Datasheet* (Appendix 13.13)
- PMG General Arrangement (2D drawings)
  - *DE-EE0008954 H3 0210 PMG General Arrangement* (Appendix 13.14)
- PMG Rotor Particulars (2D drawings)
  - *DE-EE0008954 H3 0210 PMG Rotor Particulars* (Appendix 13.15)

Additional breakdown of 0210 PMG subsystems and functions are listed below in Table 10.

Table 10 – 0210 PMG subsystems.

ID	Element	Function
0211	Stator	Electromechanical energy conversion
0212	Rotor Wheel and Segments	Provide magnetic field Transmit torque between rotor and shaft
0214	Stator Support Structure	Structural connectivity Load transfer between stator and hull
0215	Electrical Termination	Connection with electric plant
0216	PMG Cooling	Generator cooling (interfaces with 0560 Cooling)

An iterative design optimization of the active electromagnetic components of the PMG has resulted in a machine design that aligns with our targets, aside from concerns about the overall mass. The final machine specifications call for a large diameter air gap with a relatively short axial length, similar to generator designs used in previous C·Power StingRAY WECs. This is fortuitous as the general nacelle architecture lends itself to this form factor, obviating any need for extensive redesign of the hull. Select PMG characteristics are given in Table 11.

Table 11 – Select PMG characteristics.

Characteristic	Unit	Value
Maximum power output	kW	750
Air gap diameter	m	5.82
Air gap length (mechanical)	mm	6.3
Stator gross length	m	0.580

The PM generator design was optimized by Supplier 1's proprietary analytical design tool, and then modeled in 2D for transient finite element analysis. The ANSYS electromagnetics modeling facilitated the reduction in cogging with minimal impact to machine performance. The proprietary analytical design tool characterized the stator core loss, rotor eddy current loss, open circuit, and short circuit transients, shown in the machine datasheet. The resultant machine design is standards-compliant with specification IEC 60034-1 with optimized machine geometry for the StingRAY WEC application. ANSYS open circuit analysis is shown in Figure 24.

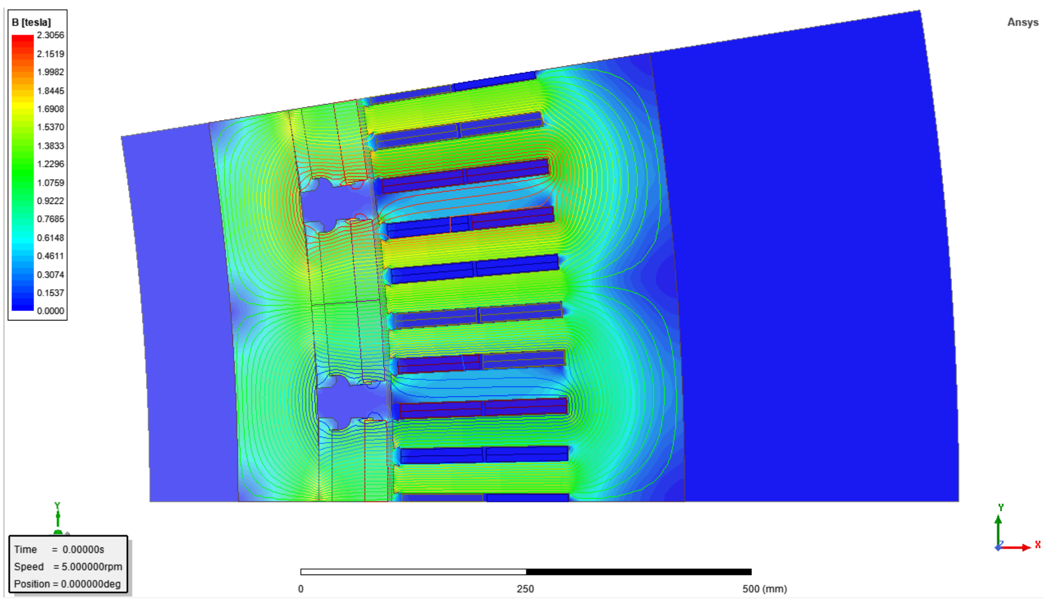

Figure 24 – Flux of optimized machine geometry of open circuit analysis

The thermal analysis was performed in 2D, show in Figure 25, with the assumption that no heat was transferred to the surrounding nacelle air, a potential yet conservative situation at the top of the nacelle where the ambient air temperature may equal the machine temperature. The model, which included the heat produced by the end windings with cooling fluid inlet temperature of 40 °C, resulted in a maximum stator core temperature of 69.3 °C. Under these worst-case conditions, the embedded cooling tubes provided ample cooling to keep the winding temperatures below 75 °C, the reference temperature of copper loses. This design meets the temperature class limits of the rated operation, per the standard.

Note that thermally the machine is rated for continuous operation at 6.8 rpm. Assuming some heat loss to the nacelle air, and nominal peak thermal load of stochastic (pulsed) wave power production, the cooling system demand is expected to be greatly reduced compared to the design assumptions. With adjustments to the design model in accordance with standards the designed number of cooling tubes could be reduced in the future. With embedded stator temperature sensors, the cooling flow control is optimized for highest

efficiency with respect to the sea state. The cooling design is in accordance with IEC code IC7A1W7 motors with machine mounted heat exchanger using a remote medium with self-circulation of the primary coolant.

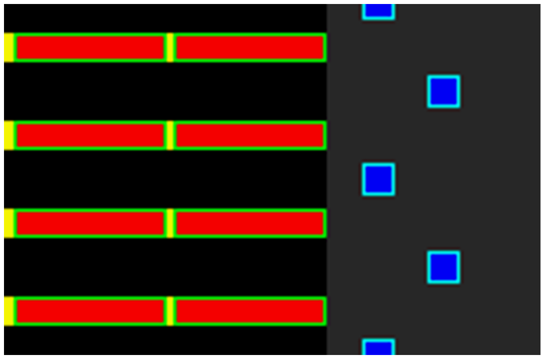

Figure 25 – Thermal model of stator back-iron

The mechanical FEA analysis of the generator design focused on maintaining the air gap under two load conditions; a 1g gravitation load case in which the structure is supported on the dock, and an extreme seas maximum load case. The basis for acceptability was contingent on the ability of the generator structural support to maintain 50% of the nominal mechanical air gap (i.e., 3.15 mm = 0.5 * 6.30 mm) under all load conditions. The fundamental structural design constrained the air gap reduction to ~1 mm in worst-case loading before magnetic forces were applied, and with unbalanced magnetic forces applied the air gap was not further reduced to 50% of nominal. The FEA analysis of deflection under maximum wave loading conditions is shown in Figure 26.

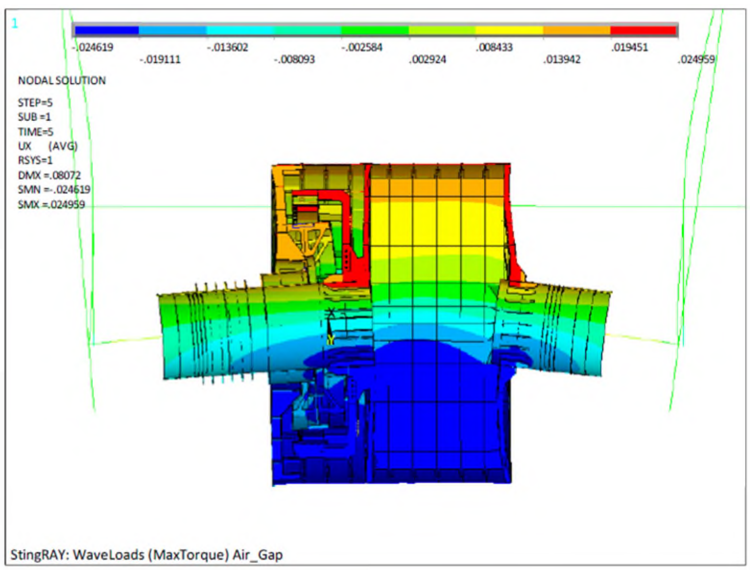

Figure 26 – Generator vertical deflection of structure under max wave loading, closure of 2.5 mm.

The generator structural design and FEA modeling performed by Supplier 1 was conducted in collaboration with Cardinal Engineering. For model validation various modeling parameters and scenarios were run to compare the two separate FEA software models. Parameters such as steel density and total mass of structural components were checked and corrected as necessary during the design development process. A comparison of air gap closures between the two FEA models is shown in Figure 27, indicating relative agreement between the two models (~20%).

The air gap and unbalanced magnetic pull values were calculated for the generator running open circuit and incorporated into the structural design analysis, noted in the generator final design report.

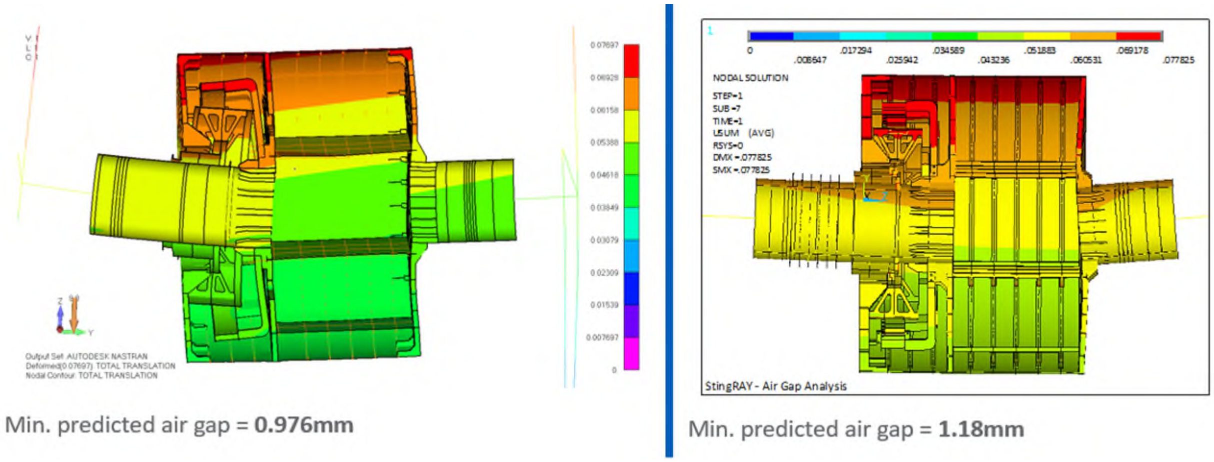

Figure 27 – Generator structural FEA comparison between Cardinal (left) and Supplier 1 (right).

The design criteria provided for machine efficiency were based on achieving set values of efficiency at fixed speed data points. The combined results of the fixed speed efficiency data points are shown in Figure 28. During design, overall efficiency in operational conditions was assessed by C·Power as estimated annual performance based on simulations in the 24 OSS.

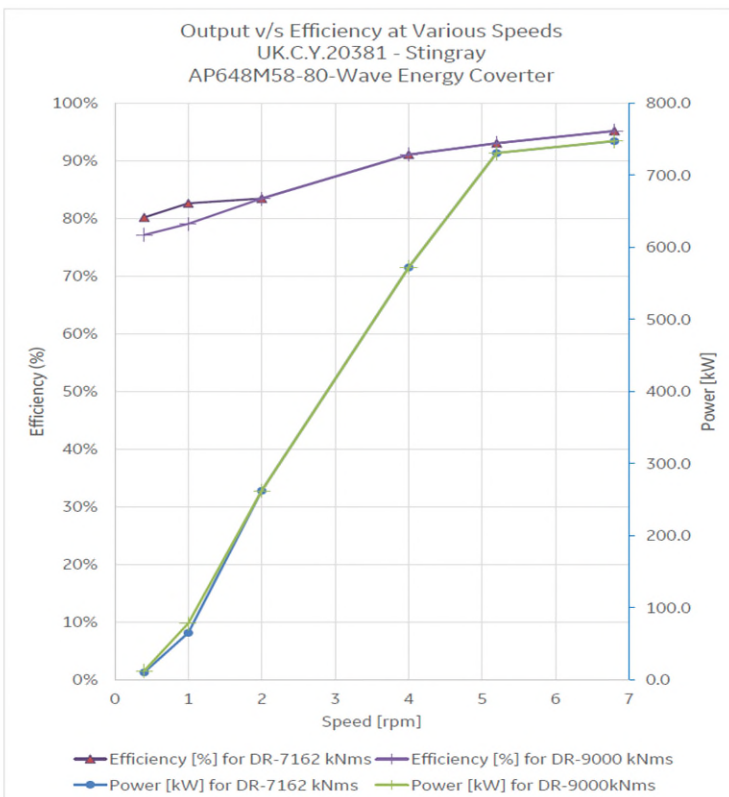

Figure 28 – Generator design criteria damping and efficiency.

6.2.2.2 PTO Mechanical Systems

The PTO mechanical systems designs are outlined below, with further details presented in the following documents:

- Main Bearings Design Reports (Appendix 13.16)
  - *DE-EE0008954 H3 0271 Primary Bearing Design*
  - *DE-EE0008954 H3 0272 Secondary Bearing Design*
- Idler Bearings 2D Drawings (Appendix 0)
  - *DE-EE0008954 H3 0275 Idler Bearing Plate 2D*
  - *DE-EE0008954 H3 0275 Idler Bearing Insert 2D*
- Shaft Seals 2D Drawings
  - *DE-EE0008954 H3 0280 Shaft Seal 2D* (Appendix 13.18)

The main bearings were designed by Liebherr. The primary and secondary bearings are both 4-point contact roller bearings (see Figure 29 and Figure 30). The primary bearing connects the nacelle tube to the shaft, and the secondary bearing connects the shaft to the starboard nacelle bulkhead. They resist radial, axial and moment loads, while permitting transmission of torque between the float and the PMG. The primary and secondary bearings are both steel (42CrMo4+QT), with outer diameters of 2.87 m and 3.57 m, respectively.

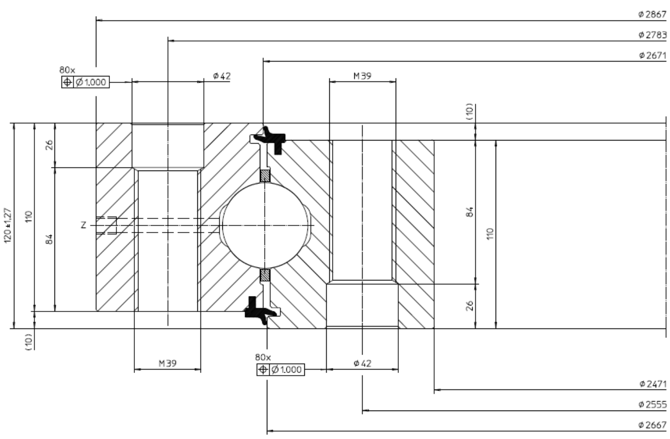

Figure 29 – Primary bearing.

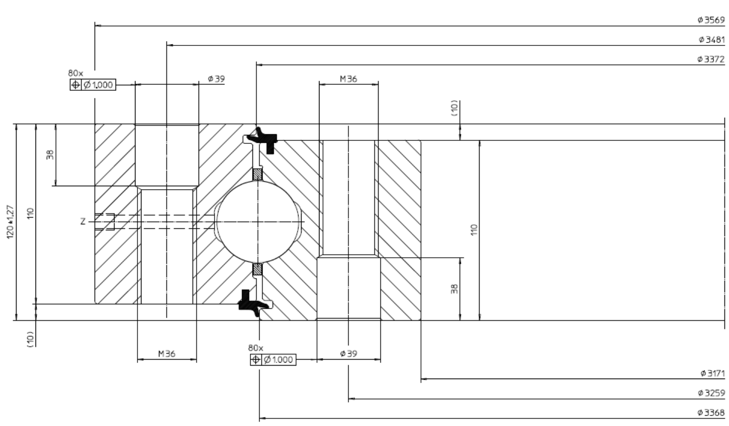

Figure 30 – Secondary bearing.

The idler bearings were designed by Vesconite (Figure 31). The idler bearings are sleeve bearings designed to support radial loads between the float arms and the nacelle tube. There is one idler bearing for the drive arm, and two for the idler arm. A stainless-steel running surface is integrated with the nacelle tube at each

idler bearing location. Each idler bearing consists of 12 segmented, curved plates which are fixed to the float arm hubs via nut inserts. Due to the segmented design the bearings can be installed and replaced without needing to remove the arms. Vesconite Superlube material is used for the idler bearings; this high load bearing material has negligible swell in water, while having low friction (coefficient of friction is 0.08) and low wear.

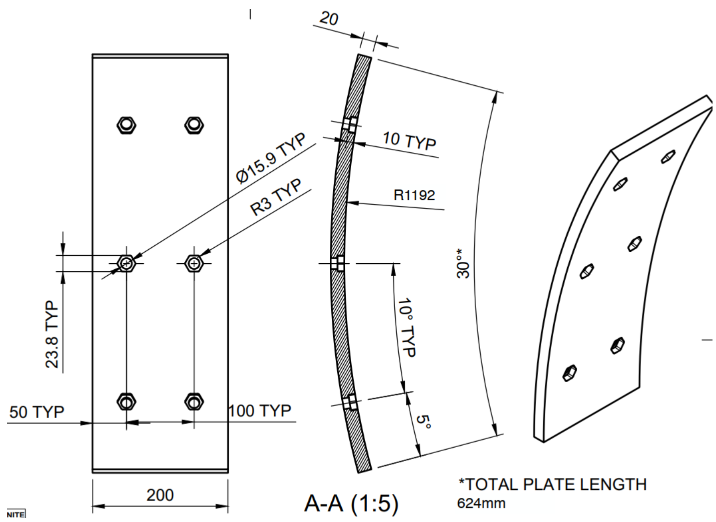

Figure 31 – Idler bearing segmented plates.

The shaft seals were designed by SKF (Figure 32). There are two sets of axial shaft seals, inner (between nacelle tube and shaft) and outer (between shaft and starboard nacelle bulkhead). Each shaft seal comprises a set of three redundant seals (red in the figure), to extend the lifetime and reduce risk. Seal carriers (medium gray in the figure) are installed onto flanges on the nacelle tube (inner) and starboard nacelle bulkhead (outer). Stainless steel running surfaces are integrated onto shaft flanges (green in the figure). The seal subassemblies can be assembled prior to installation and are located to allow for accessibility and reduced shaft deflection.

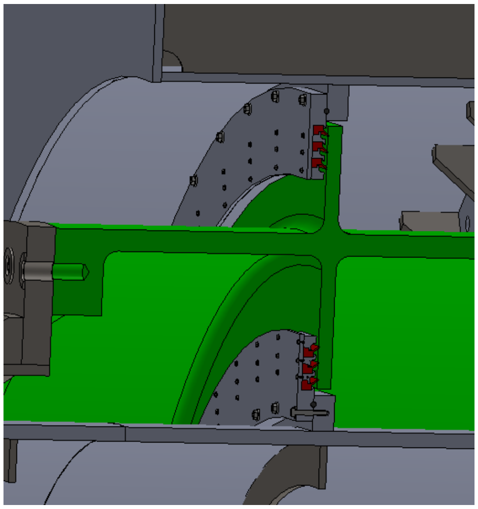

Figure 32 – Inner and outer shaft seals.

6.2.3 0300 Electric Plant

A large multinational corporation ("Supplier 1") was contracted for Electric Plant design, to be designed in parallel with the generator design. The electric plant design is outlined below, with further details presented in the following documents:

- Electric Plant Final Design Report
  - *DE-EE0008954 H3 0300 Electric Plant FDR* (Appendix 13.19)
- Electric Plant Functional Specification
  - *DE-EE0008954 H3 0300 Electric Plant Functional Specification* (Appendix 13.20)
- Electric Plant One-Line Diagrams
  - *DE-EE0008954 H3 0300 Electric Plant One-Lines* (Appendix 13.21)
- Electric Plant 2D Drawings
  - *DE-EE0008954 H3 0300 Electric Plant 2D Drawings* (Appendix 13.22)

Subsystems and functions are listed below in Table 12.

Table 12 – 0300 Electric Plant subsystems.

ID	**Element**	**Function**
0310	Motor Drives	Control and synchronize stator electric power production
0320	Drive Control	Control 0300 components and receive commands from 0400 SCADA Control and synchronize motor drives, energy storage, and grid-tie inverter Provide 0300 parameter data I/O to SCADA system
0330	Energy Storage	Short term energy storage, power smoothing for islanding.
0340	Grid-Tie Inverter	Control level and quality of power delivered to the grid Maintains system dc bus voltage level Produce voltage at output to support ancillary systems (islanding mode)
0350	Transformer	Step up voltage for electrical collection to grid
0360	Transformer Umbilical Connection	Interface transformer to umbilical cable
0370	Emergency Resistor & DC Chopper	Load for burning power in case of DC bus overvoltage
0380	Switchgear & Electrical Buses	All electrical breakers and disconnects of the Electric Plant DC link between Motor Drives and Grid-tie Inverter AC buses to transformer and station power
0390	Enclosures & Mounting	Mechanical integration into WEC Localized environmental control for hardware

Supplier 1 selected a low voltage, marine rated, motor drive configuration for controlling the StingRAY generator, for maintaining quality power flow to the grid, and to push power to and from the battery energy storage system (BESS). The low voltage motor drives are configured with two parallel AC-to-DC inverters for generator control, one DC-to-DC for battery energy storage converter (BESC), and a DC-to-AC grid converter. The configuration consists of an active front end (AFE) which is IEEE-1547 compliant for grid power quality with voltage source inverter (VSI) using pulse width modulation (PWM) for generating the regulated output voltage waveform. The design is comprised of three types of enclosure sections; power filtration, power conversion, and an incomer/cooler/controller cubical, all which are mounted on a common skid, shown in Figure 33.

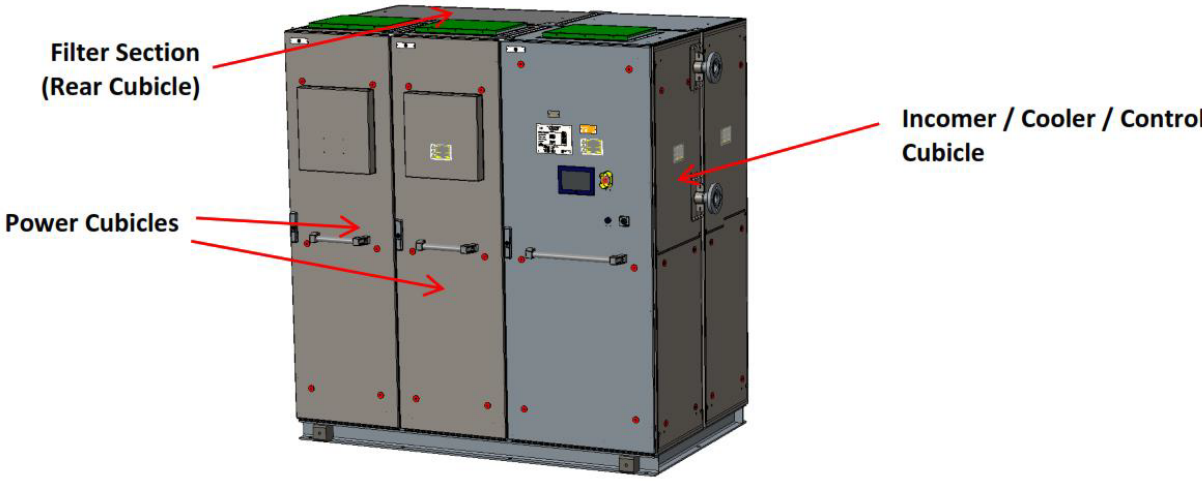

Figure 33 – Electric plant marine enclosures.

The BESC is configured for the bidirectional DC power flow from the BESS, controlling the power flow from the common DC bus to DC at battery voltage. The BESC is paired with controls and battery management system to safely maintain a state of charge appropriate for the sea state while allowing energy to be pulsed in and out of the batteries. During each wave, power generated at a level above the rating of the 375 kVA transformer is sent to the BESS. Then during the low power time of the wave, BESS power is pushed to the grid. The net effect is power smoothing. The amount of power smoothing that the BESS provides is based on controls and with respect to the sea state. At low sea states, for increased system efficiency, the BESS can provide power directly to the 0540 Station Power systems via a smaller inverter to power all StingRAY on-board loads.

The motor drive control hardware is controlled by running proprietary software developed on Supplier 1's programming tool. The communications with StingRAY SCADA will be via a MOBUS TCP/IP interface with ethernet connections to the local operator panels of BESC and grid converter. The motor drive can also be connected directly to Supplier 1's system via ethernet for remote electric plant monitoring and data analysis by the Supplier 1 service team. The motor drive control includes internal cooling control, active front end with PWM strategy control, machine torque control, and alarm handling. The motor drive controller architecture is shown in Figure 34.

The BESS system is an Orca Energy Storage System (Orca ESS) made by Corvus Energy. The Orca ESS is a large-scale modular marine grade lithium-ion battery energy storage product designed to marine industry standards for hybrid and all-electric vessels. The Orca ESS schematic is shown in Figure 35 and enclosure layout shown in Figure 36.

The Orca ESS is designed to have high gravimetric and volumetric energy density, high levels of safety and reliability with true cell-level thermal runaway isolation, integrated TR gas exhaust system, efficient thermal management, enhanced EMI immunity; all features which are ideal for StingRAY WEC application. The systems are also modularly designed for reduced IO&M and the ability to match the Orca ESS design rating to the specific application. The Orca ESS is also equipped with multiple levels of safety systems covered by the battery management system (BMS), thermal runway design, and mechanical rack integration. The BMS alarms and protects the batteries by monitoring all temperatures, voltages, state of health (SOH), state of charge (SOC), and uses advanced algorithms to compute maximum allowable charge and discharge then limits current values during operations. The BMS data is integrated into the control algorithms of the motor drive controller to manage the cyclic power flow through the BESC during real seas operations.

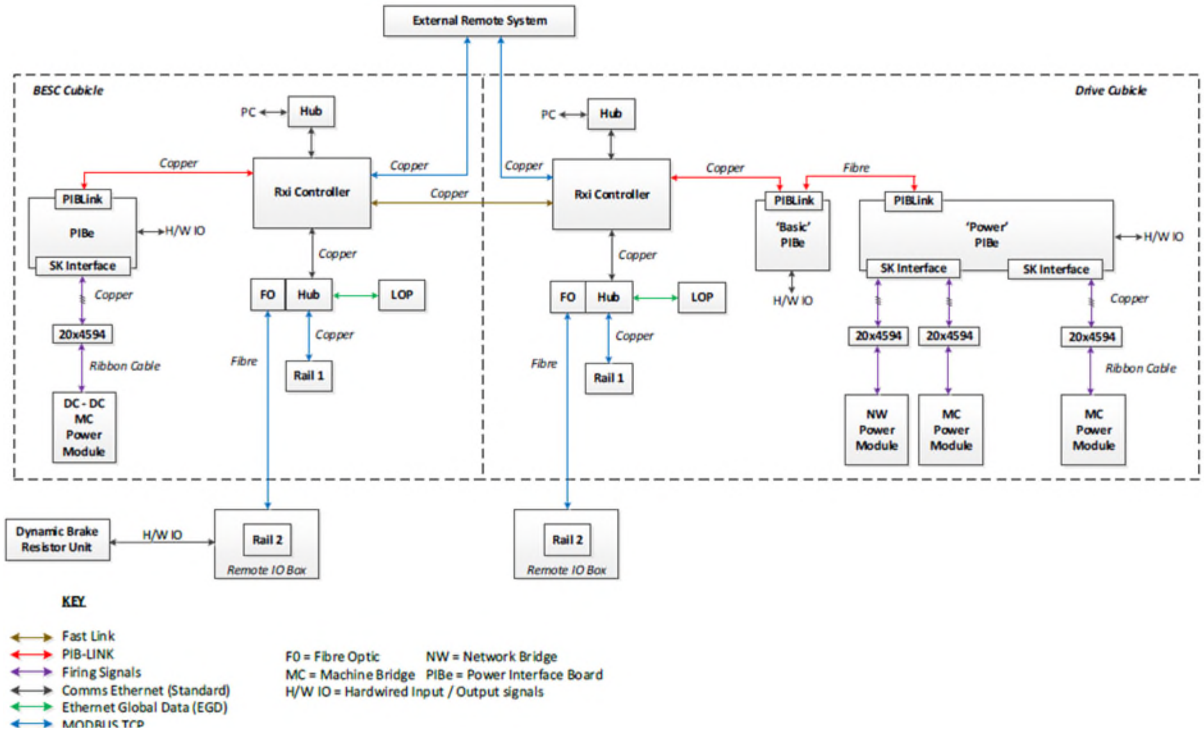

Figure 34 – Motor drive controller architecture.

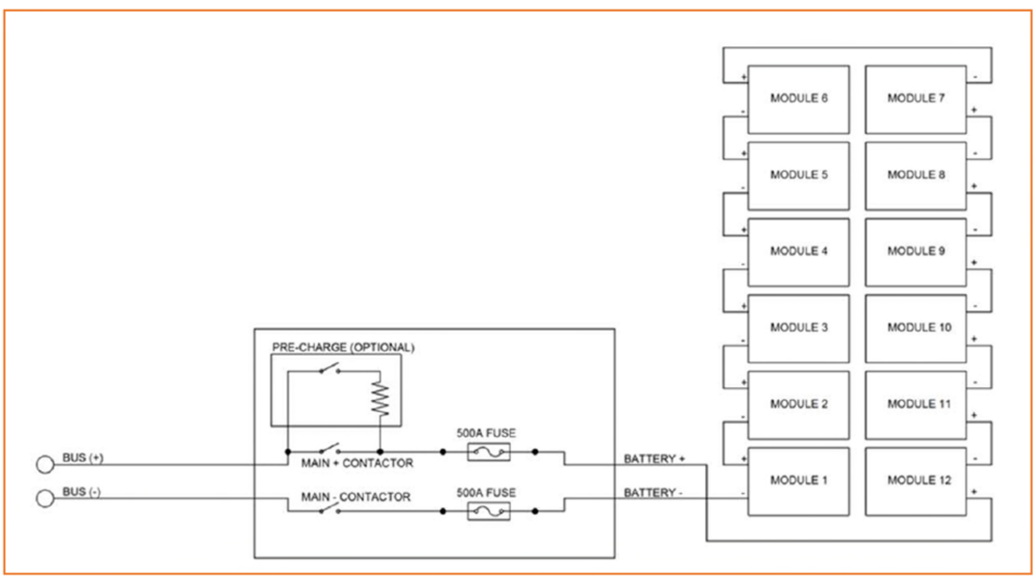

Figure 35 – Corvus Energy Orca Energy Storage System modular schematic.

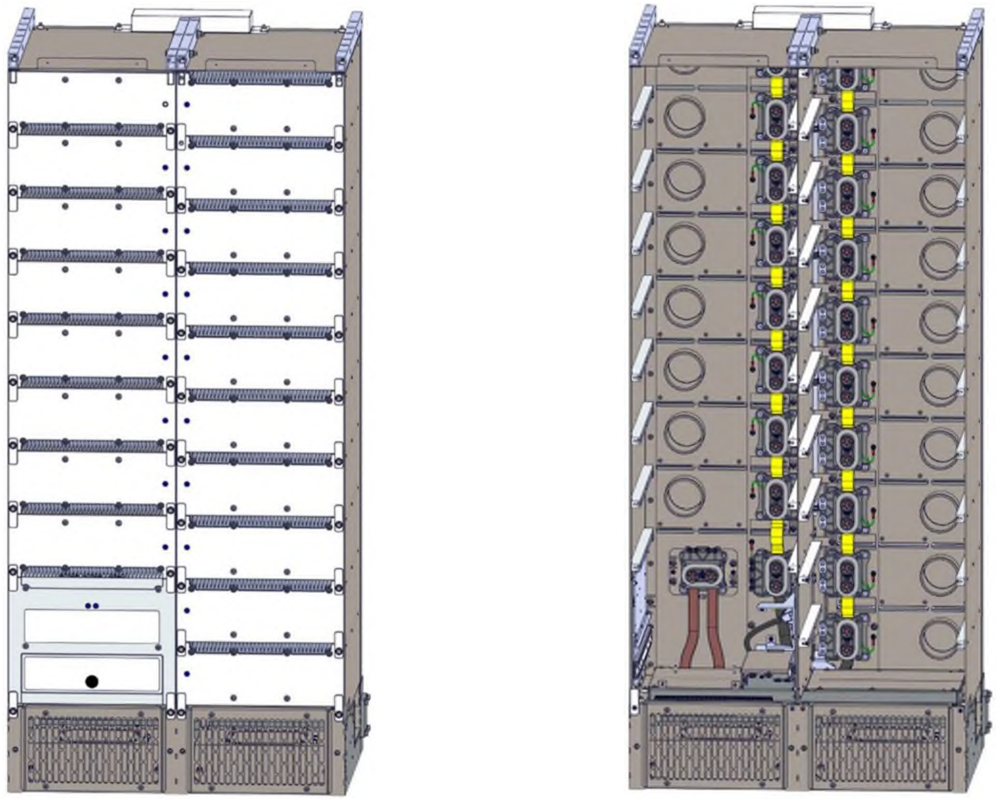

Figure 36 – Corvus Energy Orca Energy Storage System modular enclosure layout.

The grid tie inverter is designed in accordance with IEC 61800, and with the ability for grid following and forming to meet the IEEE 1547 requirements for grid quality of distributed energy sources. The grid tie inverter, converter plus filtration, pulls power from the common DC bus which is protected from overvoltage (OV) by a DC Chopper. The DC chopper limits the bus voltage below 1150 VDC by discharging power through a braking resistor.

The grid side of the inverter is connected to a 375 kVA marine grade cast resin transformer (CRT). The transformer is sized for nominal peak power production which reduces capital costs, increases the WEC capacity factor, and reduces demand for upstream electrical collection components (e.g., umbilical and grid connection ratings). This is made possible by the utilization of the BESS. The switchgear protects all the electrical components from fault contingencies, designed to avoid any cascading faults. The switchgear is also a safety controller integrated to allow for WEC islanding. Islanding mode is used to provide power to on-board equipment in case of a loss of grid power. Where-as normally all on-board systems would be powered from the grid connection. Shown in Figure 37 is the electric plant on-line with configuration and interface with the 0540 Station Power system.

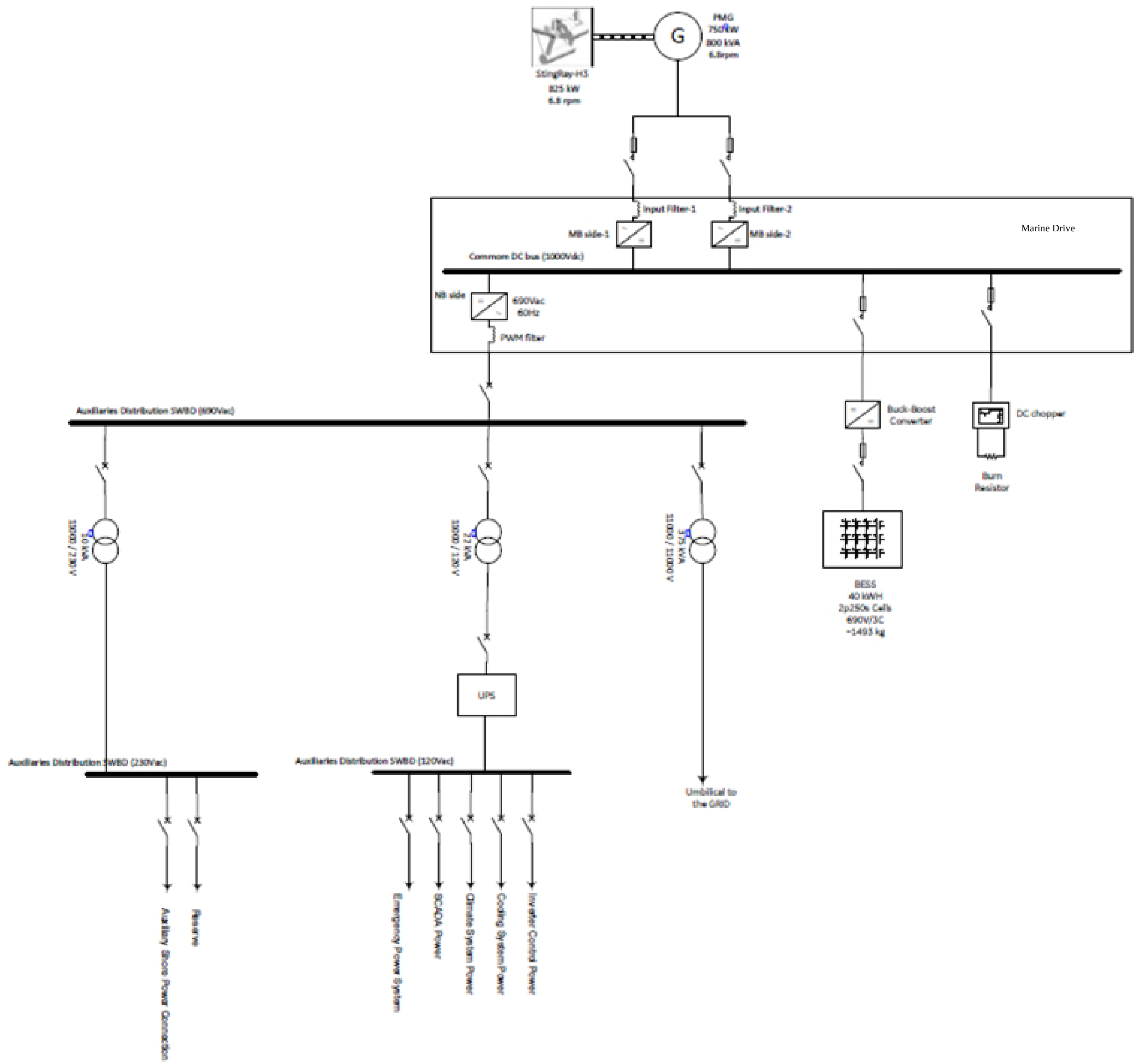

Figure 37 – Electric plant one-line configuration.

6.2.4 0400 Supervisory Control and Data Acquisition

The Supervisory Control and Data Acquisition (SCADA) system was developed by C·Power, with support from a team at NREL. Subsystems and functions are listed below in Table 13.

Table 13 – 0400 SCADA subsystems.

ID	Element	Function
0410	Sensor Network	Collect performance, loads, and other data
0420	I/O Modules	Convert analog sensor signals into digital data
0430	Control Hardware	Collect, condition, and process sensor data Calculate and issue PTO and cooling system commands
0440	Human Machine Interface (HMI)	Operator interface with SCADA
0450	Communications	Communication between WEC and shore
0460	Data Server	Store data

ID	Element	Function
0470	Software	Programming environment for SCADA
0480	Alarms, Diagnostics, & Fault Recovery	Automated condition monitoring Issue alarms & initiate corrective actions
0490	Enclosures & Cabling	Mechanical integration into WEC Localized environmental control

The SCADA system serves as the central nervous system of the H3p WEC. The primary functions of the SCADA system are to: collect, store, and transmit performance, loads, and other data; calculate and issue PTO and cooling system commands; provide communication between WEC and shore; and alarms, diagnostics, and fault recovery.

Data acquisition will be handled by a custom MODAQ (Modular Ocean Data Acquisition) system, developed by NREL. The MODAQ system utilizes National Instruments (NI) CompactRIO hardware, and a similar system was developed previously for another C·Power WEC.

The H3p MODAQ consists of four enclosures, which are indicated by numbers 1 to 4 in Figure 38. There is one main cRIO unit in the control room, whose configuration is shown in Figure 39 (labelled as unit 1 in Figure 38). There are two remote cDAQ units located on either side of the WEC to reduce wire run (units 2 and 3 in Figure 38). A third remote cDAQ unit is inside the float for load monitoring system (unit 4 in Figure 38). The three remote cDAQ units all have the same configuration, which is shown in Figure 40.

The main cRIO unit interfaces with Supplier 1's PMG controller, safety & emergency systems, pump control and monitoring (for both cooling and bilge), climate control, IMU, and GPS. The three remote cDAQ units are exclusively for the load monitoring system.

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 includes: PTO position encoders, 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, cooling water level, pressure, flow, and temperature, stator air gap measurement, seal gap measurements, bilge pump status, structural strain gauges, GPS position, WEC heading, vibration measurements, mooring tensions, electric plant voltages and currents, and stator temperatures. All instruments will undergo a documented calibration process before and after data collection to ensure high data accuracy.

The load monitoring system was designed to verify structural loading and to estimate PTO torque during operation (see Figure 38). The system consists of fiber optical and foil strain gauges to improve system reliability during sea trials. Sensor locations were selected based on structural FEA model results.

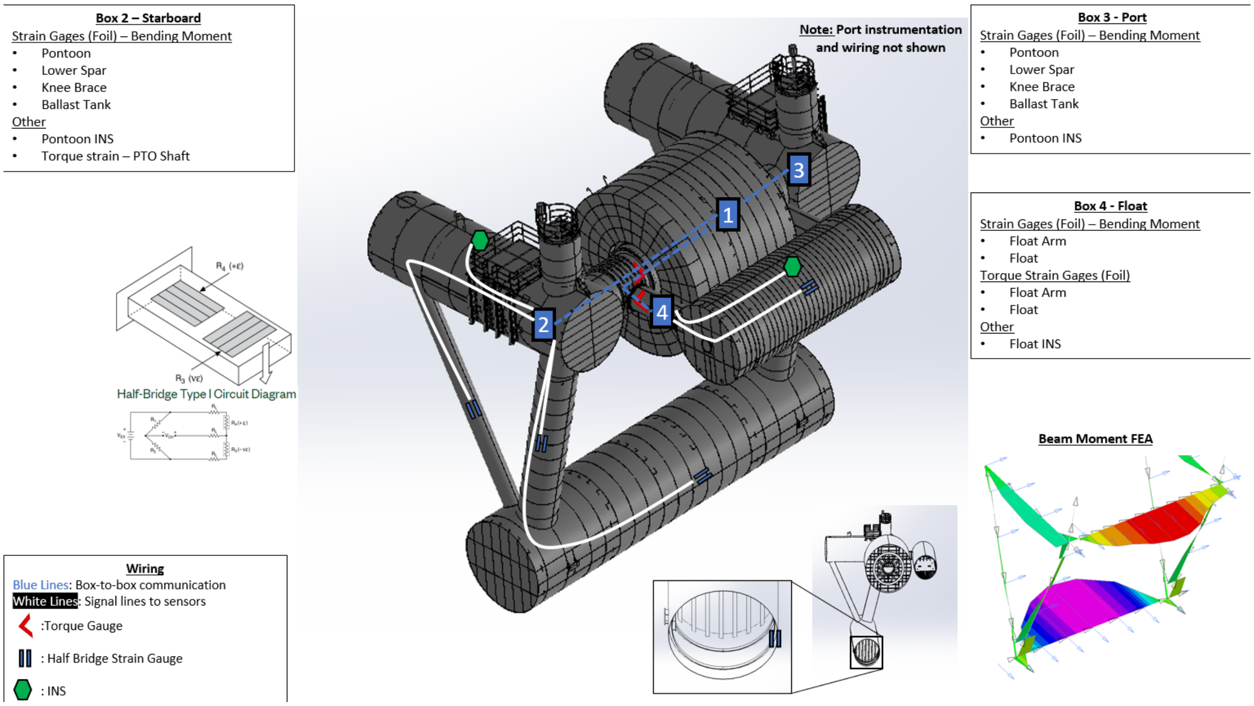

Figure 38 – Load monitoring system, and MODAQ enclosure locations.

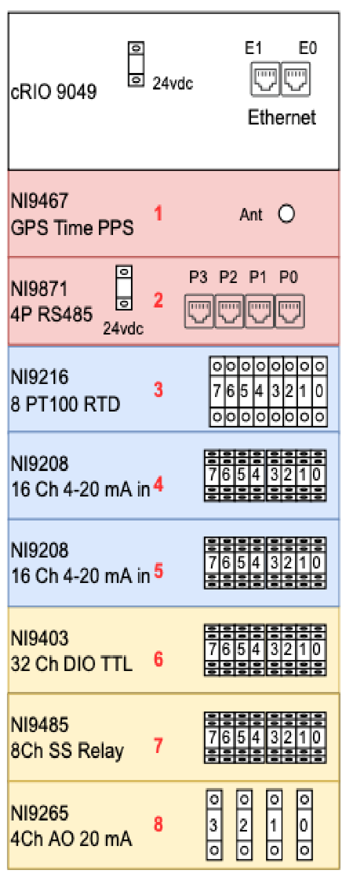

Figure 39 – MODAQ cRIO unit configuration.

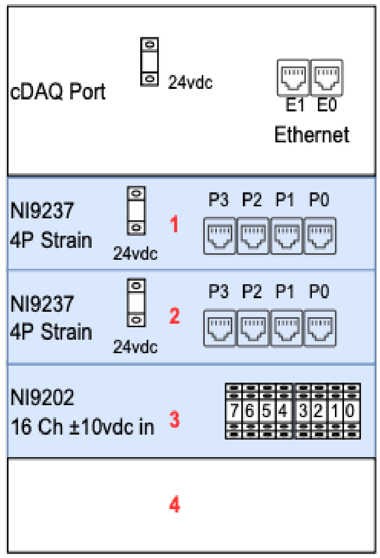

Figure 40 – MODAQ cDAQ unit configurations.

The SCADA system 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. Data will be quality controlled, processed, and stored (see Figure 41). Redundant data storage includes local WEC server, MODAQ cloud, and a land-based server (at C·Power offices). All data will be first stored to disk as calibrated time series trial data in SI units, in NI's *tdms* file format, on MODAQ's local storage. Data will be saved at the data rate specified in the tag list for each signal. Data will then be uploaded to the cloud for real time data visualization on the web server. Data on the cloud will be copied to the land-based server for further analysis within MATLAB.

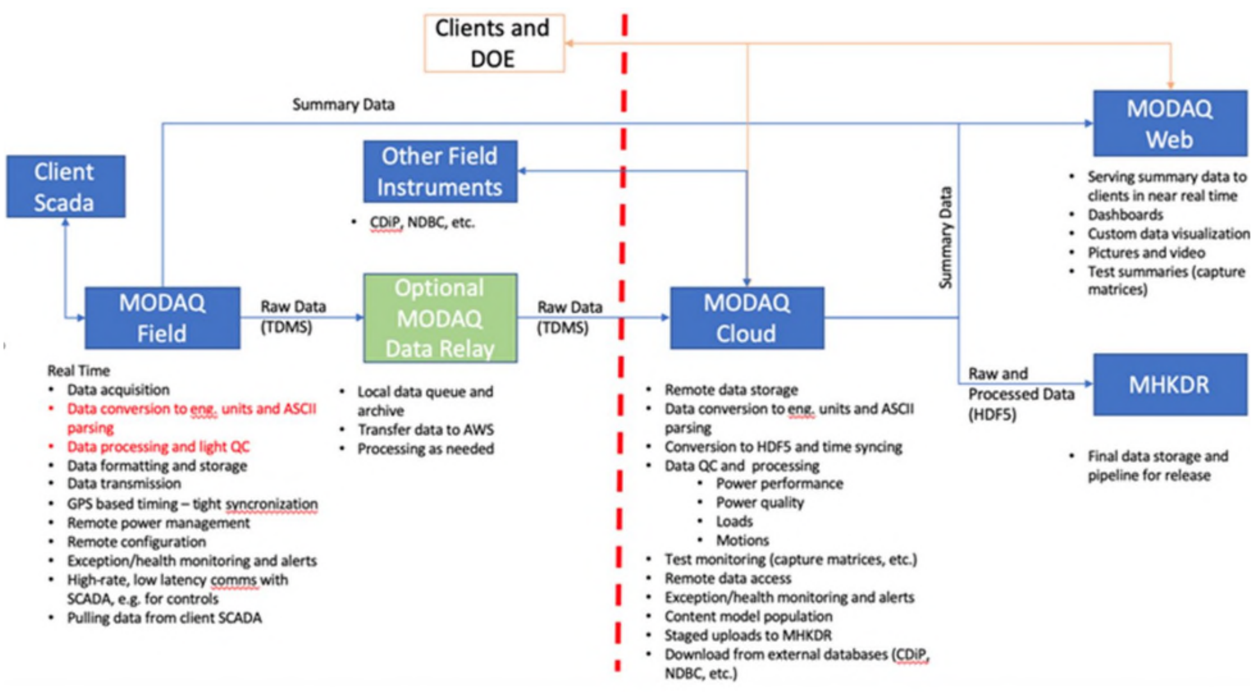

Figure 41 – SCADA data flow.

The Human Machine Interface (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 PTO, as well as the utility to start and stop data recording manually or automatically. The HMI allows for web-based display of processed data, as well as display and control via Ethernet.

The control function of SCADA provides safe control and oversight of the PTO, which is comprised of a direct drive generator and its supporting electric plant equipment, as well as the cooling systems. Operators are able to adjust all control parameters through the SCADA system to achieve desired test configurations. Low-level control of the PTO is accomplished by the electric plant motor drive, with high level strategic commands issued by SCADA. SCADA will also calculate and command the operation of the cooling system in order to minimize the total energy consumption of the system.

The communication network provides a high-speed data connection between the H3p device and operators and engineers. Several diverse and redundant communication links make up the communications network providing high availability in even the most adverse conditions. All connections to the H3p SCADA system require an authorized password before a connection can be established. Predefined user authorization levels will allow for different levels of functionality.

A short-range Wi-Fi radio will be located onboard H3p to allow operators onboard or on a nearby support vessel to connect to the SCADA system. The high bandwidth Wi-Fi will allow full SCADA functionality with no data rate limitations. Additionally, there will be hardwired Ethernet connections located on top of the spar platform and within the control room. These connections will be secured behind physical locks and will also require authorized password access.

Fiber optic channels in the umbilical and subsea cable transfer data from the WEC to the shore station. This WEC-to-shore communications is the primary link to the H3p SCADA, alarms, safety & emergency, and surveillance systems. High-speed fiber modems at both ends of this fiber optic link will convert the data to a standard Ethernet connection. This high bandwidth solution will allow full SCADA functionality with no data rate limitations.

A smart relay with ethernet is onboard H3p to allow operators to remotely power cycle SCADA, local Wi-Fi, network switches and other sub controllers (e.g., PTO controller).

In addition to the fiber channels, an industrial Ethernet radio will provide a backup data link from H3p to the shore station. This type of mid-range Ethernet radio will have a limited bandwidth (100-500 kbps) and will support a reduced SCADA user experience, limited to critical data updates only.

In addition to the fiber optic and Ethernet radio communication paths, there is an additional path that uses commercial 3G/4G cellular coverage for redundancy. Coverage may be available at the deployment site and can provide a direct link from H3p to C·Power using a commercial cellular network.

Automated alarming allows the SCADA system to rapidly respond to unfavorable conditions and 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.

The SCADA system will have alarms behavior and threshold information based on the C·Power specified tag list. The alarm utility will detect alarm events for every configured alarm at each time step. All signals are defined at three alarm levels: nominal, alert, and critical. Critical alarms can be configured to initiate a controlled shutdown.

6.2.5 0500 Auxiliary Systems

The Auxiliary Systems include all systems which support the WEC and PTO power production. Subsystems and functions are listed below in Table 14.

Table 14 – 0500 Auxiliary subsystems.

ID	Element	Function
0510	Ballast Control	Facilitate ballast operations
0520	Safety & Emergency	Automated condition monitoring and alarms
0530	Climate Control	Regulate environmental conditions in designated spaces
0540	Station Power	Power distribution to WEC systems
0550	Aids to Navigation	Alert mariners of the WEC's presence in the open ocean
0560	Cooling	Supply coolant to generator and climate control, reject excess heat
0570	Bilge	Collect and remove water from within hull compartments
0580	Surveillance	Monitor status of WEC/components, remote inspections

6.2.5.1 0510 Ballast Control

Cardinal Engineering was contracted for design of the ballast control system, along with the hull structure and bilge. The ballast control design is outlined below, with further details presented in the design documents listed for the hull (see section 6.2.1).

The ballast control system includes all hardware necessary to control the ballast. Ballast compartments are integral elements of the hull structure, and ballast control includes pipes, vents, and valves. Pumps and air compressors will be on board service vessels during ballasting operations.

The seawater variable ballasting system consists of two completely independent systems, one for the port ballast tank and one for the starboard. Each system consists of 4 pipes leading down from the upper spar deck to the ballast tank below: sounding tube, tank vent, tank fill/discharge, and stripping pipe (see Figure 42).

All seawater variable ballast filling will be performed above water by a service vessel. The service vessel will either pump seawater into ballast tanks or use compressed air to purge the tanks. All ballast control connections are on top of the port and starboard upper spars. When the WEC is in operational orientation, the connections are reached by service personnel climbing the ladder to the spar tops after boarding at the pontoon landing. When the WEC is in its towing orientation, the connections are approximately 5 ft above the water surface and can be accessed from a service vessel.

The tank fill/discharge is the primary water line and is a 6-inch pipe starting at a flanged connection above the upper spar deck leading down to the lowest point in the ballast tank to a rose box.

The stripping pipe allows the last bit of water to be removed as the WEC rotates into towing orientation. It is a 2-inch pipe starting at a flanged connection above the upper spar deck leading down to the lowest point in the ballast tank to a rose box. The stripping line terminates inside the tank at the lowest point in the towing orientation.

The tank vent/blowdown tube is an 8-inch pipe starting at a flanged connection above the upper spar deck leading down to the ballast tank top (bilge deck) located in the lower spar. A large diameter is needed to equal the in/outflow of the water to prevent air locking. A flanged float check valve is attached during seawater ballast filling and normal operations. For de-ballasting, the check valve is removed, and an air manifold is bolted to the flanged connection.

The sounding tube allows for physical measurement of the water depth in the ballast tank. The sounding tube is a 2-inch pipe with a bronze flush plug at the bilge deck (within the lower spar) leading down to a striker plate at the ballast tank’s lowest point. The bottom of the sounding tube is in the lowest point in the operational orientation.

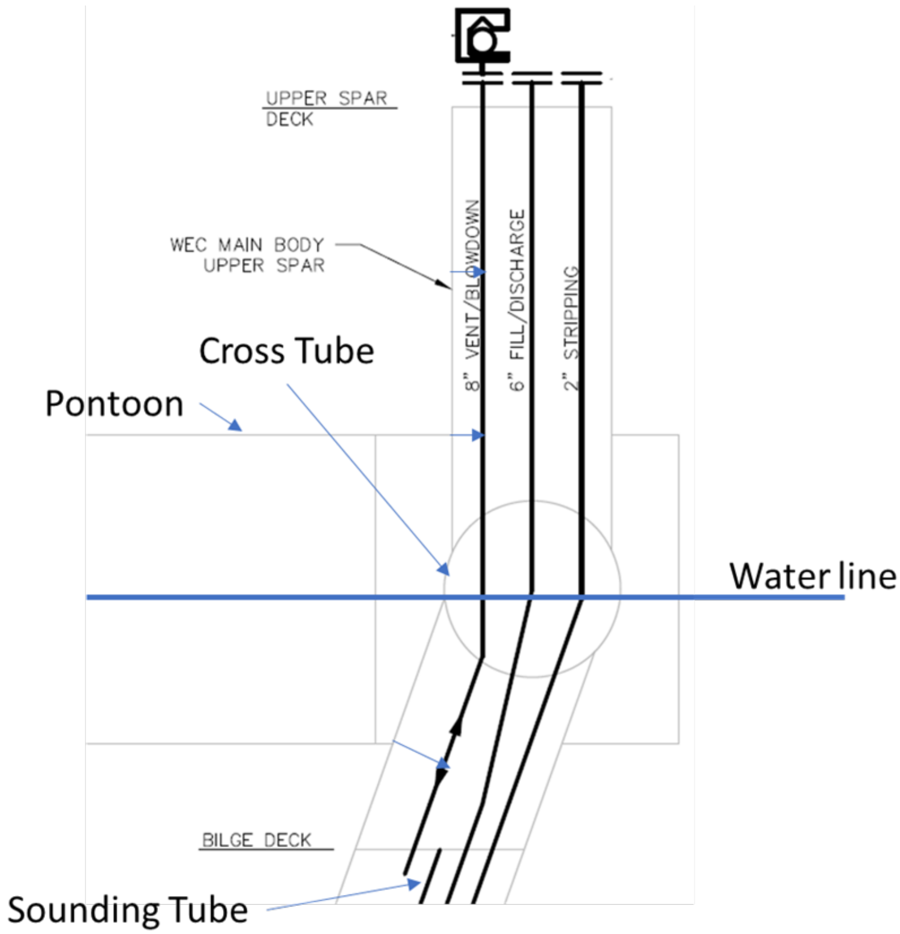

Figure 42 – Ballast control system schematic.

6.2.5.2 0520 Safety and Emergency

The safety & emergency system is a standalone system designed for exceptionally high reliability. It will identify and report on all unsafe conditions which 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 H3p for smoke/fire, temperature, humidity, equipment failures, manually activated alarms, and access interlock openings. Data from the safety and emergency system will be shared with the SCADA system for collection purposes. Air quality for safety is checked by a standalone handhold monitor when entering and in the WEC.

Subsystems and functions are listed below in Table 15.

Table 15 – 0500 Auxiliary subsystems.

ID	Element	Function
0521	Fire Protection	Automated fire monitoring, alarm, and suppression
0522	Flooding Alarms	Automated flood monitoring and alarm
0523	Evacuation Alarms	Automated evacuation alarm
0525	Access Alarms	Automated access alarm (provides notification of any hatch/enclosure access)
0526	Emergency Disconnect	Hardwired safety system connected to various WEC systems
0527	Safety Controller	Oversight of all safety and emergency systems Communicates with SCADA

ID	Element	Function
0528	Safety Communications	Multiple path communication to the safety controller (including direct fiber to shore and access through SCADA 0450)
0529	Emergency Lighting	Provides light in emergency

6.2.5.3 0530 Climate Control

The climate control system comprises ventilation, air dryers, and heat exchangers to maintain required environmental conditions.

Three marine air conditioning units installed in the port side of the nacelle cool the air; the port side houses electric plant and other sensitive equipment. The 0560 Cooling system provides cooling water and removes excess heat. The air drying of the AC units is supplemented by a dedicated dehumidifier.

While the WEC is deployed, service personnel will enter the WEC for maintenance, repair, and inspections. Ventilation is provided for personnel onboarding by blowers and ducting, providing outside air to purge the occupiable spaces and maintain required air turns. Separate ventilation systems are provided for each sealed spaced (i.e., nacelle, port pontoon, starboard pontoon), similar to the bilge system (see Figure 43).

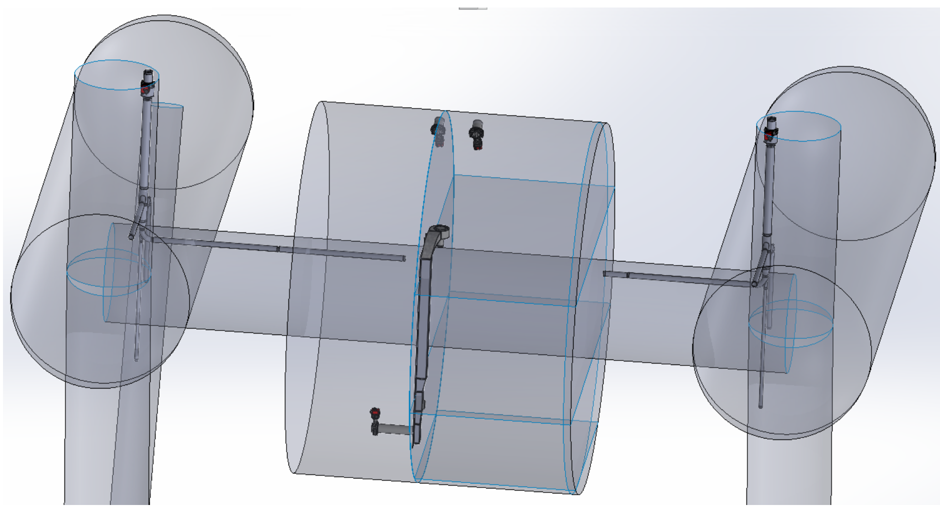

Figure 43 – Three distinct ventilation systems provide outside air to purge.

6.2.5.4 0540 Station Power

The station power system is responsible for electrical distribution to all on-board WEC loads. Station power has multiple possible power inputs for redundancy, including WEC generated power from the 0210 PMG, grid power from the 0810 Umbilical Cable, stored power from the 0330 BESS, and power from an attending vessel.

Anti-paralleling within the electrical distribution system is handled by Automatic Transfer Switches (ATS) that allow for prioritization of electrical resources to provide safe and readily available power to all required loads. A secondary ATS allows for automatic selection of power from either a secondary bus from BESS or an attending vessel based on the phase of system operation and the available energy sources. Both are secondary to the primary transfer switch between the secondary switch and the 480 VAC supply from the 0300 Electric Plant and 0810 Umbilical grid connection (see Figure 44). The interface between 0800 Electrical Collection and 0300 Electric Plant is necessarily outside the scope of the 0540 system except to point out that 0540 Station Power will present itself as a load to these systems and will not feed power back to either system.

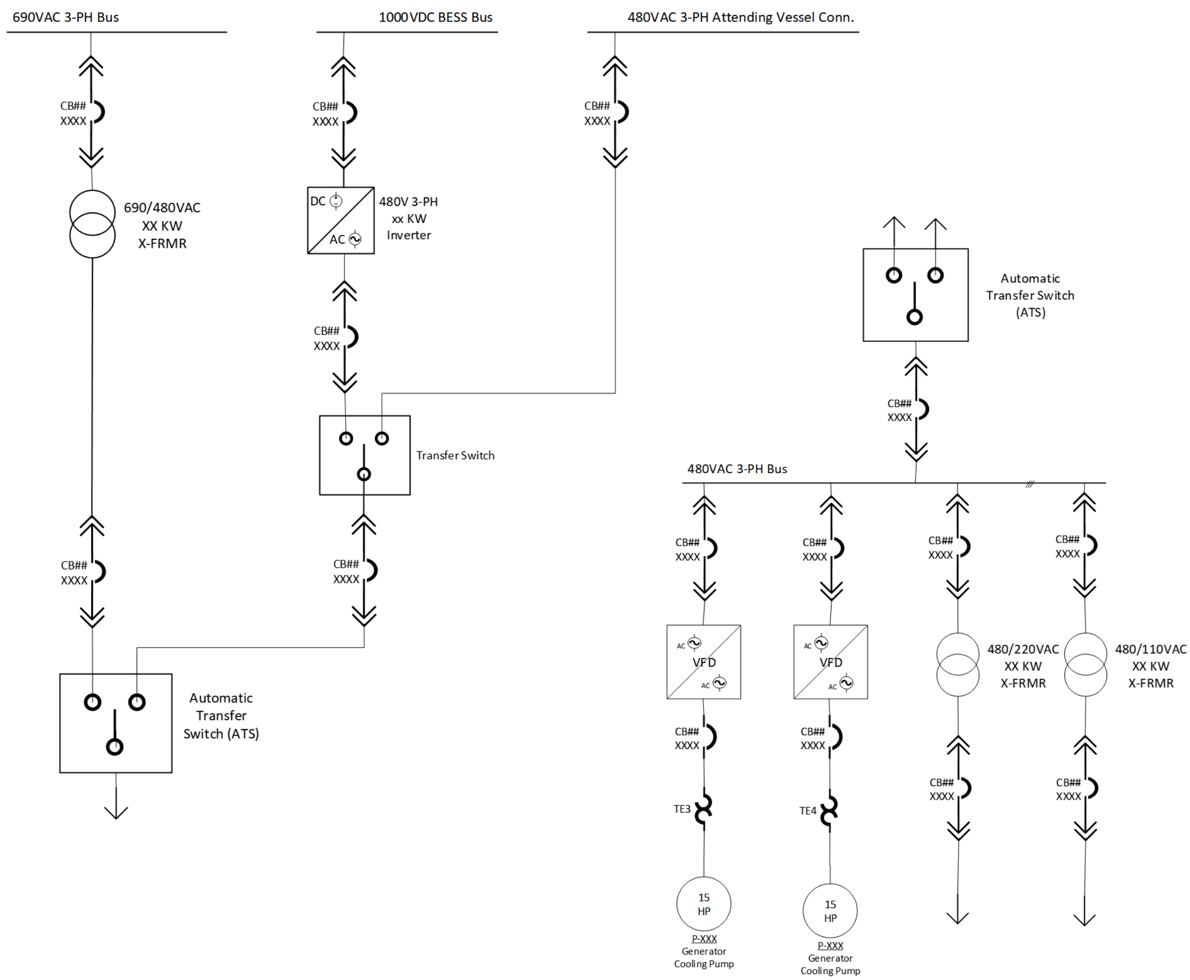

Figure 44 – Station power multiple power sources (left), 480 V 3-phase distribution bus (right).

All station critical loads have individual uninterruptable power supplies sized for their individual load requirements. These power backups will be able to support transient (< 1 min) outages that may occur during transfers between the myriad load sources for the system. During periods of extended grid disconnected, non-generating, non-vessel attended WEC operation, power will be provided for all system through an inverter connected to the secondary bus system on the BESS.

Transformers, inverters, and DC power supplies are sized to accommodate the designed bus loads but also to allow for the utilization of COTS transfer switches (see Figure 44).

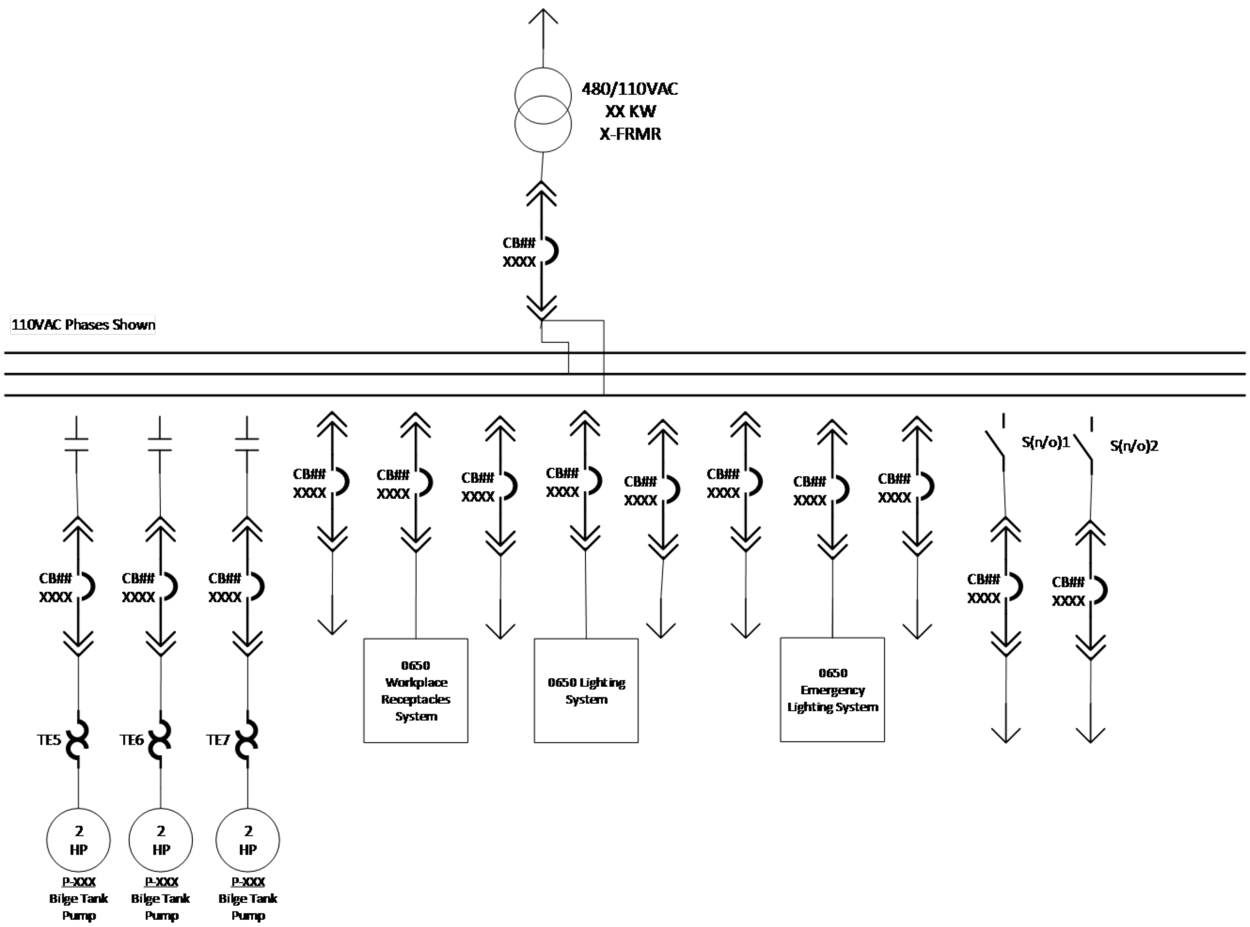

Figure 45 – 110 V station power distribution bus.

Loads within the 0540 Station Power are individually enumerated and protected from both thermal and overcurrent events on a per load basis. VFDs are deployed to optimize the pump mechanical delivery while maintaining the lowest practicable station power loads. Draw outs are also indicated (see Figure 45) to ensure that safe lock out procedures are available for all loads and components.

All loads are controllable through SCADA at an individual or system level. All switching components will be interfaced with and monitored through the SCADA system and will be capable of being controlled locally or through the SCADA interface. Additionally, all switching units will be capable of local lock out or draw out capabilities to prevent undesirable conditions of operation during maintenance and verification and validation (V&V) testing. Finally, the ATSs are intended to be actuatable based on internal state logic and will not require SCADA input to affect a transition in load sources but will allow SCADA to affect these transitions if desired.

6.2.5.5 0550 Aids to Navigation

0550 Aids to Navigation serves to alert mariners to the presence of the WEC in the open ocean, and includes black ball day shapes, low-intensity flashing lights (with bird-friendly wavelengths), and an AIS (Automatic Identification System) transceiver. Additional elements will be included if needed, to satisfy Coast Guard compliance and PWS permitting requirements.

6.2.5.6 0560 Cooling

The cooling system provides cooling water to the PMG, the electric plant motor drive cabinet, and the climate control system. Pumps, piping, manifolds, and valves provide distribution and flow control. The cooling system design uses hull-mounted keel coolers for the fresh water to saltwater heat exchange. There are two separate systems (see Figure 46), but actuated valving (not shown) provides redundancy by joining the two systems in the event of a pump failure.

Flow control is provided by actuated valves and VFD pump throttling, which is managed by 0400 SCADA system. Propylene Glycol is added to the freshwater cooling fluid to prevent freezing and inhibit bacterial growth and corrosion.

Duramax demountable keel coolers were selected for ease of maintenance and for expandable configurations. Internal piping is steel mains with PEX tubing for distribution to HVAC and PMG manifold. Connections are welded, Class 150 flanges, or NPT fittings. Cooling system details are depicted in Figure 47.

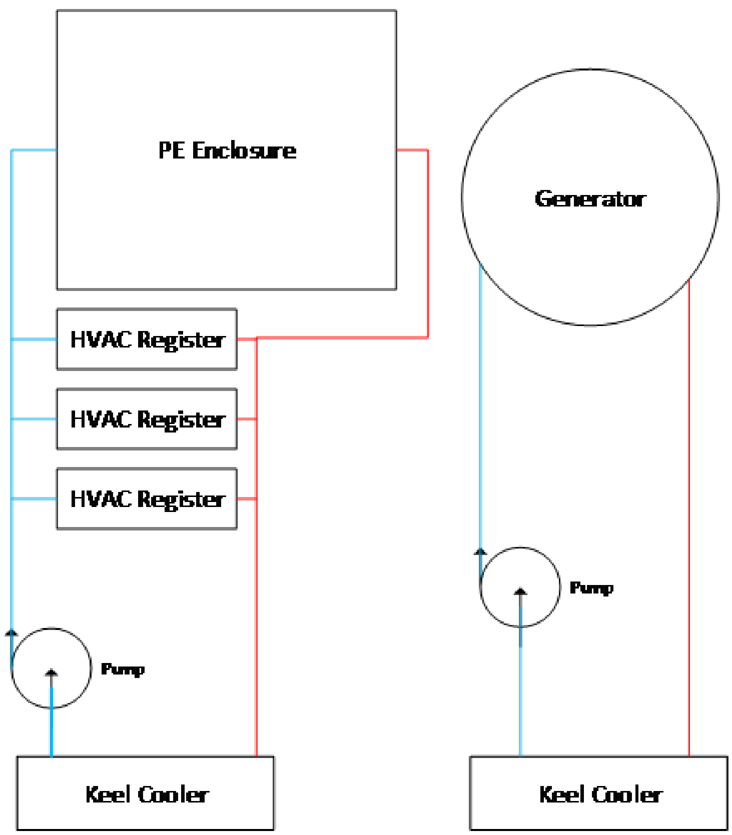

Figure 46 – Cooling system schematic.

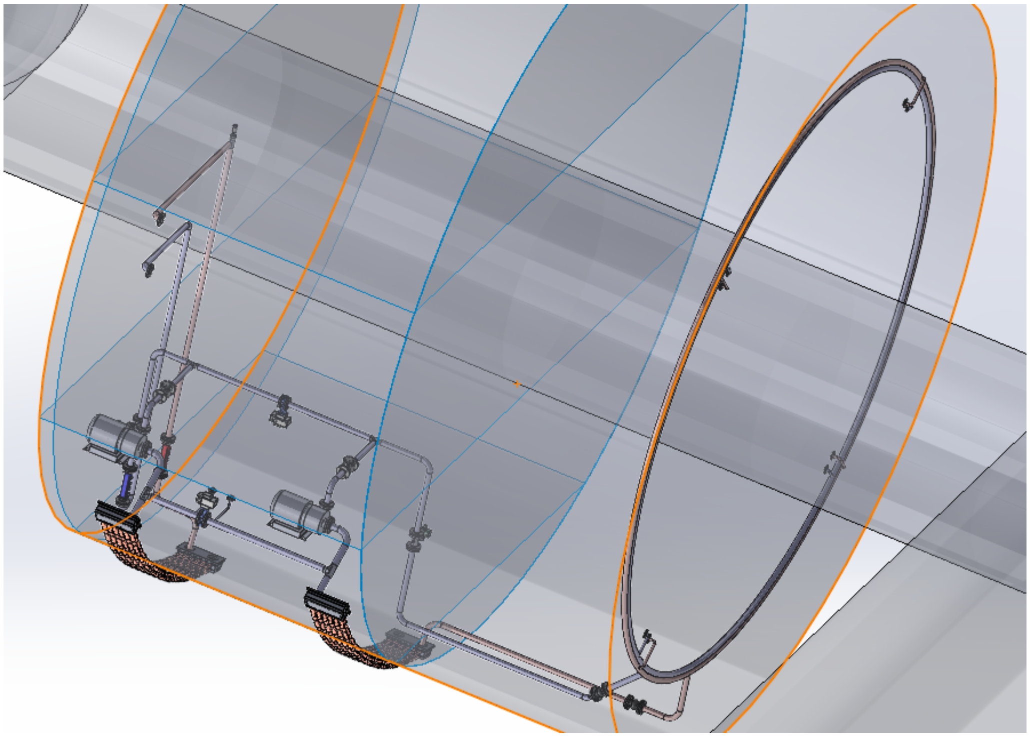

Figure 47 – Cooling system detail.

6.2.5.7 0570 Bilge

Cardinal Engineering was contracted for design of the bilge system, along with the hull structure and ballast control. The bilge design is outlined below, with further details presented in the design documents listed for the hull (see section 6.2.1).

Due to the watertight compartmenting of the hull, there are separate bilge systems for the nacelle and each of two pontoons. Most components are common between nacelle and pontoon systems, however the main differences between them are as follows: the nacelle has an oil-water separator, the nacelle has a more complex piping layout, and the nacelle has two collection tanks.

Pontoon bilge details and overview are depicted in Figure 48 and Figure 49, respectively. Each pontoon has two sump pumps, one at either end of the watertight space, activated by float levels. Bilge water is evacuated through a watertight bulkhead penetration, where it drains into the primary holding tank that is the upper portion of the lower spar. Bilge water in the upper spar or nacelle tube also drains here (note that there is a watertight bulkhead / hatch at the nacelle tube center that separates port and starboard sides). Dual discharge pumps (for redundancy) eject water outboard of the pontoons, above the waterline.

Nacelle bilge details are depicted in Figure 50. A 250-gallon bilge tank is integrated into the shell stiffening rings, towards the starboard bulkhead, and at a 45° angle (between the operational and towing orientations). Piping from the PTO shaft seal area of the nacelle tube directs any inflow directly to the tank. Sump pumps are located at the bottom of both the operational and towing orientations of the nacelle (two for operational and one for towing). The oil-water separator sits on the bottom deck; a 50-gallon sludge tank integrated into the nacelle holds any contaminants filtered out by the oil-water separator. The integrated pump of the oil-water separator is the primary means for bilge discharged out of the nacelle. An additional discharge pump (same as used in the pontoon) is added for redundancy as well as emergency situations. The maximum flow capacity for the oil-water separator is 11 GPM, and for the ‘secondary’ discharge pump is 110 GPM. Float switches are located at each sump pump to control their operation. There are also three float switches

in the bilge tank, controlling oil-water separator and secondary discharge pump. In towing orientation, only the secondary discharge pump will be used.

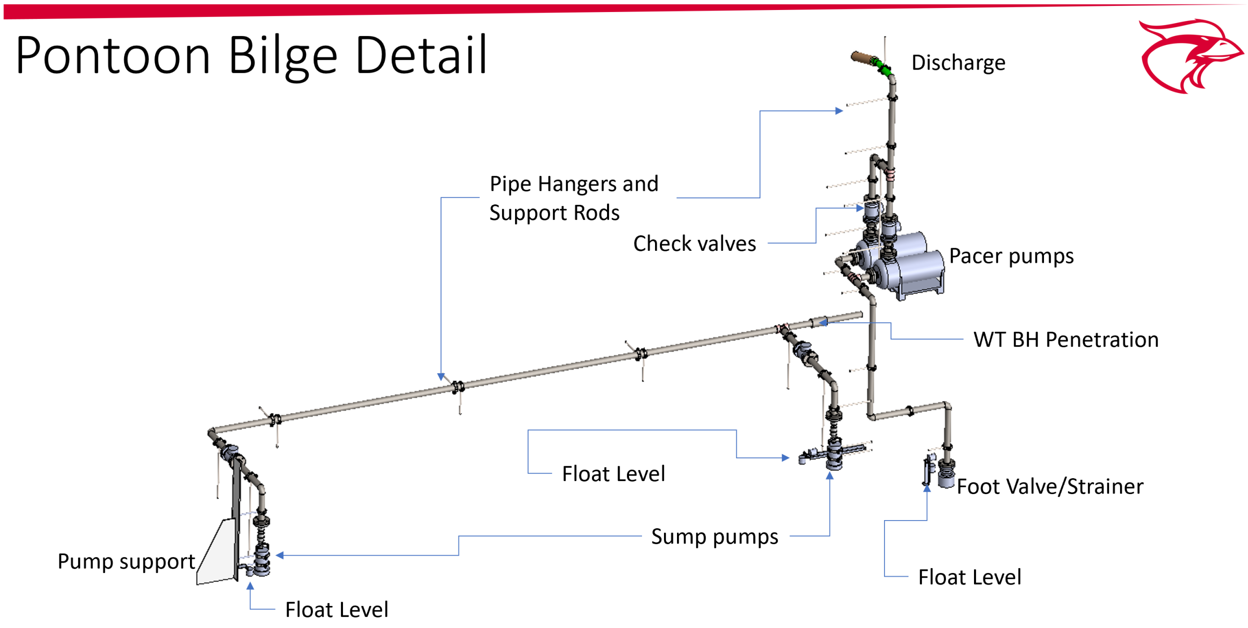

Figure 48 – Pontoon bilge detail.

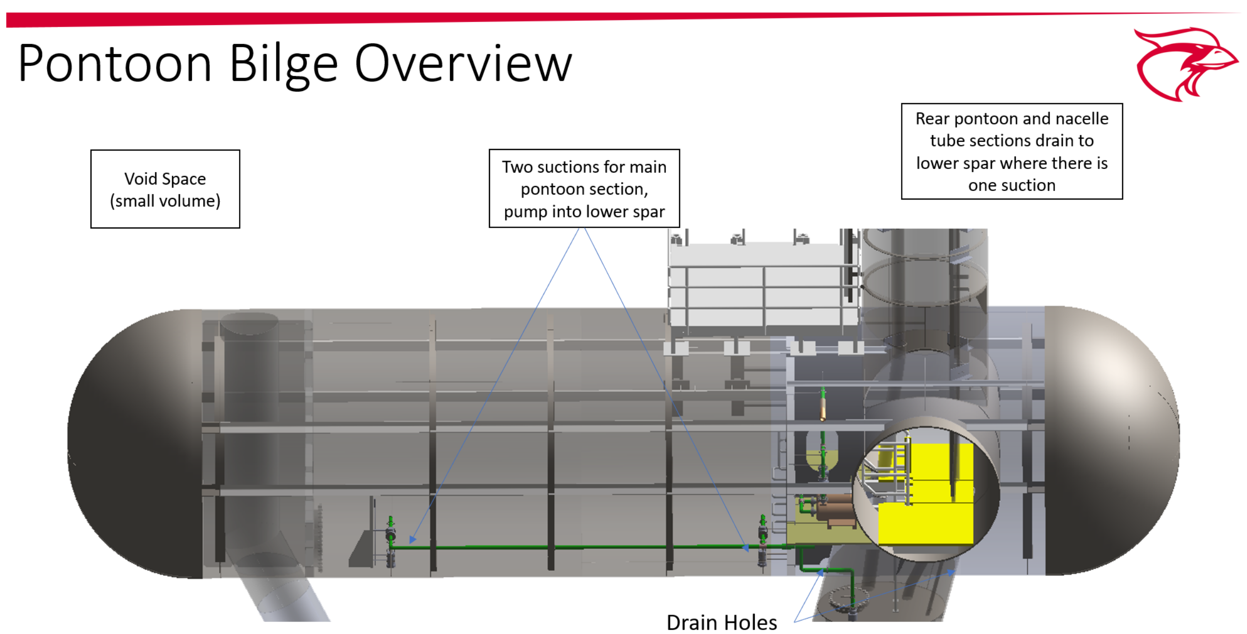

Figure 49 – Pontoon bilge overview.

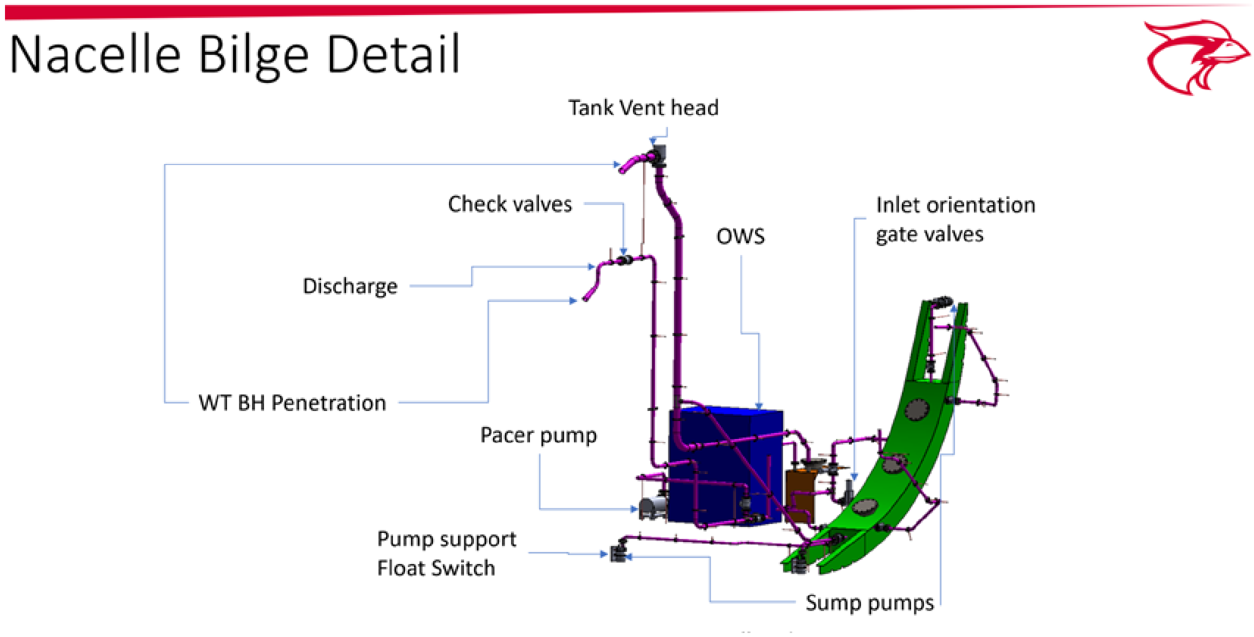

Figure 50 – Nacelle bilge detail.

6.2.5.8 0580 Surveillance

A Commercial off the Shelf (COTS) surveillance system will be used to record and stream live video inside and outside the WEC, day and night. Pan-Tilt-Zoom cameras will be placed in strategic locations to be able to inspect all critical parts of the WEC. The system will be connected to the internet for authorized personnel to be able to view any of the cameras. The system will have onboard storage of video.

6.2.6 0600 Outfit and Furnishings

Outfit and Furnishings provides additional functionality. Subsystems and functions of 0600 Outfit and Furnishings are listed below in Table 16.

Table 16 – 0600 Outfit and Furnishings subsystems.

ID	Element	Function
0610	Designation & Markings	Provide necessary safety and other information
0620	Hull Fittings	Provide for routing of pipes and cables, and other features
0630	Hull Penetrations	Maintain water tightness while providing throughput
0640	Marinization & Corrosion	Specify means to protect against marine environment Define environmental specifications for internal compartments
0650	Workspace & Lighting	Provide light and power for inspection and maintenance
0660	Emergency Equipment	Provide onboard emergency equipment
0665	Lightning Protection	Protect systems and people in event of lightning strike
0670	Stowage	Storing emergency equipment and maintenance supplies

Hull fittings includes a number of features providing equipment attachment to the hull. However, most of these details are considered a part of 0100 Hull (e.g., platforms, ladders, railings, mooring attachment foundations). Final detailing of pipe and cable attachment will be conducted during a future manufacturing stage.

Hull penetrations includes maintaining watertightness of pipe and cabling penetrations, and final detailing will be conducted during a future manufacturing stage. Hatches are included in 0100 Hull design.

Each system design accounts for marinization and corrosion (e.g., hull and rotor magnet coatings are a part of 0100 and 0210 systems). However, system 0640 serves to provide oversight and support.

Lighting and receptacles includes IP67 LED light fixtures to illuminate interior workspaces, and IP67/68 marker lights on the exterior. 120 VAC receptacles, fed by GFCI breakers, in weatherproof boxes are provided as well.

Emergency equipment and stowage includes PPE, first aid, life rafts, and other equipment (e.g., fire extinguishers).

6.2.7 0700 Mooring

A team at NREL was engaged for Mooring design. The mooring design is outlined below, with further details presented in *DE-EE0008954 H3 0700 Mooring FDR* (Appendix 13.23). Subsystems and functions are listed below in Table 17.

Table 17 – 0700 Mooring subsystems.

ID	Element	Function
0710	Single Point	Primary station keeping (anchor to ground)
0720	Bridle	Constrain WEC to weathervane Provide yaw stability
0730	Tether	Return WEC to default position in calm seas Maintain tension on mooring bridle in calm seas
0740	Accessories	Load measurement and data transmission (to SCADA)

The mooring system serves to keep the WEC on station while constraining the WEC to orient to face the incident waves (i.e., weathervane). The mooring was designed for a non-linear response, such that it has low tension during most operational conditions to minimize the effect on the WEC's wave response, but significantly increased tension in extreme conditions such that excursions are limited to relieve requirements on the umbilical power cable. The mooring system maintains tension on all lines, in all conditions, to reduce risk of entanglement and snap loading.

The final mooring system design is shown in Figure 51. The mooring system features a single main anchor line that splits into a bridle configuration. The bridle lines constrain the WEC to face into the waves as it weathervanes around the main anchor, while also providing yaw stability. The main anchor is a large gravity anchor supported by two drag embedment anchors to increase horizontal capacity for extreme conditions. Two tether mooring lines at the rear help manage the mooring system pretension and limit the range of motion during weathervaning or unusual loading directions. Floats and weighted chain sections are used on all mooring lines to strategically tune the mooring system's nonlinear response, and to maintain tension and reduce snap loading.

The main anchor line including the bridle sections is made of 240 mm nylon rope. Nylon rope was chosen for its advantageous stretch, which limits peak tensions. The large rope diameter was chosen to reduce extreme offsets. The main anchor is spaced 70 m from the WEC neutral position. This spacing was chosen to limit large offsets (longer lines result in larger stretch). The main anchor line features a large 10 m^3 buoy at a 50 m height above the anchor. The 10 m^3 buoy is the key mechanism for the nonlinear force-displacement curve; the mooring system exerts minimal force on the WEC in the typical operating range of offsets where weathervaning is desired. However, for large offsets the force steeply increases with displacement, limiting the extreme WEC offsets to comply with power cable requirements (see Figure 52).

Also on the main anchor line, 28 m from the large buoy, is a chain section that acts as a 795 kg clump weight. This mooring configuration paired with low pretension and large offsets has a tendency for slack line events on the main anchor and bridle lines. The clump weight creates a slight pretension on the main lines, thus reducing these slack line events. The clump weight size was iterated to find a weight that had

minimal impact on weathervaning while still preventing most slack line events in common sea states. Moving along the main anchor line, the bridle point and small 0.7 m³ buoy are spaced 22 m from the clump weight. The buoy was added to raise the angle of the bridle lines, potentially preventing yaw rotation in extreme sea states. This buoy size was chosen to keep the pretensions low while still sufficiently elevating the angle of the bridle lines.

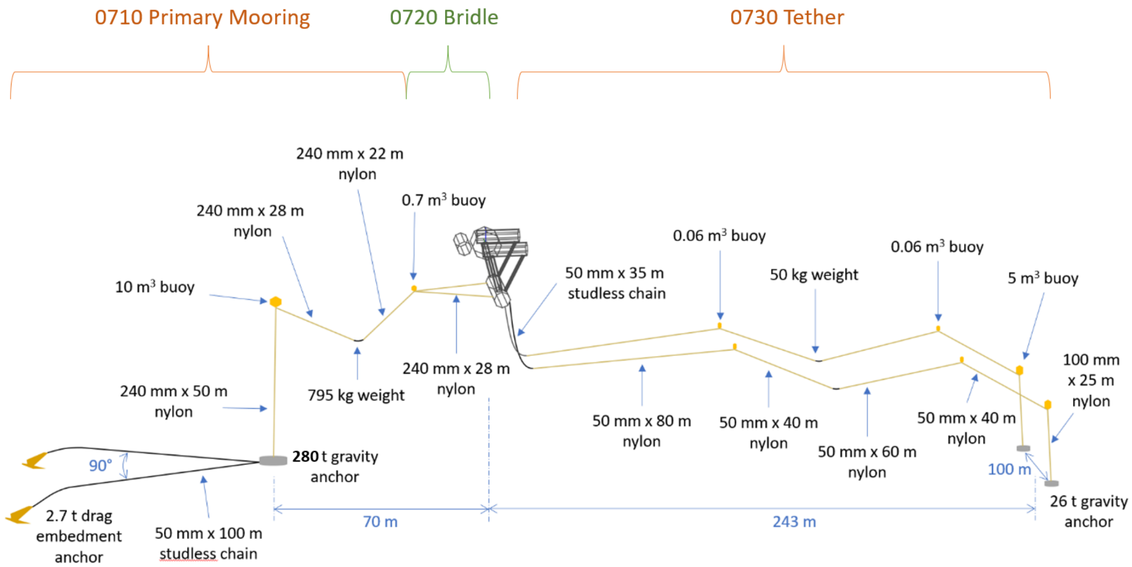

Figure 51 – Mooring system design.

To resist the multidirectional loads caused by the WEC weathervaning, as well as the large uplift load caused by the 10 m³ float, the main weathervaning mooring assembly uses a system of three interconnected anchors. A central gravity anchor is the attachment point for the main mooring line. This 280 t gravity anchor is sized to withstand the peak vertical loads on the anchor. To provide sufficient horizontal holding capacity without requiring a prohibitively large gravity anchor size, two 3.2 t drag embedment anchors are added that are attached to the gravity anchor at a spread angle of 90°. Each anchor is sized to withstand the peak expected horizontal anchor load from the mooring system. The perpendicular arrangement of two anchors provides consistent holding capacity over 90° of load directions, which exceeds the expected range of multidirectional anchor loads that have a significant horizontal component.

The mooring design features two tethers for improved yaw stability while keeping a light restoring force. Starting from the WEC attachment point, the first section of each tether is 35 m of chain, which attaches to ballast tank pad eyes. This chain section was chosen for its weight and catenary shape. As shown in Figure 51, the tethers hang in a steep catenary from the ballast tank. This nearly vertical declination angle means that the tethers impose very little horizontal force on the WEC, allowing more freedom for weathervaning. The chain section is followed by four sections of nylon rope, with alternating buoys and clump weights. The buoys and clump weight are sized very small (0.06 m³ and 50 kg, respectively) so that they contribute little added tension while maintaining the desired profile shape of the tether. As shown in Figure 53, the tether components create an accordion shape that allows a high degree of extension. This shape was chosen to allow as much weathervaning freedom as possible while imposing some limits on the watch circle, especially for negative offsets (i.e., towards the primary anchor). The last section of the tether features a 25 m nylon section to a 5 m³ buoy. This larger buoy was chosen to maintain tension on the last segment of line so that the line does not clash with the seabed or anchor. The gravity anchors for the tether mooring lines have a similar construction as the main gravity anchor; they are significantly smaller (26 t each) and are sized to withstand both horizontal and vertical loads.

An OrcaFlex model was used to simulate the WEC and the mooring system in design load cases. The H3p WEC was modeled as a set of 6 DOF buoy objects, using cylindrical dimensions provided by C·Power. Design load cases and partial safety factors are detailed in sections 4.4 and 4.5, respectively. Additional DLCs were simulated to assess combinations of wave and current directionality (see Figure 54). An additional PSF of 1.2 was applied multiplicatively to non-redundant elements, together with the 1.67 that was applied to all mooring system elements. The lines were oversized from a strength perspective, as the stiffness of large diameter lines was needed to meet excursion limits under extreme conditions. Maximum assessed tensions and allowed tensions are listed below in Table 18.

The maximum backwards excursion in head-on seas was assessed as 68 m, and the maximum forward excursion in calm seas (with no waves and an offshore current) as 15 m, with respect to the neutral position in still water. The maximum backwards excursion in weathervaned conditions is similarly 68 m (after accounting for weathervaning revolution). This is illustrated in Figure 55.

Design modeling indicated that weathervaning increases with increasing H_{m0} and decreasing T_e (i.e., weathervaning is correlated with increasing wave drift force), see Figure 56. Misaligned currents, in small sea states, were shown to dominate the weathervaning response (see Figure 57). Weathervaning performance increases with a softer tether response, however a softer tether design provides insufficient restraint for the forward drifting DLC. While this modeling study indicated imperfect weathervaning in moderate and small sea states, a limited study performed within the scaled tank test indicates that the effect of weathervaning on performance over sea states incident $\pm$ 29° to be negligible (as discussed in section 9.2).

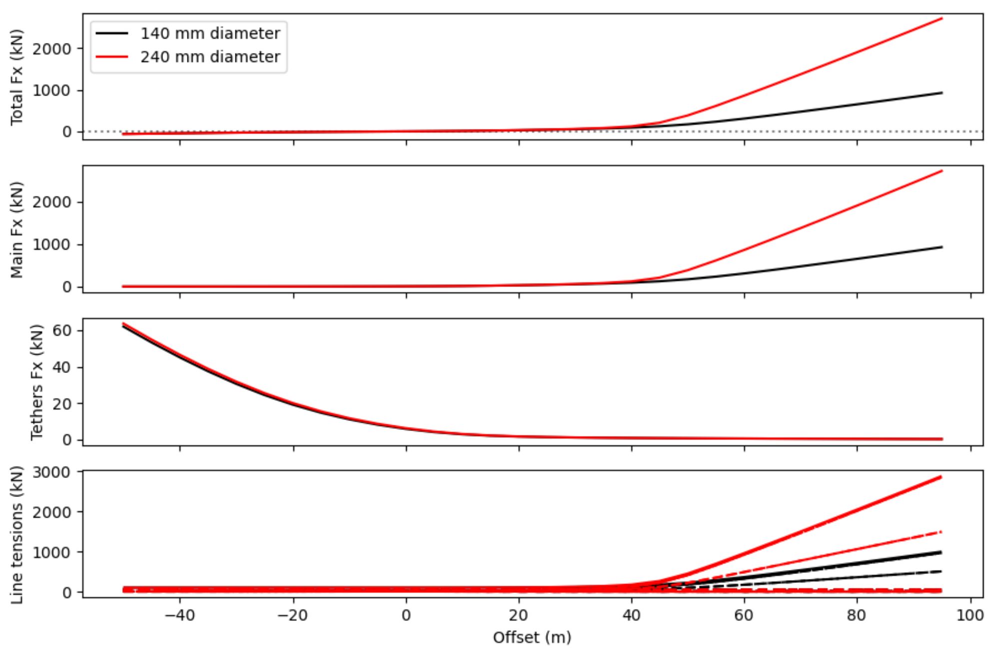

Figure 52 – Non-linear load-extension mooring response.

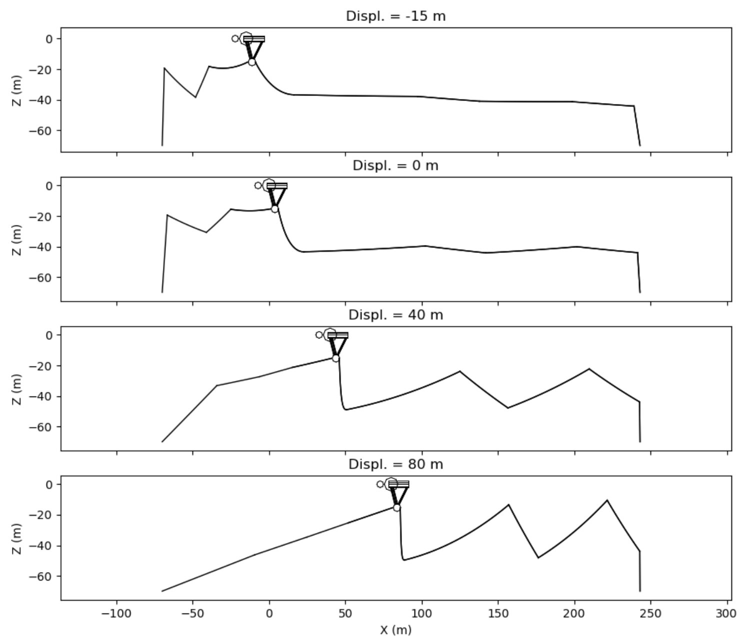

Figure 53 – Primary mooring and tether profiles under various excursions.

Figure 54 – Wave and current directionality combinations for DLCs.

Table 18 – Mooring line maximum and allowed tensions.

Line	Maximum Tension [kN]	Allowed Tension [kN]
Anchor line (240 mm nylon)	1660	4810
Bridle lines (240 mm nylon)	1140	4810
Chain tether (50 mm chain)	74	2740
Nylon tether (50 mm nylon)	54	209
Nylon tether (100 mm nylon)	61	834

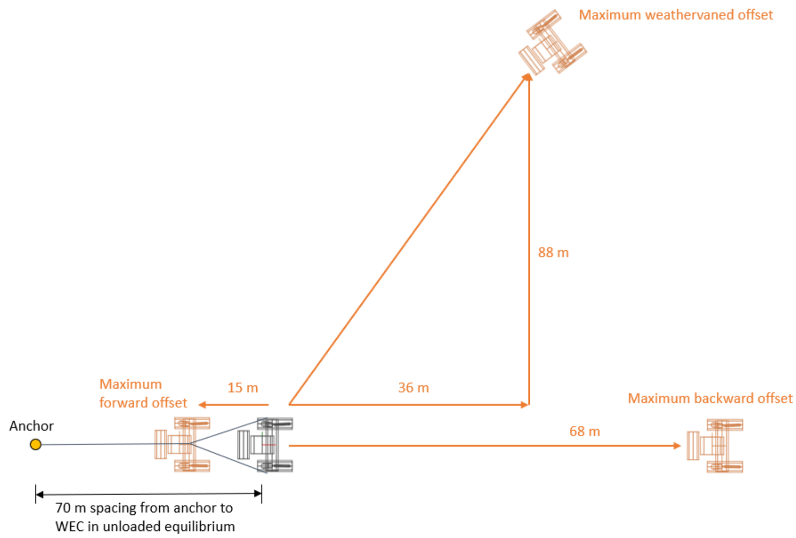

Figure 55 – Maximum assessed excursions.

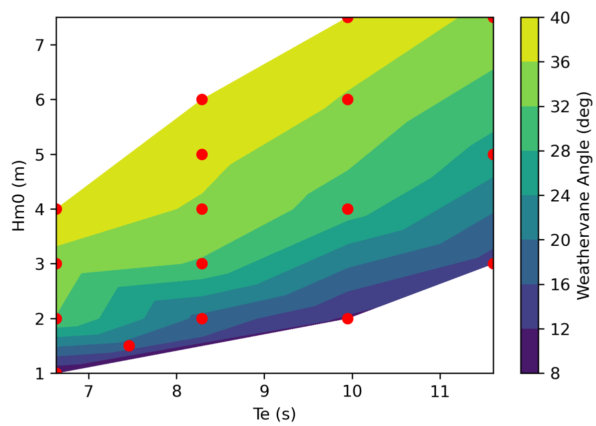

Figure 56 – Assessed weathervaning angle in 45° incident sea states, with no current.

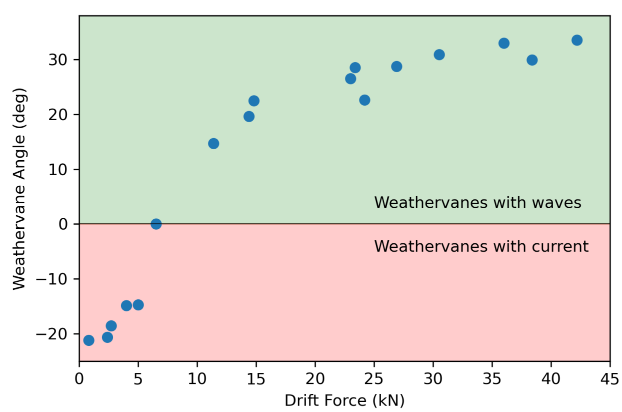

Figure 57 – Weathervaning in misaligned waves and currents.

Load cell shackles were specified for instrumentation of both bridle lines and both tether lines. Instrumentation of the mooring lines is intended to allow monitoring of mooring line tensions during operation to use in understanding performance and potential fatigue accumulation, and also to monitor peak mooring tensions for understanding margins on the mooring system and structure strengths.

The SHK-B load cell shackles (Figure 58) were identified as a suitable option based on their rating for offshore applications, wide range of sizes, and standard bow shackle shape. Having standard bow shackle dimensions and strength characteristics allows for easy integration into the mooring system, including compatibility with a range of loading directions as is expected at the bridle attachment points. These shackles have an ultimate strength that is a factor of 3.0 times their rated strength, meaning that they can be an integral part of the mooring system and do not require a mechanical bypass to provide the required safety factors.

Figure 58 – Load cell shackle.

The mooring system installation procedure is designed to allow the mooring system and dynamic power cable (umbilical) to be pre-installed before the WEC is deployed and to not require underwater operations by divers or ROVs. The installation steps are summarized in the following paragraphs. These steps are intended to account for the key logistical requirements in the installation process.

In the anchor installation stage, illustrated in Figure 59, the anchors are laid, along with portions of the mooring lines and temporary buoys terminating the lines at the sea surface. At the end of this stage, the anchors are installed, and the attached mooring line segments are available at the surface via three temporary buoys.

In the subsequent mooring line installation stage, illustrated in Figure 60, the majority of the remaining mooring line segments are installed, and they are joined together centrally with a temporary buoy. This temporary buoy takes the place of the WEC prior to its installation, supporting the installed primary and tether mooring lines, as well as the umbilical. Connections and disconnections can be made out of water by lifting this temporary buoy. At the end of this stage, all of the mooring system is installed except for the bridle lines, which will be pre-connected to the WEC before the WEC is moved into position. The dynamic power cable can be installed and attached to the temporary buoy at this point.

In the WEC installation and connection to mooring stage, illustrated in Figure 61, the WEC is moved into position, the mooring lines are individually disconnected from the temporary buoy and connected to the WEC, and the temporary buoy is removed. This stage will use three vessels: one to position the temporary buoy, one to position the WEC, and one to raise and lower the mooring lines that are being individually detached and reattached. Because the anchors and large floats are already installed, the weights and tensions of the mooring components being worked with are small, meaning that large, specialized vessels are not required.

For removal, the operations are similar but performed in reverse order. If the WEC is being removed temporarily, the temporary buoy can be installed to support the mooring lines and umbilical in lieu of the WEC.

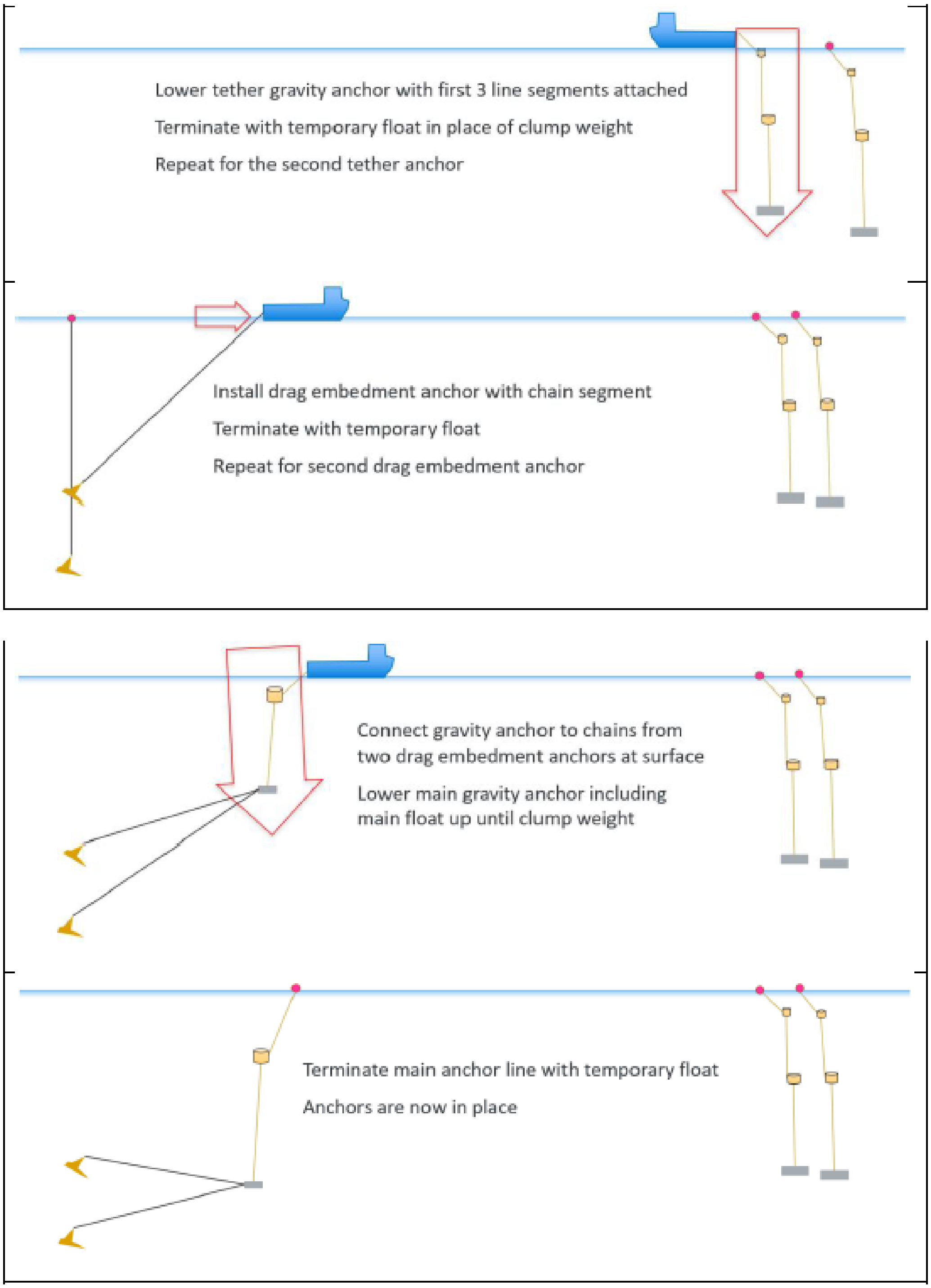

Figure 59 – Anchor installation sequence.

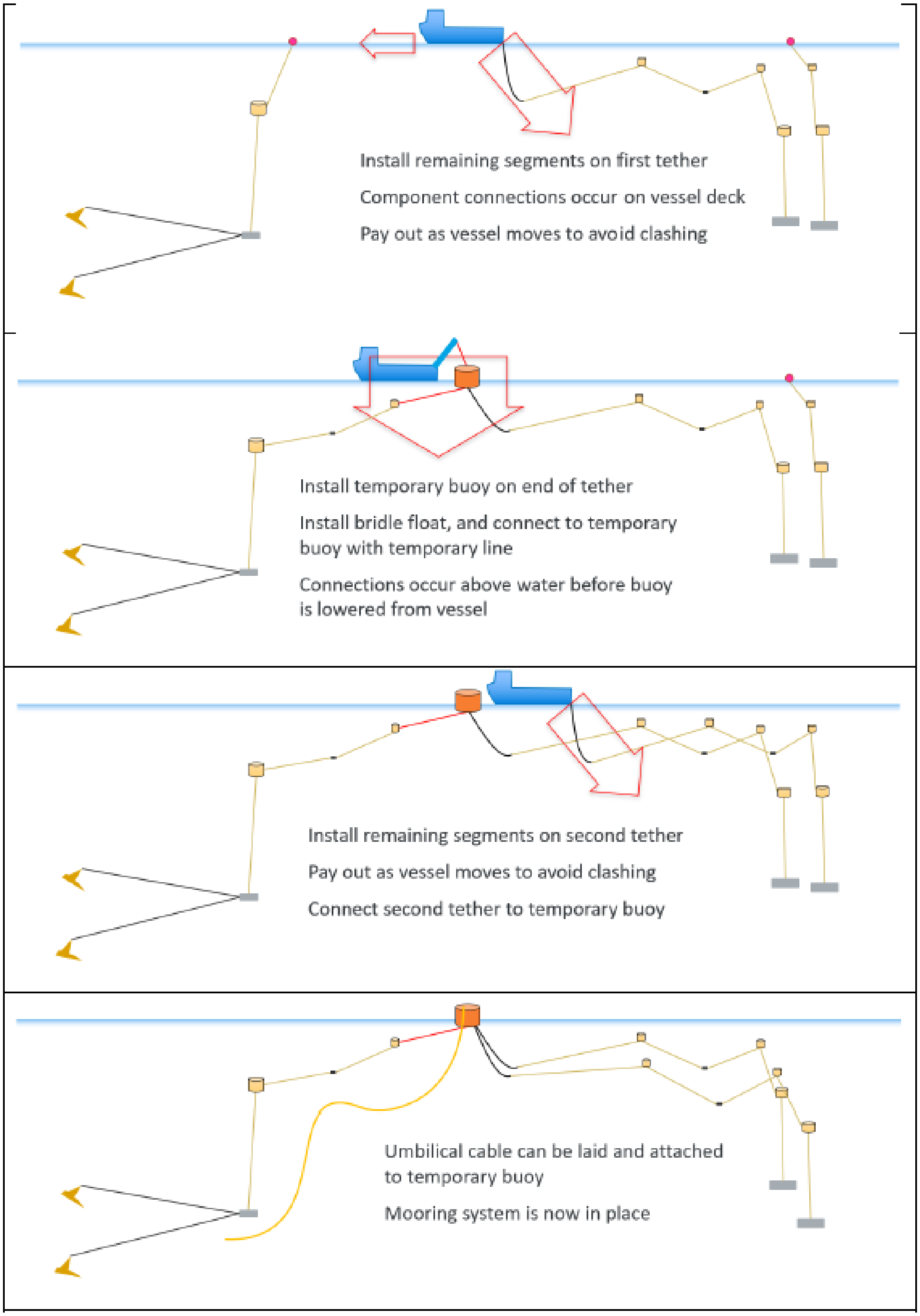

Figure 60 – Mooring lines installation sequence.

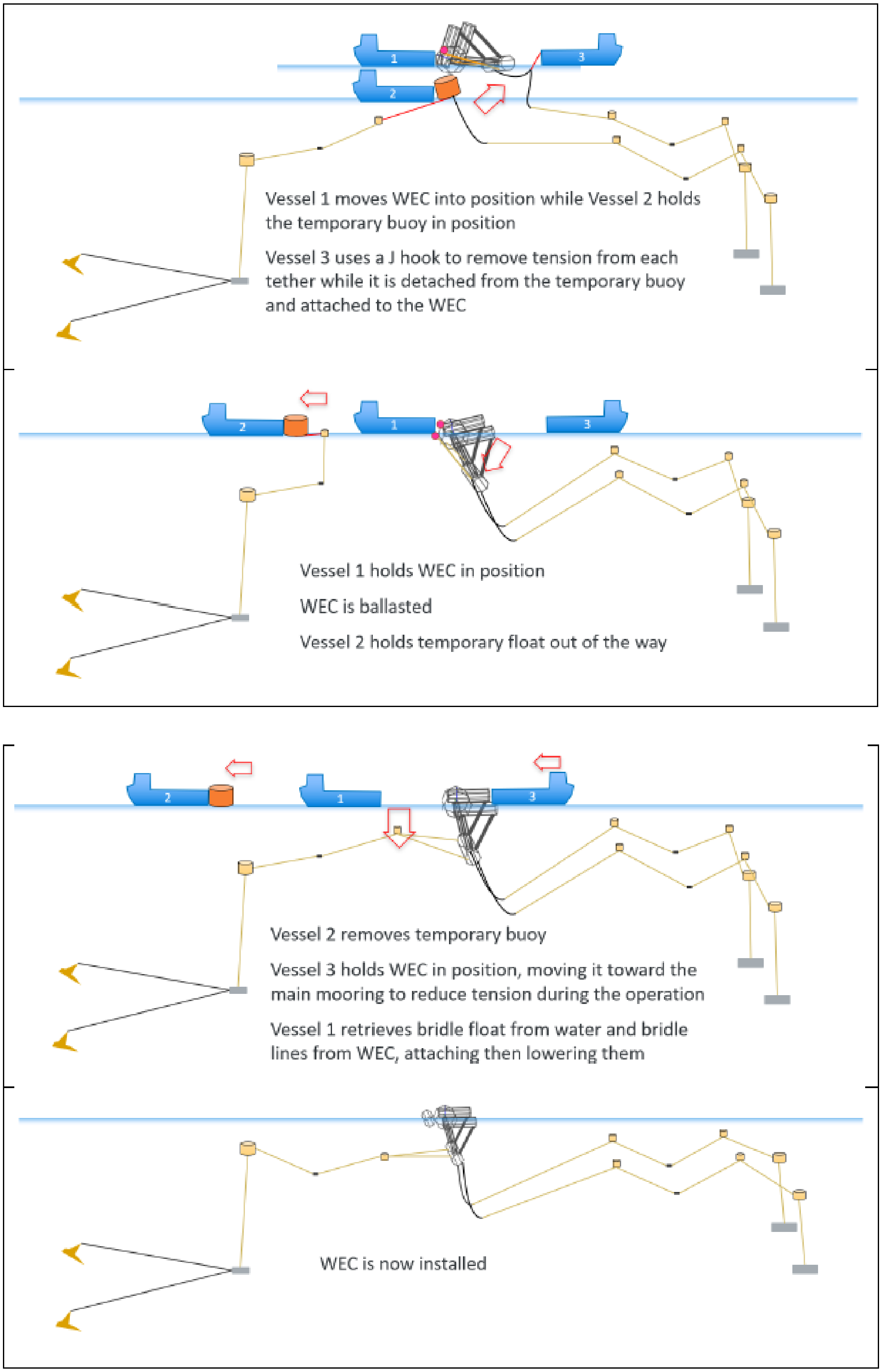

Figure 61 – WEC installation and connection to mooring sequence.

6.2.8 0800 Electrical Collection

Blue Frontier Engineering (BFE) was contracted for 0800 Electrical Collection design. The electrical collection design is outlined below, with further details presented in the following documents:

- Umbilical Cable Final Design Report
  - *DE-EE0008954 H3 0800 Umbilical Cable Design Report* (Appendix 13.24)
- Umbilical Dynamic Analysis Report
  - *DE-EE0008954 H3 0800 Umbilical Dynamic Analysis Report* (Appendix 13.25)
- Umbilical Cable Dynamic System Components
  - *DE-EE0008954 H3 0800 Umbilical Cable Dynamic System Components* (Appendix 13.26)
- Umbilical Cable Installation Plan
  - *DE-EE0008954 H3 0800 Umbilical Cable Installation Plan* (Appendix 13.27)
- Umbilical Cable General Arrangement
  - *DE-EE0008954 H3 0800 Umbilical Cable General Arrangement* (Appendix 13.28)
- Umbilical Cable Cross-Section
  - *DE-EE0008954 H3 0800 Umbilical Cable Cross-Section* (Appendix 13.29)

Subsystems and functions are listed below in Table 19. Note that subsystems 0850 through 0870 are provided by PWS.

Table 19 – 0800 Electrical Collection subsystems.

ID	Element	Function
0810	Umbilical Cable	Conduct power and data between 0820 WEC and 0860 submarine cable (at 0850 recovery frame)
0820	Spar Junction Box	Provides medium voltage electrical connection at spar platform to terminate the umbilical cable
0830	Umbilical Anchor	Provide stable umbilical positioning at sea floor
0840	Dry-mate Connector	Provide power and data connectivity between umbilical and submarine cable
0850	PWS Subsea Recovery Frame	Facilitate recovery of wet ends of umbilical and subsea cable
0860	PWS Submarine Cable	Conduct power and data between subsea junction and onshore substation
0870	PWS Onshore Substation	Condition, monitor, and transmit power between WEC and grid

The electrical collection system serves to conduct power and data between the WEC and shore. PWS will provide the 0860 Submarine Cable, along with the 0850 Subsea Recovery Frame (with one-half of the dry-mate connection), and the 0870 Onshore Substation. The BFE design includes the dynamic umbilical cable, along with necessary dynamic components, and interfaces with the WEC, sea floor, and subsea cable.

The dynamic umbilical cable was selected based on mechanical, electrical, and fiber optical considerations (see Figure 62 for cross-section). It is a dual-layered steel armored cable, with inner and outer LLDPE (Linear Low Density Polyethylene) sheathing. The dual layered armoring comprises two layers of galvanized steel wire which are contra-helically applied over the sub-bedding layer. This provides sufficient strength and protection for cable installation and in-service dynamic effects.

There are three insulated power cores, which are designed with Water Tree Retardant Cross-Linked Polyethylene insulation to 8.7/15(17.5) kV. The voltage rating of the power core allows the cables to be used at the project specified nominal system voltage of 12.5 kV, with maximum system voltages up to 17.5 kV. The continuous current rating of 171 A far exceeds the maximum expected current of 30 A.

The fiber optic sub-cable comprises 12 single-mode fibers, supported in a water repellent gel within a stainless-steel tube, protected by inner polyethylene sheath, galvanized steel wire armor, and an outer polyethylene sheath.

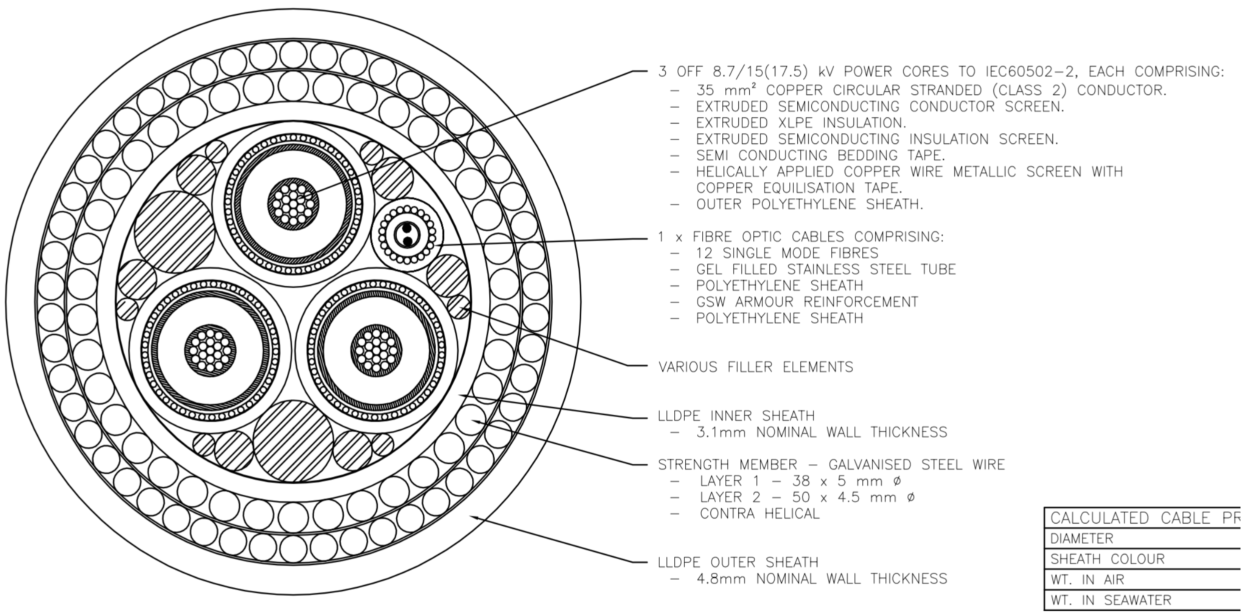

Figure 62 – Dynamic umbilical cable cross-section.

A “Lazy Spring” dynamic configuration was specified (see Figure 63), which accommodates the required range of motion of the WEC, while reducing the likelihood of seabed contact or interference with the mooring system. A dynamic bend stiffener provides umbilical cable protection at the point of departure from the WEC. Four SeaSpring modules are utilized to provide buoyancy for the Lazy Spring configuration, which have integrated bend protection. Abrasion protection is provided along the portion of the cable where touch-down to the sea floor is accomplished. A hold-back clamp and two anchors provide fixity to the sea floor; bend restrictors at either end of the hold back clamp to reduce risk of overbending of the cable during installation. A bend restrictor and interface flange make the connection with the PWS subsea connector.

To ensure the cable is technically robust, BFE has performed global dynamic analysis using the 3D time domain finite element software OrcaFlex. Dynamic analysis considered ultimate and fatigue loading, as well as other dynamic factors (e.g., bending, touchdown, interference).

The results for the ultimate loading analysis demonstrate generally good system performance for the chosen configuration. For all cases considered, no cable tension violations are calculated, which confirms that the Lazy Spring arrangement has adequate system pliability to accommodate the large WEC offsets. The calculated curvature is also within allowable limits throughout the majority of the cable length, the only exceptions being isolated and infrequent infringements at the WEC connection point. At this location, low occurrence peak responses are found to cause instantaneous transient curvatures within the cable dynamic bend stiffener region. The low probability and transient nature of the bending indicates an acceptably low risk of cable damage. A heavier and stiffer cable was also considered but is not recommended as it generates higher overall system loads.

Fatigue loading analysis was conducted based on calculated cable component factors and appropriate SN data. The analysis was performed in a highly conservative manner, using cable response data extracted from an extreme seas case (i.e., a 50-year return storm ULS conditions). Using this approach, the work calculates

that the cable fatigue life is 7 years (under the highly conservative assumption of continuous extreme conditions), exceeding the 5-year requirement.

The interference assessment confirms that the cable does not interfere with the WEC device after exit. It also confirms that the cable does not contact the mooring lines. The only exception being at cable dynamic fixity point on the WEC. However, the interference observed was removed by moving the cable-WEC take-off position from the front of the ballast tank to the bottom.

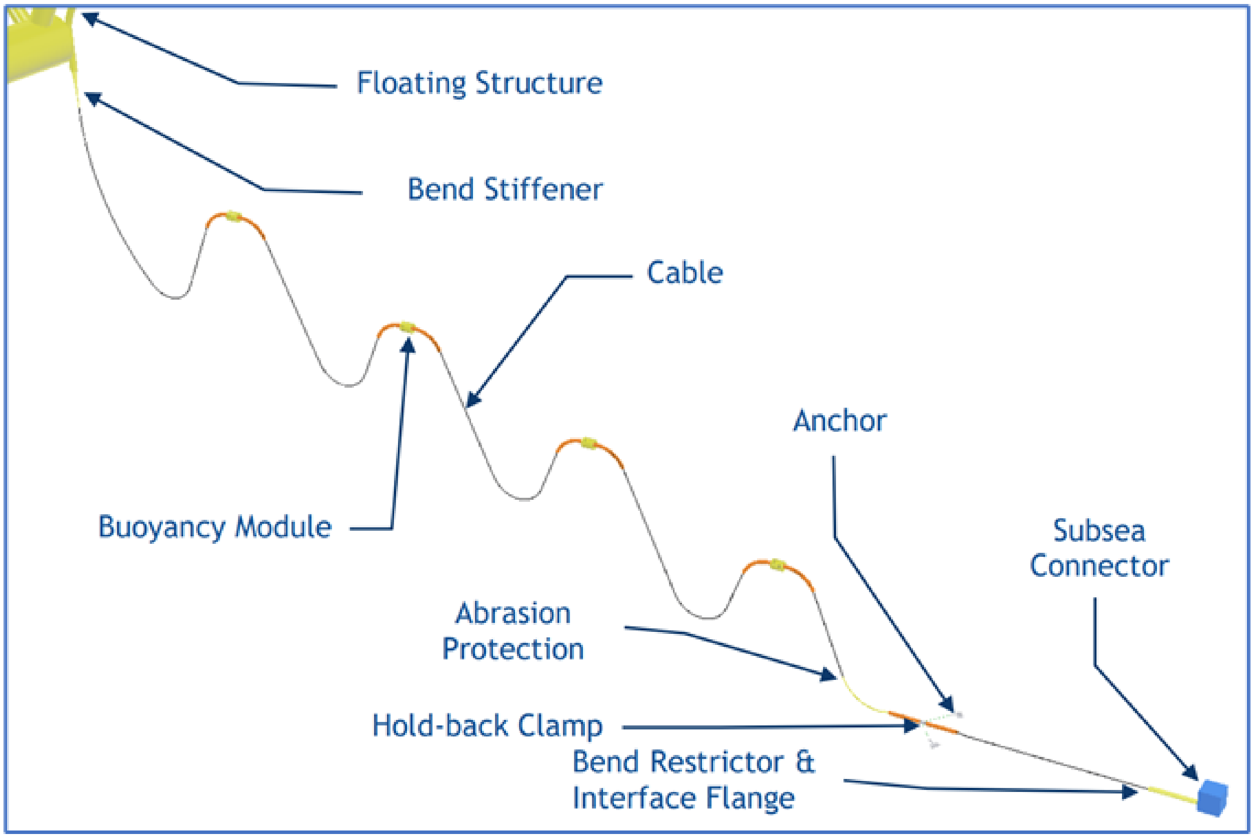

Figure 63 – "Lazy Spring" configuration of dynamic umbilical cable.

A high-voltage (HV) junction box, installed on the port upper spar and accessible from the pontoon platform, serves as the interface for the broken-out conductors and optical fibers. The junction box is rated IP66 and is deluge tested.

An 18-in outer diameter steel I-tube routes the umbilical cable from the HV junction box down to the WEC take-off point, where the bend stiffener is installed. The I-tube penetrates the pontoon, runs along the back of the lower spar, and penetrates the ballast tank (see Figure 64).

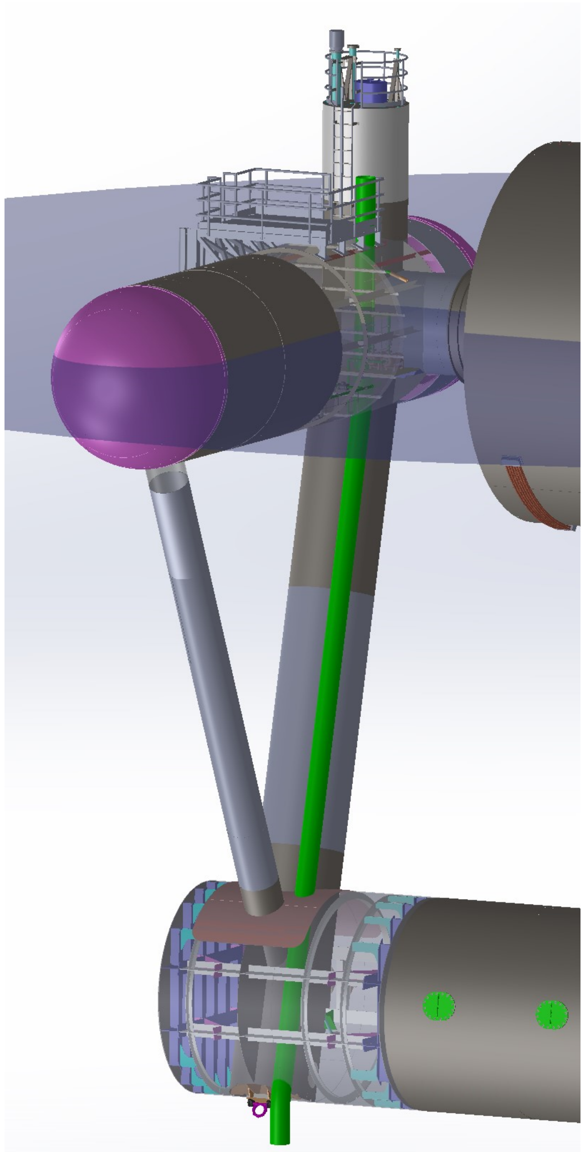

Figure 64 – I-tube (green) routes umbilical cable from top-side interface to sub-sea hang-off point.

The umbilical is planned to be installed alongside the mooring, prior to bringing the WEC on-station. The PWS frame will first be recovered, and a dry-mate connection made on deck with the umbilical. Using a cable reel, the umbilical will be paid out *en route*. Ancillary equipment (e.g., hold back clamp, buoyancy modules) will be installed at pre-defined marked points (see Figure 65). The pull-in head will be installed at the WEC-end of the cable and will be secured to the temporary buoy (see Figure 60 of mooring installation sequence).

Once the WEC is on-station and connected to the mooring system, the connection of the umbilical to the WEC will be made. The pull-in head is then connected to a messenger line, which will have been pre-installed in the I-tube. A temporary jib-crane is installed onto the port upper spar and is used to pull the umbilical through the I-tube (see Figure 66). Once in place, the bend stiffener locks into position at the base of the I-tube (see Figure 67). A flange at the top of the I-tube secures the umbilical (see Figure 68). The pull-in head is then removed, revealing the cable tails. The cable tails are then routed to the HV junction box. At this stage the WEC is moored, and the umbilical installed; the WEC is ready for commissioning.

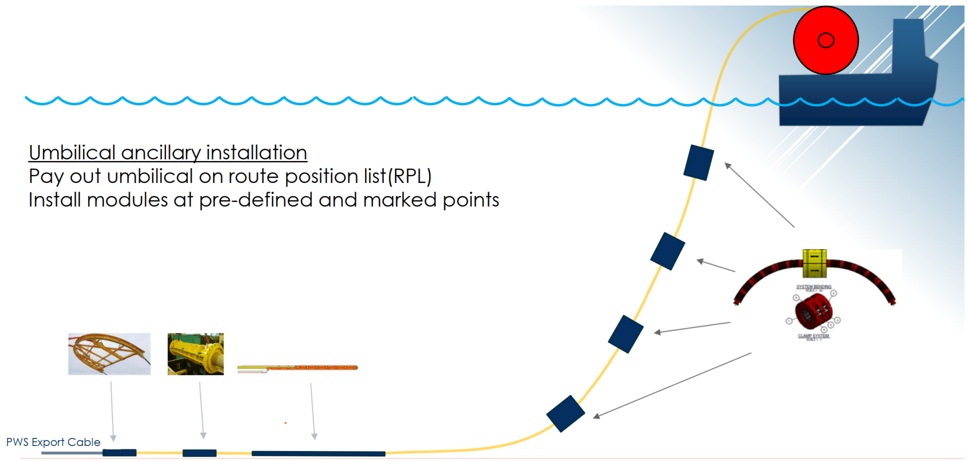

Figure 65 – Umbilical paid out *en route*, and ancillary equipment installed.

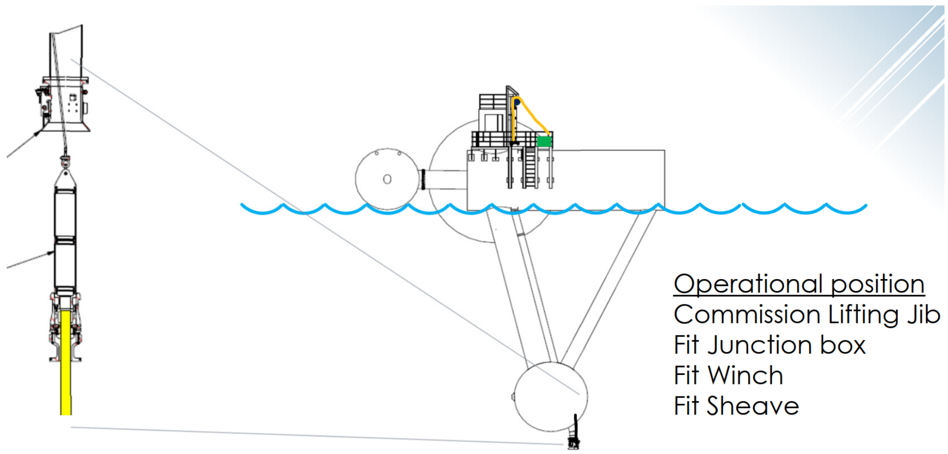

Figure 66 – Umbilical cable pulled through I-tube using jib-crane and messenger line.

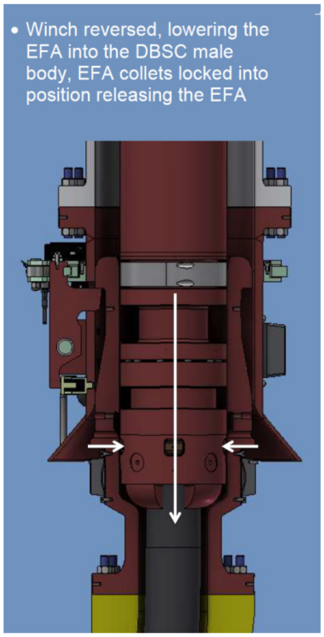

Figure 67 – Bend stiffener locks into position during umbilical installation.

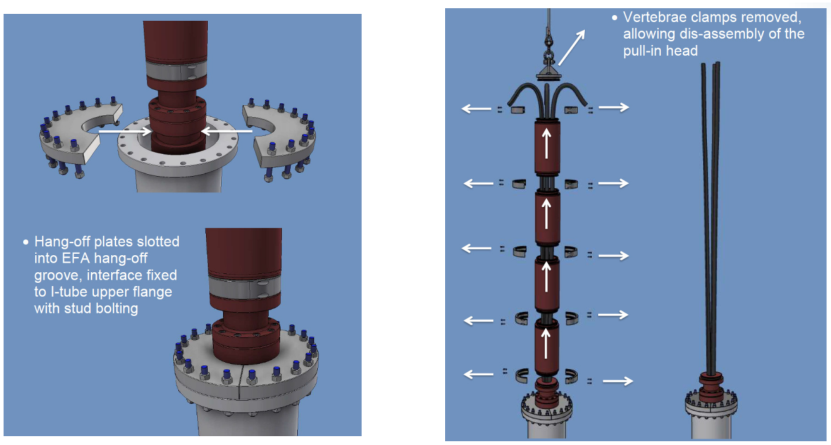

Figure 68 – Flange at top of I-tube secures umbilical (left), and conductors broken out (right).

6.3 Mass Estimates

Preliminary and Final mass estimates for the H3p are given below in Table 20. Structural mass estimates include a 5% margin for mass variance, a 3% margin for welds, and a 4% margin for coatings. All other systems include a 5% margin for mass variance. The weight calculations for hydrostatic analysis are detailed in *DE-EE0008954 H3 Weight Calcs for Hydrostatics* (Appendix 13.11).

Significant mass increases were realized during final design, resulting in a non-optimal mass distribution. The hull structure mass increase stands out as the most significant. Additional steel was required to handle the assessed wave loads, but the largest driving factor was the need for increased stiffness to accommodate the PMG air gap tolerance. The next largest system mass increase was the PTO, which was also driven largely by the need for stiffness to meet the air gap tolerance requirements. C·Power believes that development of a PMG interface that allows for some increased elasticity, such as C·Power's Localized Airgap Reduction System (LARS), could greatly reduce the mass (and cost) of the hull and PMG.

The increase in active mass reduces the amount of ballast that can be installed and results in raising the overall center of gravity. Hydrodynamic simulations indicate a reduction in performance with a higher center of gravity (with respect to the center of buoyancy). This problem was partially mitigated by adding additional buoyancy in the form of hemispherical ends added to the pontoons. Further mitigation was provided by adding additional ballast, to account for this additional buoyancy, and additionally to reduce the freeboard by 0.3 m with respect to the original draft line. In total this increased the total displacement by 139 mt (as shown in Table 20), lowered the center of gravity, and mitigated the performance losses that had resulted from system mass increases.

Table 20 – H3p mass estimates.

Description	Preliminary [mt]	Final [mt]
0100 Hull	266	445
0200 PTO	79.0	116
0300 Electric Plant	8.40	14.8
Other equipment	10.7	16.1
Hard ballast (sand)	289	166
Water ballast	306	340
Total mass (ballasted)	959	1098
Dry mass	653	758
Active mass	364	592
Structure only	256	430

6.4 Advanced Controls

Advanced controls development was supported by Sandia National Laboratories (SNL). SNL linearized the time domain hydrodynamic model results (i.e., WEC hydrodynamic response) provided by C·Power and then implemented complex conjugate control to this linearized model. Controller optimization was first conducted in the frequency domain to determine the range of optimal controller coefficients to be considered for each sea state. Time domain optimization was completed subsequently, with non-linear PTO efficiency model and constraints (i.e., PTO torque limits), to further refine the settings.

The time domain model output provided by C·Power consisted of results from 12 sea states that covered the majority of expected power production, with significant wave height from 1 to 3 m and energy period from 5 to 15 s. Each sea state was simulated both with PTO disabled (freewheeling), and PTO enabled (in this case, with a white noise torque profile).

The H3p's default control mode is linear damping (i.e., proportional gain, or P control). The addition of an integral control term (PI control) increased power capture outside of the H3p resonant response band (i.e., over wave frequencies where the WEC's response is already robust due to optimization of the mass and geometry). However, the addition of a derivative control term (PID control) did not significantly improve performance, and also introduced a risk of instability. SNL results are summarized below in Figure 69.

SNL results were not replicated when PI control was implemented in C·Power hydrodynamic models. Verification of the performance gains is planned at-sea during the PWS deployment. A self-tuning controller will be developed for the deployed WEC, which should mitigate uncertainties inherent in the estimated hydrodynamic characteristics used in controls development.

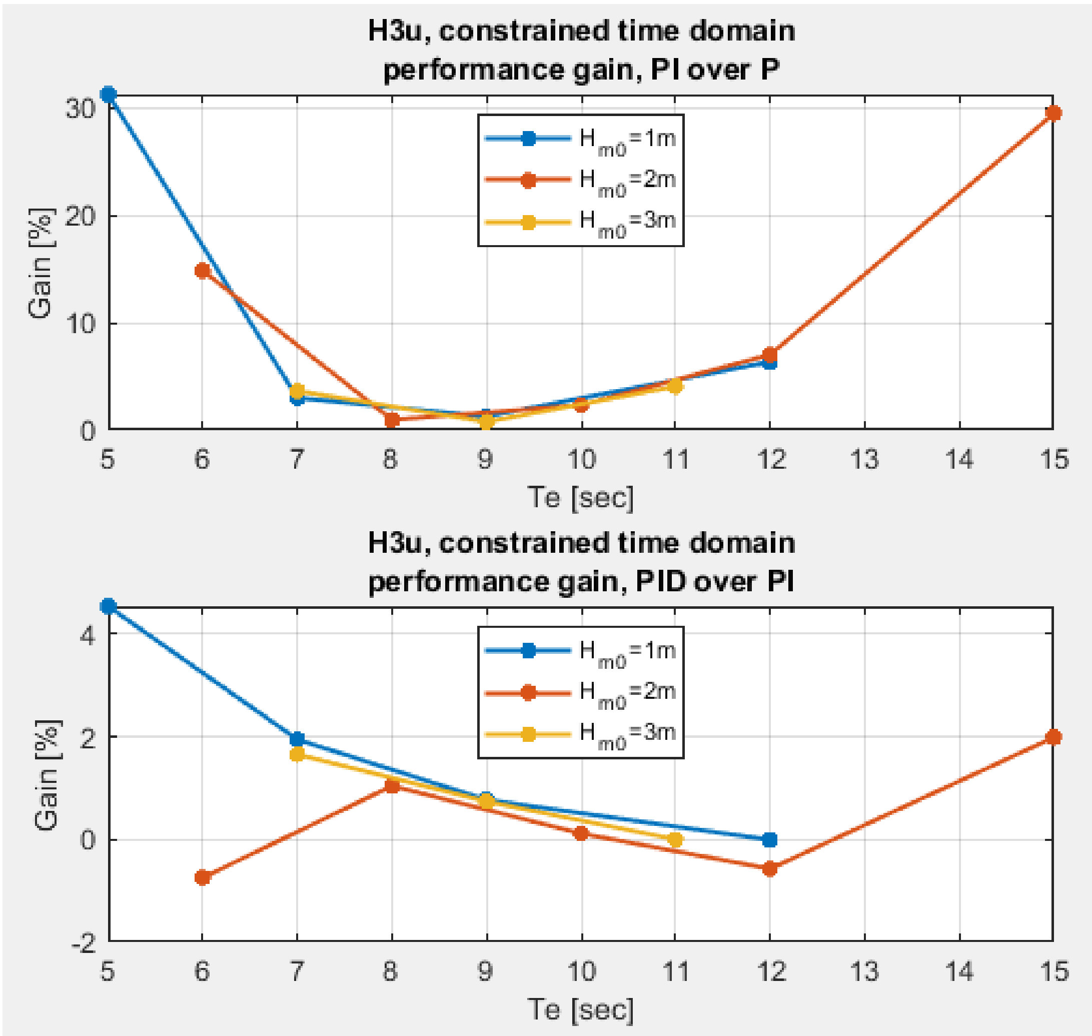

Figure 69 – Advanced controls performance gains results.

6.5 Performance Estimates

Performance estimates were assessed for both the H3p and H3u. Performance estimates are described briefly below, and in greater detail within *DE-EE0008954 H3-PRF-6.7.a Performance Estimates* (Appendix 13.30). Due to the proprietary nature of the design, some details (e.g., power matrices, annual power estimates) are excluded from this "Unlimited Data" document but are included in the "Protected Data" appendix.

6.5.1 Modeling and Assumptions

Three different wave resources were used in estimating annual performance: PWS, EMEC, and Humboldt (DOE reference resource).

PWS is positioned 12 km offshore of the Port of Newport, Oregon, and the depth ranges from 62 to 78 m. C·Power acquired the resource data for performance estimate reporting from the DOE System Advisory Model (SAM, accessed online at https://sam.nrel.gov/download). The PWS resource is characterized using a 30-year hindcast data set, at a model node located at 44.567 °N, 124.229 °W.

The EMEC resource reflects the 70 m deep test site offshore of the western edge of the Orkney mainland, at Billia Croo outside Stromness (Scotland). C·Power characterized the resource based off a 20-year hindcast provided by EMEC.

The DOE reference resource is based on conditions offshore of Humboldt, California (40.8418 °N, 124.2477 °W). C·Power acquired the resource data from DOE SAM (accessed online at https://sam.nrel.gov/download). The site is assumed to be at 70 m depth and situated 5 km offshore.

Hydrodynamic simulations for a given WEC model were performed over 176 sea states (parameterized by significant wave height, H_{m0} and energy period T_e), and the results were used to develop power matrices (mapping performance over $\mathrm{H_{m0}}$ and $\mathrm{T_e}$). H_{m0} and T_e are discretized at 0.5 m and 1 s respectively and cover a range from 0.5 to 8 m and 5 to 18 s, respectively. The power matrices were used along with resource occurrence matrices to estimate annual energy production (AEP) for each resource of interest.

Power matrices were developed for total mechanical power extracted by the WEC (before any mechanical or electrical losses), and as well as for several stages in the power conversion chain, including net electrical power generated by the WEC at the point of AC export (grid quality and net of power drawn by auxiliary systems).

The hydrodynamic modeling, and the performance estimates, comply with the requirements specified by the DOE in *Standardized Cost and Performance Reporting for Marine and Hydrokinetic Technologies* [7].

Hydrodynamic modeling simulations were performed using ANSYS AQWA v16.0. The simulations were fully coupled, and all relevant loads were considered in the calculations, including hydrodynamic loading, inertial loading, and functional loading from PTO and mooring. The hydrodynamic loads included hydrostatic, Froude-Krylov, viscous drag, added mass, and drift forces. Simulations were performed in the time domain using the AQWA NAUT module.

Dimensions and mass characteristics for the H3p and H3u WEC models follow the final designs (summarized in Table 21).

Table 21 – WEC model primary dimensions

Characteristic	**Units**	**H3p**	**H3u**
Displacement	mt	1100	3030
Height	m	22.8	31.9
Draft	m	18.1	25.7
Freeboard	m	4.7	6.2
Beam width	m	20.5	28.1
Length, fore-to-aft	m	22.9	32.7
Nacelle OD	m	8.8	12.5
Float OD	m	4.3	6.2

Performance estimates account for the following losses: PTO mechanical friction, PMG losses, electric plant losses, station power losses, and export losses. The AQWA models apply frictional torque and generator torque in real-time; all other losses are calculated in post processing.

The PMG is modeled with linear damping, but additional controls saturate torque maximum levels, and further torque limits are applied to keep from exceeding the maximum power limit. Linear damping (in

MNm per rad/s), and maximum torque and power limits are listed in Table 22. PMG losses are modeled based on detailed loss calculations provided by Supplier 1 and include copper, back iron, and stray losses. Cooling losses are accounted for as part of the station power.

Table 22 – PMG characteristics.

Characteristic	Units	H3p	H3u
Damping	MNm s^{-1}	9	40
Torque limit	MNm	1.5	7
Power limit	kW	750	2500

The electric plant losses are modeled based on detailed loss calculations provided by Supplier 1 and include machine bridge, network bridge, and energy storage losses. Control and cooling losses are accounted for as part of the station power.

Station power losses include power consumed for cooling, climate control, controls, and safety systems. Additionally, estimates are made for cabling and switchgear losses, and transformer losses (when generated power is insufficient, and the grid is used to supply station power).

Export losses include estimates for the transformer, umbilical, and subsea cable losses. Conservatively, the 17 km submarine cable length of PWS is used for all three resource sites.

The power flow strategy adopted mimics our operational plan and seeks to decrease the losses associated with the oversized power electronics (PE) system. At very low generation (i.e., right around the speed zero-crossing) the PMG and electric plant are idled. At low generation, the power from the PMG goes through the electric plant machine bridge (MB) and is used to charge the battery energy storage system (BESS). At mid-generation, power flows through both the MB and the network bridge (NB), and is exported (through transformer, umbilical, and subsea cable to shore). During excess generation (i.e., power generation exceeds the transformer rating), power up to the transformer rating is exported, and excess power flows from the MB to the BESS. During overspeed events, the PMG and electric plant are idled to protect the electric plant from over voltage.

Once the BESS charge state exceeds a specified upper limit, the BESS discharges to supplement export (through the NB to transformer, umbilical, and submarine cable). Supplemental BESS discharging is curtailed once the charge state falls below a specified lower limit. This power flow strategy was modeled in post-processing of the H3p simulation data. It was not directly implemented with the H3u simulation data as detailed loss models are not available for key H3u subsystems. Instead, mean annual efficiencies were determined for sub-stages of H3p power conversion (see Table 23), and these efficiencies are used for H3u analysis. The efficiencies are seen to be similar at each of the resources, and a mean efficiency over all three is calculated. This mean efficiency was used to estimate performance at each stage for the H3u, based on the total mechanical power calculated from the simulation results.

Table 23 – Power chain conversion efficiencies.

Conversion Efficiency	PWS	EMEC	Humb.	Mean
Mechanical	97.6%	97.6%	97.6%	**97.6%**
PMG	84.1%	84.8%	83.7%	**84.2%**
PE	86.1%	85.7%	86.4%	**86.1%**
Station power	97.1%	97.1%	97.0%	**97.1%**

Conversion Efficiency	PWS	EMEC	Humb.	Mean
Export out umbilical	96.0%	96.5%	95.9%	**96.1%**
Export to shore	98.9%	98.9%	98.9%	**98.9%**

Mean annual power production was calculated by summing the element-wise products of power and resource matrices. Interpolation of the power matrix was performed if needed, but no extrapolation was performed (i.e., power is assumed to be zero outside of the simulation domain). Performance estimates assume 100% availability.

6.5.2 Potential Improvements

In addition to the primary performance estimates, additional estimates were made based on potential near-term improvements. The potential improvements described in this section include advanced controls, efficiency improvements, and mass distribution optimization (made possible by PMG and structural mass reductions). Note that these are only the earliest and most exploitable improvements expected to be pursued by C·Power, and that additional R&D efforts are anticipated that will take the H3p further along the path to utility-scale cost-competitiveness.

The first area of potential improvement is advanced controls. A study performed in-Project by Sandia National Laboratory (SNL), implementing complex conjugate controls, showed potential for performance improvements by broadening the WEC's frequency response (see section 6.4). These results need to be confirmed at PWS and so were not included in the primary performance estimates. The relative improvement found by SNL is shown in Figure 69. Taking the average value at each period (and interpolating where needed), a gain was estimated as a function of energy period. The gain below 5 s is assumed to be zero, and the gain above 15 s is assumed to plateau at 30%. This gain was applied to the primary mechanical power matrix.

The second area of potential improvement explored is efficiency, particularly for systems where the design efficiency falls below reasonable targets. Primary among these is the PE system where the design is not well matched to the pulsed nature of wave power and was overrated with respect to the H3p output. C·Power posits that with continued co-development of the PMG and PE systems, the originally targeted efficiencies of 86 and 92%, respectively, are reasonably achievable. Additionally, incremental improvements are reasonably achievable for the station power (where there is much room for optimization of PMG and PE cooling) and power export (by downsizing the transformer, along with PE optimization). The Project-realized efficiencies are shown alongside these reasonably achievable efficiency targets below, in Table 24.

Table 24 – Reasonable targets for improved efficiencies.

Conversion Efficiency	Project, mean	Reasonable targets
Mechanical	97.6%	97.5%
PMG	84.2%	86.0%
PE	86.1%	92.0%
Station power	97.1%	97.5%
Export out umbilical	96.1%	98.0%
Export to shore	98.9%	99.0%

The third area of potential improvement is mass distribution. The significant mass increases in final design correspond to raising the center of gravity for the central body, which reduces the WEC performance. The mass increases are largely due to PMG, and structural mass increases to reduce the risk of failure to maintain the PMG air gap. Using the mechanical power performance estimated for the preliminary design, where the mass of the PMG and structure were aligned with expectations, was used as a proxy in this analysis for performance with improved mass distribution. Significant improvements in mass distribution are achievable with a change to PMG topology, such as the LARS system under development by C·Power.

Impacts of these potential near-term performance improvements for the H3p are summarized below, and in Table 25.

For the H3p at PWS, assuming improved performance from SNL assessed advanced controls increases total mechanical power by 3.4%. If reasonable targets for efficiency are assumed, then the net electrical power increases by 12%; if advanced controls are considered along with efficiency improvements, the net power increases by 16%. If improved mass distribution is assumed, the mechanical power increases by 6%; if advanced controls and improved efficiencies are also assumed, the net power increase is 23%. Similar improvements are shown for EMEC and Humboldt, with gains of 23 and 26%, respectively, if all three areas of improvement are assumed.

For the H3u at PWS, assuming advanced controls, target efficiencies, or improved mass distribution individually yields performance increases of 3.5, 12, and 6%, respectively; taken together a performance increase of 23% is estimated. Similar improvements are shown for EMEC and Humboldt, with gains of 22 and 23%, respectively, if all three areas of improvement are assumed.

Table 25 – Impact of potential improvements on performance estimates.

StingRAY	PWS	EMEC	Humboldt
H3p	22%	23%	26%
H3u	23%	22%	23%

The discussion of performance estimates, potential improvements, and their impact on Project metrics is continued in section 7.

6.6 Manufacturing Plan and Cost Estimates

Manufacturing planning and capital expense (CapEx) estimates are described briefly below, and in greater detail within *DE-EE0008954 H3-CAPEX-6.4 H3 Capital Expense Estimates* (Appendix 13.31). Due to the proprietary nature of the H3p WEC design, the actual cost estimates are excluded from this "Unlimited Data" document but are included in the "Protected Data" appendix.

6.6.1 Manufacturing Plan

The H3p is to be fabricated and assembled at a shipyard on the Columbia River (e.g., Vigor). Once fully assembled the H3p will be prepared to roll into the Columbia River for ballasting, and pre-installation verification testing as outlined in the preliminary IO&M plan (see section 6.7).

The stator, rotor magnets, and rotor are to be manufactured by Supplier 1. After pre-assembly and testing, they will be shipped to the primary H3p fabrication and assembly site. The stator is composed of four sections to facilitate shipping. A preliminary PMG and H3p nacelle assembly plan has been developed with significant consultation with Supplier 1 and Cardinal.

Some systems will require additional engineering during the manufacturing stage, including but not limited to the following.

The hull structure requires an additional design verification iteration, as the system mass has increased significantly during the final design, requiring a reassessment of the design loads. The dynamic response of the WEC (e.g., loading) needs to be reassessed considering the significant changes to WEC mass distribution of the final design. This structural assessment will include the hemispherical pontoon heads, which were added late in the design process in response to the increased active mass, and the damaged stability assessment. Finally, design modifications at several fatigue critical areas were proposed, and require final analysis to verify suitability. Following this, the detailed drawings will be used as a basis for fabrication drawing package.

The generator manufacturing process requires detailing by Supplier 1, as it is a bespoke generator and not a commercial product. Magnet installation and pole alignment procedures will also be detailed.

Several critical design requirements were not sufficiently addressed by Supplier 1 during the electric plant design. Firstly, peak accelerations and angles of inclination of the H3p are greater than what is covered by marine standards, and Supplier 1 did not address the survivability and operability of the electric plant in these elevated requirements. Secondly, anti-paralleling and generator control for islanding mode, in the case of loss-of-grid fault, was not directly addressed by Supplier 1's design. Finally, while Supplier 1 did design over-voltage protection, there are questions about system longevity due to the potentially high rate of incidence. Supplier 1's cost estimate for manufacturing includes NRE to address these issues.

Furthermore, as discussed earlier, the electric plant design is poorly matched to the pulsed nature of wave power and is overrated with respect to the H3p output. Significant gains in performance, and possibly system longevity, are achievable with further optimizations of controls, switching frequencies, and switching hardware for ultra-low frequency operation with non-standard duty cycle (stochastic wave cycling).

Supplier 1 has proposed scope for the electric plant manufacturing stage that includes design modifications to address these issues, improving survivability, reliability, and performance.

SCADA hardware will be finalized according to current equipment standards at the time of fabrication. Software for the electric plant and WEC SCADA systems will be integrated and programmed.

Detailed manufacturing and assembly plans will be developed during an anticipated follow-on manufacturing stage.

6.6.2 H3p Cost Estimates

H3p cost estimates were derived from a mix of supplier quotes and estimates where possible, and from engineering estimates otherwise.

The 0100 Hull manufacturing cost estimate is based on a rough order of magnitude estimate provided by Vigor, and includes fabrication drawings, assembly, and coatings.

The 0210 PMG and 0300 Electric Plant estimates are provided by Supplier 1 and include non-recurring expenses (NRE) for tooling, engineering, and testing. The 0200 PTO mechanical component cost estimates (bearings and seals) are based on vendor estimates.

The 0400 SCADA, 0500 Auxiliary, and 0600 Outfit & Furnishing cost estimates are primarily based on vendor quotes and estimates, with engineering estimates for the remaining components.

The 0700 Mooring estimate is provided by NREL and is a mix of vendor and engineering estimates. NREL engineering estimates are based on feedback from industry partners in previous projects.

The 0800 Power Export estimate is based on vendor estimates, and includes NRE for engineering, as well as a spare cable for risk reduction (due to long lead time for replacement).

System cost estimates are given in a “Protected Data” appendix (Appendix 13.31). Preliminary estimates are shown alongside the final estimates, to illustrate the substantial cost estimate increase that came from the detailed design.

The largest cost increase came from the PMG; the ring generator design required more active material than originally estimated, along with significant stiffening to maintain the air gap under wave loading while integrated into the nacelle hull. The second most significant cost increase was for the hull, most of which was to provide additional stiffness to, again, maintain the PMG air gap. Other significant cost increases were borne by the electric plant and umbilical (electrical collection) systems. The electric plant design is not a good fit to the low-frequency pulsed power and is overrated; C·Power believes there is significant room for improvement in terms of performance and cost. The umbilical system cost was underestimated in C·Power’s preliminary assessment. Finally, inflation has had a significant effect on cost estimates over the course of the Project.

C·Power believes that the cost of the generator and electric plant as estimated by Supplier 1 is unreasonably high, and results primarily from difficulties in comprehending and designing towards the stochastic, pulsed power inherent in the StingRAY’s wave driven power profile. With some additional codevelopment of the PMG and electric plant systems, C·Power believes that the cost can be reduced significantly.

One promising avenue considered for additional cost reduction is the further development and implementation of C·Power’s proprietary PTO technology, which has the potential to reduce the air gap while also allowing for more structural deflection. Dubbed LARS, or Localized Airgap Reduction System, this system will reduce the structural cost (as the stiffness requirement will be much less) as well as the generator cost (as less active material is required).

See Appendix 13.31 for C·Power quantitative estimates of CapEx achieved withing the Project, along with estimates of anticipated cost reduction associated with the improvements discussed here.

6.6.3 H3u Cost Estimates

Due to the fact that the H3p received detailed design within this Project, but Project metrics assume a WEC optimally sized for utility production (i.e., the H3u), it was necessary to estimate H3u costs based on the H3p design. As the StingRAY H3 is a scalable system, it was possible to make reasonably accurate estimates for the H3u. For example, the ballast control system is essentially piping, so the cost was assumed to scale linearly with length (the H3u is 1.40 times greater in length than the H3p, and 1.40^3=2.76 times greater in volume). Coatings must necessarily cover the same surfaces, so the cost was assumed to scale linearly with area (i.e., length squared, 1.40^2=1.97). On the other hand, the SCADA system would be identical for both H3p and H3u, so the cost is constant for both. All cost scaling assumptions are detailed in Appendix 13.31.

H3u costs do not include non-recurring expenses (NRE), as the estimate is intended to reflect a commercial development. H3u CapEx estimates based on the design achieved in-Project, as well as with improved cost targets (for PMG/PE codevelopment, and for LARS implementation), are given in Appendix 13.31, along with the cost scaling assumptions. The same cost scaling assumptions are used to scale from H3p cost estimates achieved in-Project, as well as from the improved H3p cost estimates.

6.7 IO&M Plan and Cost Estimates

Installation, operation, and maintenance (IO&M) planning and expense estimates are described briefly below, and in greater detail within *DE-EE0008954 H3-IOM-6.5 IO&M Plan* (Appendix 13.32). Due to the proprietary nature of the H3p WEC design, the actual cost estimates are excluded from this “Unlimited Data” document but are included in the “Protected Data” appendix.

6.7.1 *IO&M Plan*

The IO&M plan covers all in-water procedures, starting with launch into the Columbia River after assembly and integration are completed, and ending with recovery from PWS following completion of testing. The IO&M plan developed in-Project is preliminary and allows for risk assessment and cost estimates. Detailed, actionable plans will be developed during an anticipated follow-on phase comprising manufacturing and at-sea testing.

PWS is a pre-permitted facility and has provided C·Power with available information on regulatory and permitting requirements, and monitoring programs, pertaining to acoustics, entanglement and collision, organism interactions, EMFs, pinniped haul-out, and water resources. The IO&M plan includes an outline of best management practices aimed to address: safety and emergency response; protected species monitoring, protection, and mitigation; environmental monitoring, protection, and mitigation; WEC monitoring; and reporting and log keeping. During detailed operations planning, C·Power will ensure practices and procedures in place to comply with all applicable requirements and regulations as communicated by PWS, and relevant federal, state, and/or local agencies.

The IO&M plan organizes all procedures into four high-level areas: pre-installation verification and validation; installation; operations and maintenance; and recovery.

The first stage, pre-installation verification and validation (V&V), is conducted in-river near to the fabrication site and prepares the assembled WEC for in-water transportation to PWS. The WEC will be towed to a deep draft site in the Columbia River, where V&V tests will be conducted. V&V will include towing, ballasting, and PTO motoring and generation. At the conclusion of V&V, the WEC will be towed to a sheltered location and prepared for transport to PWS.

The installation stage comprises three sub-stages: PWS site preparation, transport to PWS, and WEC installation. Site preparation comprises pre-installation of mooring and umbilical systems, simplifying and streamlining the subsequent WEC installation. Mooring and umbilical installations are already covered in detail in sections 6.2.7 and 6.2.8, respectively.

The H3p WEC is designed for shallow draft towing under its own buoyancy. With variable sea water ballast absent, the WEC floats in its horizontal towing orientation. The H3p will be towed down Columbia River (165 km), and then south along the coast to the PWS site (185 km). A towing speed of 4 knots is assumed, corresponding to 47 hours underway. If deemed necessary, the WEC could be towed into Newport Harbor (e.g., for additional inspection, or to await installation).

Once the WEC is at PWS it will be connected to the pre-installed mooring and umbilical systems and ballasted into operational orientation. This stage requires the use of three vessels: one to position the temporary buoy, one to position the WEC, and one to raise and lower the mooring lines that are being individually detached and reattached. Because the anchors and large floats are already installed, the weights and tensions of the mooring components being worked with are small, meaning that large, specialized vessels are not required. These procedures are described as parts of the mooring and umbilical installations (sections 6.2.7 and 6.2.8, respectively).

The procedure for detaching the WEC from the mooring and umbilical systems and recovering the mooring and umbilical system generally follows the reverse of the installation procedure. The WEC can be detached from the mooring and umbilical system by using a temporary buoy and one-by-one detaching each mooring line from the WEC and attaching it to the temporary buoy. However, if the entire system is to be removed, the temporary buoy does not need to be used. If only the WEC is to be removed, the temporary buoy used during installation can be used again to take the place of the WEC, allowing the mooring system and power cable to remain in place. Once installed the WEC will remain on location under continuous operation for two years.

Scheduled inspection and maintenance comprise any task which is pre-planned and requires on-site personnel. Remote monitoring via sensors, cameras, and microphones will be ongoing, and reduces the need for onsite visits.

Inspection and maintenance tasks are performed by trained technicians who are transported to the WEC via marine vessels. Table 26 outlines the scheduled inspection and maintenance tasks; the schedule may need to be adapted on a seasonal basis (i.e., during appropriate weather windows). These quarterly inspections are expected to take no more than one day per event. For safety, a minimum of two personnel will be on the WEC, and one aboard the service vessel, during onboard operations.

Onboard environmental conditions will be monitored, and air exchange will be forced (via 0530 Climate Control) as required prior to and during human access. Communication will be maintained between personnel on board the WEC and service vessel. Repeaters will be installed, and field tested, to ensure reliable communication during onboard events.

Table 26 – Scheduled maintenance tasks.

System	Component	Cycle	Description
0100	Hull	3 months	Visual internal (accessible spaces) and external (via ROV if possible) inspection. Biogrowth cleaned via divers if necessary.
0200	PTO	3 months	Visual inspection (as possible from control room).
0300	Electric plant	3 months	Visual inspection.
0400	SCADA	3 months	Visual inspection.
0500	Auxiliary systems	3 months	Visual inspection of pumps, piping, etc.
0600	Outfit and furnishings	3 months	Visual inspection of penetrations.
0700	Mooring	6 months	Visual inspection with ROV.
0800	Umbilical	6 months	Visual inspection with ROV.

Any unplanned maintenance activities resulting from a failure of any WEC system will be diagnosed by onboard SCADA sensors, and internal and external surveillance cameras, if possible. The level of corrective action, and the impact of the unscheduled maintenance depends on the severity of the failure and will be addressed at the time of occurrence.

6.7.2 IO&M Cost Estimates

Costs have been estimated for operations comprising the four major IO&M stages: pre-installation V&V, installation, O&M, and recovery. These cost estimates are detailed in the *IO&M Plan* (Appendix 13.32). A 50% contingency has been added to the estimates to account for uncertainty in this preliminary estimate.

7 PROJECT METRICS ESTIMATES

Project metrics estimates are described briefly below, and in greater detail within *DE-EE0008954 H3-PRF-6.7.b Project Metrics Estimates* (Appendix 13.33). Due to the proprietary nature of the design, the actual metrics estimates are excluded from this “Unlimited Data” document but are included in the “Protected Data” appendix.

The Project metrics identified in the Statement of Project Objectives (SOPO) are Levelized Cost of Energy (LCOE), Peak-to-Average Mechanical Power (PAMP), and Capture Width Ratio (CWR, also known as Relative Capture Width, RCW). Targets were identified in the SOPO for the two resource sites of interest, PacWave South (PWS) and the European Marine Energy Center (EMEC). An LCOE estimate for the DOE reference resource, offshore of Humboldt, California, was also calculated. The Project metrics targets and estimations are based on the utility-scale H3u.

The RCW is calculated for each sea state based on the net electrical power out of the WEC (before transmission to shore), the average wave power of the sea state, and the characteristic dimension of the device.

$$Capture\ width\ ratio = \frac{capture\ width\ [m]}{characteristic\ dimension\ of\ the\ device\ [m]}$$

$$Capture\ width = \frac{absorbed\ wave\ power\ [kW]}{wave\ resource\ [\frac{kW}{m}]}$$

The PAMP is calculated for each sea state based on the total mechanical power before any conversion losses. The peak power estimates are taken as the maximum from the 50 Hz hydrodynamic performance simulations.

$$Peak\ to\ average\ power = \frac{peak\ absorbed\ power\ [kW]}{average\ absorbed\ power\ [kW]}$$

The LCOE provides an estimate of the cost of energy. The LCOE model and assumptions used in this analysis are compliant with Department of Energy (DOE) guidance [7]; the model is a function of Installed Capital Cost (ICC), Fixed Cost Rate (FCR), Operations & Maintenance (O&M) costs, and Annual Energy Production (AEP).

$$\mathrm{LCOE} = ((\mathrm{ICC} * \ \mathrm{FCR}) + \mathrm{O\&M}) \div (\mathrm{AEP})$$

LCOE estimates were calculated within the DOE SAM model ("SAM 2022.11.21 for Windows", accessed online at *https://sam.nrel.gov/download*). Assumptions and calculations are detailed in the *Project Metrics Estimates* (Appendix 13.33).

Project metric estimates are provided below for RCW, PAMP, and LCOE in Table 27. Note that some assumptions have changed between preliminary and final estimates, as explained below, and that the estimates provided in Table 27 follow the assumptions made at the time of estimates.

Due to the proprietary nature of the design, the actual metrics estimates are excluded from this "Unlimited Data" document (see the *Project Metrics Estimates* report in "Protected Data" Appendix 13.33); here the metrics are presented relative to the SOPO targets. These primary estimates account for results achieved within the Project. Note that there were no targets established for Humboldt within the SOPO, thus no relative results can be shown.

Due to issues with supplier designs and a few other things, some Project metrics don't meet the established targets. However, C·Power has identified a pathway to meet all targets, as explained in more detail below.

The final RCW estimate (higher is better) for PWS exceeds the SOPO target, while for EMEC the final estimate does not. Final PAMP estimates (lower is better) exceed the SOPO targets for both PWS and EMEC. Final LCOE estimates (lower is better) fall short of the SOPO targets for both PWS and EMEC and are further off from the targets than the preliminary estimates.

There have been several major impacts to the metrics estimates over the course of the Project. First, the wave resource data set used for PWS estimates has changed several times, with wave power decreasing at the time of preliminary estimates with respect to the SOPO targets. For the final estimates, the resource

characterization from NREL SAM model was used, which has a similar wave power with respect to the time of establishing SOPO targets.

Table 27 – Project metrics estimates (relative to targets), primary.

	Preliminary Estimate	Final Estimate
PacWave South		
RCW	+13%	+3%
PAMP	+2%	-8%
LCOE	+29%	+50%
EMEC		
RCW	-3%	-18%
PAMP	-10%	-11%
LCOE	+3%	+41%

Secondly, no improvement for advanced controls is included in the final primary performance estimates, whereas such an improvement was assumed in establishing SOPO targets and calculating the preliminary estimates.

Finally, and most significantly, the final metrics estimates suffer from increased losses and costs established in the final design stage. The increased losses are primarily due to the poor efficiency of the Supplier 1-designed power electronics, and to a lesser extent the Supplier 1-designed PMG (along with their cooling systems). Furthermore, significant mass increases, both for the Supplier 1-designed PMG and PMG-led requirements for structural stiffness, resulted in a non-optimal mass distribution and reduced power performance.

These areas of performance and cost impacts, and potential scenarios for improvement in the near-term, are discussed in detail in *Performance Estimates* (Appendix 13.30) and *Capital Expense Estimates* (Appendix 13.31). Based upon these potential performance and cost improvements, alternate Project metrics are presented in Table 28. Three improvement scenarios are outlined below, with additional details found in the *Performance* and *Expense* reports.

The first area of potential improvement is advanced controls. A study performed in-Project by Sandia National Laboratory (SNL), implementing complex conjugate controls, showed potential for performance improvements by broadening the WEC's frequency response. These results need to be confirmed at PWS and so were not included in the primary performance estimates. Implementation of these advanced controls leads to modest improvements in all metrics, on the order of 3 to 4%.

The second area of potential improvement assumes continued co-development of the PMG and PE systems, resulting in performance and cost in line with C·Power targets. Largely due to difficulties in working with Supplier 1 discussed elsewhere, these systems are poorly matched to the pulsed nature of wave power and are overrated with respect to the H3p output. C·Power believes that there is significant room to improve these systems in terms of cost and performance, and that these targets represent reasonable values that could have been achieved in-Project. Implementation of these PMG and PE cost and performance targets result in significant improvements of RCW (12% increase) and LCOE (25% decrease) metrics. Combined with

advanced controls, the improvements are somewhat greater: RCW increases by 15 to 16%, and LCOE decreases by 27%, compared to the primary results.

Table 28 – Project metrics estimates (relative to targets), potential improvements.

	Project Achieved	**w/ Adv. Controls**	**… and Target PTO / PE**	**… and LARS**
PacWave South				
RCW	**+3%**	**+6%**	**+19%**	**+26%**
PAMP	**-8%**	**-11%**	**-11%**	**-16%**
LCOE [$/kW-h]	+50%	+45%	+9%	**-9%**
EMEC				
RCW	-18%	-15%	-5%	**+1%**
PAMP	**-11%**	**-14%**	**-14%**	**-18%**
LCOE [$/kW-h]	+41%	+37%	+2%	**-15%**

The third area for potential improvement assumes further development and implementation of C·Power's proprietary Localized Air gap Reduction System (LARS) PTO technology, which has the potential to reduce the air gap while also allowing for more structural deflection. This system would reduce the structural cost / mass (as the stiffness requirement will be much less) as well as the generator cost / mass (as less active material is required). The significant reduction in active mass will also allow for a more optimal mass distribution, increasing performance. C·Power originally intended to pursue LARS development within this Project, but resources were insufficient. This scenario assumes the same efficiency improvements as the second scenario (i.e., targeted PTO/PE), but further reduces cost while also improving mechanical power performance. Implementation of the LARS development assumptions result in significant improvements of RCW (18% increase), PAMP (6% decrease), and LCOE (37% decrease) metrics. Combined with advanced controls, the improvements are even greater: RCW increases by 22 to 23%, PAMP decreases by 9%, and LCOE decreases by 40%, compared to the primary results.

As highlighted with green text in Table 28, several Project metrics are achieved by the primary Project results, and all metrics can be achieved by implementation of the near-term improvements outlined here. The improvements outlined here will bring the StingRAY H3p WEC to a state of cost-competitiveness for the near- and medium-term markets identified in the *Commercialization Plan* (section 5 and Appendix 13.7). However, these are only the most immediately obvious improvements to be pursued by C·Power, and additional R&D efforts are anticipated that will take the H3p further along the path to utility-scale cost-competitiveness.

8 RISK MITIGATION

8.1 Risk Management Plan and Registers

The Risk Management Plan (RMP) was developed based on C·Power's FMECA-based risk assessment process. The risk assessment process resulted in the population and maintenance of Risk Registers (RRs). Each major system (and as needed, subsystem) has a distinct RR, allowing each system or subsystem to be assessed individually.

The RMP and RRs are described briefly below, with further details presented in the following documents:

- Risk Management Plan
    - *DE-EE0008954 H3-RMP-1.2 Risk Management Plan* (Appendix 13.34)
- Risk Registers
    - *DE-EE0008954 H3-RR-6.3 Final Risk Assessment* (Appendix 13.35)

The RMP specifies a risk assessment process which includes identification, analysis, and mitigation of risks. Failure Modes, Effects, and Criticality Analysis (FMECA) was conducted to systematically identify all potential failure modes and their effects on the system, and to analyze the criticality of each risk based on the likelihood of the event and the severity of the impact. All systems, modes of operation, and life-cycle phases were considered. Actions were recommended to mitigate the criticality of risks, if needed, either by reducing the likelihood of the risk or the severity of its impact. As actions were taken, risks were reassessed with consideration thereof. The risk assessment was executed iteratively as an integral part of the design process.

The occurrence class is an estimated probability of occurrence. The occurrence classes are specified below in Table 29. Note that the failure rates specified are upper bounds (e.g., occurrence class 4 is assigned for annual failure rate, r, such that $0.01 < r \leq 0.1$). The H3p WEC is a novel technology and failure rates are not generally available; the estimations were made with engineering judgment.

Table 29 – Occurrence classes.

Occurrence Class	Description	Annual Failure Rate	Return Period [years]
1	Exceptionally unlikely	1E-04	10,000
2	Unlikely	1E-03	1,000
3	Rarely	1E-02	100
4	Likely	1E-01	10
5	Common	1E+00	1

The severity class identifies the significance of the consequences of a given failure. The severity classes are specified below in Table 30. For each registered risk, a severity class was assigned to each of the four consequence categories: human safety, environment, WEC operation, and assets. The anticipated post-failure response (such as logistics and assets required for repair) was included in the consideration of consequence.

Table 30 – Severity classes.

Severity Class	Description	Human Safety	Environment	WEC Operation	Assets
1	Insignificant	Negligible injury and/or health effect (e.g., band-aid)	Negligible effect on environment	Negligible effect on performance	[2k USD]
2	Minor	Minor injuries and/or health effects (e.g., stitches)	Minor effect on environment	Minor system degradation	Repairable, at next maintenance interval [20k USD]
3	Major	Major injuries and/or health effects (e.g., broken bone)	Major effect on environment	Major system degradation or loss of operation for 1 month	Repairable, outside maintenance interval [200k USD]
4	Critical	Significant injuries and/or health effects (e.g., lasting disabilities)	Critical effect on environment	Critical system degradation or loss of operation for 3 months	Significant but repairable, outside maintenance interval [2M USD]
5	Catastrophic	Catastrophic injuries (e.g., fatality)	Catastrophic effect on the environment	Irreparable damage, operations cease prematurely, complete failure	Total loss, salvage necessary [20M USD]

The risk criticality ranking is based on the occurrence and severity classes, following the risk matrix presented in Table 31. For each registered risk, a risk ranking was assigned for each of the four consequence categories.

The risk criticality rankings were used to identify and prioritize risk mitigation activities. Note that the highest risk ranking for a registered risk governs; for example, if a registered risk has three low criticality rankings and one high criticality ranking, it is considered as being high criticality risk.

Registered risks with a high criticality are identified as having an *intolerable* level of risk over the course of the H3p life cycle; action is required to mitigate these risks. Registered risks with a low criticality are identified as having a *tolerable* level of risk over the course of the H3p life cycle; no action is required to mitigate these risks. Registered risks with a medium criticality are identified as having an *undesirable* level of risk over the course of the H3p life cycle. Undesirable risk items are reviewed to determine if further engineering action is required to mitigate risk. C·Power's goal is to design "in the yellow"; while high risks are clearly intolerable, low risks may be indicative of costly overdesign.

Table 31 – Risk criticality matrix.

	Severity				
Occ	**1**	**2**	**3**	**4**	**5**
5	Med	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med

The safety level (see section 4.5) specified for a given design element was considered in the risk assessment. Because a safety level of 3 (SL3) explicitly specifies a higher failure rate than SL2, the occurrence class for SL3 elements was increased by one (1) compared to SL2 in the initial risk assessment. For example, for SL2 elements, ultimate loading failures were typically assigned an occurrence class of 2, whereas degradation (e.g., corrosion and fatigue) failures were assigned an occurrence class of 3. For SL3 elements, ultimate and degradation failures were assigned occurrence classes of 3 and 4, respectively. As discussed earlier, the hull structure was designed as SL3 while all other elements were SL2.

The RRs have guided the design process by identifying critical risks. Many engineering actions recommended to mitigate risk were carried out during this Project and are documented in the RRs. The RRs are also a critical component of the Certification Plan, as discussed in section 8.3.

8.2 Standards Conformity

The primary design standards identified are *IEC TS 62600-2 Design Requirements for Marine Energy Systems* and *IEC TS 62600-10 Assessment of Mooring System for Marine Energy Converters*. The primary standards reference numerous other standards for specific design aspects. The referenced standards are generally IEC or ISO. However, alternate standards from national organizations were considered and adopted provided they are equally applicable and sufficiently robust. C·Power's experience using DNV standards, as well as engagement of DNV for Technology Qualification, led to their being widely adopted.

A detailed listing of all standards utilized in design is included in the *Technology Assessment* (Appendix 13.36). Additional details on use of standards, and exceptions if any, are included in the relevant design documents (see Appendices).

C·Power's experience implementing the IEC Technical Specifications (TS) in design yielded several lessons. *IEC 62600-2* served to provide a road map for the design, however it was found to cover structural

design more completely than it did for other systems (e.g., PTO, power electronics, power export). Most of the detailed design requirements and procedures were in referenced ISO/IEC documents; as discussed above, C·Power's experience with DNV led to the adoption of DNV standards as alternates to the ISO/IEC references. One shortcoming of *IEC 62600-2* is its treatment of safety levels and associated safety factors. While the TS allows for one of three safety levels to be selected by the designer, safety factors are only specified for a single safety level.

IEC 62600-10 was found to be more comprehensive in its treatment of design. Still, a need to refer to alternative standards for mooring design was deemed necessary (e.g., design fatigue factors are not sufficiently covered).

8.3 Technology Qualification

DNV was contracted to support Technology Qualification (TQ) of the H3p WEC, as a means of risk reduction. The TQ is described briefly below, with further details documented within the following documents:

- Certification Basis
    - *DE-EE0008954 H3-TQ-CB Certification Basis* (Appendix 13.36).
- Technology Assessment
    - *DE-EE0008954 H3-DB-2.3 Technology Assessment* (Appendix 13.37).
- Certification Plan
    - *DE-EE0008954 H3-TQ-CP Certification Plan* (Appendix 13.38).
- Certification Report
    - *DE-EE0008954 H3-TQ-CR Certification Report* (Appendix 13.38).
- Statement of Feasibility
    - *DE-EE0008954 H3-TQ-SOF Statement of Feasibility* (Appendix 13.39).

The TQ was conducted in accordance with *DNV-SE-0120 Certification of Wave Energy Converters and Arrays* [8]. The scope of work undertaken within this Project is illustrated in Figure 70.

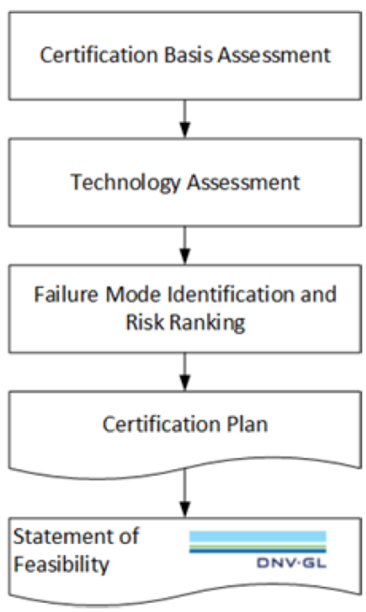

Figure 70 – Technology Qualification scope of work.

The *Certification Basis* (CB) defines the expectations of the novel H3p WEC in the absence of directly applicable codes, procedures, and standards. The CB includes requirements, targets, and limits, regarding descriptive characteristics, failure targets, site conditions, environmental conditions, fatigue and loading, materials, power characteristics, safety parameters, fabrication, installation, operation, and maintenance.

The *Technology Assessment* (TA) divides the WEC into a number of manageable elements (e.g., systems, subsystems, components) and the primary functions of each element are specified. The TA division follows that in Table 7, but with additional levels of breakdown. The purpose of the TA is to determine which technology elements are not completely covered by an existing set of adequate acceptance criteria and identify their key challenges. Novel aspects of each element are identified, particularly those which may pose challenges. The novelty of the element is specified, as well as the novelty of the application; together these lead to a technology class, which is used in determining the qualification methods and the required level of DNV activity. Novel elements (classes 2 – 4) are subject to TQ, while proven elements (class 1) can be covered using applicable standards and guidelines. Of the 68 identified technology elements, 27 were considered proven, and 41 considered novel. Of the 22 identified phases and activities, 11 were considered proven, and 11 considered novel. The TA also specifies the safety level and minimum design life for each element, and lists the standards used to support qualification.

The Failure Mode Identification and Risk Ranking is described above in section 8.1. The objective of the risk assessment process was to identify all relevant failure modes of concern for the elements defined as new technology in the TA, assess the associated risks, and specify recommended risk mitigation activities as warranted. Actions identified included analysis and testing, as well as data collection and review of procedures and plans intended to reduce the likelihood of failure or the resulting consequences.

Recommended actions to mitigate risks were consolidated into the *Certification Plan* (CP), considering the identified novelty of each element as specified in the TA. The CP presents a comprehensive set of actions to be carried out with the intention of proving that the design meets the requirements listed in the CB. Many of the actions identified in the RRs and the CP were carried out as part of the Project design scope and are noted in the RRs.

At the conclusion of the TQ process, DNV issued a Statement of Feasibility (SOF). The SOF affirms that the H3p WEC, in accordance with the CB, is conceptually feasible and suited for further development and qualification. Additional qualification activities (e.g., Design Assessment, Manufacturing Survey) leading up to a Prototype Certificate will be considered for future work.

9 TANK TESTING AND MODEL VALIDATION

A tank test experiment was conducted, the primary objective of which was to characterize the WEC response sufficiently for hydrodynamic model validation. The tank test and model validation are described briefly below, and in greater detail within *DE-EE0008954 H3-TST-3.2 Tank Test and Model Validation* (Appendix 13.40).

Tank testing was conducted over a period of four weeks during April 2022. Characterization of the wave conditions was performed in April 2021, without the presence of the model WEC. Testing was originally planned for May 2021, but issues with the original model WEC were insurmountable. The original model WEC utilized a fabrication approach that was new for C-Power, in which all structural hull components were 3D printed using polylactic acid (PLA) feedstock. This approach was intended to reduce fabrication costs and accelerate the schedule but resulted in a hull that leaked at multiple locations via multiple failure modes. Additionally, the single-stage belt drive was not capable of transmitting the required torque (i.e., belt skipping teeth when oscillating).

The redesign solved the two problems that prevented testing of the original model. The aluminum hull eliminated the problem of water weeping through a honeycomb structure, welded construction mitigated leaking at glued joints, and improved seal design prevented leaks at hatches and penetrations. The two-

stage belt drive, and wider belt, mitigated the power transmission slip observed with the original PTO. Further design details are given in the following section.

9.1 Tank Testing

Testing was performed in the Directional Wave Basin (DWB) of the Hinsdale Wave Research Laboratory (HWRL). The DWB is 48.8 m long, 26.5 m wide and 2.1 m deep (maximum operating depth of 1.5 m). The wavemaker consists of 29 individually actuated piston-type paddles and is capable of generating regular and irregular waves which can be normally incident, oblique or multi-directional, as well as solitary or tsunami-like waves. Wave conditions were measured using a double directional wave gauge array offshore of the WEC, with an additional four wave gauges located along the motion tracking frame perimeter.

Prior to testing, a subset of wave conditions was run without the WEC installed. The wave measurement instrumentation was identical to the test configuration, with the addition of another wave gauge located at the nominal WEC location. Measuring wave conditions without the presence of the WEC allowed for characterization of undisturbed conditions, and assessment of variation of conditions with location.

The scale WEC model was designed and built, to the degree practical, as a 1:28 scale model of the H3p WEC; the scale model WEC is referred to as H3t. Froude scaling is used in all aspects of this scaled experiment, as inertial and gravitational forces dominate.

The hull was primarily an aluminum fabrication (Figure 71). A Delrin lid was fitted atop the nacelle, covering a flat watertight hatch which allowed access to the PTO inside the nacelle. Watertight end caps were also installed on either side of the float and ballast tank, allowing for installation of ballast. Gusset plates at the pontoon-to-upper spar intersection facilitated lifting operations. Eyebolts were fitted to the ballast tank to facilitate mooring connections. Primary dimensions are given in Table 32.

The PTO consisted of a dual stage belt-drive to a PMG motor (Figure 72). AT5 timing belts reinforced with hi-flex steel provided high tension, stiffness, and tooth shear strength for accurate positioning and low backlash. A dual-tensioning system allowed for independent tensioning of either belt. A brushless permanent magnet generator was selected to minimize cogging forces and cut-in speed. Fixed resistance was used to set generator damping characteristics, and multiple resistor values were available for selection (using an externally mounted, rotary switch) to set the damping value. A torque transducer was installed on the high-speed shaft.

The mooring system was modeled with horizontal elastic lines, running from the hull interfaces to vertical stanchions fixed to the tank floor. The two bridle lines were connected towards the port and aft ends of the front face of the ballast tank and came to a single stanchion in front of the WEC (mimicking the large subsurface buoy of the primary mooring). The tether line attached to the ballast tank at bottom dead center and run aftwards to a stanchion. S-beam load cells were installed inline, for each mooring line, and their output connected to the HWRL DAQ system.

Figure 71 – Schematic depicting H3t scaled model (left), and photo of deployed model (right).

Table 32 – Key characteristics of scaled model.

Characteristic	Unit	Value
Displacement	kg	41.3
Draft	cm	63.3
Width	cm	72.8
Length (incl. float)	cm	73.9

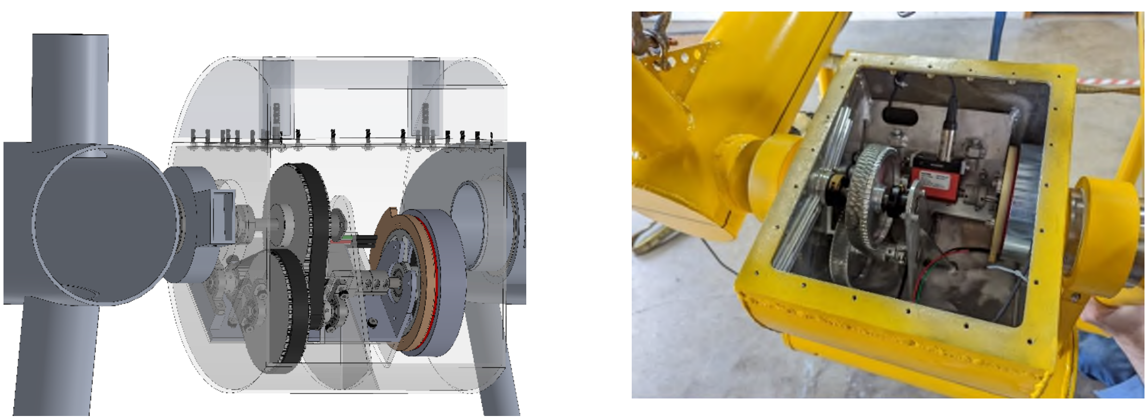

Figure 72 – PTO assembly schematic (left), and photo (right).

An optical motion tracking system (Qualisys) was used to measure the positions of the central and float bodies in real time. The system utilizes infrared cameras and reflective, passive markers mounted on the bodies of interest. Both above- and under-water cameras were used, purportedly allowing for the float's motion to be tracked even if submerged or overtopped (and upside down).

Data acquisition was set up and handled by HWRL. The HWRL DAQ monitored and recorded all signals, including:

- Wavemaker trigger, displacement, and surface elevation at the wave board
- Wave gauges
- Qualisys 6 DOF WEC body motions
- PTO torque transducer
- Mooring load cells

Test conditions included modifications to WEC (e.g., PTO damping, float ballast, float position), as well as a diverse set of wave conditions (e.g., regular waves, operational seas, extreme seas).

9.2 Test Results and Model Validation

The WEC response was characterized for each real seas or regular wave analysis window, where sufficient quality controlled (QC'd) data was available (see discussion of QC below). In some cases, multiple observations were available due to repetitions of trials. In these cases, the final results are the arithmetic means of the observations (i.e., the expected value of the result). These repetitions were undertaken to evaluate, and quantify, uncertainty in the experimental observations.

The optical tracking system yielded position and orientation in 6 DOFs for the two bodies comprising the WEC. The structural constraints of the WEC make it such that 7 DOFs are sufficient to describe the position and orientation of the WEC: surge, sway, heave, roll, pitch, and yaw of the nacelle, along with the pitch of the float about the nacelle. Sometimes it is more useful to discuss the pitch of the float w.r.t. to the nacelle as this relative pitch actuates the generators. Thus position, velocity and acceleration were archived in 8 DOFs.

Torque on the high-speed shaft was measured with a torque transducer. The remaining torque (i.e., friction on low- and intermediate-speed shafts) was estimated from generator speed using data from dry PTO tests. The dry tests consisted of the float being released from top dead center, to fall under force of gravity, with the main body of the WEC support on the floor of the empty (i.e., dry) tank. The motion tracking system was used to calculate the position, speed, and acceleration of the float. The friction was estimated as the additional torque necessary result in the observed path of the falling float.

The Qualisys position tracking system consists of four above-water cameras and six underwater cameras. One of the six underwater cameras was taken offline at the beginning of testing due to malfunction. Unfortunately, the Qualisys software experienced difficulties combining data streams from above-water and underwater cameras, which ended up dropping all data from the underwater cameras. With only 4 out of 10 cameras functionally online, the tracking system could not properly track many body orientations as markers were blocked from the field of view either by WEC itself or by the water surface. This was especially true for the float as it has a small surface area above the water, and often experiences large motions which in extreme cases can result in submerged float or float flipping over the top to rest upside down behind the nacelle. This resulted in only 17% of extreme sea trials having at least 10% of QC'd, usable data and 0% for heavy aft trials (where additional ballast is added to the float). Another issue with the optical motion tracking system was the water reflection from the sun and indoor lighting. When sunlight was reflected into a camera, it overcame the light reflected by the tracking markers and caused the system to lose track of those markers. This issue was partially mitigated by installing curtains around the wave tank to block environmental light. To admit more trials for response characterization and model validation, a low QC threshold of 10% was established. Even with this low threshold a significant number of trials do not pass. The tables below show the percentage of trials that have at least 10% of data passing the QC criteria. It is noted that regular wave, operational sea, and extreme sea trials respectively have 52, 72, and 17% of trials passing QC. It is further noted that some experiments (i.e., heavy aft float, spread extreme seas) have zero trials passing QC.

A numerical model was developed using ANSYS AQWA v16.0 NAUT. The WEC was modeled at full scale, using scaled-up characteristics of the as-built model WEC and measured wave conditions.

Simulations data were processed following the same methodology as the experimental data and the results were compared.

Table 33 – Number of trials passed QC, regular waves.

Regular Waves	# of trials	# of trials passed QC	% of trials passed QC
Amp scan	13	5	38%
PTO damping scan	13	5	38%
Freq scan	34	21	62%
Total	**60**	**31**	**52%**

Table 34 – Number of trials passed QC, operational seas.

Operational Seas	# of trials [-]	# of trials passed QC [-]	# of trials passed QC [%]
Float start in aft	6	0	0%
Bimodal quartering	3	2	67%
Bimodal	6	6	100%
PTO damping	20	16	80%
Heavy aft float	6	0	0%
Off angle	10	7	70%
Default	65	51	78%
Spectral seed	6	4	67%
Spectral shape	7	4	57%
Spread seas	18	16	89%
Total	**147**	**106**	**72%**

Table 35 – Number of trials passed QC, extreme seas.

Extreme Seas	# of trials [-]	# of trials passed QC [-]	# of trials passed QC [%]
Float start in aft	1	1	100%
PTO damping scan	2	1	50%
Default	12	2	17%
Spectral shape	1	0	0%
Spread seas	1	0	0%
Heavy aft float	5	0	0%
Spectral seed	2	0	0%
Total	**24**	**4**	**17%**

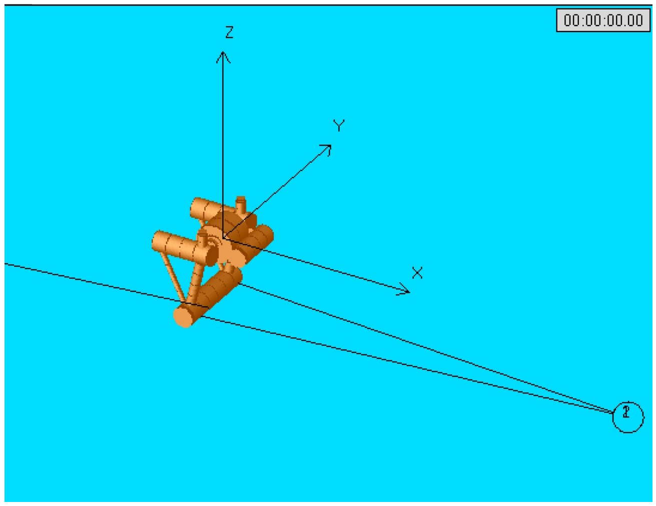

Figure 73 – AQWA simulation WEC model shown in definition position.

Power performance estimates for experiment and simulation in OSS are shown in Figure 74. PTO pitch speed response for OSS and ESS is shown in Figure 75 and Figure 76, respectively. The numerical model performance and motion response results closely match those of the experimental data, though the numerical model tends to overpredict. Potential factors contributing to prediction error include error include low-speed shaft torque estimation, tank scale effect on viscous drag, and low-quality motion tracking data. Overprediction of the response indicates a likelihood of conservative design loads (for Project design of the H3p).

Weathervaning was demonstrated in tank testing over a range of sea states, with the WEC weathervaning within 10° of the waves regardless of wave height or period.

Unfortunately, no torque data was recorded during the weathervaning trials (due to a technical error made in setup that day). In lieu of torque data, PTO rms speed was used to make a comparison between performance for head on and weathervaning trials; no appreciable difference in performance was observed.

Mooring loads were overpredicted significantly by C·Power's numerical model. Note however that the in-Project mooring designer used the tank test results to calibrate their mooring models.

Float overtopping occurred only in extreme conditions, and only with the float freewheeling. Overtopping was correctly predicted by the numerical model. Note however that the tank test WEC float has significantly higher inertia than that of the Project designed H3p (roughly 4x), and thus may not be a reliable predictor of its behavior (in-Project WEC models show significantly more overtopping, in more conditions).

Overall, the numerical model predicts performance and motion response trends with reasonable accuracy in operational and extreme seas, giving confidence to modeling efforts supporting Project design of the H3p.

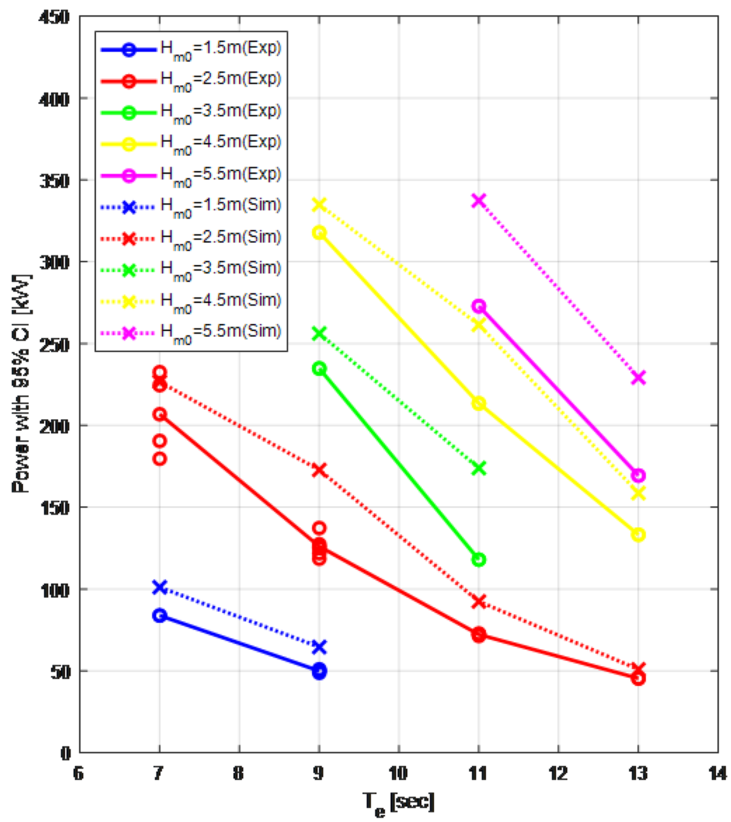

Figure 74 – WEC power in operational real seas.

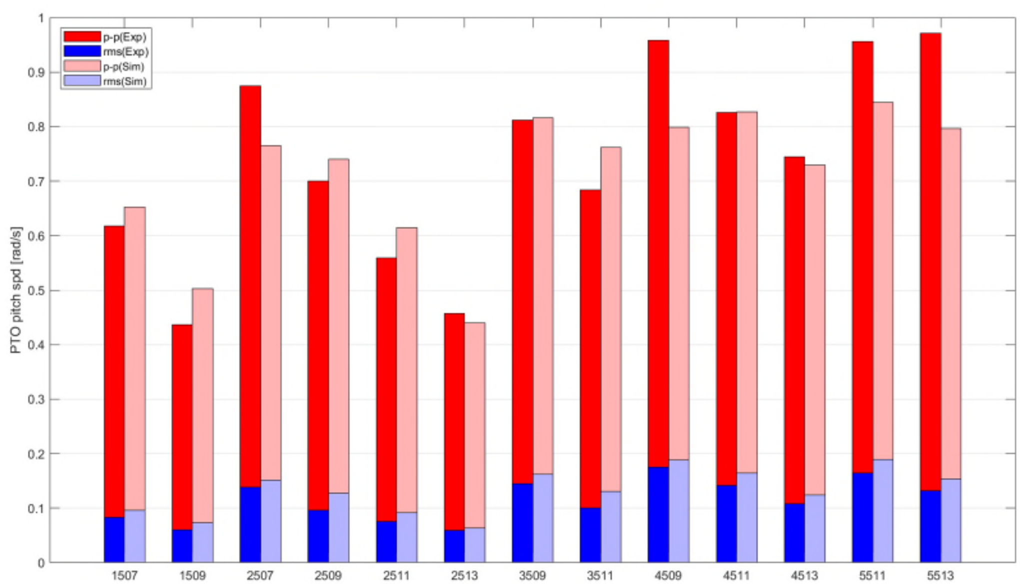

Figure 75 – PTO pitch speed in operational real seas.

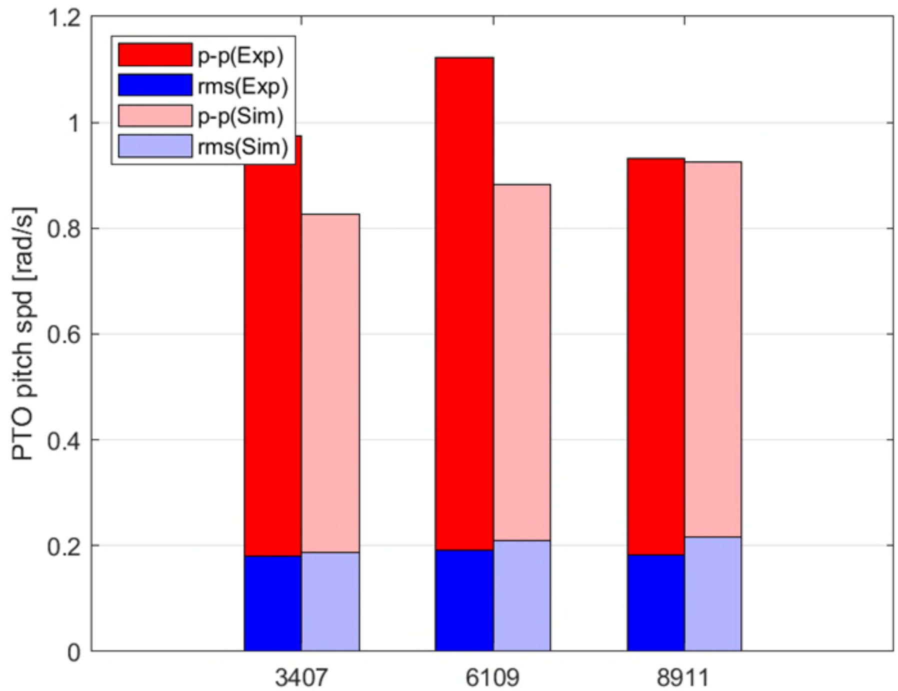

Figure 76 – PTO pitch speed in extreme real seas.

10 ISSUES, RESOLUTIONS, AND LESSONS LEARNED

10.1 Unresolved Issues and Resolutions

0100 Hull Structure

A final design verification iteration is required for the hull structure prior to manufacturing. The dynamic response of the WEC (e.g., loading) needs to be reassessed considering the significant changes to WEC mass distribution of the final design. This structural assessment will include the hemispherical pontoon heads (which were added late in the design process in response to the increased active mass), and the damaged stability assessment. Finally, design modifications at several fatigue critical areas were proposed, and require final analysis to verify suitability. Ideally these tasks would have been carried out in-Project, but resources were exhausted. C·Power intends to seek out opportunities to carry out this final structural design verification.

0300 Electric Plant

Several critical design requirements were not sufficiently addressed by Supplier 1 during the electric plant design. Firstly, peak accelerations and angles of inclination of the H3p are greater than what is covered by marine standards, and Supplier 1 did not address the survivability and operability of the electric plant in these elevated requirements. Secondly, anti-paralleling and generator control for islanding mode, in the case of loss-of-grid fault, was not directly addressed by Supplier 1's design. Finally, while Supplier 1 did design over-voltage protection, there are questions about system longevity due to the potentially high rate of incidence. Supplier 1's cost estimate for manufacturing includes NRE to address these issues.

Furthermore, as discussed earlier, the electric plant design is poorly matched to the pulsed nature of wave power and is overrated with respect to the H3p output. Significant gains in performance, and possibly system longevity, are achievable with further optimizations of controls, switching frequencies, and switching hardware for ultra-low frequency operation with non-standard duty cycle (stochastic wave cycling).

Supplier 1 has proposed scope for the electric plant manufacturing stage that includes design modifications to address these issues, improving survivability, reliability, and performance. C·Power intends to seek out opportunities to address these design deficiencies.

Mass Reduction

Significant mass increases were realized during final design, resulting in a non-optimal mass distribution. A mass reduction campaign ahead of manufacturing would be highly desirable, with multiple potential benefits including reduction of fabrication costs and improved wave power performance.

The hull structure mass increase was the most significant, followed by the PTO. The largest driving factor for both was the need for increased stiffness to accommodate the PMG air gap tolerance. C·Power believes that development of a PMG interface that allows for some increased elasticity, such as C·Power's LARS, could greatly reduce the mass (and cost) of the hull and PMG. Reducing active mass will result in additional ballasting, lowering the center of gravity, and improving wave power performance.

Subsequent to this Project, C·Power has initiated a work package that includes LARS development.

10.2 Lessons Learned

H3 LCOE Improves with WEC Size

Early in the Project, during the Concept Design stage (see section 4.6), C·Power focused on optimizing for LCOE when selecting the WEC size. More than 700 unique WEC configurations were modelled (more than 25,000 simulations) to estimate performance, including a wide range of WEC displacements (860 to 4600 mt). Baseline cost estimates were based on previous work and were scaled for other sizes and power levels in a manner similar to that described in section 6.6.3. C·Power's modeling and analysis confirmed that performance increased with size (see Figure 12), with a positive correlation over the entire range of sizes assessed. Estimated LCOE was shown to decrease with size, up to around 3000 mt displacement where the trend plateaued over the assessed range (see Figure 13). These findings led C·Power to target a displacement of around 3000 mt for the utility-scale H3u StingRAY. This learning is critical to the long-term commercial success of the StingRAY.

Project-Targeted H3p Size and Rational Development

The size selected for optimal commercial development (i.e., H3u) generated concern that the design was being pushed towards a scale that was cost- and risk- prohibitive at this stage of product development, and that designing this large of a system for a near-future build and demonstration project at PWS would likely outstrip potential funding sources available for that next step. The delay expected as a result would disrupt the expected product development flow and achievement of the Project objective to deliver a system design that can be built and deployed at PWS in the very near future.

To mitigate these potential risks and provide a better fit between expected capital costs and potential funding, C·Power focused on selecting a comprehensively appropriate design scale, while also maintaining focus on the primary objective of designing a cost-effective utility-scale unit. In selecting an appropriate WEC size for in-Project development, C·Power considered it essential that the H3p WEC be similar enough in size to the H3u that its deployment would validate performance and load models, and present similar logistical challenges.

With DOE concurrence, a moderately-sized system (weighing around 1000 mt) was deemed appropriate to deliver the best balance between system validation and likely available resources. This decision led C·Power to develop in-Project the detailed design of the H3p. As discussed in section 5, the H3p StingRAY is directly applicable to several near-term market opportunities that are well served by its more modest production levels.

New Contracting Relationships Brought Challenges

The unique requirements and operational considerations of marine energy converters in general, and the StingRAY in particular, can be challenging to communicate effectively and comprehensively to contractors. Experts in their fields are used to typical applications, which can prove to be a barrier to understanding the atypical modes of operations of the H3p.

A pertinent example of such a difficulty is illustrated by the challenges we faced bringing Supplier 1 into the PMG and electric plant designs. Supplier 1 has a wealth of experience working with wind turbines, but the quasi-steady state nature of wind turbine operation stands in stark contrast to the stochastic, pulsed power of a direct-drive, wave driven power plant. Multiple rounds of misunderstanding of the communicated design requirements by Supplier 1 slowed down the design process, and ultimately led to a sub-optimal design.

On the other hand, our efforts to educate Cardinal about the chaotic wave loading on the hull structure took some time, but both sides learned much from the process, and we intend to maintain the working relationship. A further example is Blue Frontier, who also designed the umbilical for the previous H2 StingRAY; due to the earlier collaboration, the design for the H3p proceeded swiftly and smoothly.

In the future, C·Power will adamantly ensure that design requirements are understood at the earliest design stages; engineering work will not be permitted to proceed until C·Power is satisfied that all requirements are fully comprehended. Furthermore, positive design relationships will be maintained, to leverage established understanding and workflow.

Large Companies Can Be a Mixed Blessing

It is highly desirable to recruit large, multinational corporations like Supplier 1. However, the Supplier 1 contracting process took months and a significant amount of unplanned effort by C-Power to get Supplier 1 contracted and productive, with contracting starting at the end of 2020 and not ending until June 2021; once the contract with Supplier 1 was in place, tangible efforts were not seen for several more months.

With Supplier 1, initial quotations for multiple systems far exceeded budget, and reasonable payment terms that appropriately matched tangible progress with payment were repeatedly pushed back on by Supplier 1's commercial team. C-Power has learned in prior projects that that it is critical to enforce multiple design checks with payment approvals only coming after satisfactory progress is achieved.

Additionally, the novelty of the WEC system requirements and associated contract scope took some time to adequately impress upon the Supplier 1 team and continued to present issues throughout the design process. After extended negotiations, and six iterations of Supplier 1's proposed Scope of Work, we managed to reduce the quoted price substantially and were successful in obtaining acceptable payment terms. This lengthy process was exacerbated by Supplier 1's slow corporate response time. While large companies are desirable partners for numerous reasons, C·Power has learned that, in most cases, they represent an unusually difficult, time-consuming challenge within a schedule- and budget- constrained project, as they are not equipped to move quickly.

Compounding Supplier 1's impact on the Project schedule, C·Power appropriately prioritized the generator design ahead of other systems to ensure that this critical design element was accommodated by all other system designs. The prolonged effort with Supplier 1 resulted in serial delays with other system designs, e.g., electric plant and hull.

Vendor Support Difficult without Imminent Build

C·Power found that it was often difficult to engage necessary vendor support without an imminent build order. Because this Project is design-only, and there is no certainty or schedule for a build phase, several system design efforts suffered from a reluctance of vendors to provide design support.

The PTO rotary seals, for example, were originally intended to be designed by Trelleborg. While Trelleborg indicated their interest in providing a design, their responses were very slow, and little was gained. Late in the Project, they finally shared their reluctance to involve themselves in this design effort without a build order in hand.

Similarly, C·Power efforts to engage a shipyard for detailed review of manufacturing plans and cost estimates were rebuffed by several potential.

Localized Airgap Control is Critical for Large Diameter Generator

C·Power had originally intended to further develop its proprietary Localized Airgap Reduction System (LARS) in-Project. LARS, which was first designed and tested under DE-EE0006399, facilitates tight-tolerance air gaps for large diameter, inherently elastic structures. As discussed in previous sections, LARS has the potential to reduce cost and mass of PTO and the hull, while also improving performance. Unfortunately, while pursuing quotes from potential designers it became clear that the available resources under Project 8954 were insufficient.

A decision was made to instead work with Supplier 1 towards a modified-COTS generator solution. The intended trade-off was a design that was expected to be sub-optimal from a performance perspective, but that would be sufficient for the anticipated PWS demonstration while also streamlining the Project schedule and fitting within the available budget. While the Supplier 1 design was intended to save time, as discussed above, it resulted in Project delays. Integration of the generator into the hull required an overbuilt structure to constrain the air gap deflections, leading to both generator and nacelle structures being considerably heavier than anticipated, and negatively impacting cost and performance. These are the very issues that LARS is intended to address, providing a clear indication that LARS development is critical to the long-term success of the StingRAY.

Given the resource constraints in-Project, C·Power believes that they made the correct decision at the time in delaying LARS development. However, the cost and performance impacts to the Project-designed StingRAY have magnified our understanding of the critical importance of LARS. Rather than waiting for the next funding opportunity, subsequent to the Project C·Power initiated a work package targeting the two highest priority improvements (i.e., co-development of generator and electric plant, and LARS development), which will be self-funded at least through Phase 1 (conceptual design). C·Power intends to design, fabricate, and validate the performance of these systems with a comprehensive dynamometer test program.

Composites Present Significant Issues when Prototyping

In an effort to reduce fabrication costs and schedule, C·Power undertook a novel effort within this Project to use a 3D printed prototype for the tank test model. While the model's fabrication methodology hadn't been specified in the original Project planning, an opportunity was seen to develop a rapid, cost-effective method of delivering small-scale prototypes. Unfortunately, the prototype had significant leak paths and issues with maintaining engagement of the PTO belt drive. Fortunately, these issues were discovered during C·Power's pre-test V&V efforts, rather than during tank testing. Efforts to mitigate these failures were undertaken (e.g., retrofitting leak-prone hatch closures, and modifying PTO interfaces to allow additional belt tensioning), but even though significant, unplanned effort was invested to remediate the faulty 3D-printed prototype, the unit was deemed non-usable.

A new, metal-based unit was designed, fabricated, and successfully tested. While C·Power believes there is merit in the 3D printed approach, we have learned within this Project that small-scale prototyping in

composites presents significant issues due to the difficulty in manipulating composites post-manufacture. While less of an issue once in normal production, novel designs rarely do not require post-fabrication adjustments. This experience parallels a lesson C·Power has learned for large-scale composite prototypes in previous projects.

11 CONCLUSIONS

The goal of this Project, which was successfully achieved, was to develop a standards-compliant, fabrication-ready design of C·Power's next-generation WEC, the StingRAY H3p. The H3p is intended for electrical power generation suitable for micro-grids or remote loads. The H3p was designed for grid-connection and at least two years of continuous testing and operation at the proposed PWS test site. To deliver the Project goals, several objectives were achieved, as discussed below.

A design basis was developed to establish key system requirements, targets, and operational limits. The H3p was designed for grid-connection and at least two years of continuous testing and operation at the PWS test site. Metocean conditions at PWS were characterized, and design load cases were developed. A safety level of three (low risk) was defined for the hull structure due to low risk of human injury and minor environmental and economic consequences, and a safety level of two (normal risk) was defined for mooring due to greater consequences of failure; a safety level of two was defined for all other systems due to lack of support in relevant standards for alternate safety levels. The design basis later informed the Certification Basis, as a part of the Technology Qualification discussed below.

A hydrodynamic modeling study was performed to establish the primary characteristics of the H3p WEC, including hull dimensions, ballast mass, and generator torque limit. Parameterized cost and mass estimates were developed for over 700 unique WEC configurations, and model results were assessed for performance, leading to the identification of configurations that had favorable cost-to-performance ratios. The study indicated that a large WEC (~2800 mt displacement) minimized estimated LCOE and was optimally sized for long-term commercial development. However, due to the high costs and logistical challenges of such a large device, concerns arose that a WEC of this size was not a rational next step in the technology development path. To limit C·Power and stakeholder financial and operational risks and increase the likelihood of keeping project costs for the anticipated build and deployment in-line with future funding opportunities, smaller WECs were considered. With DOE concurrence, C·Power decided to design a smaller prototype WEC within this Project (i.e., H3p), while maintaining long-term focus on a larger commercial WEC (i.e., H3u), allowing for Project technology development goals to be met while reducing near-term technical and economic risk to manageable levels. The commercialization plan developed in-Project and described below, identified offshore market opportunities for the H3p, further justifying the decision. The StingRAY product line is intended to serve a full range of power needs, from remote offshore loads up to utility-scale applications.

The Project metrics target values established in the Statement of Project Objectives (SOPO) assumed the original, optimally sized utility-scale WEC, as described above. To maintain the measurement of Project success against the SOPO metrics, the metrics estimates developed in this Project are based on the larger StingRAY WEC, which is referred to as the H3u. To be clear, the H3p is the full-scale system designed within this Project. For comparison to the original SOPO metrics, the H3p design was scaled up to the H3u. The H3p WEC was deemed to be similar enough in size to the H3u that its deployment would validate performance and load models, and present similar logistical challenges. The inherent scalability of the StingRAY design enabled this approach and the opportunity to make reasonably accurate estimates for the H3u.

A commercialization plan was developed to ensure the StingRAY design aligns with C·Power's market strategy. The ultimate market for StingRAY is utility-scale electricity generation, however, utility-scale wave farms for wholesale markets are a number of years from implementation. The Project-targeted H3p is specifically intended to service non-terrestrial loads of near-term markets (e.g., diesel genset replacement,

at-sea vessel charging, remotely operated and autonomous underwater vehicles, etc.) and will be well-placed for terrestrial applications when those become available. C·Power's market study suggests that the H3p system will have a near-term addressable market value of approximately $6 Bn, and that the total StingRAY addressable market opportunity (i.e., H3p, H3u, and subsequent models) will be approximately $120 Bn in 2030. This Project represents a key step to delivering the initial prototype for a later validation project and subsequent near-term market development and is a practical and concrete step towards future development of the larger utility-scale H3u.

Systems designs began with the development of detailed engineering design requirements. While Project efforts led to a final design that aligns with Project objectives and is ready to take into a fabrication stage, C·Power believes that an additional round of component and mass optimization would yield a significantly more cost-effective system.

C·Power contracted outside expertise for design support on critical systems. The hull structure is a steel fabrication, primarily comprised of stiffened, cylindrical shells. The hull structure houses all equipment, provides sufficient stiffness for the tight tolerances required by the generator, and is subdivided into watertight compartments to limit the risk of sinking. The direct-drive generator features a large diameter air gap to meet the performance requirements. However, the stiffening required of the hull and generator support structure to maintain the air gap tolerance under inertial and wave loading resulted in a final mass exceeding the established target. The electric plant comprises a marine-rated drive and a battery energy storage system. The battery system improves performance by storing energy when production is low (and filtering losses are onerous) and when production is high (more than export capacity) and exporting energy to supplement generation during moderate production (when filtering losses are acceptable). The compliant mooring system allows the WEC to align with the incident waves, while keeping the WEC on-station. The mooring was designed for a non-linear response, such that it has low tension during most operational conditions to minimize the effect on the WEC's wave response, but significantly increased tension in extreme conditions such that excursions are limited. The mooring system maintains tension on all lines, in all conditions, to reduce risk of entanglement and snap loading. The umbilical cable was selected based on mechanical, electrical, and fiber optical considerations. The Lazy Spring configuration accommodates the required range of motion of the WEC, while reducing the likelihood of seabed contact or interference with the mooring system.

Preliminary plans were developed for manufacturing, and installation, operation, and maintenance of the StingRAY H3p. The H3p will be fabricated and assembled at a shipyard on the Columbia River, and once fully assembled the H3p will be rolled into the Columbia River for ballasting, verification & validation, and transport to PWS. The H3p will be towed, under its own buoyancy, down the Columbia River and then south along the coast to PWS. Once the WEC is at PWS it will be connected to the mooring and umbilical systems (which will be preinstalled and left on-station to simplify WEC installation) and ballasted into operational orientation. Once installed the WEC will remain on location under continuous operation for at least two years. Inspection and maintenance operations are planned to occur quarterly, and remote monitoring will be ongoing to reduce the need for onsite visits.

A Risk Management Plan was developed, specifying a risk assessment process which includes identification, analysis, and mitigation of risks. FMECA was conducted iteratively to systematically identify all potential failure modes and their effects on the system, and to analyze the criticality of each risk based on the likelihood of the event and the severity of the impact. FMECA was conducted iteratively to systematically identify all potential failure modes and their effects on the system, and to analyze the criticality of each risk based on the likelihood of the event and the severity of the impact. Engineering actions to mitigate risk were developed and documented. The Risk Registers resulting from this process guided the design process by identifying and prioritizing critical risks and providing a road map for the Certification Plan described below. Engineering actions that were carried out within the Project were documented, and the effected risks reassessed. Other actions are meant to be carried out in later stages (e.g., during manufacturing or while deployed).

Technology Qualification was conducted, with support from DNV, in accordance with *DNV-SE-0120 Certification of Wave Energy Converters and Arrays*. A Certification Basis was developed that defines the expectations of the novel H3p WEC, including requirements, targets, and limits of operation. A Technology Assessment was performed, classifying the novelty of the systems and components, identifying applicable standards, and specifying the required level of DNV involvement in qualification and certification activities. Recommended actions to mitigate risks from the Risk Registers were consolidated into a Certification Plan, comprising a comprehensive set of actions to be carried out during certification of the H3p WEC. At the conclusion of the Technology Qualification process, DNV issued a Statement of Feasibility, affirming that the H3p WEC is conceptually feasible and suited for further development and qualification.

Tank testing was performed in the Directional Wave Basin of the Hinsdale Wave Research Laboratory, over a period of four weeks. The scale WEC model was designed and built, to the degree practical, as a 1:28 scale model of the H3p WEC. The model was an aluminum fabrication, with a PTO consisting of a dual stage belt-drive to a PMG motor. Test conditions included a diverse set of wave conditions, including operational and extreme seas, and modifications to WEC controls and ballasting. Overall, the numerical model predicted the performance and motion response trends observed in tank testing with reasonable accuracy, in operational and extreme seas, giving confidence to the modeling efforts supporting Project design of the H3p.

The Project metrics were based on the utility-scale H3u and include Levelized Cost of Energy (LCOE), Peak-to-Average Mechanical Power (PAMP), and Capture Width Ratio (CWR). Targets were established for both PWS and EMEC, and the final H3u metrics estimates yielded mixed results. The final H3u CWR estimate for PWS exceeds the target, while for EMEC the final H3u estimate does not. Final H3u PAMP estimates exceed the targets for both PWS and EMEC. Final H3u LCOE estimates fall short of the SOPO targets for both PWS and EMEC; performance and cost issues impacting final H3u LCOE estimates, and identified mitigating improvements, are described in the following paragraph.

Factors negatively impacting the final metrics estimates were identified, and the potential for improvement in the near-term was assessed. Three areas for potential improvement of cost and performance were considered achievable in the near-term and further explored, including performance gains from advanced controls; efficiency and cost improvements from co-development of the generator and electric plant; and cost, mass, and performance improvements from implementation of C·Power's Localized Airgap Reduction System (LARS). Based upon these potential areas of performance and cost improvements, C·Power estimates that all targets can be met in the near-term, bringing the StingRAY H3p WEC to a state of cost-competitiveness for the near- and medium-term markets identified in the Commercialization Plan.

These near-term improvements, listed in order from highest priority, along with their estimated individual impact on LCOE are: efficiency and cost improvements from co-development of generator and electric plant (-25%); cost, mass, and performance improvements from implementation of C·Power's LARS (-17%); and performance gains from advanced controls (-3%).

In light of these potential gains and subsequent to this Project, C·Power has initiated a work package targeting the two highest priority improvements (i.e., co-development of generator and electric plant, and LARS), which will be the primary focus in 2024 for StingRAY development. The effort will be self-funded at least through Phase 1 (conceptual design), while C·Power actively pursues additional funding opportunities. C·Power intends to design, fabricate, and validate the performance of these systems with a comprehensive dynamometer test program. The development of advanced controls is also being planned, though at a lower priority. These improvements will yield significant benefits in terms of performance and cost-effectiveness and will bring the StingRAY WEC a long way towards cost-competitive commercial wave power generation.

The goal of this Project was successfully met: to develop a standards-compliant, fabrication-ready design of the StingRAY WEC, intended for grid-connected operation at PWS for at least two years, with electrical power generation suitable for remote loads or the utility grid. The H3p design delivers an innovative, high-

performance, survivable, and reliable device that is acceptable to potential customers, regulators, and other stakeholders, while also demonstrating the StingRAY's path towards cost-competitive electricity generation. Risk was assessed and mitigated in-Project through tank testing, FMECA, and DNV-supported Technology Qualification. The H3p design provides a strong platform for prototype demonstration and near-term markets, while the H3u concept points the way towards long-term utility-scale market share.

12 REFERENCES

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13 APPENDICES

13.1 Appendix: Final Design Report
DE-EE0008954 H3-FDR Final Design Report PD v2.0 09-15-2023.pdf

13.2 Appendix: Design Objectives, Requirements, and Constraints
DE-EE0008954 H3-DB-2.1 Objectives PD v1.3 08-26-2021.pdf

13.3 Appendix: Concept of Operations
DE-EE0008954 H3-DB-2.2 ConOps PD v1.6 04-07-2023.pdf

13.4 Appendix: PWS Site Characterization
DE-EE0008954 H3-DB-2.6 PWS Site Characterization PD v1.8 03-02-2023.pdf

13.5 Appendix: EMEC Site Characterization
DE-EE0008954 H3-DB-2.6.b EMEC Site Characterization PD v1.0 09-21-2020.pdf

13.6 Appendix: Design Load Cases
DE-EE0008954 H3-DB-2.7 Design Load Cases PD v1.6 12-08-2021.pdf

13.7 Appendix: Final Commercialization Plan
DE-EE0008954 H3-fCP-6.6 Final Commercialization Plan PD v3.0 03-10-2023.pdf

13.8 Appendix: Hull Preliminary Design Report
DE-EE0008954 H3 0100 Hull PDR PD v1 03-31-2022.pdf

13.9 Appendix: Hull Final Design Report
DE-EE0008954 H3 0100 Hull FDR PD v3 09-22-2022.pdf

13.10 Appendix: Hull 2D Drawings
DE-EE0008954 H3 0100 Hull 2D drawings PD v1 09-26-2022.pdf

13.11 Appendix: Weight Calculations for Hydrostatics
DE-EE0008954 H3 Weight Calcs for Hydrostatics PD v1 09-23-2022.xlsx

13.12 Appendix: PMG Final Design Report
DE-EE0008954 H3 0210 PMG FDR PD v2 09-20-2022.pdf

13.13 Appendix: PMG Datasheet and Characteristic Curves
DE-EE0008954 H3 0210 PMG Datasheet PD v3 10-11-2022.pdf

13.14 Appendix: PMG General Arrangement

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13.15 Appendix: PMG Rotor Particulars

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13.16 Appendix: Main Bearing Design Reports

DE-EE0008954 H3 0271 Primary Bearing Design PD v2 11-22-2022.pdf

DE-EE0008954 H3 0272 Secondary Bearing Design PD v2 11-17-2022.pdf

13.17 Appendix: Idler Bearing 2D Drawings

DE-EE0008954 H3 0275 Idler Bearing Plate 2D PD v1 11-03-2022.pdf

DE-EE0008954 H3 0275 Idler Bearing Insert 2D PD v2 08-10-2022.pdf

13.18 Appendix: Shaft Seals 2D Drawings

DE-EE0008954 H3 0280 Shaft Seal 2D PD v1 10-24-2022.pdf

13.19 Appendix: Electric Plant Final Design Report

DE-EE0008954 H3 0300 Electric Plant FDR PD v2 12-16-2022.pdf

13.20 Appendix: Electric Plant Functional Specification

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13.21 Appendix: Electric Plant One-Lines

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13.22 Appendix: Electric Plant 2D Drawings

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13.23 Appendix: Mooring Final Design Report

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13.24 Appendix: Umbilical Cable Final Design Report

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13.25 Appendix: Umbilical Cable Dynamic Analysis Report

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13.26 Appendix: Umbilical Cable Dynamic System Components

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13.27 Appendix: Umbilical Cable Installation Plan

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13.28 Appendix: Umbilical Cable General Arrangement

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13.29 Appendix: Umbilical Cable Cross-Section
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13.30 Appendix: Performance Estimates
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13.31 Appendix: Manufacturing Planning and Capital Expense Estimates
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13.32 Appendix: IO&M Planning and Cost Estimates
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13.33 Appendix: Project Metrics Estimates
DE-EE0008954 H3-PRF-6.7.b Project Metrics Estimates PD v1.2 07-10-2023.pdf

13.34 Appendix: Risk Management Plan
DE-EE0008954 H3-RMP-1.2 Risk Management Plan PD v1.2 06-15-2020.pdf

13.35 Appendix: Final Risk Assessment (Risk Registers)
DE-EE0008954 H3-RR-0100 PD v3.3 08-04-2023.xlsm

DE-EE0008954 H3-RR-0200 PD v3.3 09-05-2023.xlsm

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13.36 Appendix: Certification Basis
DE-EE0008954 H3-TQ-CB Certification Basis PD v1.4 09-05-2023.xlsx

13.37 Appendix: Technology Assessment
DE-EE0008954 H3-DB-2.3 Technology Assessment PD v1.6 09-05-2023.xlsx

13.38 Appendix: Certification Plan
DE-EE0008954 H3-TQ-CP Certification Plan PD v1.2 09-12-2023.pdf

DE-EE0008954 H3-TQ-CR Certification Report PD v1 09-27-2023.pdf

13.39 Appendix: Statement of Feasibility
DE-EE0008954 H3-TQ-SOF Statement of Feasibility PD v1 09-27-2023.pdf

13.40 Appendix: Tank Test and Model Validation
DE-EE0008954 H3-TST-3.2 Tank Test and Model Validation PD v1.21 03-13-2023.pdf