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Authored	E. Hammagren, K. Terrasa, Z. Zhang		
Reviewed	R. Calder, R. Lesemann		
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1 EXECUTIVE SUMMARY

Project DE-EE0008627 (Project) aimed to design, build, and test a novel, low-power wave power system (WPS) for remote, non-grid applications. Over the duration of the Project, the system design was expanded to include energy storage and the ability to support external assets – a groundbreaking innovation that improved the overall state of the art and helped establish a novel market for wave energy technologies. Dual-use features and functionality built into this prototype were added later in the process and were based on feedback from a wide range of maritime customers and suppliers. The resulting novel solution was the SeaRAY Autonomous Offshore Power System (AOPS), a fully integrated offshore power and data communications mini-grid intended to lower the cost, complexity, and carbon-intensity of current offshore operations and enable new, robust capabilities not possible today.

The overall Project period of performance was severely disrupted by the COVID-19 pandemic. These impacts were experienced across supply chains, as well as manufacturing and testing schedules and resource availability. Despite these challenges, the C-Power team worked diligently to adapt to shifting conditions to meet key milestones and continue to progress the Project forward. Nonetheless, the overall Project experienced unavoidable delays—estimated to be up to 12 months—due to impacts from the pandemic.

At the highest level, the final system design was aimed at demonstrating high techno-economic potential for the marketplace, appropriately balancing survivability, cost, and ease of handling/servicing with a clear path for future open-water testing at larger scale, in array configurations, and in deeper water.

Top-level design requirements were defined by metrics established in the Statement of Project Objectives (SOPO), commercial targets, and system operational limits. Metocean conditions at both PacWave North and Wave Energy Test Site (WETS) were characterized, and design load cases were developed. Safety levels were defined for the hull structure, mooring, and other key systems.

A Risk Management Plan and subsequent Risk Registers were 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.

Once fabricated, the SeaRAY AOPS underwent extensive bench testing, integration, and in-harbor verification. This included pre-deployment integration testing of two subsea assets the AOPS was intended to power during deployment: a seafloor data gathering sensor and an autonomous underwater vehicle (AUV). Although the assets were not able to be tested during the SeaRAY AOPS in-water operation, the onshore integration testing and validation confirmed the capability of the system to provide a viable interface and bidirectional communications to customer assets.

All required permits for operations at WETS were received prior to deployment. After multiple months awaiting available vessels and an acceptable weather window, the SeaRAY AOPS was successfully deployed in October 2023. The Project team worked through various unexpected challenges both during and after the deployment, including adjusting the system ballasting and initiating all systems operations in a low wave environment. The SeaRAY AOPS remained operational for four weeks before the system's starboard mast was g damaged by a third party, causing water to infiltrate part of the nacelle and for communications with the system to be severed. This damage necessitated recovering the unit. Once recovered, the C-Power team made extensive notes of design and operational improvements to be made to mitigate the risk of similar future incidents; this included stronger masts, bilge system adjustments, and the addition of exterior signage on the surface unit dissuading third party interaction with the system.

The data collected during operation was analyzed and used to validate and refine performance modeling. Although the in-water testing period of this Project was limited to four weeks as opposed to the targeted six months, the demonstration provided critical information, lessons learned, and team experience. In addition, the design, build, and test cycle of this Project produced baseline, target, and resulting techno-economic metrics—in the table below—identifying key continued research and development (R&D) to target to improve overall system efficiency. Many of these identified improvements were incorporated into the upfit and second deployment of the SeaRAY AOPS, under DE-EE0007347, with the goal of extending beyond what was achieved through this Project.

Metric	Unit	Baseline	Target	SeaRAY (DOE reference site*)	SeaRAY (WETS)
Levelized cost of energy (LCOE)	$/watt-hour(Wh)	0.324	0.048	0.126	0.110
Annual energy production (AEP)	kWh/year	629	2139	3527	4049
Power to weight ratio (PWR)	W/kg	0.061	0.111	0.041	0.047
Peak to average power ratio		40.7	24.0	43.3	41.1

The results of the Project were used to refine system design, improve installation, operation, and maintenance (IO&M), and more efficiently meet the needs of the commercial market that C-Power established through this Project.

LIST(S) OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

Table 1 – Symbols, abbreviations, and acronyms.

AEP	Annual Energy Production
AOPS	Autonomous Offshore Power System
AUV	Autonomous Underwater Vehicle
BA	Biological Assessment
CATEX	Categorical Exclusion
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CAD	Computer-aided Design
COTS	Commercial Off-The-Shelf
DARPA	Defense Advanced Research Projects Agency
DLC	Design Load Cases
EA	Environmental Assessment

EFH	Essential Fish Habitat
EOM	Electro-Optical-Mechanical
ESA	Endangered Species Act
FAT	Factory Acceptance Testing
FEA	Finite Element Analysis
FMECA	Failure Modes Effects and Criticality Analysis
GPS	Global Positioning Satellite
HSS	High-Speed Shaft
IMU	Inertial Measurement Unit
IO&M	Installation, Operation and Maintenance
LCOE	Levelized Cost of Energy
LSS	Low-Speed Shaft
MCBH	Marine Corps Base Hawaii
NAVFAC EXWC	Naval Facilities Engineering and Expeditionary Warfare Center
NEPA	National Environmental Policy Act
NETS	North Energy Test Site
NMFS	National Marine Fisheries Service
NOAA	National Oceanic Atmospheric Administration
NREL	National Renewable Energy Lab
PCN	Pre-Construction Notification
PE	Power Electronics
PID	Proportional, Integral, Derivative
PoE	Power over Ethernet
PTO	Power Take-Off
PWR	Power to Weight Ratio
R&D	Research and Development
RHIB	Rigid-Hulled Inflatable Boat
RMP	Risk Management Plan
ROV	Remotely Operated Vehicle
RPM	Revolutions Per Minute
RR	Risk Register
SBU	Seafloor Base Unit

SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
SOPO	Statement of Project Objectives
UH	University of Hawai'i
USFWS	U.S. Fish and Wildlife Service
USV	Uncrewed Surface Vessel
VPN	Virtual Private Network
V&V	Verification and Validation
WETS	Wave Energy Test Site
WPS	Wave Power System
NREL	National Renewable Energy Laboratory
NOAA	National Oceanic and Atmospheric Administration
NMFS	National Marine Fisheries Service

2 INTRODUCTION

The original goal of the DE-EE0008627 Project – awarded under DOE-FOA-0001837 – was to design, deliver, and test a prototype low-power wave power system (WPS) that would lower the total cost of ownership and provide robust, new capabilities for customers in the maritime environment. This novel, early-stage system – which built off C-Power's prior research and development (R&D) efforts and a novel prototype designed, built and delivered for a Defense Advanced Research Projects Agency (DARPA) project in 2017 – was intended to be a mobile and deployable power system for maritime sensors, monitoring equipment, communications, and other similar payloads and was expected to be a predecessor system for larger-scale, more powerful WPS for autonomous underwater vehicle (AUV) recharging. The expected applications were to be in both shallow- and deep-water locations that lacked desirable, resident, cost-effective, and/or sufficient power sources for Powering the Blue Economy applications. The Project prototype was referred to in the original proposal as the "dataRAY."

The dataRAY was to be designed as a surface WPS connected to a seafloor gravity anchor (i.e., concrete block) with the ability to be rapidly deployed and at a cost point to allow for multiple units to be positioned throughout an area to support required operations. It was to include necessary equipment on board to deliver continuous power as required. The Project objectives were outlined in the original Statement of Project Objectives (SOPO) as the following:

- Gather system requirements (e.g., performance, cost, and environment) from potential market participants/stakeholders (e.g., scientific, industrial, defense, and national security).
- Determine optimal energy storage technology and capacity to deliver the required continuous power in most sea states; likely electrochemical storage (lithium-ion battery or supercapacitor), with investigation of supplemental solar energy harvesting in very low energy sea states.
- Build upon this knowledge-gained and the Project team's previous work and experience, identify and evaluate innovative system and sub-system concepts that can deliver high technoeconomic potential; defined as meeting the identified market requirements, being technically feasible, and promising cost competitiveness for the target market.
- Design a prototype, next generation WPS that delivers high technoeconomic potential.
- Through open-water testing, validate Project numerical performance modeling and demonstrate that the prototype can achieve high-performance with a clear path towards testing larger scale devices in deeper water.

After award, C-Power started a market discovery process in a range of market sectors in the U.S. and Europe to help inform the Project's technical direction. The overall response was highly favorable. Significant value was placed by potential customers and their supply chain on systems with non-complex logistics and transportation profiles that were able to support a wide variety of assets in a diverse range of locations globally; and could deliver energy as required for the operation of the suppliers' or their customers' assets. The value proposition for the market participants came from one or more of the drivers:

- Removal of liquid fuel and the cost, complexity, and shore dependencies it brings
- Industrial decarbonization
- Substitution or replacement for power and data cables that had failed, were failing, or were too expensive to install
- Removal of vessels to perform operations and activities that could be locally uncrewed
- Enabling activities not possible with legacy equipment

The market discovery process also confirmed the widespread need for energy supplies at the watt and kilowatt level for assets on the surface, in the water column, and on the seafloor. This new knowledge highlighted a gap in the targeted system design: energy storage and delivery capable of meeting customer requirements. While some storage was envisioned for the dataRAY, sufficient capacity to sustain third-party asset operation for extended periods was not. This represented a fundamental change in C-Power's view of system operation, changing from how much power can be produced by the WPS to the need to provide sufficient energy to meet the load profile of the third-party asset. Additionally, the need for communications to provide command, control, monitoring, and reporting of the third-party assets was identified. This required even more power to be produced and stored, as component complexity was significantly increased by the need for bi-directional, high-speed communications between the seafloor and surface. These commercially identified gaps coupled with the stated desire for a fully featured system drove a change in the Project-targeted design.

The market had uniformly expressed the need for a fully integrated power generation, energy storage and delivery, and communications system; a self-contained power and data mini-grid. As such, the targeted WPS was non-representative of the required feature set. A new term was devised – autonomous offshore power system (AOPS) – to better describe required system functionality. A WPS is a major component within an AOPS (Figure 1). Additionally, the WPS name was changed from dataRAY to SeaRAY to reflect the upgrade in supported assets from primarily data-gathering sensors to include robotics and operating equipment.

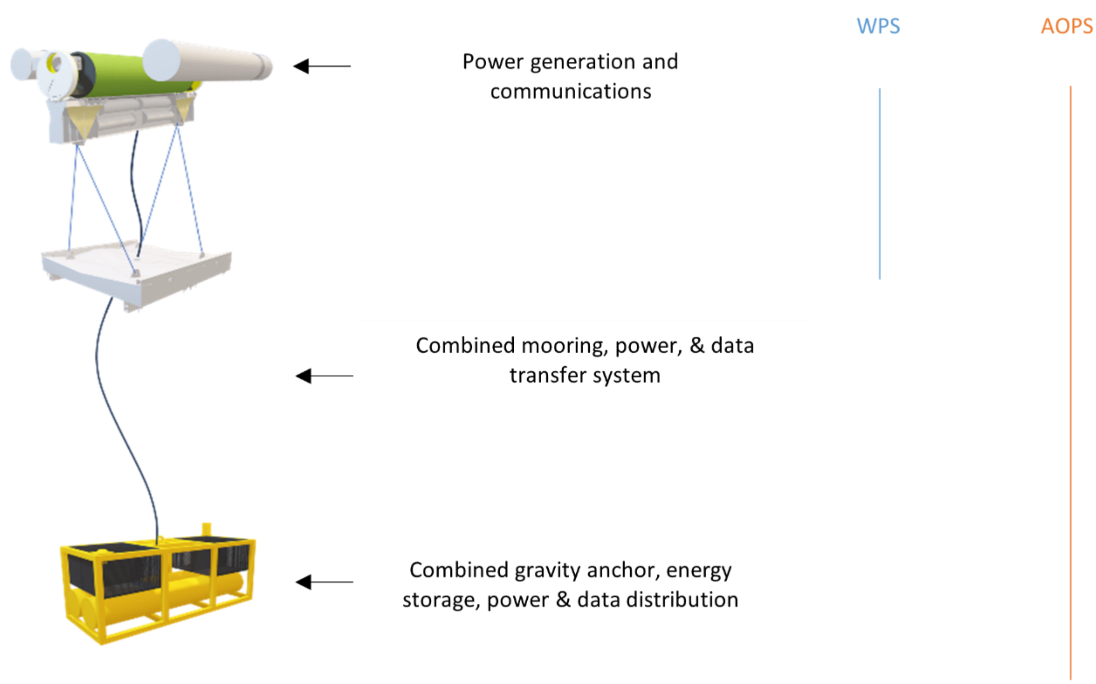


Figure 1 - WPS vs. AOPS

The revised central objective for the Project was to develop a mobile, rapidly deployable AOPS suitable for a range of applications, including provisions for subsurface energy storage and payload support for both fixed and mobile payloads in both shallow and deep-water locations. The Project objectives from the original SOPO remained the same in the final revised SOPO. However, the tasking was revised to encompass the following actions:

- Construct and test the novel SeaRAY AOPS prototype, which includes a novel fiber-optic data transmission cable integrated into the single point mooring system, facilitating bi-directional power and data transfer between the floating portion of the WPS and the seafloor gravity anchor and energy storage system.
-

- Confirm the AOPS' techno-economic potential by demonstrating a proof-of-concept system for potential market participants

The purpose of this Report is to summarize the technical accomplishments through Project DE-EE0008627, from design development and integration testing to deployment, operations, and recovery to model validation, lessons learned, and conclusions. Supporting documents are referenced throughout and collected in the Appendices.

3 DESIGN DEVELOPMENT

3.1 Design Objectives and Evolution

As outlined in Section 2, market guidance and customer input were major drivers on the design evolution of this Project, in parallel to satisfying the main SOPO objectives. At the start of the Project, initial market research indicated an interest in offshore, low-maintenance power sources from 10W to 10kW. C-Power's initial assumption was target applications would be primarily environmental monitoring and oceanographic research. This would only require a relatively small amount of power generation, a small energy storage system onboard the WPS, and a basic sensor package that would transmit data in bursts. Thus, the original scope was to design, deliver, and test a prototype WPS that generated an annual average of approximately 250W. The WPS was to be paired with a simple mooring and gravity anchor. The prototype was to be transported in a standard 20 ft shipping container. The entire system would be handled by a small vessel commonly available to research facilities.

However, as market discovery efforts progressed, C-Power found there was mounting macro- and micro-pressure in these offshore markets to move away from the people-, carbon- and capital-intensive status quo to an operational environment that could be less expensive, safer, cleaner, and more connected. In addition, these customers – some of whom had the most significant pain points and thus, the most immediate need for remote power offshore – were from a wider range of market sectors than C-Power's initial focus. These customers included major offshore energy companies and defense and security entities, as well as their supply chains, interested in solutions that could provide primary, redundant, or emergency power supply for resident all-electric subsea and surface operating equipment and subsea and surface robotics (e.g., AUVs and uncrewed surface vessels (USVs)).

With this market research, the Project design objectives evolved to encompass higher WPS power generation, more versatility to meet the needs of broader range of customer assets and geographic locations, and a fundamental shift to the AOPS topology (i.e., replacing the basic gravity anchor with a seafloor base unit (SBU) with integrated energy storage and asset management). These objectives were translated into the following top-level design requirements:

- Average energy generation above 1 kW per year
- Low-mass/high power to weight ratio (as light as possible while still being able to produce target average energy generation)
- Rapidly deployable in less than 1 day
- System fits within standard ocean container(s)
- Minimal assembly work dockside
- Able to use smaller, lightly manned vessels
- Mooring, data, and communications combined into one line
- Fully-integrated energy storage
- Capable of delivering continuous power as required
- Designed for PacWave North and Hawai'i's Wave Energy Test Site (WETS)

Furthermore, in order to prove out the full capabilities of this first-of-its-kind SeaRAY AOPS, and to complement the extensive market discovery process, C-Power chose to collaborate with partners and selected assets to co-demonstrate alongside during the deployment period. More specifically, C-Power was interested in utilizing the available energy storage in the SBU to provide power and data communications to both mobile and static seafloor assets. This integration and testing were seen as critical to commercially advancing the SeaRAY AOPS.

There were initially four assets committed to co-demonstration. Due to scheduling conflicts and personnel changes, that was reduced to two assets: an omnidirectional environmental monitoring sensor and an AUV.

3.2 Preliminary Design

At a high-level, the SeaRAY AOPS consists of a surface expression comprising three cylindrical bodies for power generation (the WPS), a mid-column heave plate providing a stable platform for the WPS to react against, and an SBU serving as gravity anchor and energy storage. The SeaRAY AOPS was designed to generate and store electrical energy and provide the stored energy to various interfacing payloads. A description of the preliminary design is below, with further details in Appendix 14.1.

The central body of the WPS is called the nacelle and houses the power take-off (PTO), controls, data acquisition, and power electronics. The other two bodies are called the fore and aft floats and were initially of equal length (see Figure 4). The preliminary design utilized two PTOs connected to the fore float. The nacelle is held relatively still in the water due to the connected heave plate, allowing the wave swell to move the fore float about the nacelle. The relative motion between float and nacelle actuates both PTO drivetrains, transferring the rotational motion into two sets of gearboxes and generators, and producing electricity.

The electric plant inside the nacelle provides control of the generators and conditions power for onboard loads and for storage in the SBU. The batteries are normally maintained with a trickle charge, as they provide power to power regulators which power the Supervisory Control and Data Acquisition (SCADA) and other auxiliary systems.

The SCADA system collects data, issues commands, controls the electric plant, and provides communication, alarms, and fault recovery. A robust suite of onboard sensors monitors data of interest, including PTO position and speed, generator voltage and current, accelerometers, temperatures, battery voltages, umbilical voltages and currents, and mooring tension.

The heave plate is a shallow rectangular prism, fabricated from steel, and ballasted with lead and sea water in operation. It is suspended from the nacelle's mooring yoke via four bridle lines and provides resistance to nacelle heave motion. The heave plate also supports a mid-column junction connecting the upper and middle sections of umbilical cable.

The umbilical cable serves as the single point mooring line below the heave plate, as well as electrical and data connectivity, between the nacelle and the SBU.

The SBU serves as a gravity anchor, primary energy storage, and provides interfaces for the various payloads. The SBU comprises a commercial seafloor energy storage product used extensively to support offshore energy needs. Energy storage is provided by lithium-ion battery cells.

3.3 Design Load Cases

Details of the design load cases (DLCs), hydrodynamic simulations, and design loads are further described in the Appendix 14.2.

Historical test site data for modeling tasks was gathered for two initial potential test sites, PacWave North and WETS. From these sites, three sets of DLCs were defined as follows:

- WETS extreme sea
    - Hm0 = 7.57 m
    - Te = 10.6 s

    - Wave spreading index = 9 (AQWA s index = 4)
    - Wave direction = head-on and side
    - PTO damping
        - Freewheeling
        - Damped
            - Fore = 20000 Nms
            - Aft = 40000 Nms
    - Simulation duration = 3 hours for each simulation configuration
    - Time step size = 0.002 sec
- PacWave North (previously North Energy Test Site (NETS)) extreme sea
    - Hm0 = 17.31 m
    - Te = 16.57 s
    - No wave spreading
    - Wave direction = head-on and side
    - PTO damping
        - Freewheeling
        - Damped
            - Fore = 20000 Nms
            - Aft = 40000 Nms
    - Simulation duration = 3 hours for each simulation configuration
    - Time step size = 0.002 sec
- WETS operational sea
    - 24 sea states: T3-DLCv3_1.1a
    - Wave spearing is enabled
    - PTO damping sweep range
        - Fore = 10000:5000:30000 Nms
        - Aft = 20000:5000:60000 Nms
    - Simulation duration = 1 hours for each simulation configuration
    - Time step size = 0.02 sec

Figure 2 shows the 100-year return in extreme sea conditions at both WETS and PacWave North. Figure 3 highlights the modeled system performance at both locations against average wave height and period over the course of a year. Performance of the SeaRAY is determined by both significant wave height and wave period. For example, during summer months when significant wave height is less than 1.5m, average power output can reduce up to 400W per second increase in wave period. This gradient reduces as wave height increases and wave period increases.

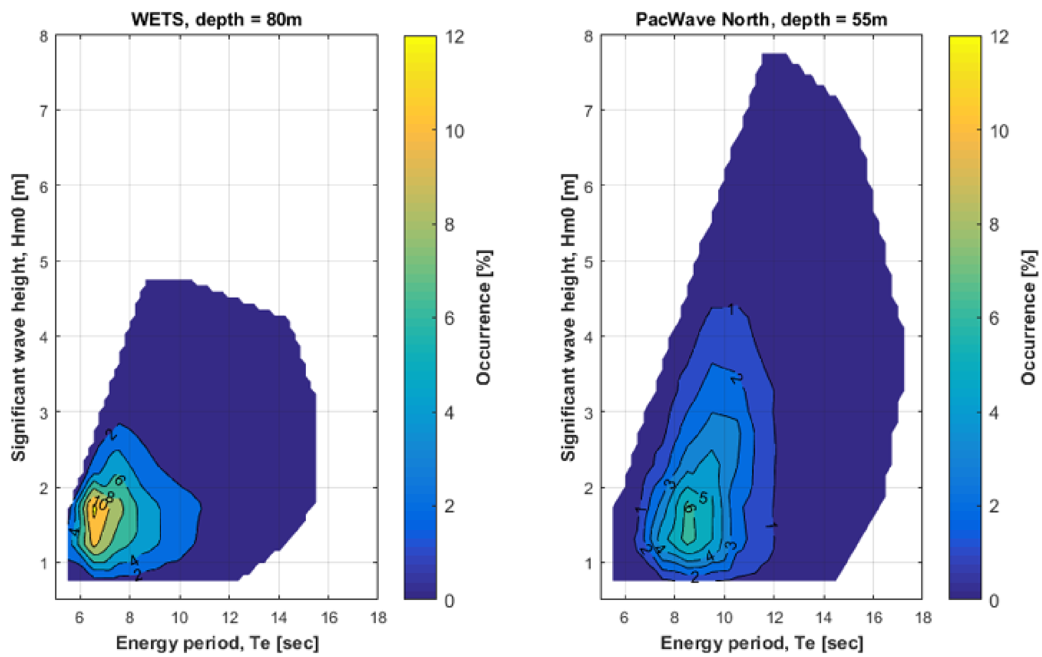


Figure 2 - 100-year return extreme sea condition, WETS and PacWave North

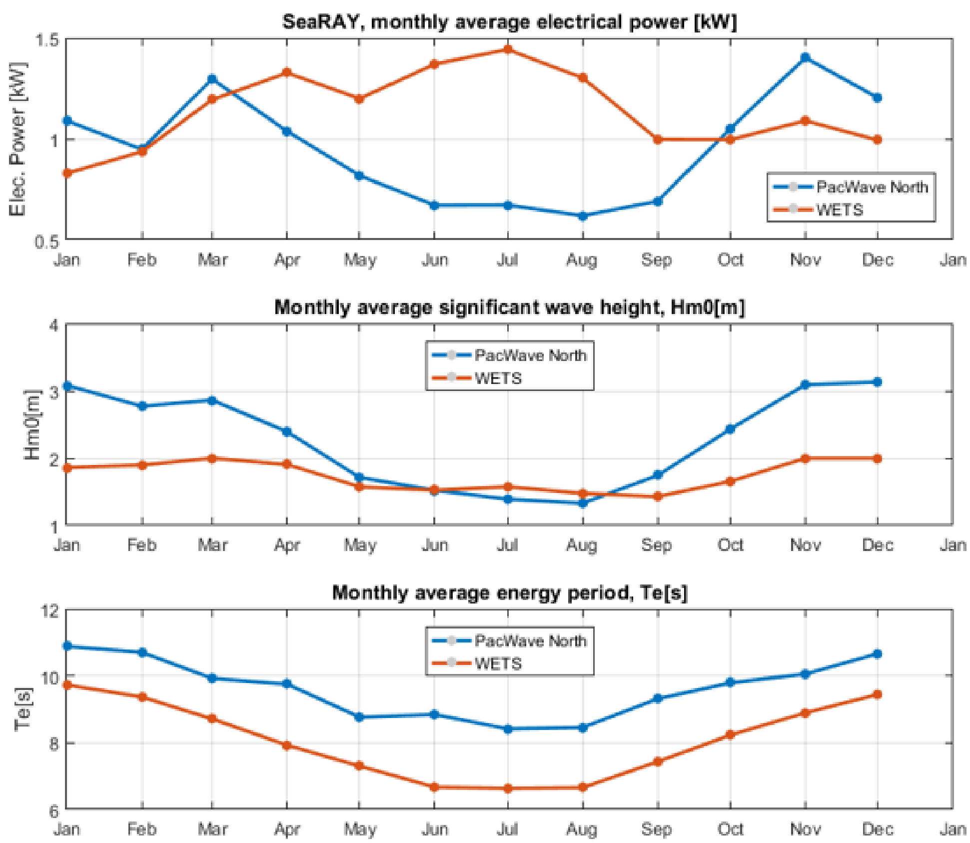


Figure 3 – Modeled SeaRAY system performance using 12-month average wave resource, WETS and PacWave North

The system was initially intended for deployment at PacWave North. As the Project progressed, the DOE and C-Power team agreed to shift the deployment to WETS. Thus, the DLCs at WETS were primarily used for modeling analysis and validation efforts.

The DLCs informed modelling and evaluation of both major component performance and overall system performance, considering survivability metrics such as peak acceleration, bearing load, and slam pressure. The resulting simulations informed changes and refinements between the preliminary design and final design.

3.4 Final Design

The SeaRAY AOPS 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, if necessary, using numbers within each ‘hundred series’ (e.g., 0700 Mooring/Umbilical > 0750 Seafloor Base Unit).

Additional descriptions and more renderings of each system are available in Appendix 14.3

3.4.1 0100 Hull

More detailed engineering drawings are available in the 13.17 Appendix: Wave Generator Nacelle Drawings.

Because WETS was ultimately selected as the site for deployment, the SeaRAY hull was designed to accommodate the sea states at WETS.

The float arms of the concept design were of equal length with the forward, wave-ward float driving two generators, while the aft was fixed to the nacelle and reacted to the torque applied to the nacelle by the forward drive float. This design was not feasible in the higher energy seas. The simulations showed the floats colliding at speeds as high as 8 m/s creating possible fatigue failure. After multiple attempts to mitigate the speed and frequency of the float collisions, the design was altered to a nested float arrangement with each float driving one the two PTOs. The revision increased the aft float width and arm length allowing it to overtop the nacelle and fore float to avoid float collision. Figure 4 shows the changes to the float arms from preliminary design to final design.

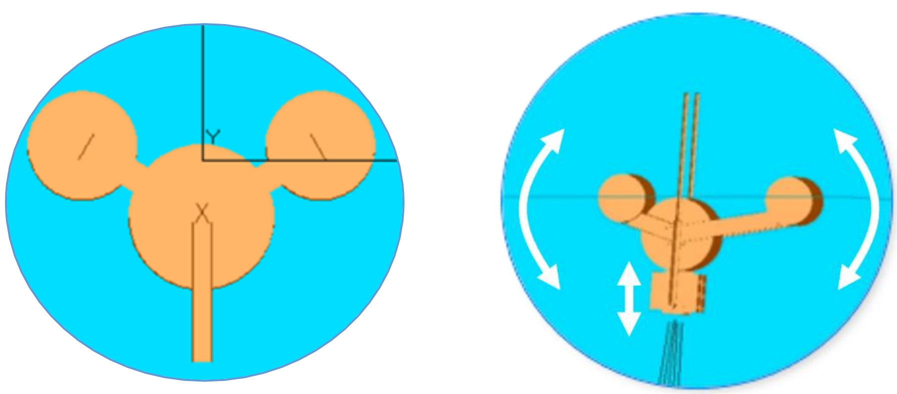


Figure 4 - Equal length float arms in preliminary design (left) vs. nested float arms in final design (right)

The nesting floats required the aft float arms to be too long to be transported in a standard shipping container – project goal enabling rapid deployment. This issue was addressed by adding a hinged float arm. The arm allows shipment in a standard container and may be quickly extended and secured on site prior to deployment.

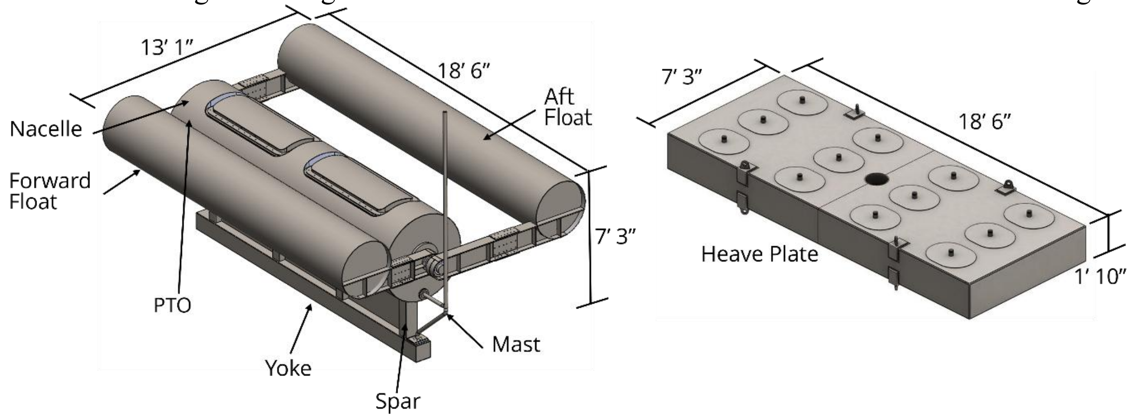
C-Power uses ANSYS AQWA for hydrodynamic simulations. Initial simulations of the nesting float design showed a performance reduction of ~30%. The fore float would occasionally go over the top of the WPS to the aft side position. With both floats on the same side there was no reaction force to drive the floats, significantly reducing the power being generated. However, if each float drove one of the two PTOs individually, with the yoke added to provide the reaction torque, the performance was only slightly reduced when the floats were nested but increased during normal orientations. The floats were modified, repositioned, and ballasted so the offset of the center of gravity and center of buoyancy caused each float to return to its nominal operating position passively. These changes brought the nested float design performance back to within 5% of the concept design.

Thus, the following high level design constraints were applied to the hull to reduce loads and increase power:

1. Nacelle
    a. Specific gravity should be as low as possible to provide upper mooring (bridle) pre-tension.
    b. Specific gravity should be higher than floats to reduce peak PTO speed in extreme seas.
    c. Center of gravity should be as low as possible to reduce peak PTO speed in extreme seas.
    d. The combined nacelle reserve buoyancy and upper mooring pre-tension must be reduced as much as possible but positive for both performance and ease of the float return motion requirements. However, reserve buoyancy must be high enough to accommodate the bio-growth over the deployment.
    e. The yoke should be long to provide restoring torque, with plates added to the yoke to damp nacelle pitch motion and improve performance when floats are flipped during extreme seas.
2. Floats
    a. Specific gravity close to 0.5 optimizes performance.
    b. Increasing specific gravity reduces lower mooring peak tension as it reduces total WPS reserve buoyancy.
    c. Reducing specific gravity reduces peak PTO speed when WPS is fully submerged during extreme seas.
    d. Center of gravity lower and closer to the nacelle than center of buoyancy provides bias in float motion to stay at its designed still water position.
3. Heave plate
    a. Should be as heavy as nacelle design constraints allow.

- Center of gravity should be as low as possible to improve stability.

The resulting design and dimensions are shown in Figure 5



. The hull thickness and additional structural reinforcement were sized using third party standards. The loading between the bodies was taken from the hydrodynamic modeling and post-processed to determine minimum thicknesses and sizes. This sizing was refined via conducting a Finite Element Analysis (FEA) model to optimize the structure.

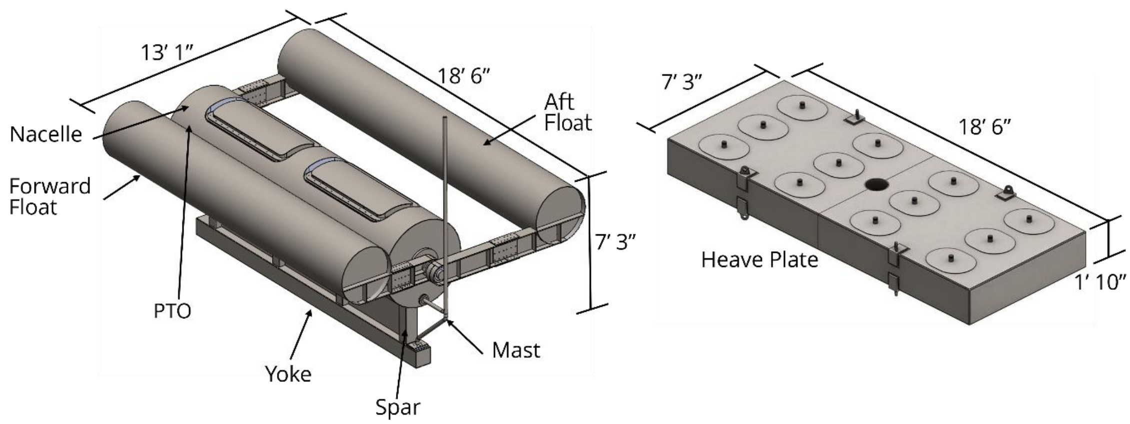


Figure 5 - Labeled SeaRAY hull and heave plate with dimensions.

3.4.2 0200 Power Take-Off

The gearbox ratio was selected to optimize the generator input rotational speed. Target efficiency is 80% or higher for complete annual PTO performance, including the combination of all bearings, gearbox, and generator in an oscillating real seas environment. This target comes from experience and previous experimental data as there is no manufacturer provided data for this type of oscillating application. Higher efficiency was obtained with an increased gear ratio, but terminal voltage also increased, and that trade-off had to be optimized. Optimization is based on the discrete options available for generators, confidential manufacturer winding options, and gear ratios available to maximize performance based on the hydrodynamic model data and power electronics capability.

Modeling included numerous runs at different generator damping. As the wave drives the float, the generator commands a torque based on how fast the float is moving. This is characterized by a damping coefficient. Different damping coefficients were established for various sea states. The selection of damping coefficients optimizes the float motion to sea state to maximize power harvesting. During operation, the WPS autonomously selects a damping value based on forecasted conditions.

During peak accelerations, the rotor inertia of the generator exceeds the rated torque of the gearbox. Thus, a torque limiter, a coupler that disengages when torque between the two shafts exceeds a threshold, is a crucial part of the drive train. The torque limiter on the SeaRAY protects the PTO from higher-than-design torque in these conditions. During brief instances, the torque will spike, and the torque limiter will disengage, not allowing the torque to travel between the gearbox and motor which might damage components. The torque limiter then reengages when the torque is below the threshold. These devices are an important safety mechanism in various industries.

A cutaway rendering of the SeaRAY PTO can be seen in Figure 6.

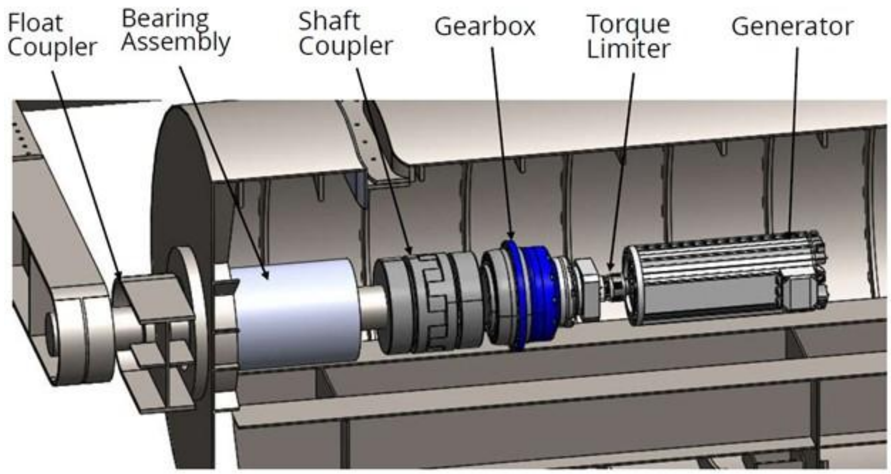


Figure 6 - Labeled SeaRAY PTO layout

3.4.3 0300 Electric Plant

The electric plant is comprised of a 3-phase AC generator, an AC to DC intermediate bus, power conditioning, a burn resistor, WPS energy storage for hotel loads, and DC transmission to the seafloor battery (Figure 7). These components take the noisy AC power from the generator terminals, convert to DC, condition the power for use from other devices, burn off excess power that cannot be used or sent to the SBU for storage to power end use payloads.

The electric plant has interfaces to most systems, establishing design constraints for the electric plant. The PTO topology chosen drove the input voltage range for all the power electronics limiting the selection of the motor used as a generator. The input power values generated from the hull determined the sizing of many of the components. The relatively low median input voltages, compared to the peak, required high efficiency components to keep the power production high. The damping values found to optimize the performance of the WPS defined the range of components used to command that torque.

The layout, function and requirements of the components that make up the electric plant were specified.

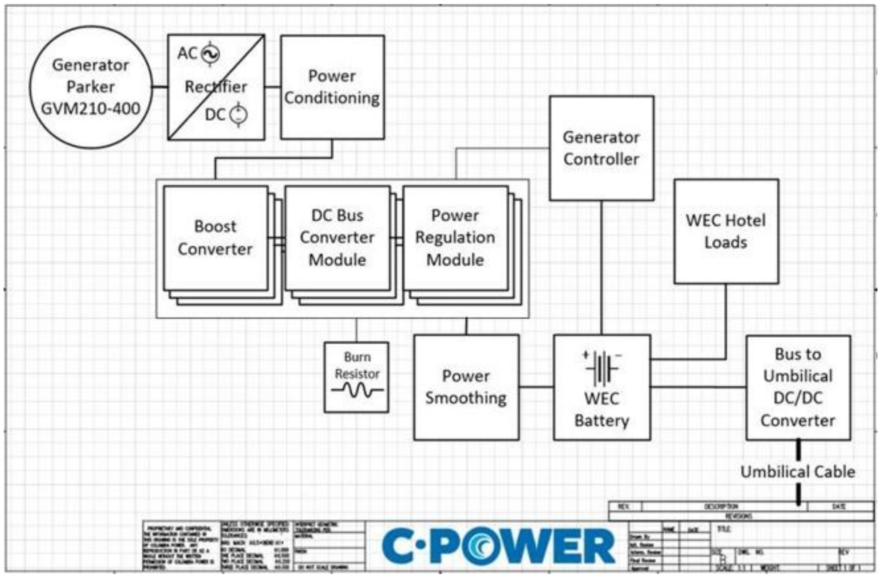


Figure 7 - SeaRAY electric plant system block diagram

3.4.4 0400 SCADA

The National Renewable Energy Laboratory (NREL) was chosen as a partner to design and build the SCADA system for SeaRAY. From a different existing DOE project, NREL developed a system known as MODAQ that is intended to be adapted to various energy converters. This system is comprised of sensors throughout the WPS, communication throughout the WPS and onto the internet, and the decision-making code for PTO and emergency system control.

The sensors, signals, user interaction, motor and Power Electronics (PE) interface, and alert levels were identified and integrated with MODAQ. Rules for these controls were coded into NREL's SCADA software and recorded on a spreadsheet for easy visual representation.

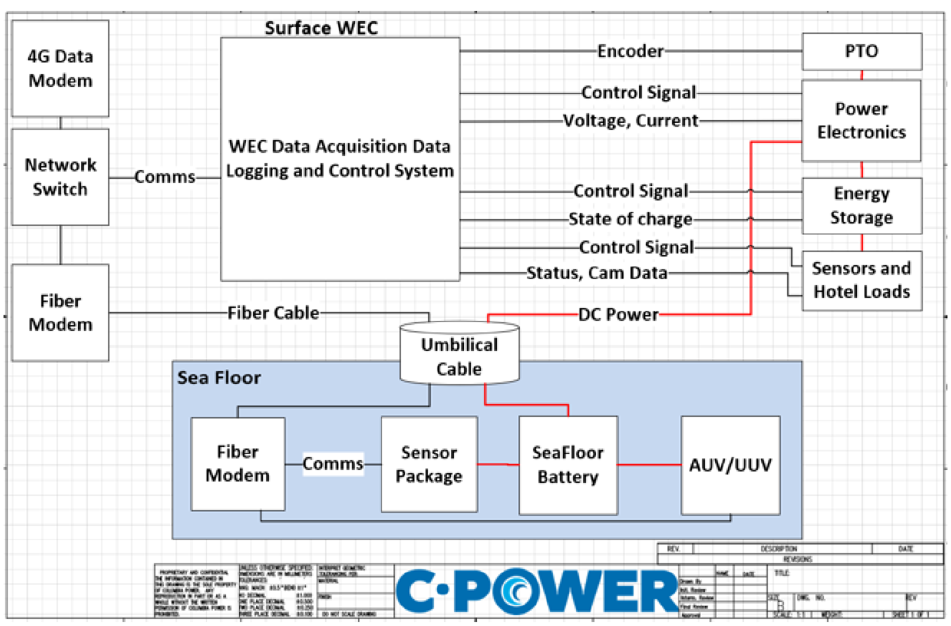


Figure 8 - SCADA system block diagram

3.4.5 0500 and 0600 Auxiliary and Outfit and Furnishings

The onboard emergency system design included fire detection, flooding detection, access alarms, and condition communications. The bilge system was designed to remove water from the hull compartments. The surveillance system included a Global Positioning Satellite (GPS) antenna, and an Inertial Measurement Unit (IMU).

3.4.6 0700 Mooring / Umbilical

The power and communications mooring system is a specialized component that created a significant technological challenge for this Project and for the SeaRAY technology development as a whole. Maintaining the single line design was important for meeting market needs as well as reducing costs.

The mooring's mechanical properties were split into two functional groupings: the upper connection between the heave plate and the WPS, and the lower connection between the heave plate and the SBU, see Figure 9. The upper connection was stiff in tension to maintain a high load between the heave plate and the WPS to create the interaction necessary for optimal performance. The upper section was the supplier's stretch hose in parallel with a nylon bridle. The lower connection required a flexible cable which lowered the load capacity requirement for all sea states. The flexible cable allowed the WPS to travel a further distance which allowed the energy to be dissipated over a larger distance, thus lowering the peak load. The solution for the lower section was a supplier's stretch hose.

This stretch hose had previously only incorporated an ethernet cable for data transfer. Because the standard for ethernet is limited at 100m and a single 30m stretch hose contains 90m of cable length, the cabling was modified to use fiber optic. This change also provided a future proof solution cable for ethernet connections at distances up to 120km. The supplier built and tested multiple prototype electro-optical mechanical (EOM) cable that had various types of integrated fiber lines and fabrication methods. One option was selected as it performed better than the rest during all phases of testing.

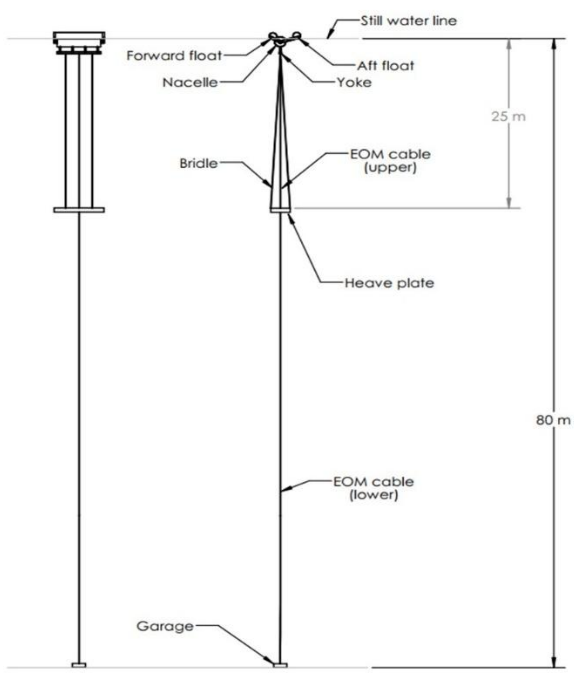


Figure 9 - Single-line diagram of surface to seafloor mooring. The integrated fiber optic lines are in the EOM cable and the SBU is represented by the box labeled 'garage'.

3.4.7 0750 Seafloor Base Unit

The SBU needed to serve as a gravity anchor and energy storage system for this Project. C-Power worked with the selected SBU supplier to design and fabricate this component according to the specifications of the order.

The lithium ion battery sizing was optimized for incoming power generated on the WPS and the outgoing power to potential subsea payloads. C-Power worked with the supplier to modify its existing SBU product to meet the requirements for this Project. The final SBU had 55kWh of energy storage, 38.5kWh of which were useable. See Figure 10 for a graphic rendering.

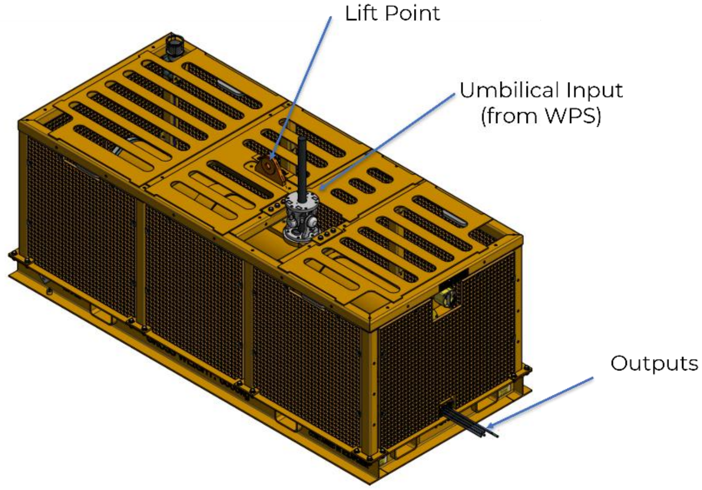


Figure 10 - Labeled SBU rendering.

4 PROJECT AND RISK MANAGEMENT

The Project experienced significant delays due to the COVID-19 pandemic, which disrupted supply chains, delayed critical components, and restricted travel for key personnel. Stay-at-home orders and workforce limitations further impacted design and manufacturing timelines, pushing back deployment schedules and extending the overall Project timeline.

Throughout the uncertainty the COVID-19 pandemic presented, the C-Power team prioritized mitigating risk to personnel and advanced the Project forward where possible. The C-Power team communicated regularly with DOE personnel to provide updates on Project progress and anticipated delays.

Additional best management practices used throughout this Project can be found in Appendix 14.4.

4.1 Risk Management Plan and Risk Registers

The Risk Management Plan (RMP) was developed based on C-Power's Failure Modes, Effects, and Criticality Analysis (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 FMECA followed a four-step process of identification, evaluation, classification, and determination of criticality as follows:

a. Comprehensive identification of potential failures modes which would have undesirable effects. Failures are detailed with respect to the systems functional hierarchy.

b. Evaluation of the likely cause(s) for each identified failure mode, as well as the effect. Unique combinations of failure mode and failure cause are registered and analyzed separately, as both the expected rate of occurrence and recommended actions to mitigate the risk will generally be different.
c. Classification of the registered risk item with regards to severity and probability of occurrence. Engineering design and preventative detection that reduces the likelihood of failure is considered in assigning an occurrence rating. Logistics and assets required for repair are considered in assigning severity ratings.
d. Determinations of the risk ranking of each registered risk item. Rankings are determined separately for each of the four severity classes: human safety, environment, WPS operations and assets.

The FMECA occurred in parallel to the design process and was an iterative process which allowed for design changes to overcome deficiencies in the analysis. The process was performed by a team of experts qualified to estimate the expected occurrence, magnitude and consequences of failure modes and design inadequacies. The collaborative team effort ensured a thorough analysis for each system, failure mode, and operating mode. The areas of design expertise included electrical engineering, mechanical engineering, controls engineering, systems engineering, software engineering, naval architecture, industrial manufacturing engineering, environmental engineering and maintenance operations support.

See Appendix 14.5 for additional information describing how C-Power managed and mitigated risk in this Project and Appendix 14.6 for system risk registers.

5 FABRICATION AND ASSEMBLY

The overall approach taken to procure and fabricate the AOPS was to procure commercial-off-the-shelf (COTS_ products where possible and leverage local shops to minimize the costs for future commercialization. When required, some of the parts procured for various systems were customized. The details of the plan for each system are explained in further detail in Appendix 14.7. Additionally, some of the more costly parts were procured from suppliers outside Oregon, when the value of the parts was determined to be superior in quality and technical specification. These decisions to purchase customized parts from specialized suppliers were made after careful consideration because of the lead time as well as the costs to the overall Project. Furthermore, customization and unique procurement may have larger implications for the industry in the future. The cost of customized parts and unique items that were procured could have the potential to become lower when procured at scale.

The potential upside to procuring parts that were fabricated locally in Oregon is the downstream impact to the ocean wave energy industry. That is, other technology developers that will deploy their systems at PacWave will have local manufacturers to source in Oregon. Some of the benefits of local fabricators in Oregon and within driving distance of PacWave, are suppliers that are familiar with the ocean wave energy industry, reduction in time to understand the intrinsic requirements of WPS, and scalability in fabricating that lowers costs at scale. The familiarity with the ocean wave energy industry that C-Power is creating with local suppliers and fabricators has a cascading effect for future WPS developers.

Because the AOPS for this Project was intended for deployment at WETS, the logistics involved various modes of shipment in addition to ground transportation – air, sea – before final assembly of the entire AOPS. As a result, there were unique considerations that were necessary to account for shipping from Oregon to Hawai'i and from suppliers in the UK and the East Coast of the USA.

Below is a high-level summary of the fabrication and assembly of each major component of the AOPS. Note any reference to assembly at C-Power refers to C-Power's offices in Corvallis, OR. Any reference to assembly at NREL refers to NREL's Flatiron Campus in Boulder, CO.

5.1 SeaRAY WPS

Competitive bids were considered from shops in Oregon and Washington to fabricate the SeaRAY hull. A local Oregon shop was selected. The hull was shipped from the fabricator to a separate vendor for the coating. Acceptance testing was conducted at C-Power in addition to the integration of key components, e.g. alignment of the float arms and masts before shipping to WETS. Assembly of hull components and cable penetrations for antennas, aids to navigation, mooring attachments, and sensors were all conducted at the fabricator's shop, NREL, and at the staging area in Hawaii. Furthermore, marine foam was installed in the floats to ensure buoyancy in the event of a leak in one of the floats. Final assembly for other components took place in the port near WETS because the hull was shipped to Hawai'i in multiple shipping containers.

The final mass of components was larger (approximately 200 kg) than originally estimated. Mass reduction measures were implemented to remove some material in the nacelle hull and change the steel enclosures to aluminum. Low density foam structures were added to the yoke to increase volume the WPS displaces, but without increasing the mass of the unit. This in turn increased the overall buoyancy of the WPS to achieve the desired water line from simulation.

The PTO was assembled from COTS components that were specified from the basic loading, torque and speed determined in the modeling. Assembly of the PTO into the nacelle was conducted at NREL where the PTO dynamometer testing took place.

The layout, function and requirements of the components that make up the electric plant were specified and parts were selected or designed if a COTS item could not be adapted. C-Power collaborated with a supplier to contract the required work for this system. Force majeure had an impact on the EP due to supply chain challenges during the COVID-19 pandemic, resulting in shipment delays and personnel changes. Additionally, regional forest fires affected several suppliers. Initial design and testing of power electronics took place at the supplier's facilities. In parallel, prototype EP units were tested at C-Power.

The SCADA hardware was integrated into its own enclosure and connected to the rest of the WPS and power electronics enclosures at NREL. Sensors were installed, calibrated, and code entered for data collection. A user interface was developed for control and analysis of the WPS. This interface was used during testing at NREL and during deployment.

Auxiliary systems were primarily COTS components and systems. Outfit and furnishings required customized hatches. Assembly of auxiliary systems and outfit and furnishing components took place both at NREL and in Oregon (C-Power facilities and manufacturing facilities).

At the hull fabricator's shop, the heave plate, nacelle and floats were attached to their standard shipping frames (Figure 11). The fore float was assembled onto the PTO shafts for transportation and the aft float was fastened to the shipping frame. All the tools and additional buoyancy modules were loaded into crates. All the parts were then loaded onto a truck, accepted for shipment by the transport company, and sent to California to await vessel loading. Once the shipment entered California, it was found that the trailer was overloaded and had to return to Oregon. The components were unloaded, and secondary arrangements made. The crates and the two shipping frames had to be split up to accommodate shipping schedules and truck limitations.

Figure 11 - Heave plate and WPS loaded onto 45' flat rack.

5.2 Mooring

The mooring cable was one of the long lead items that were sourced. A test hose was built with four different types of fiber optic construction inside of it. One of those options passed all tests and went into final production. After selecting the fiber optic specifications for the test hose, the three final hoses could be built.

The mooring vendor assembled all the components at their facility to check final fitups and to test continuity of all the connections as well as test the losses in the complete fiber optic assembly.

The mooring system from the supplier was composed of four couplers, three cables, four universal joints, and a strain gauge coupler. These components were procured, test fit, and tested for functionality in their final configuration.

5.3 SBU

C-Power partnered with a supplier to provide the system components. The entire assembly consisted of the mooring anchor mass, mooring connection points, battery storage for payload and WPS use, and payload interfaces. The SBU was identified as a long lead item. The primary cause of the lengthy time was due to the SBU being a first-of-its kind commercial unit. The supplier also explored various battery options before deciding to integrate COTS batteries into the SBU. At the time and as a small company, the supplier manufactured each unit to order, including the custom subsea enclosure for the COTS batteries and the tailored intelligent asset management system.

Scope was added during the final design phase of this Project to integrate assets into the SBU. These assets had specific interface specifications that required changes in the power and data connections. Extra hardware and the layout of the internal components to the SBU were modified to satisfy the requirements of the assets. These changes were implemented as quickly as possible to meet the schedule. Simulators were developed to mimic the asset’s connection to the SBU during Factory Acceptance Testing (FAT).

6 LAB TESTING

C-Power followed a detailed and rigorous test plan for the entire integrated AOPS as well as for each major sub system for this Project. Appendix 14.8 describes these plans in more detail.

6.1 NREL

Five primary pre-deployment testing goals were accomplished over 17 months at NREL.

1. Established PTO efficiency: The PTO was tested on a custom hydraulic dynamometer (dyno). The nominal torque applied to the PTO for a majority of the testing ranged up to 10,000 Nm with a maximum torque limit set by the magnetic torque coupler at 13,640 Nm during over-voltage events. Speeds at the low speed shaft (LSS) during testing ranged from 0 RPM to 50 revolutions per minute (RPMs). Most testing was conducted in the 0.4 RPM to 17 RPM range to correspond with expected hydrodynamic conditions at sea.
    a. Tested conversion of mechanical power input (LSS torque and speed) to electrical power (voltage and current to DC bus/Energy Storage)
    b. Constant speed test
        i. Combinations of speed and torque, both directions
    c. Oscillation test (with real wave profile)
        i. Validated PTO efficiency and torque estimator calculations measured in constant speed test
        ii. Multiple 30-minute speed profile tests
        iii. Tested SCADA control of switching from charging the battery to using burn resistor for energy dissipation
2. Torque limiter response characterization: Oscillating test conditions derived from WETS sea-state data was used. To validate the torque limiter performance, over speed scenarios were simulated to over torque the device, causing a slip event at the torque limiter. The torque limiter was evaluated based on its ability to reengage and dissipate generated heat.
    a. Tested combined effects of mechanical friction using data from constant speed test and oscillation test
    b. Updated generator model to estimate mechanical torque and electrical power
        i. Voltage constant verification
        ii. Torque constant verification
3. PE verification & SCADA function test: The SCADA system was integrated into the PTO after the PTO efficiency was documented and recorded. The SCADA interfaced with the low and high speed shaft (HSS) encoders and the generator. The total system was then tuned over a series of constant speed and ramp tests to create damping curves. Electricity was produced during this test and was directed to a burn resistor.
    a. Verified data sync between dyno and SCADA
    b. Verified SCADA controls power electronics correctly
    c. Verified electrical system (PE + SCADA) functions correctly
        i. PTO control logic
        ii. Nacelle battery charging
        iii. Data logging and data flow
        iv. Other switches control (i.e. burn resistor)
    d. System power draw – efficiency of all components
4. SBU interface verification
    a. Verified SBU simulation works using Regatron as a DC real seas simulated power source

    b. Validated SBU interface controls using Regatron SBU simulator connected to SeaRAY umbilical
5. Survival mode test
    a. Engaged torque limiter to reduce HSS speed by commanding over-torque from the generator
    b. Monitored PTO (generator, PE, gearbox, bearing, torque limiter) status (temperature, vibration)

The performance of three main PTO components were characterized:

- Mechanical torque due to bearings and seals as a function of shaft speed
    - Torque[Nm] = LSS-Speed [rad/s] * 252 + 292
- Generator and rectifier (AC-DC) efficiency
    - 89.3% when input mechanical power > 2kW
    - Efficiency below 2kW was not measured due to PE instability
- Power electronics (DC-DC) efficiency
    - 93.3%
    - Idle loss 275W

On occasion, the power electronics were damaged from shipping back and forth between NREL and the power electronics supplier for the dynamometer testing. Everything damaged was either replaced or repaired. Once the components were reinstalled at NREL, testing resumed. Changes to the components over the duration of testing resulted in the power consumption of the power electronics increasing and was greater than previously calculated. Idle loads of PE increased from 150W per PTO to 275W per PTO. Solar panels were selected as the path forward.

Two 144W solar panels were selected and purchased to be used on the nacelle to help offset hotel loads. Each solar panel was mounted to a hatch on top of the nacelle. The cabling was ported through the hatch via glands drilled through the hatches. The large door at NREL's high bay was opened so the solar panels could get sun to confirm functionality.

Once testing was finalized, the enclosures and cables were all marked so they could be plugged back into the same location. All the cables were then removed. It took several weeks for the enclosures to be mounted securely inside the nacelle and all the cables reconnected, routed, and secured. The enclosures all fit as designed without interference.

Once the enclosures were installed, several dynamometer tests were conducted to ensure all components were reconfigured and wired correctly.

A long duration (over 2 weeks) SCADA stability test was conducted where the system was left on continuously in an idle state to check for any signals of instability. No issues were discovered during this testing. The successful completion signaled the end of testing at NREL.

6.2 Suppliers

A test was devised to test four different fiber optic lines in the mooring. The testing of various alternative fibers and their sleeves/jackets was meant to evaluate different fibers for survivability during stretch testing. A secondary goal was to verify and improve the manufacturing process used in constructing the cables.

The hoses were delivered to the supplier to prepare for testing. After preparing, the stretch testing was performed outdoors, following a pre-agreed testing plan. Electrical and optical testing were performed prior to, during, and following the stretching, according to the test plan, and included testing of both fiber optic cables and copper conductors. The testing demonstrated the capabilities of the fiber optic conductors in the cables under stretch conditions, showing the production cables behaved well electrically and optically.

Additionally, the complete SBU FAT took place at the supplier's facility with a C-Power representative on site when needed. This testing included a trial of all functionalities of the various systems of the SBU software tests, alarms, data uploading, asset interface finalization and simulation, heat generation characteristics, communication checks, charging/discharging characteristics, faults, seal tests, etc. All issues that arose were resolved to a level of acceptance by C-Power.

7 AOPS ASSEMBLY, INTEGRATION, AND DOCKSIDE TESTING

Final AOPS integration and assembly occurred at a dock in Honolulu, Hawai'i.

Once all SBU components were received in Hawai'i, the supplier performed the final assembly and basic system checks remotely with C-Power personnel onsite. First, a site receipt inspection was performed, which included torque checks of fasteners on structural components, battery status checks, charging test, and general visual inspections for any damage. No material issues were found. The unit remained in storage until the WPS was delivered. The marine operations vendor performed monthly battery charge status checks and charged if necessary to maintain the minimum state of charge (SOC).

After arriving in Hawai'i, the floats were assembled to the nacelle for its final assembly configuration. Proper alignment was checked by rotating the floats and shafts with the forklift (Figure 12). The float was put in place and the arms were attached via fasteners that were torqued to their specification.

Figure 12 - SeaRAY float assembly.

As mentioned in section 3.1, two assets were planned to be connected to and powered by the AOPS. Each individual asset had a cable and a recovery line associated with it. A plastic crate was used to store both cables on top of the SBU. The crate was divided to hold each cable individually. A large tube was attached to the top of the SBU to store the recovery lines (Figure 13). Netting was used on both ends to keep fauna out of the enclosure. One end of each recovery line was attached to the main lifting shackle and the other end was staged and attached to the acoustic release.

Figure 13 - Recovery line storage on SBU.

7.1 Full System Dockside Testing

The C-Power team finalized verification and validation (V&V) steps of the AOPS and prepped the system for deployment. It was noted during initial test of the mooring there was a failure in one of the fiber optic lines. It was deemed a smaller risk to the Project overall to redo some of the component installations than it was to leave the fiber optic system without any redundancy. Thus, the fiber optic lines and bulkhead in the nacelle were replaced to restore both fiber optic lines to full functionality. After the repair, the system was checked and both lines were operable. A pair of small batteries were added inside the nacelle to provide redundancy to power the bilge. Marine insurance for the system was then issued to perform in-water testing.

In the deployment configuration, the WPS is electrically and optically connected to the SBU via the umbilical composed of three segments. As a first step, one segment was used. Many checks were performed prior to the first connection to ensure proper polarity, voltage, and power were configured to not damage any components. The system was stepped through sending power in both directions and assessing power levels. After these tests were successful, all three segments were assembled and tested.

Variable transformers were purchased to connect into the system in place of the generators in the nacelle. A portable gasoline generator was used to send power to the transformers, used to adjust voltage via a dial on the top. The output of the transformers were connected to the output terminals of the generator connected to the power electronics in the nacelle. These transformers were an efficient way to test the full functionality of the system.

With the transformers acting as the power source, the system was able to be run through its various modes. These modes had to be stepped through as they would in the deployment to bring the system online and get it into various configurations. These configurations included sending power from the WPS to the SBU to charge it as well as using the SBU to keep the WPS batteries full, a significant capability when there are no waves. Operational situations were also simulated with the complete system to measure power flow and consumption. These simulations included the initial system start-up after deployment while waiting for waves, staying alive between sufficient sea states, and re-starting the system from a complete shutdown.

NREL added an enclosure to include networking components (switches, Power over Ethernet (PoE), 5G communications, etc.). These components were installed into a separate enclosure from the SCADA enclosure to make them accessible during testing and to add the PoE for the AUV operator's use. Small modules that transmit fiber-optic light failed in the SCADA enclosure and were replaced with the Network Enclosure installation. NREL came on site in Hawai'i, disconnected and removed the SCADA enclosure from the nacelle, removed the networking components, moved the components into the new Network Enclosure, reinstalled both enclosures, and tested full functionality successfully.

Additionally, a desire of C-Power's was to ensure that if the nacelle filled with water, the floats would have enough reserved buoyancy that the WPS would not sink. Final calculations were performed that showed there needed to be an additional buoyant body attached to the WPS. It was determined that the best place would be the aft float. A 'float cap' was designed to be attached to the outer edge of the aft float so that it would not interfere with the masts, the fore float, or the performance of the device (see Figure 24 for view of float cap).

During full system dockside testing, C-Power demonstrated the viability of an AOPS creating power, storing energy from that power, converting it to a usable form, and using that power to run various assets. Additionally, bi-directional data communications capabilities between the data cloud and supported assets were confirmed.

7.2 Asset Integration Testing

The AOPS and both assets successfully completed dockside integration testing and validation (Figure 14).

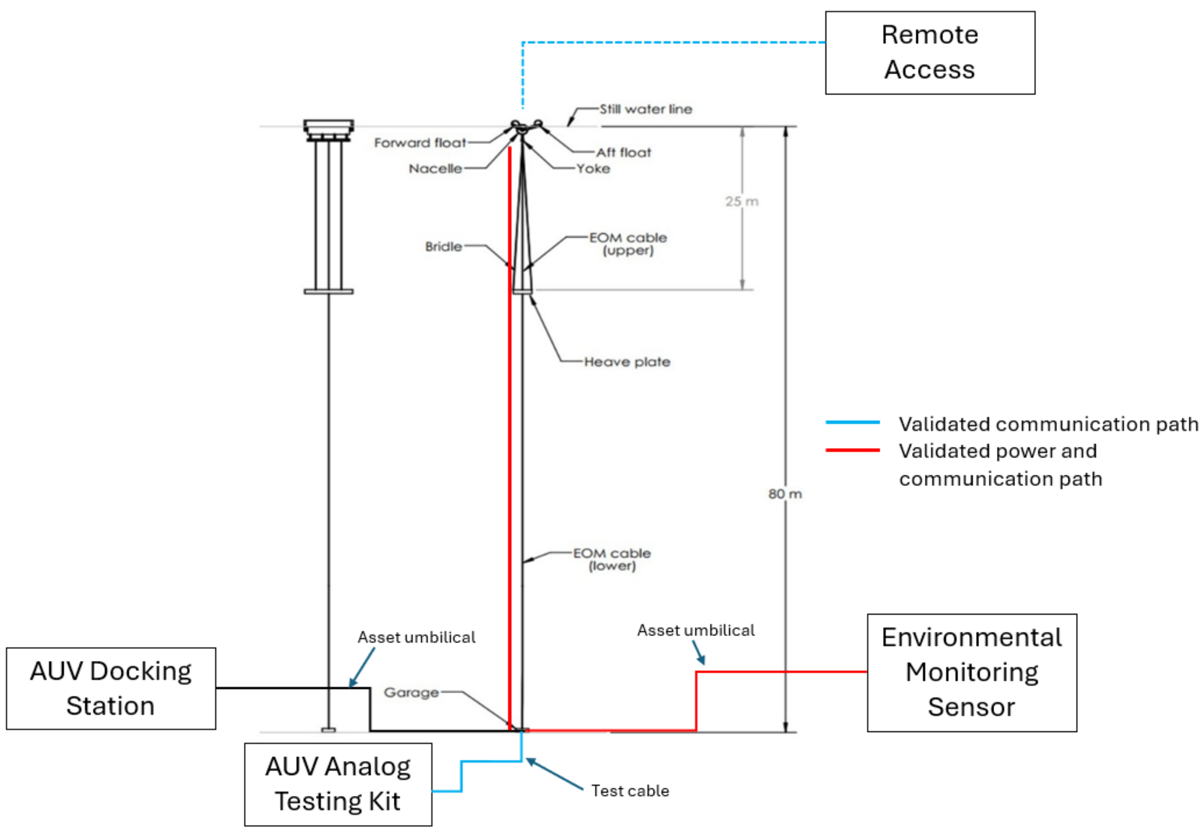


Figure 14 - Validated power and communication pathways.

The general steps taken for onshore integration testing were as follows:

1. Omnidirectional environmental monitoring sensor

   Prior to the sensor's arrival in Hawai'i, the network was configured with its remote virtual private network (VPN) encrypted tunnel, and the interface to the umbilical was configured to route power to the sensor and bidirectional communication through the SeaRAY network. Data communications via gigabit speed ethernet was demonstrated.

   Upon arrival of the sensor on site, it was connected in its at sea configuration with its subsea umbilical to the SBU. Power was applied to the sensor from the SeaRAY control system to power up the sensor. Once the sensor controls and communications had powered up, those functions were validated by personnel in Seattle, Washington operating the sensor in Honolulu, Hawai'i. The onboard sensors can only be powered on when the device is in the water so full power draw could not be confirmed. To the extent possible on dry land all power flow, control, and data flow were validated as expected at sea.

   In numerous pre-deployment visits, the sensor operators tested their real-time monitoring software modules and outputs. These outputs included graphical user interfaces that showed features such as total coverage area, live marine mammal tracking, and detection alerts.

2. AUV

   The network was configured with its remote VPN encrypted tunnel, and the interface to the umbilical was configured to route power to the AUV docking station and bidirectional communication through the SeaRAY network.

   An analog testing kit was provided by the AUV operator that included an analog camera, an AUV simulation computer, and a media converter to simulate the AUV camera interface. This equipment was connected via the fiberoptic connection and a network switch to test the simulation equipment for end-to-end communication. The AUV analog demonstrated data throughput from the virtual docking station through gigabit speed network. AUV operators were able to control and interface with their simulation equipment from their office in Michigan with bidirectional communication and control validated.

   A backup long-range point to point antenna was installed on the SeaRAY communication mast and tested separately with the AUV analog simulator and another long-range point to point antenna. This antenna provided backup distress communication to the AUV. If the AUV encountered an emergency and surfaced during an autonomous mission and was unable to communicate via satellite, it would be able to communicate with the SeaRAY and send a distress signal to the operators onshore and receive the attention required.

   Configurations for power were validated per the design specification utilizing handheld voltmeters and validated with equipment from the AUV operator.

8 PERMITTING

Permitting efforts for this Project included coordination with multiple government agencies; more detailed information can be found in Appendix 14.9.

In April 2003, a Finding of No Significant Impact was signed for a U.S. Navy Environmental Assessment (EA) for WETS. The 2003 WETS EA analyzed the impacts of phased installation and operational testing of up to six WPSs offshore of Marine Corps Base Hawaii (MCBH). The SeaRAY was the sixth deployment at WETS.

C-Power prepared a Categorical Exclusion (CATEX) for Naval Facilities Pacific that addressed the deployment and operation of the WPS at the 80m berth. This document was prepared per Navy's OPNAVINST 5090.1D Environmental Readiness Program and in compliance with the National

Environmental Policy Act (NEPA) (1969), as implemented by the Department of the Navy under 32 Code of Federal Regulations (CFR) Part 775, 69 CFR 8108.

A Biological Assessment (BA) and Essential Fish Habitat Assessment (EFH) were prepared to address potential impacts this WPS deployment may have on species listed under the Endangered Species Act (ESA).

A Nationwide Permit Pre-Construction Notification (PCN) was prepared for the US Army Corps of Engineers Honolulu District prior to the WPS installation. The PCN provided a complete description of the proposed activity, as well as identifying direct and indirect adverse environmental effects the activity could cause. A Water Quality Certification, in accordance with Section 401 of the Clean Water Act, from Hawai'i Department of Health was applied for and acquired.

At Naval Facilities Engineering and Expeditionary Warfare Center's (NAVFAC EXWC) direction, the plan changed to require the entire project – SeaRAY AOPS plus assets – to be permitted together. All contingency time was expended to gather pertinent description of the assets for the permitting process. All asset information was distributed to necessary parties in the Navy and National Oceanic and Atmospheric Administration (NOAA).

Due to extensive delays in permitting, C-Power, DOE, and the Navy made a joint decision to bifurcate the AUV support demonstration from the balance of the Project, with approval of the AUV to be sought later.

NAVFAC EXWC prepared a proposed update to the BA for the existing programmatic consultation that broadly covered operation of WETS. It was determined that the SeaRAY WPS was found to be within the existing scope and parameters of the previous NEPA environmental assessment and related CATEX. NAVFAC EXWC requested an ESA Section 7 letter of concurrence with this determination from the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS). Additionally, NAVFAC EXWC secured a Nationwide Permit from the U.S. Army Corps of Engineers and Private Aids to Navigation permit from the U.S. Coast Guard.

After the Navy received NOAA NMFS verification that the SeaRAY and seafloor sensor conformed to the 2020 Programmatic EFH Consultation for WETS, the Navy secured the NMFS ESA programmatic concurrence.

Planning and specifications for the AUV were incorporated into separate permitting documentation and submitted to NAVFAC EXWC and NOAA for review. The AUV operator provided specifications of the AUV and docking station to be deployed. All sensors onboard were described to specify their function, size, acoustics, and any light emissions. After an 8-month long process, NMFS EFH and ESA concurrence were reached.

9 INSTALLATION, OPERATIONS, AND MAINTENANCE (IO&M) PLAN

The IO&M plan for the SeaRAY AOPS was built around utilizing an 84-foot marine vessel equipped with a 10-ton A-frame and owned and operated by the Project's local marine operator in Hawai'i. The proposed configuration would have the heave plate positioned on the sea vessel next to the knuckle crane and the SBU positioned under the A-frame. The mooring lines would then be connected to the WPS, heave plate, and SBU. The WPS is then placed into the water and towed to the test site.

When the installation area was determined to be clear of ESA species, the WPS would be untethered from the marine vessel and tended by a smaller vessel. The heave plate would then be lowered onto the surface of the water with a knuckle crane. The heave plate would remain positively buoyant for this portion of the operation. The SBU would be lowered to the seafloor using the A-frame crane at the stern of the sea vessel. The heave plate would then be flooded with seawater and sunk to its operational position at an approximate depth of 22 meters. Figure 15 shows a high-level storyboard of the planned installation operation. Figure 9 provides a rendering of the entire system deployed.

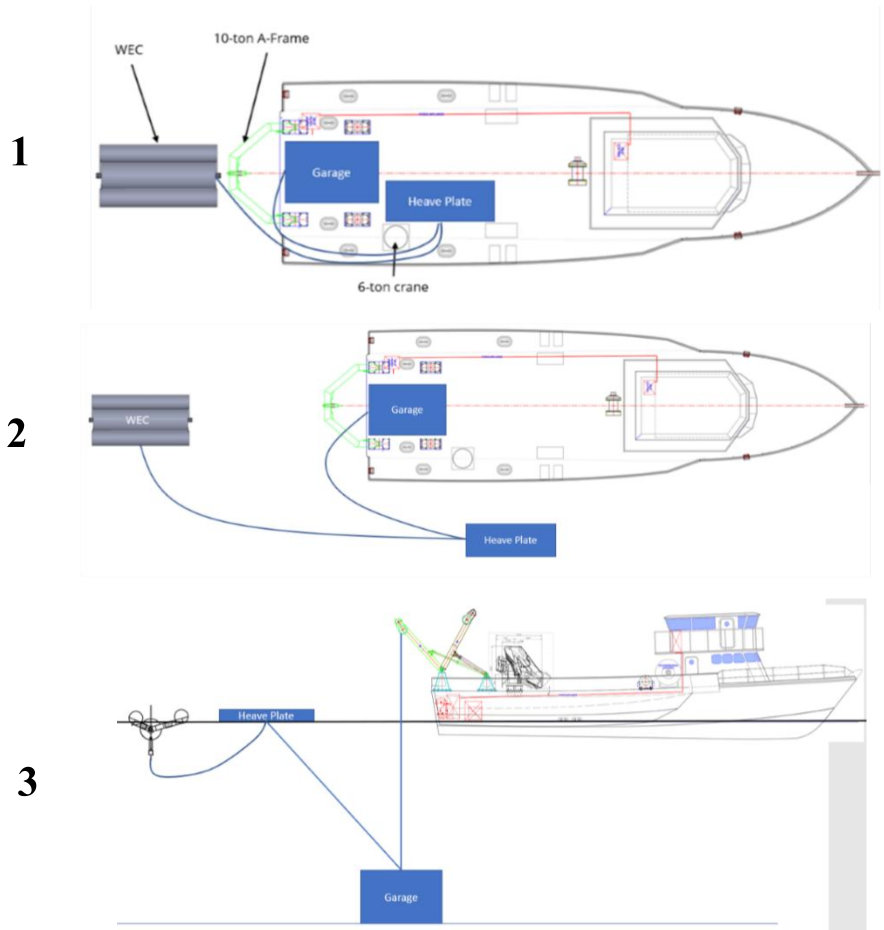


Figure 15 - Storyboard depicting three primary steps in SeaRAY AOPS deployment plan.

In order to practice the installation procedures prior to deployment, an in-harbor operational test was planned utilizing the selected marine vessel.

9.1 In-Harbor Operational Test

An in-harbor operational test was performed in Honolulu harbor prior to deployment. This test allowed C-Power to modify the ballast of the system to ensure proper waterline and tension in the bridle lines. C-Power team members and the marine services operator collaborated to develop story boards for all activities in Hawai'i including assembly, ballasting checks, full system verification and validation, and deployment operations. These storyboards ensured both parties were in alignment.

To prepare for the ballasting and deployment testing, the WPS was assembled into its final configuration and the masts were installed with all the sensors and equipment to accurately represent the mass for ballasting. The WPS, heave plate, and SBU were then moved from their assembly and testing site to the edge of the pier (Figure 16).

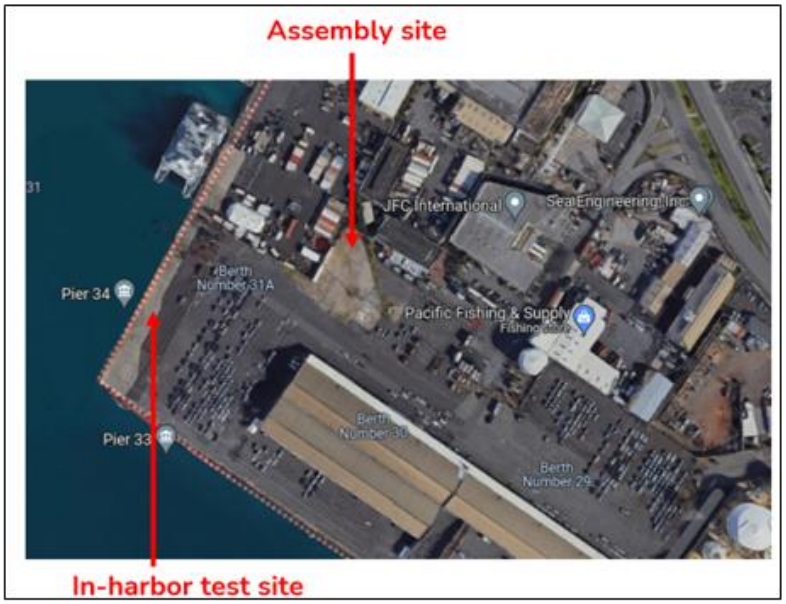


Figure 16 - Map view of assembly site and in-harbor test site

The crane used the main hook to pick up one end of the heave plate and the whip line to pick up the other end. The heave plate was slowly lowered into the water until it floated with the crane lines slack (Figure 17). This was initially performed with all the valves closed to keep it floating to check the waterline and surface stability.

Figure 17 - Heave plate lowered into water for in-harbor operational test

The WPS was then picked by the crane with the main hook connected to two chokers on the nacelle and the whip line was attached to the bottom of the yoke (Figure 18). This method provided stability of the three rotating bodies as the aft float swings below the nacelle when lifted. The WPS was placed in the water with the crane and once floating, a Rigid-Hulled Inflatable Boat (RHIB) was used to pull the WPS away from the pier while the heave plate was maneuvered between it and the pier (Figure 19).

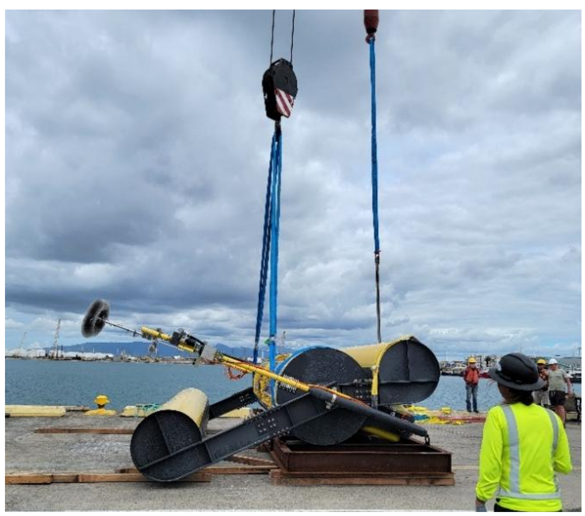


Figure 18 - WPS with crane attachments.

Figure 19 - Heave plate maneuvered into position
while RHIB tends to WPS.

The heave plate was connected to the WPS via four bridle lines that were shorter than those used for the deployment as the water depth at the pier limited the depth the heave plate could go to. Once the bridle lines were connected, the heave plate was flooded to rest below the WPS (Figure 20). With the heave plate suspended below the WPS, the WPS was upright in the water and the waterline was inspected (Figure 21). On the first test, the WPS was sitting 2 inches higher than nominal. It was calculated that two of the yoke balloons needed to be removed. These were removed overnight, the whole system retested the following day, and the optimal waterline was achieved.

Figure 20 - Heave plate beginning to flood.

Figure 21 - SeaRAY upright in the water after heave
plate flooded to operational position.

The SBU was tested separately from the WPS and heave plate. It was loaded onto the sea vessel and positioned into its transit location (Figure 22). Measurements were taken between it and all the deck components around it to get a proper layout. The SBU was lowered into the water enough that it was fully submerged to get an accurate depiction of how the sea vessel would sit in the water as it was being lowered to the sea floor. Testing was conducted of the backup communication to the SBU via the acoustic release that can be seen in the forefront of Figure 23 being lowered into the water via the blue and purple lines. C-Power was initially informed that the marine operations vendor considered this a successful test confirming that the sea vessel is fit to deploy the SBU.

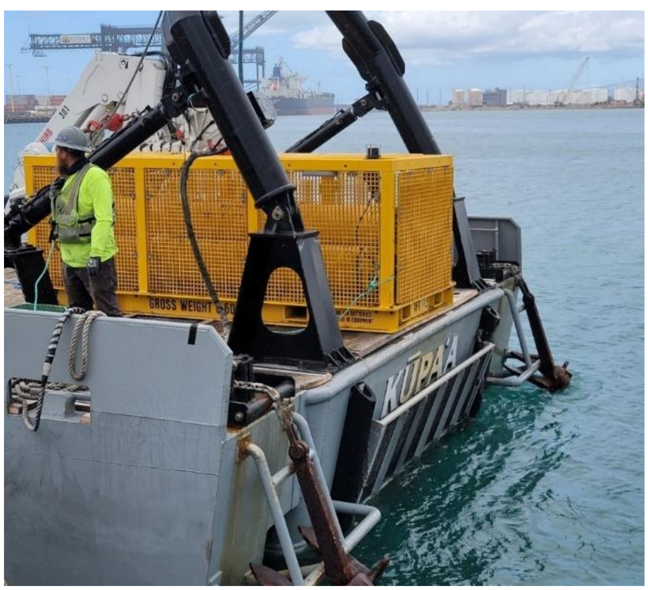


Figure 22 - SBU staged on back of vessel.

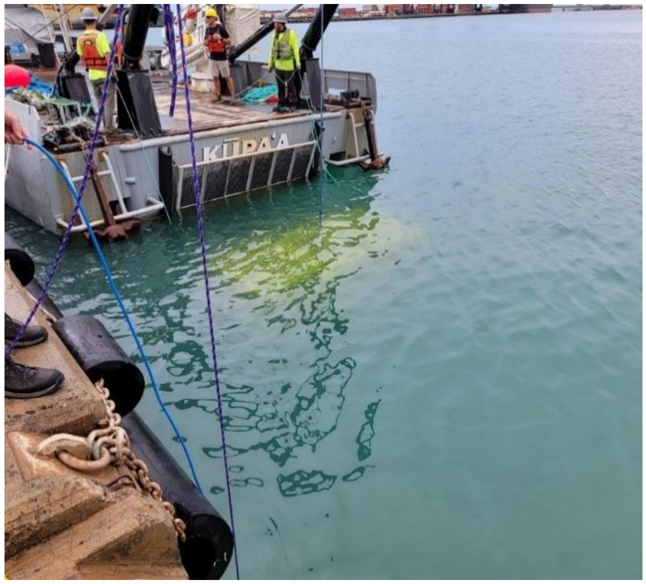


Figure 23 - SBU lowered into water.

However, after completion of the in-harbor operational trials, the marine operations vendor informed C-Power that the sea vessel crane intended for deployment could not handle deploying the SBU in the sea states that it was originally intended to deploy. This issue was identified as a discrepancy in understanding between static loading and dynamic loading capabilities of the crane. Alternate deployment plans were investigated.

One option considered performing the original deployment plan with the addition of towing the heave plate with the WPS instead of having it on the marine vessel. A naval architect was contracted to analyze the towing of this configuration. Other options considered the use of alternate vessels based in or frequenting Hawai’i.

10 DEPLOYMENT, OPERATIONS, AND RECOVERY

After the in-harbor sea tests were completed, the team readied the components for deployment. C-Power continued to pursue various deployment options. On behalf of the Navy, the University of Hawai’i (UH) secured a contract with a marine construction contractor to work at WETS with one of their crane barges for cable work. The Navy and UH subsequently agreed to allow C-Power to deploy the SeaRAY in conjunction with their work. This allowed C-Power to use a large stable platform and crane sufficiently sized to pick all components.

Once this path was determined to be accepted by all involved parties, the WPS, heave plate, SBU, and mooring were all loaded onto the barge (Figure 24, Figure 25). Once on the barge, the masts were installed in their final configuration and all external components marinized. The components were all lashed down to the deck of the barge and inspected by a marine surveyor. Once all components were loaded, finalized, and secured to the barge, the teams had daily meetings to review the weather forecast and determine if the weather was satisfactory for execution.

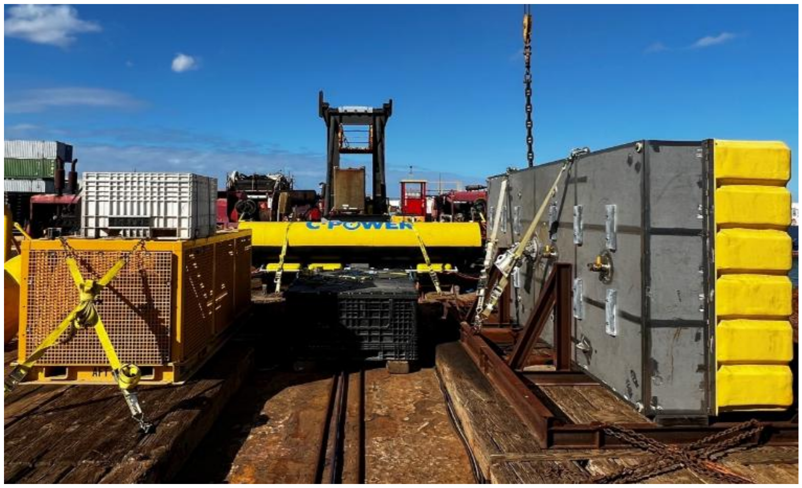


Figure 24 - SBU (left) and heave plate (right) loaded onto barge.

Figure 25 – WPS loaded onto barge.

10.1 Deployment

After five months of repeated planning cycles, a crane barge, two tugs, the marine operator's sea vessel, and RHIB were used to deploy the AOPS. One of the tugs towed the barge from Honolulu Harbor to WETS. Once on site, the other tug was used to transport people and keep the barge stationary while the mooring was established. While the barge was on site and the mooring was being set up, the C-Power crew performed final checks on the system and connected all components to one another (Figure 26, Figure 27). During final checks on land, it was discovered a communications cable that connected the SBU to the bottom of the mooring hose was not properly functioning. The C-Power team overnighted a replacement; it was installed at-sea prior to deployment.

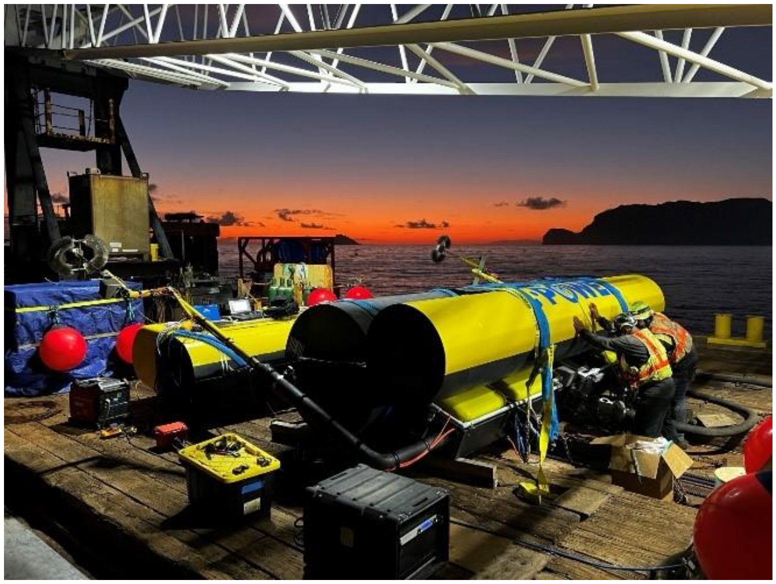


Figure 26 – Final system preparation prior to deployment.

Figure 27 - Final connection of heave plate to SeaRAY with bridle lines and mooring.

The first step of the deployment was to crane the SeaRAY into the water (Figure 28). Care had to be taken with the attached bridle and mooring lines. Six lifting lines were used to ensure stability. While the marine vessel tended the SeaRAY away from the tug, the crane lifted the heave plate into the water (Figure 29). After the nacelle and heave plate were in the water, the SBU was lifted over the stern of the barge via the crane. Once under water slightly, the SBU load was transferred to the deck winch that then lowered it to the seafloor. With the SBU on the seafloor, the lower two mooring lines were stretched from 60m to 80m to the heave plate on the surface. Divers were then used to open valves on the heave plate to flood it into place below the nacelle.

Figure 28 – SeaRAY placed into the water via crane.

Figure 29 – Heave plate lifted from the barge via crane

When the heave plate was flooded into position, one of the bridle lines got wrapped around the heave plate. Divers were able to attach a lift bag to that corner to remove enough tension in the line to get it unwrapped. This caused moderate chaffing on the bridle line (Figure 30). Plans were made to replace the chaffed bridle in-situ.

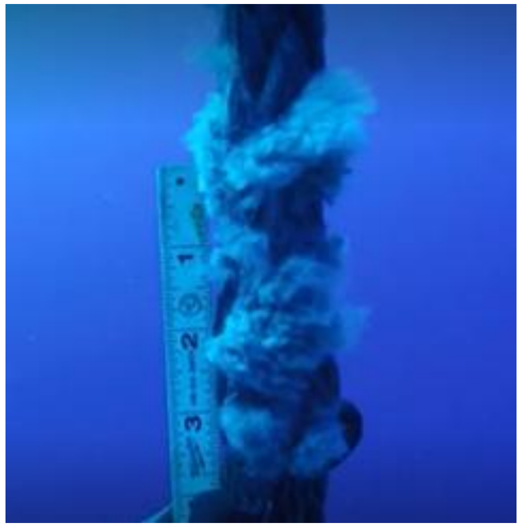


Figure 30 - Chaffing on bridle line

With the system fully deployed, a ballasting check was conducted. The observed waterline was found too high, indicating the WPS was riding lower in the water than desired. To compensate, lead weights intended for adjusting ballast were removed from the heave plate. This raised the nacelle’s waterline but was not sufficient to get to nominal position. Later, the team determined that the moored depth of the heave plate balloons and the mid-column float compressed the contained closed-cell foam and affected buoyancy negatively as well as some fabrication issues with foam inside the heave plate balloons. This decreased buoyancy added more tension in the mooring line which affected the nacelle’s position in the water. Plans were made to further adjust buoyancy to achieve nominal position. All deployed AOPS components can be seen in Figure 31, Figure 32, and Figure 33.

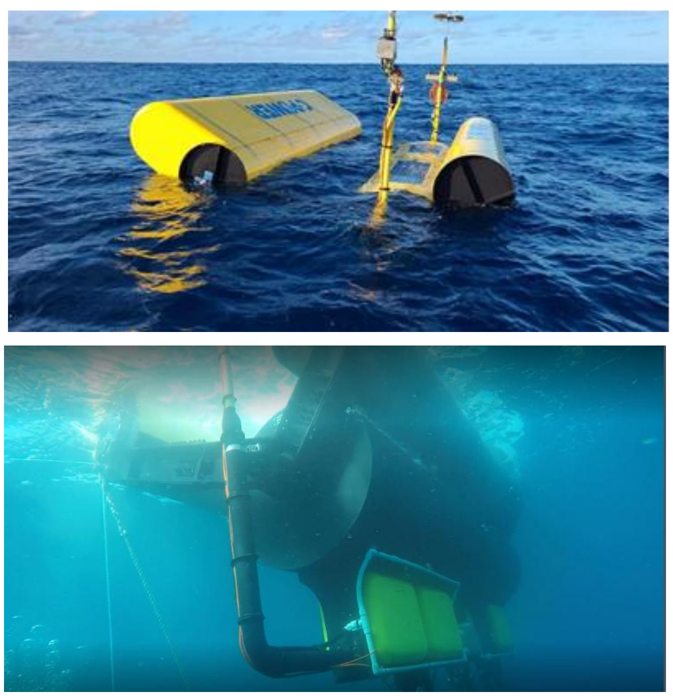


Figure 31 - Topside (top) and underwater (bottom) view of deployed SeaRAY prior to ballasting correction

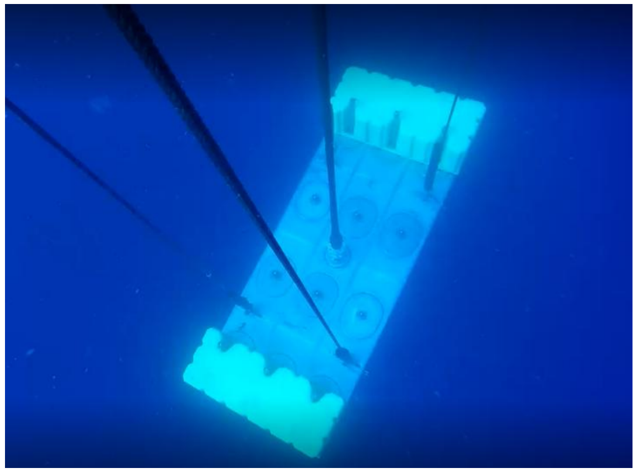


Figure 32 – Deployed heave plate and bridle lines.

Figure 33 - Deployed SBU.

The environmental monitoring sensor was originally intended to be deployed at the same time as the SeaRAY AOPS. However, while on site, multiple issues developed related to the subsea cable connected to the SBU, preventing deployment. Plans were made to deploy the sensor during the next appropriate weather window and dependent on vessel availability.

10.2 Operation

While deployed, the system functioned as expected. The SCADA web interface reported system performance consistently and accurately. The SCADA web interface screen capture (Figure 34) shows that both PTOs generated power. The starboard generator showed more consistent power production. Thus, the system turned on the starboard side first. As the onboard capacitors charged, the port side was then turned on. The sea state during this time window was such that it was not large enough to keep both sides on full time so the SCADA system shut one side off. This showed the system was working properly and to optimize production, the hotel loads were reduced by turning off some of the power electronics. For more details on power production see Section 11.3. In addition, the heading of the device was recorded and reported in the web interface (Figure 35).

Figure 34 – SCADA web interface showing power for both PTOs.

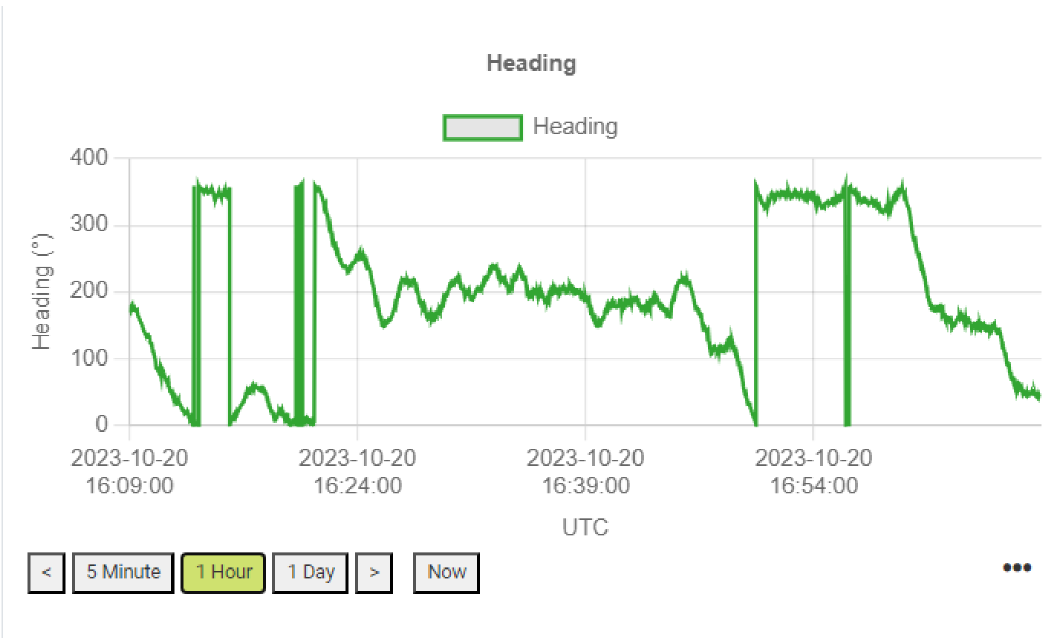


Figure 35 - SCADA web interface showing heading.

During extended periods of system tuning or low energy sea states that fall below the annual averages, the system will not produce enough power to keep itself charged. This was expected behavior that can either be addressed with manual topside charging or additional energy storage in the SBU. Manual charging was a planned deployment operation and due to the challenges described in Section 11, the C-Power team performed several manual charging cycles. A local fisherman was commissioned to assist. This reduced the costs of the inspection and charging visits and gave more flexibility and availability for the C-Power team to go out and charge when needed. Figure 36 shows the system being charged while the vessel maintained a safe distance. During topside charging operations, both the SBU and nacelle batteries are charged either independently or simultaneously. The standard operating procedure was to begin with charging both sets of energy storage simultaneously. The nacelle batteries completed charging much faster due to a smaller kWh rating, and thus the remaining of the topside charging operation was spent charging the SBU independently. Future SeaRAY design considerations will include adding a "blackstart" capability to recharge the onboard batteries from a fully depleted condition by capturing small amounts of wave energy until the system can be brought back online.

Figure 36 - At-sea manual charging activities.

10.3 Damaged Starboard Mast

On the evening of Oct 20, 2023, the web interface indicated the AOPS was offline. The shoreside camera at MCBH was not assistive in the response process because it was too dark. Following the procedure, the marine operations contractor was contacted to see if they could transit out to the device to perform a visual check. Personnel arrived on site shortly thereafter and confirmed that a mast was missing, the lights were off, and the nacelle was riding lower than expected. The following morning, C-Power personnel went on site and confirmed the starboard mast was sheared off. The mast was hanging from the nacelle by the attached cabling. It was determined that water was entering the nacelle through the bilge air intake valve attached to the broken mast and held upside down under water. Both bilge lines were capped off to prevent further water ingress. It was hypothesized that a vessel had tied off to the mast and sheared it off.

On October 22, C-Power went on site with equipment to remove damaged lines and masts and pressurize the nacelle with air to remove the internal water. This operation was successful, and the device was left in a stable condition.

10.4 SeaRAY and Heave Plate Recovery

A plan was made to recover the SeaRAY and heave plate by towing the device into Kaneohe Bay with a tug. Once on site, it was found that the port mast had also been damaged by being bent outward. This additional mast damage further validated the hypothesis that the damage to the masts was caused by a third party tying off to the device.

The recovery process was performed as expected. The heave plate was brought to the surface with lift bags. Then, the mooring line was disconnected from the bottom of the heave plate. This allowed the SeaRAY and heave plate to be towed in a string via a tug (Figure 37). The SBU was left on the seafloor for a subsequent recovery effort. Once in the bay, the device was temporarily moored (Figure 38).

Figure 37 - SeaRAY and heave plate towing recovery.

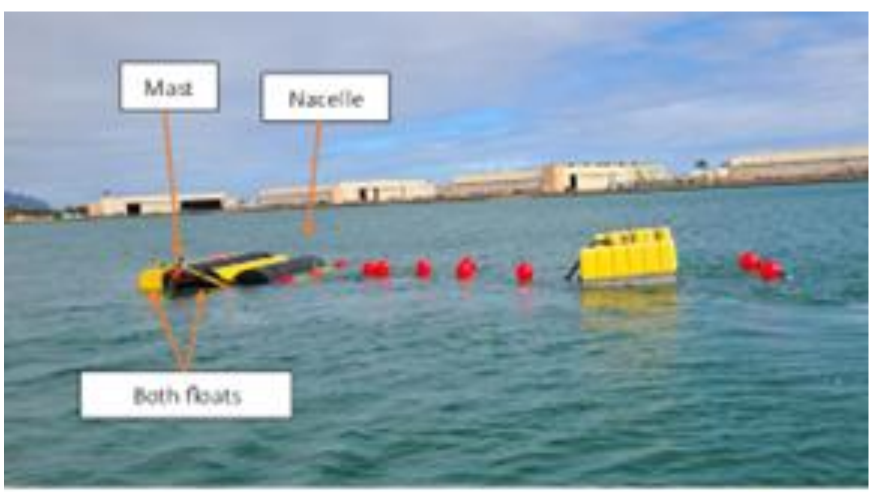


Figure 38 - Temporary mooring in Kaneohe Bay.

The SeaRAY and heave plate were removed from the water via an onshore crane and were loaded onto a flat rack (Figure 39).

Figure 39 - SeaRAY and heave plate loaded onto truck.

The SeaRAY nacelle was shipped to Oregon where the C-Power team removed all enclosures and inspected the system for water damage (Figure 40, Figure 41). The enclosure that was in the bottom of the nacelle indicated water intrusion and consequently sustained damage (Figure 42).

Figure 40 – Nacelle at C-Power's facility.

Figure 41 – Enclosures removed for inspection.

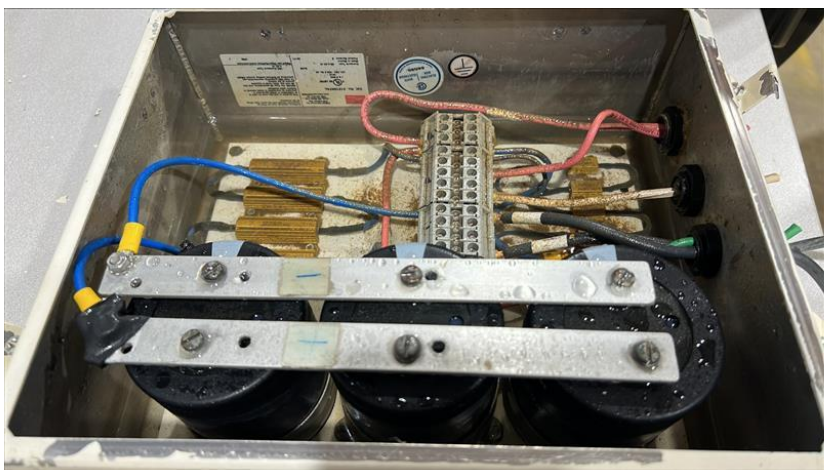


Figure 42 - Water damage in enclosure.

10.5 SBU Recovery

The SBU was left in the water while the SeaRAY and heave plate were removed because there was no method to remove the SBU with the vessels available during the initial recovery operation. Given the elapsed time since initial system recovery, it was expected the batteries in the SBU were nearing deep discharge, in which case permanent damage would be done. A plan was made to go out and attempt to charge the base unit. A remotely operated vehicle (ROV) was sent down to inspect the state of the equipment before a charge was attempted. The ROV found that the lower mooring line had wrapped around the SBU and was stuck in the lower c-channel of the frame (Figure 43). A vessel was used to pick up the free end of the mooring line and transited in a circular pattern that unwound the cable. Once unwound, the cable was brought up to the vessel and a charge of the SBU was attempted (Figure 44). The voltage and current while attempting the charge indicated a short. It was believed that the cable had been pinched around the tight bend in the c-channel, causing the short. The cable was then secured for future recovery.

Figure 43 – Mooring line wrapped around SBU.

Figure 44 – SBU charging attempt through lower umbilical

After the mooring cable had been laid on the seafloor for storage, the acoustic release for the SBU recovery line was triggered. This line was stored subsurface for expediency once on site for full SBU recovery. The acoustic release was inoperable and did not release the recovery line. During the following two days, a plan was created to send an ROV with a hook on the end to connect another line to the recovery line to bring it to the surface (Figure 52). This operation was successful. The full recovery line was then brought to the surface and the SBU was recovered.

Figure 45 - ROV hook used to retrieve SBU recovery line.

11 RESULTS AND DISCUSSION

11.1 Data Collection

The AOPS deployed on Oct 6, 2023. System tuning was completed on Oct 18 and set to automation mode. The test stopped on the night of Oct 20 due to damage to the mast. Figure 46 shows an overview of each of the deployment phases. The MODAQ system was active when appropriate during the tuning phase (~70%) and the testing phase (100%). Positive power output from the power electronics occurred during about 40% of the testing phase. Performance data was collected during the testing period, and motion data during times of interest was analyzed (for example, when AOPS heading did not correlate with PTO status).

Figure 46 - Deployment phases.

The PE was designed to turn on gradually. During the first half of the testing phase, only the fore PTO was on. The aft PTO was turned on momentarily but shut down if input power was not high enough to supply the hotel loads for the power electronics, which were ~300W for each PT. Figure 47 and Figure 48 show the PTO status during the deployment testing phase against observed sea states and significant wave heights, respectively.

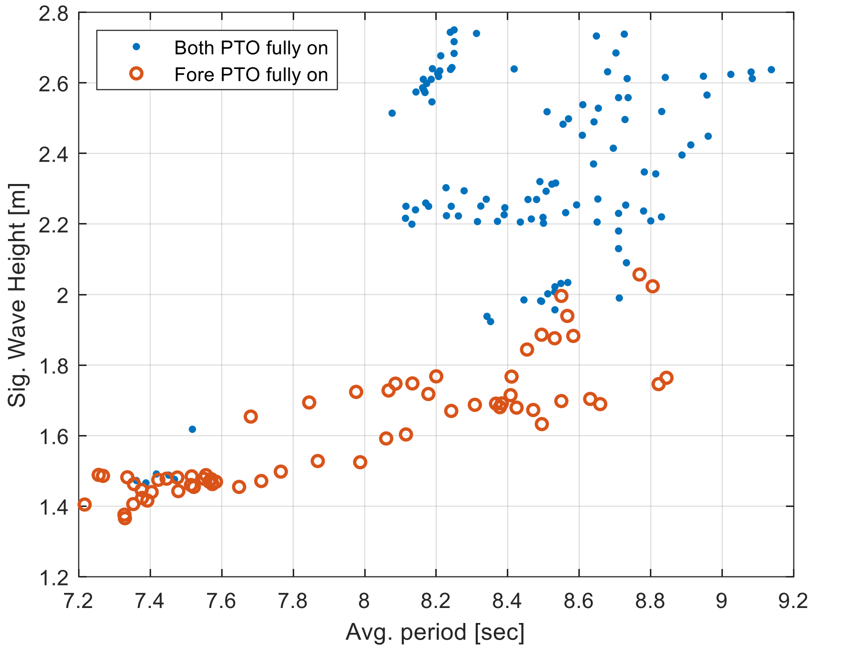


Figure 47 - Observed sea states and PTO status during test phase.

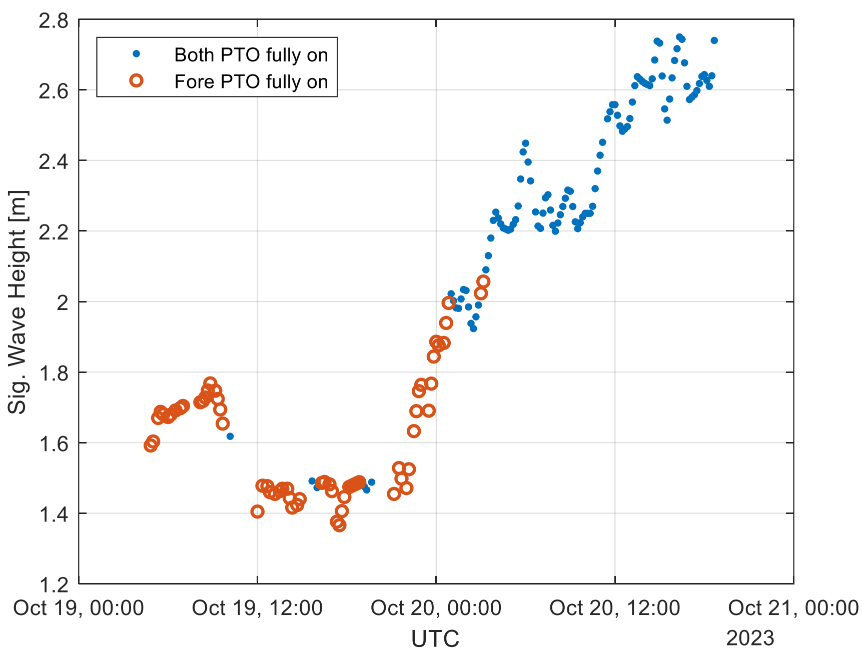


Figure 48 - Observed significant wave height and PTO status during test phase.

There were 20 customized wide-range DC-DC modules made by the PE supplier, which, combined with the SCADA, controlled the PTO torque. Each PTO was controlled by ten units, and each group of five units were separately controllable. This allowed for half of the units to be shut off during low energy sea states to limit power loss.

Figure 49 shows the total number of PE units that were on during the deployment test phase. Gaps in the plot above indicate when only half of the PE were on either side.

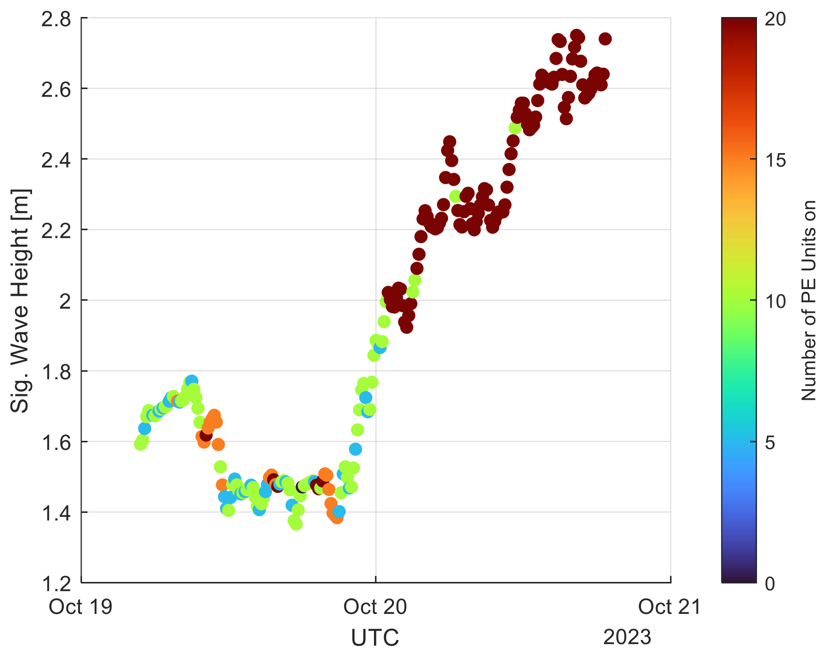


Figure 49 - PE status during deployment test phase.

11.2 Divergence From Design and Discussion

In this section, factors that affected the AOPS performance are described.

11.2.1 Mass and displacement

The ballast was adjusted to reach the designed freeboard during the Honolulu in-harbor operational test before deployment. However, the mass of the system changed in specific locations after deployment. Those changes significantly increased the AOPS mass which caused the SeaRAY nacelle to become fully submerged. Sections below describe each factor and show how the total mass change was estimated.

11.2.1.1 Mid-column float on the lower section of stretchable umbilical

The mid-column float supplied by the manufacturer of the stretchable umbilical hose was between the two 100 feet hoses below the heave plate (Figure 50). It is designed to offset the mass of the hoses. When the AOPS was retrieved, it was discovered that the foam inside this float collapsed under pressure (Figure 51). The exact amount of lost buoyancy was not measured, but the total changes in mass and displacement are estimated in Section 11.2.1.4.

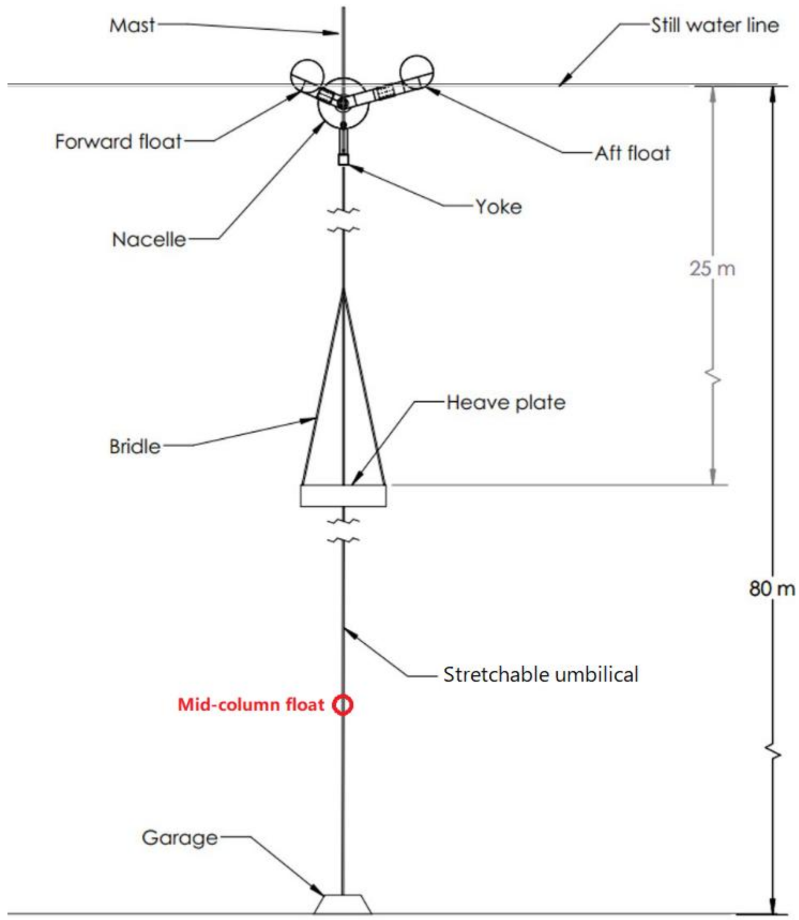


Figure 50 - AOPS mooring diagram with mid-column float highlighted in red.

Figure 51 - Collapsed foam inside the mid-column float.

11.2.1.2 Heave plate floats

There are two floats on top of the heave plate. During the inspection after recovery, cracks were found near the bottom of the float and it appeared water was leaking out of them (

Figure 52). The float was cut open for further inspection. Inside the float, it was discovered foam boards were used instead of the specified spray foam, allowing space for water to fill-in and reduced structural strength (Figure 53). Additionally, the foam appeared to be compressed which indicated the foam selection was not appropriate for the depth.

Figure 52 - Cracks at the bottom of the heave plate float.

Figure 53 - Foam boards inside heave plate float.

11.2.1.3 Stretch umbilical

The 50-foot upper stretch umbilical hose has a specification dry mass of 154 kg. It was measured on site after system recovery at 151.2 kg. However, the wet mass of the 50-foot hose specification was 88.8kg, but it was measured at 45.4kg post-deployment. A total of 250 feet of hose was used. The total wet mass decreased by 217.0 kg compared to the design target.

11.2.1.4 WPS mass estimation with float position

As the total system mass increased, the nacelle freeboard reduced, which changed the mean angle between floats and the nacelle (Figure 54). Those float angles were calculated using data from the absolute encoders on the PTO shaft and IMU on the nacelle.

Zero-degree float position is when the float arms are in a horizontal position. Figure 55 shows how those angles changed over time as the SeaRAY AOPS mass increased.

When the AOPS freeboard is at the design target, the fore float (i.e. float with the shorter float arm) angle should be -8.1 deg (pitch up from horizontal). The aft float (i.e. float with the longer float arm) angle should be 3.7 deg (pitch up from horizontal). The design target float angles are the red dashed lines in Figure 55.

The relationship between the float angles and the AOPS mass also depends on which side of the nacelle that floats are positioned on. There are four combinations of float positions. Each was modelled to estimate the AOPS mass. Additionally, since all causes of the mass change occurred at the heave plate or below the heave plate, the heave plate mass was used to adjust the AOPS mass in the model. See Figure 56. Based on the float angle, the estimated heave plate mass during the testing period was between 11550 kg and 11600 kg. (Figure 57). The design target mass was 11085 kg.

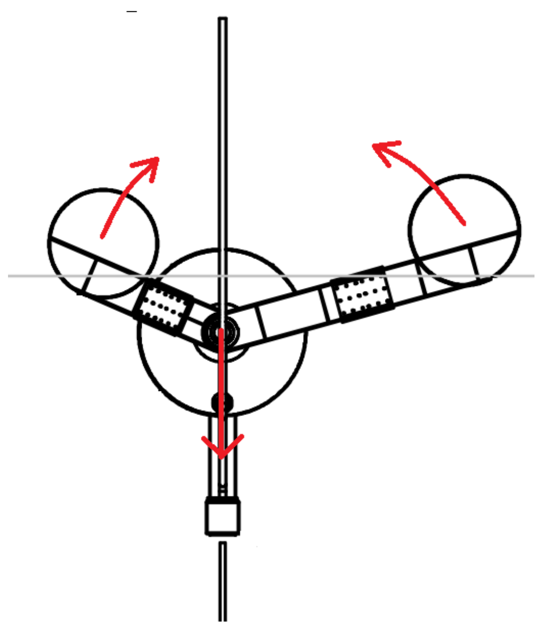


Figure 54 - AOPS changes orientation due to mass increase.

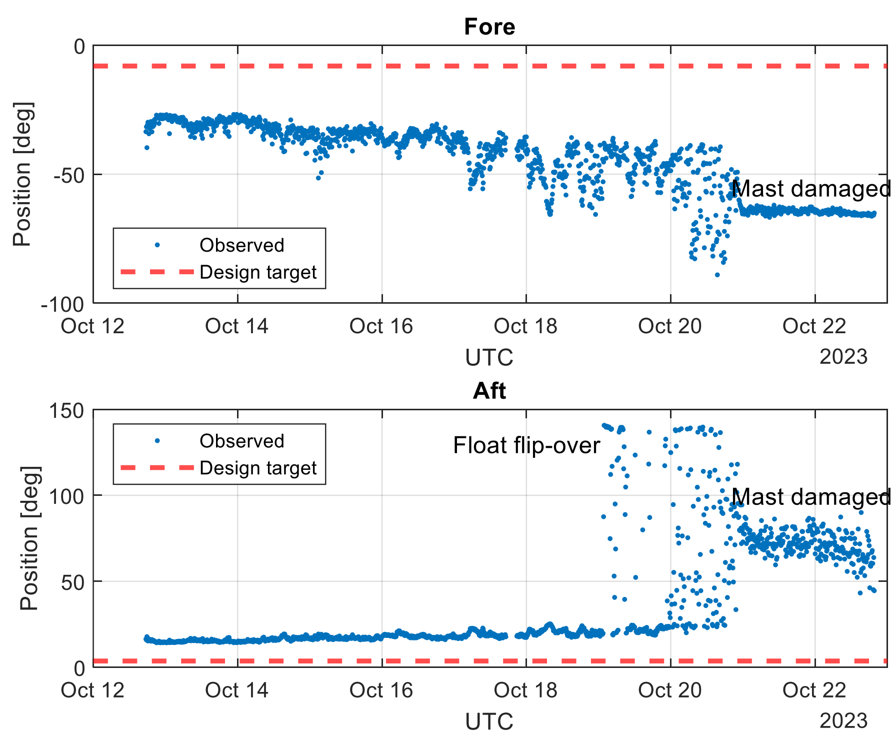


Figure 55 – SeaRAY float mean position vs time.

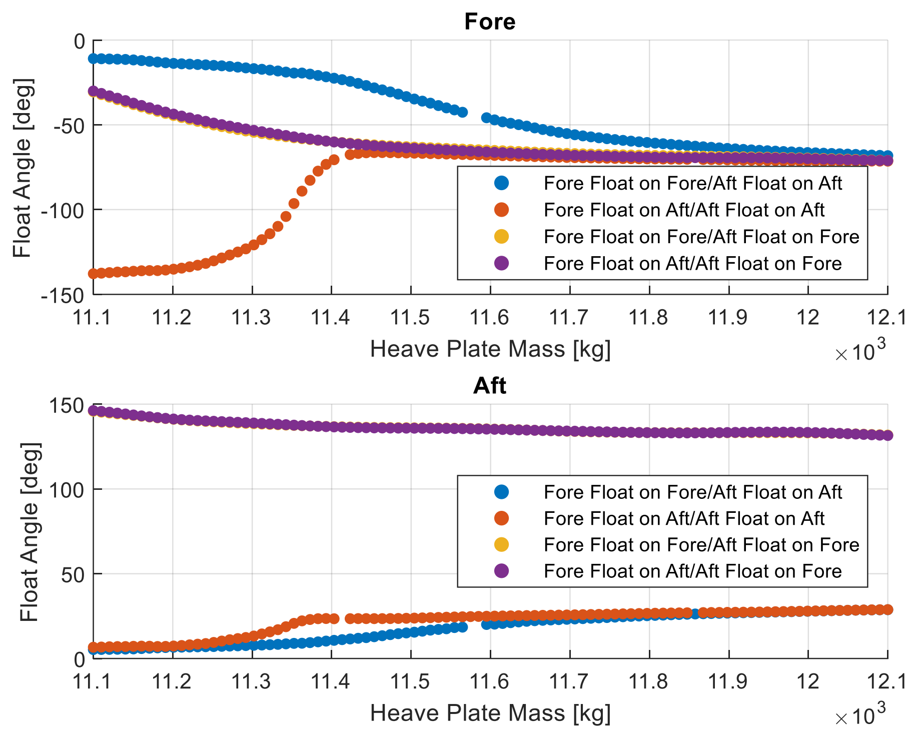


Figure 56 - Expected SeaRAY float position vs heave plate mass.

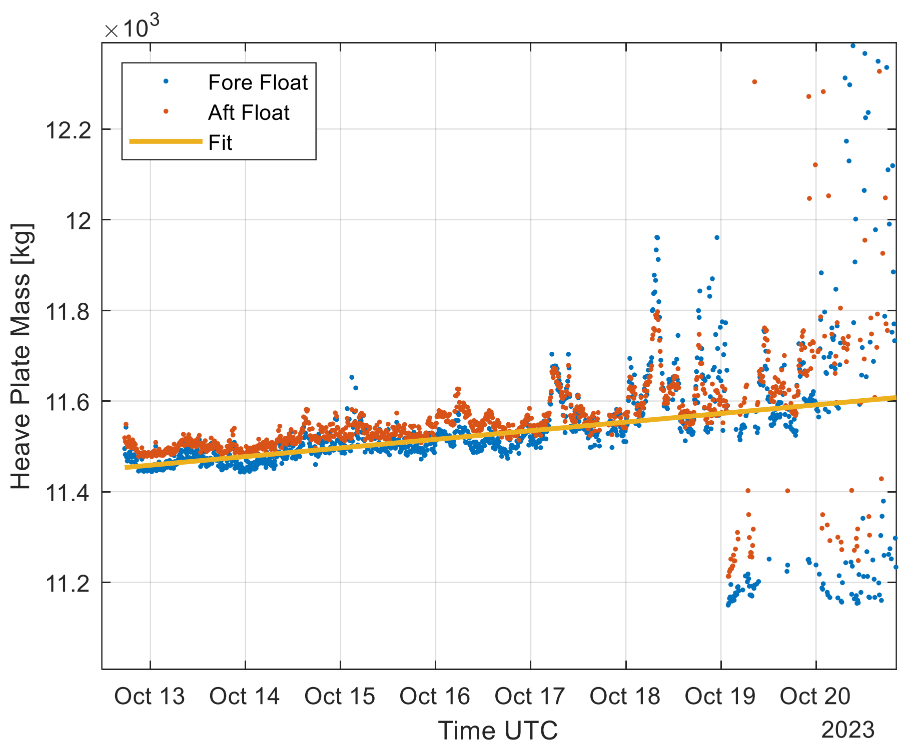


Figure 57 - Estimated heave plate mass based on SeaRAY float angle

11.2.2 Bridle line damage

During the system tuning phase, a diver found one of the bridle lines that connected the nacelle and the heave plate was damaged. The damage occurred at the end of the line near the thimble (Figure 58), which cut into the cable over time. Figure 59 shows the uneven bridle line tension.

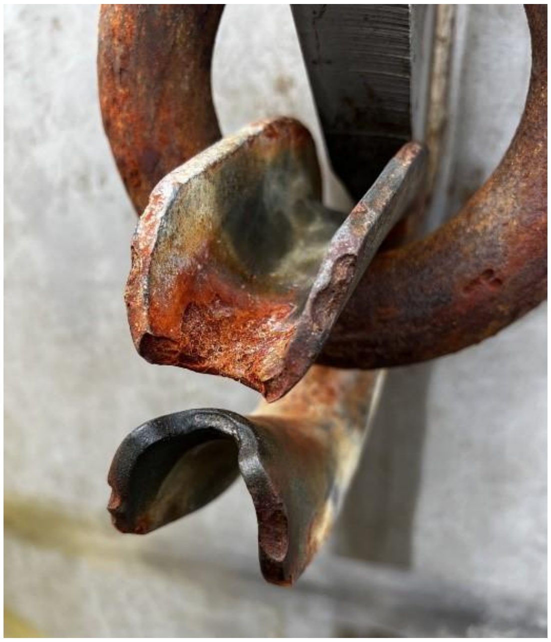


Figure 58 - Shackle near the damaged portion of bridle line.

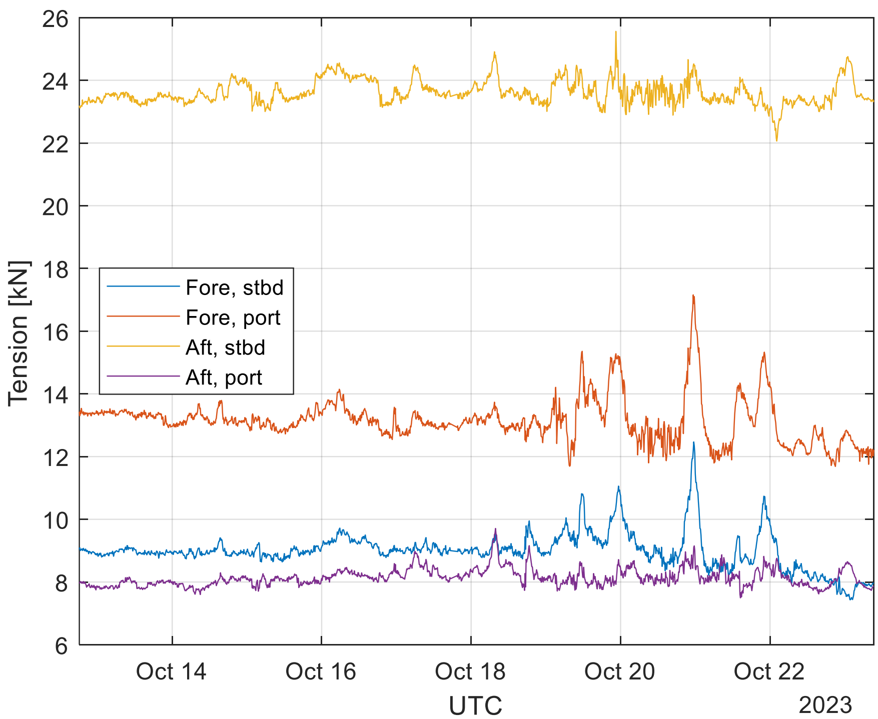


Figure 59 - Bridle line tension.

11.2.3 Power electronics instability

The wide range DC-DC converter converts DC power output from the rectifier to the low voltage bus. It takes a 4-20mA command from the SCADA which it used to control its output power (Figure 60). The purpose of this 4-20mA command was to keep a sea state dependent constant ratio between its input voltage and input current which is the PTO LSS speed and torque.

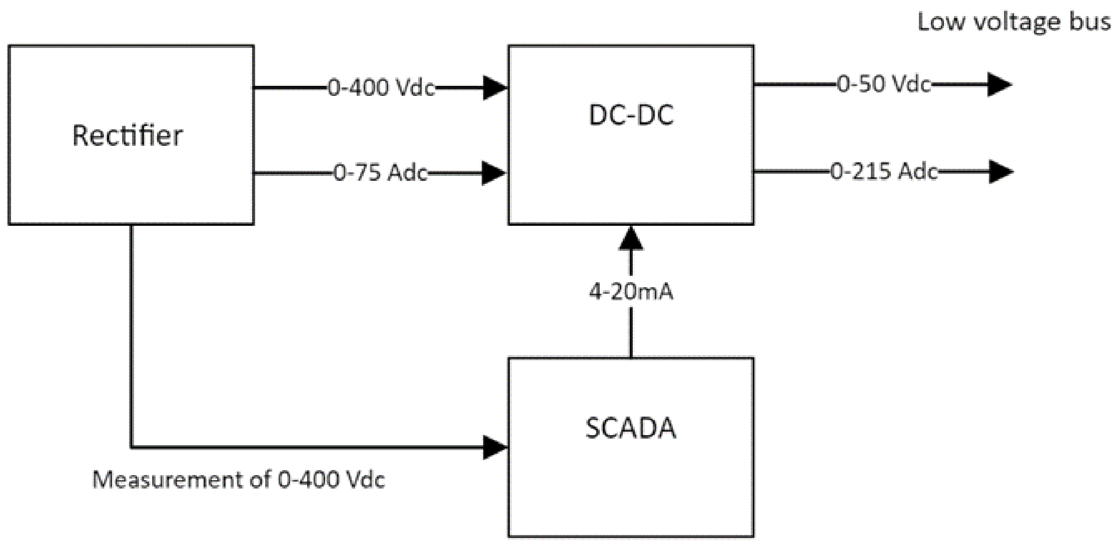


Figure 60 - Torque control schematic.

There are two cascading proportional, integral, derivative (PID) controllers, one in the DC-DC converter and another in the SCADA. The PID controller in the DC-DC converter controls the output current to achieve the output power set by 4-20mA command. The PID in the SCADA controls the 4-20mA command to the DC-DC converter to achieve its input current as a function of its input voltage. The amount of accumulated delay from end to end and non-linearity at each stage of this control scheme, combined with insufficient loop speed caused torque control to become unstable (Figure 61, Figure 62).

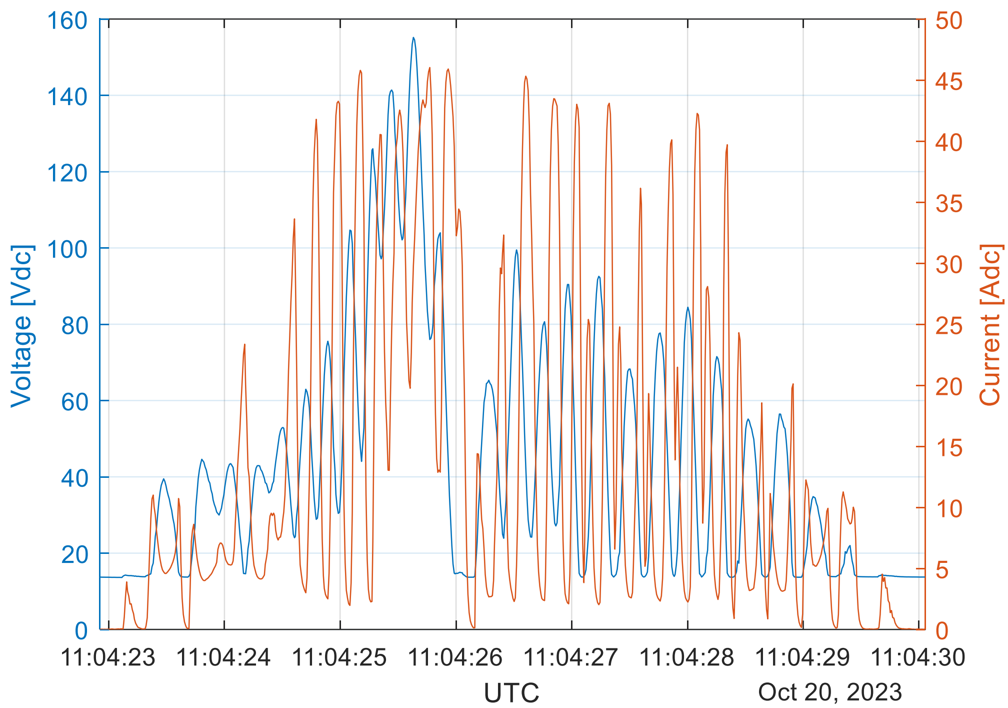


Figure 61 - Example of unstable torque control during deployment test phase.

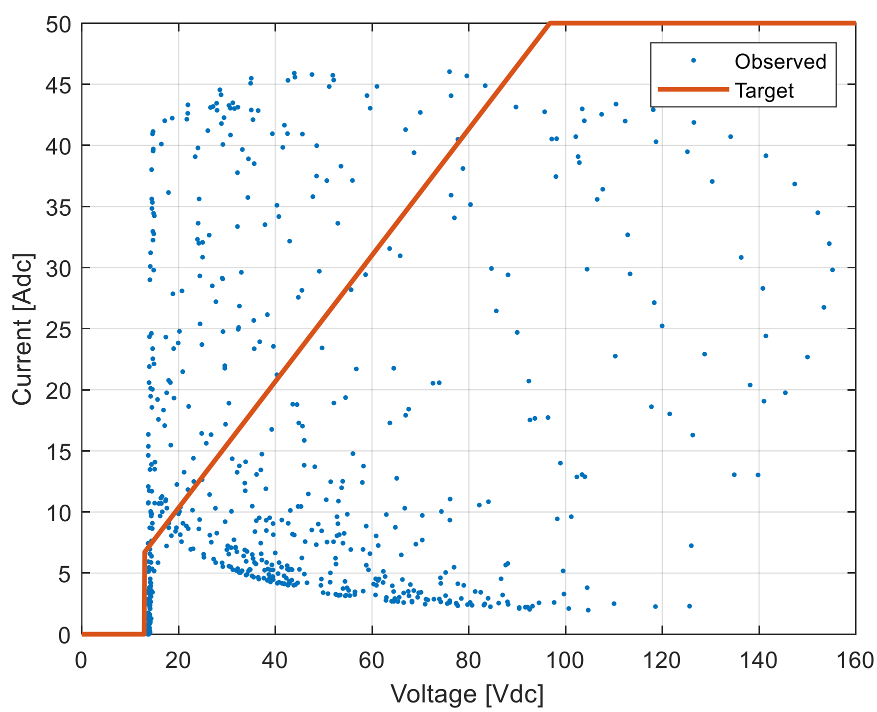


Figure 62 - Observed vs. targeted relationship between PE current and voltage that control torque

11.3 Power

Power conversion is either directly measured or estimated using models built from the dynamometer test data for the four stages shown below (Figure 63). Power output from the PE goes to the energy storage.

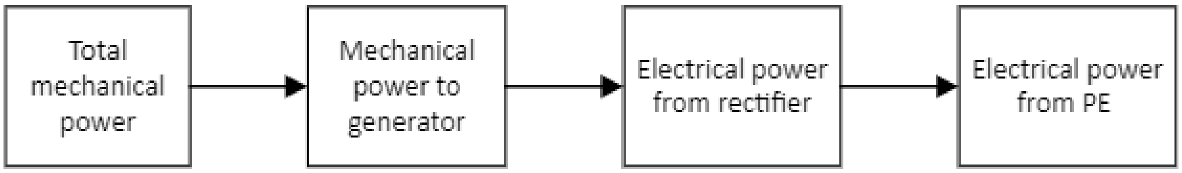


Figure 63 - Power conversion stages.

Power capture, power efficiency, and power loss of each power conversion stage for the deployment test phase are plotted below (Figure 64, Figure 65, Figure 66). See Figure 49 for the state of the individual PE units during that time. While efficiency of the mechanical system and the generator are between 80%~90%, the efficiency of the power electronics (DC-DC converter) is insufficient at low power level due to its base hotel load of ~30W per unit, for a total of ~600W when the system was fully switched on. Power is only plotted when all PE units are fully switched on (i.e., all 10 units on each PTO).

Even with the nacelle submerged, the fore and aft power capture was still balanced. However, the total power production was significantly reduced. See model validation section for further comparison.

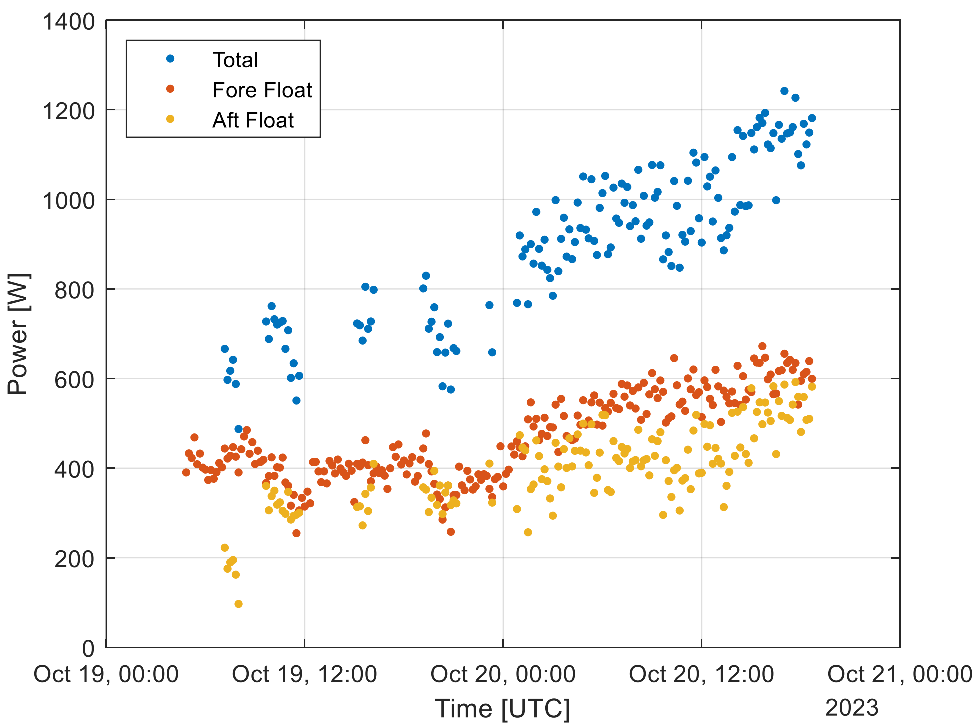


Figure 64 - Observed mechanical power capture.

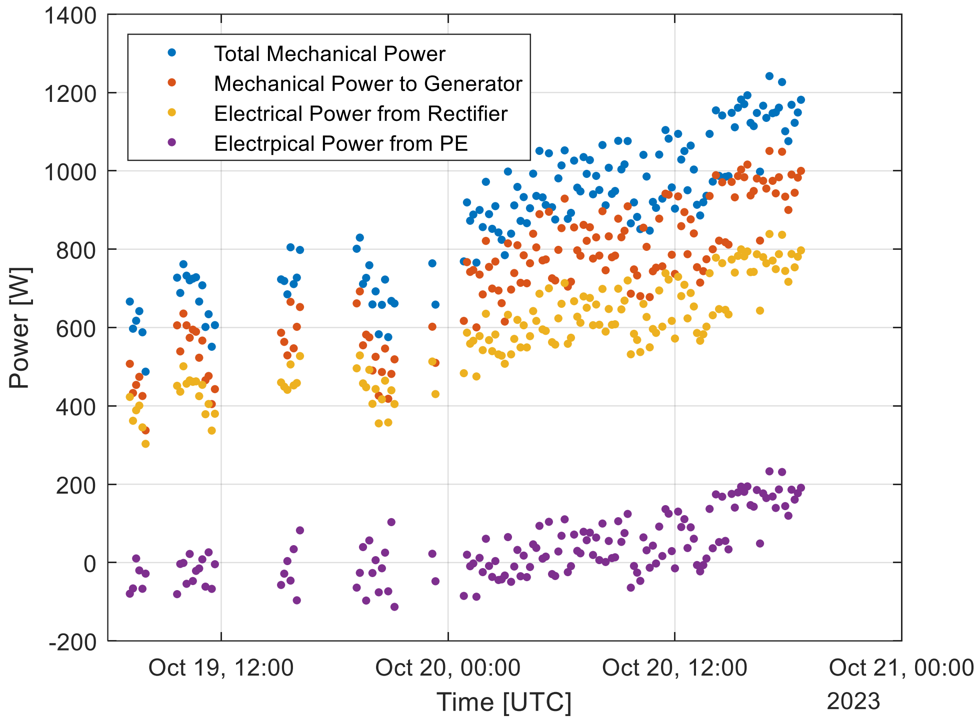


Figure 65 - Observed power at each power conversion stage.

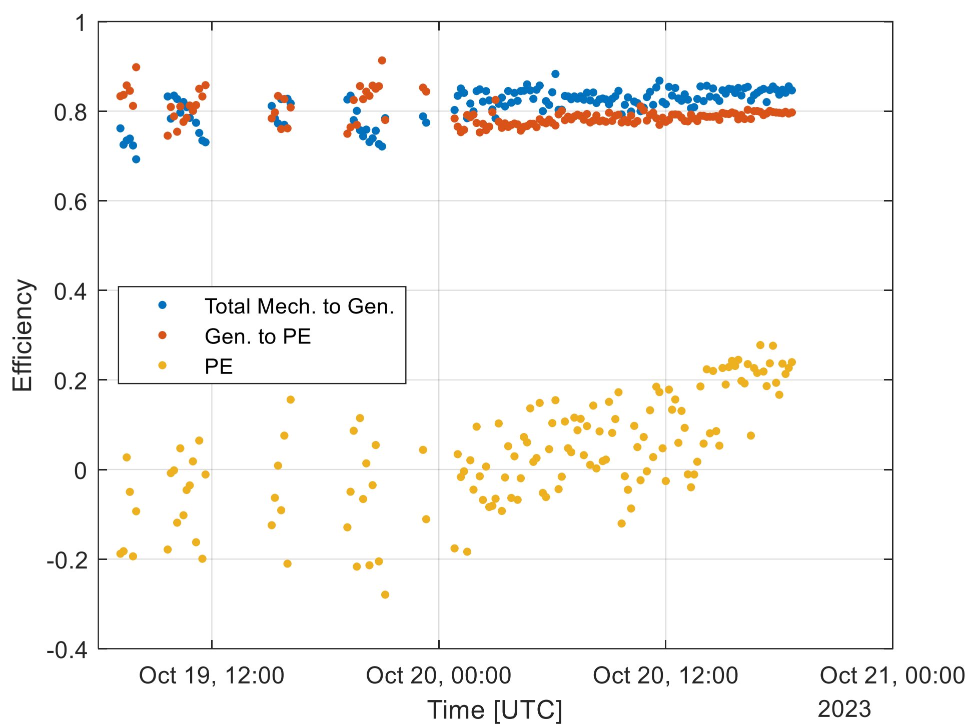


Figure 66 - Observed power conversion stage efficiency.

The DC-DC converter's efficiency was low at low power range but will increase as power level increases. The red line in Figure 67 is the model built from dynamometer test data. This model assumes all DC-DC converter units were on. However, the observed data at low power range have PE either off or partially off, which caused the difference between the two.

Power loss is shown in Figure 68 at each power conversion stage. PE loss should be no less than ~600W if all DC-DC converter units are on the entire time.

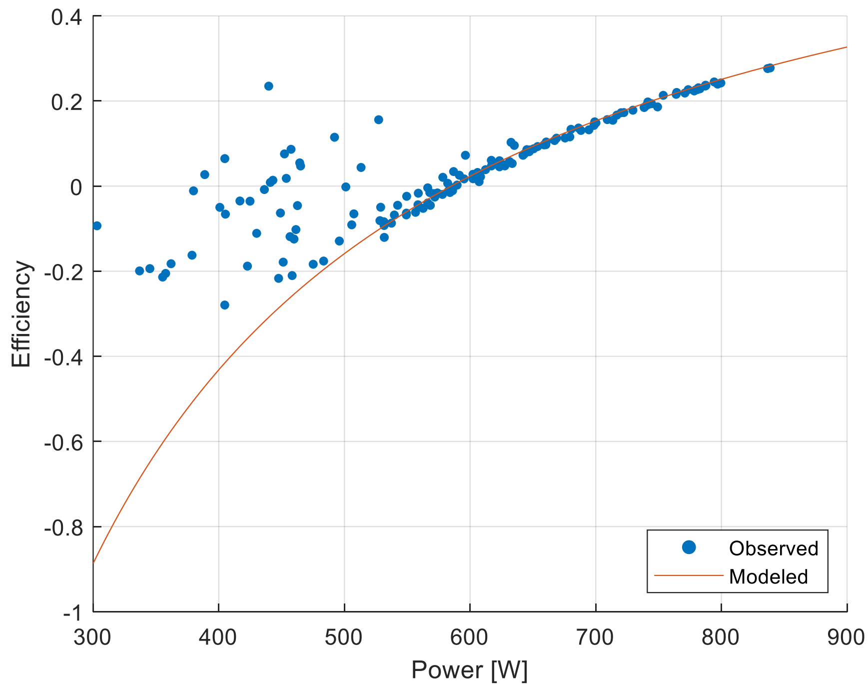


Figure 67 - PE efficiency vs input power.

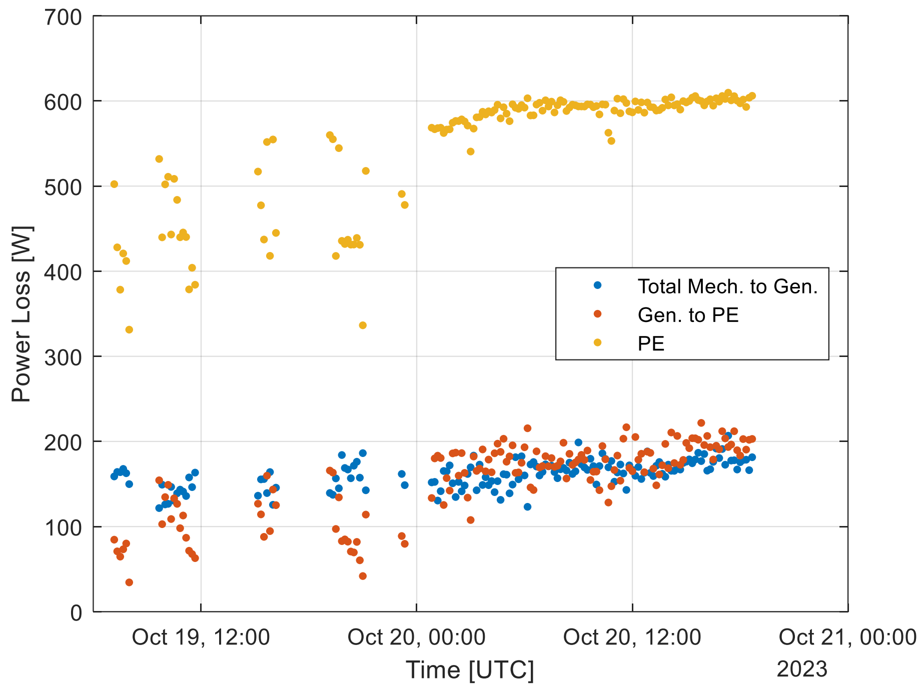


Figure 68 - Power loss across power conversion stage.

The fore float power production was not strongly correlated to the aft float's status (Figure 69). There is no data to show if aft float power production was correlated to fore float's status.

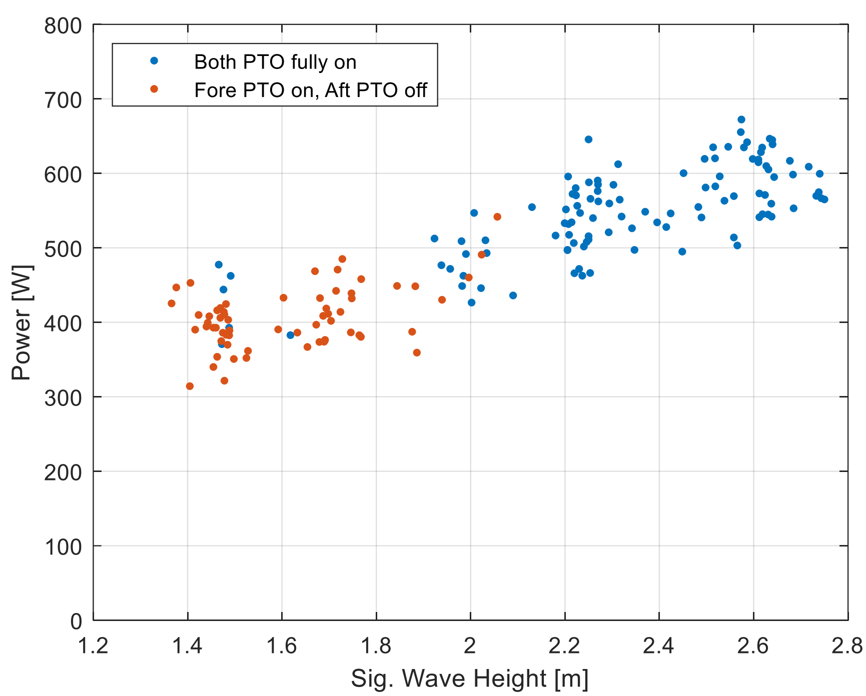


Figure 69 - Fore PTO, total mechanical power to generator.

Total mechanical power production of the SeaRAY AOPS was shown to be insensitive to the AOPS heading (Figure 70). The power matrix as a function of sea state is shown in Figure 71.

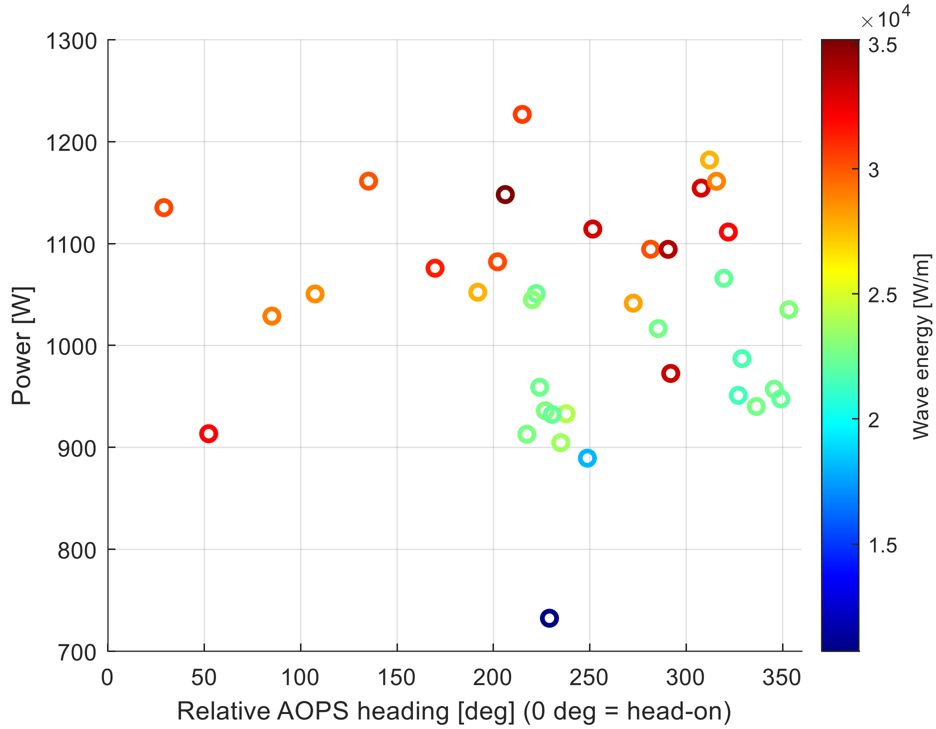


Figure 70 - Total mechanical power vs relative AOPS heading.

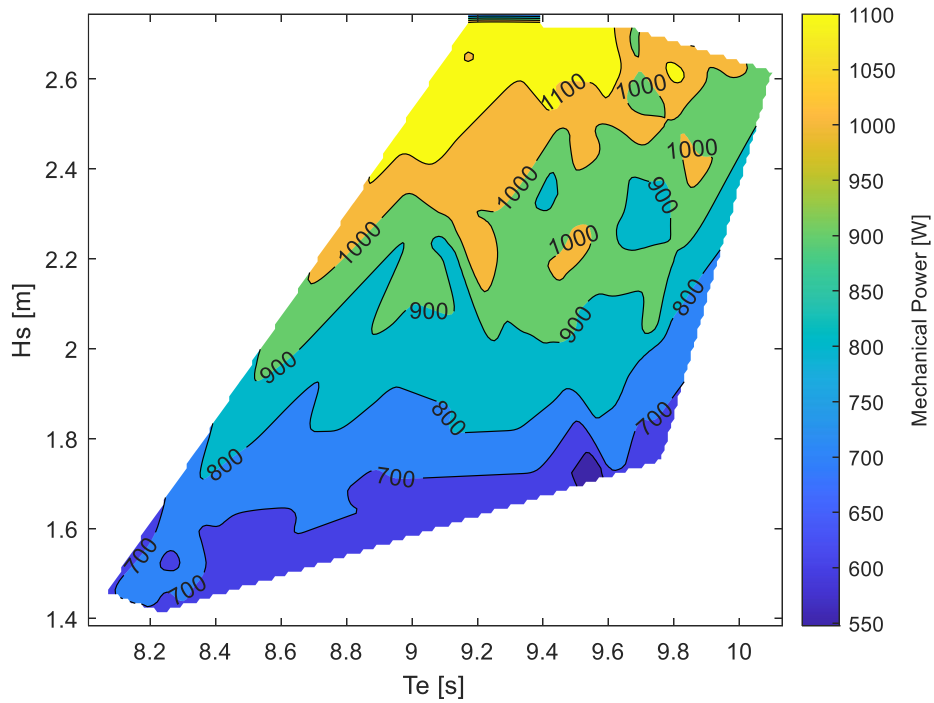


Figure 71 - Observed total mechanical power as function of wave height and period.

11.4 Watch circle

The direction of the WPS drifting did not align with wave direction, current, or wind direction alone Figure 72, Figure 73, Figure 74). Data during any maintenance period where there were interactions between the AOPS and service boats has been removed. It is not known if there are other interactions with civilians (e.g., fisherman) that affected this data set. The AOPS drifted slowly and data shows no correlation between wave height and the drift distance (Figure 75). Unfortunately, the mooring load cell on the seafloor was damaged and could not be used to analyze the AOPS drifting force.

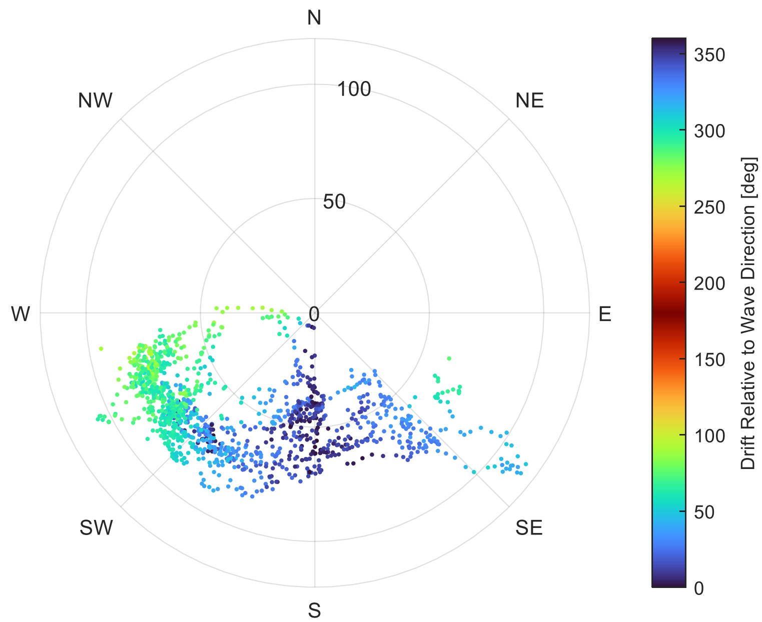


Figure 72 - Watch circle with wave direction.

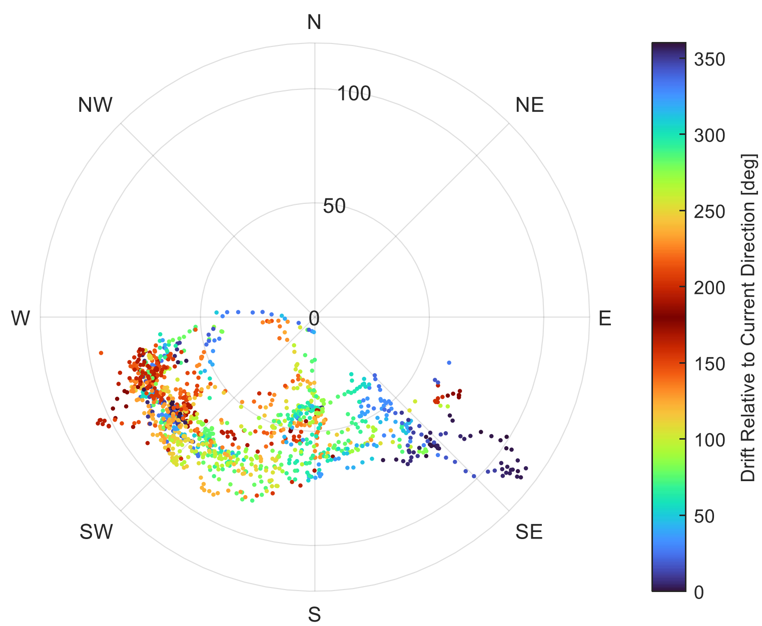


Figure 73 - Watch circle with current direction.

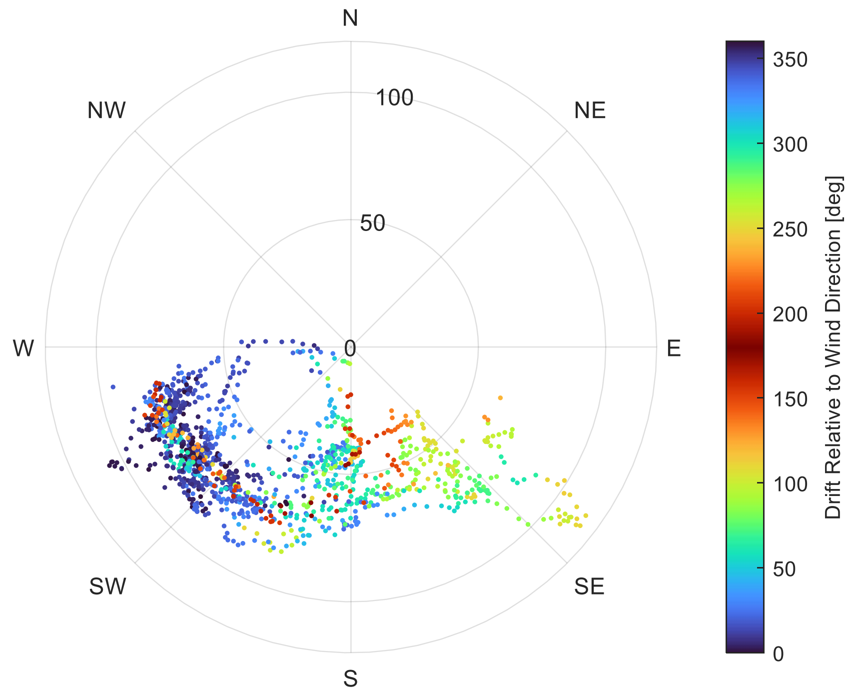


Figure 74 - Watch circle with current direction.

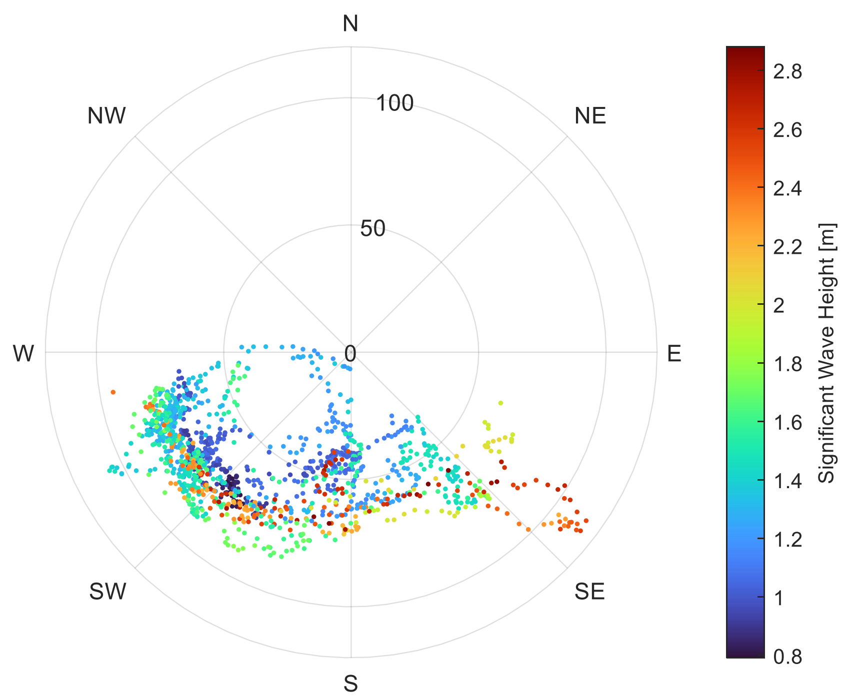


Figure 75 - Watch circle with wave height.

11.5 Motion

The AOPS was stable and balanced in roll with only 0.12 deg bias towards the port side. The occurrence heat map in Figure 76 shows the mean nacelle roll position vs AOPS relative heading to the wave direction, where 0 degree of relative heading means the fore float was facing the incoming wave direction. It also shows that the AOPS had its side facing the wave in most cases.

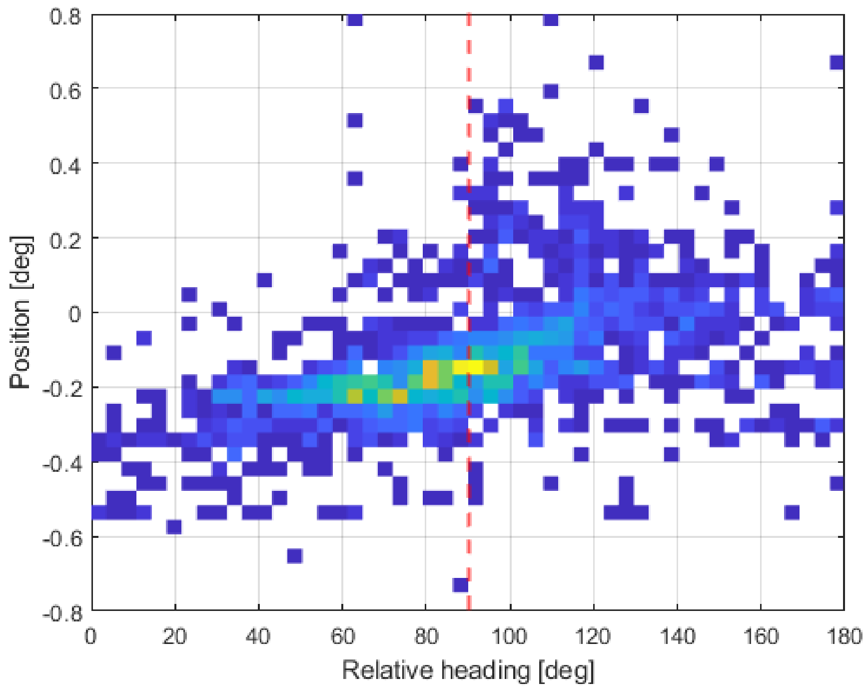


Figure 76 - Nacelle roll vs heading heat map.

AOPS's heading was stable within +-1 revolution until one hour before the first known time when the mast was damaged (red vertical line in Figure 77). During this last hour, the AOPS rotated 6 revolutions in one direction without significant changes in both wave height and wave direction.

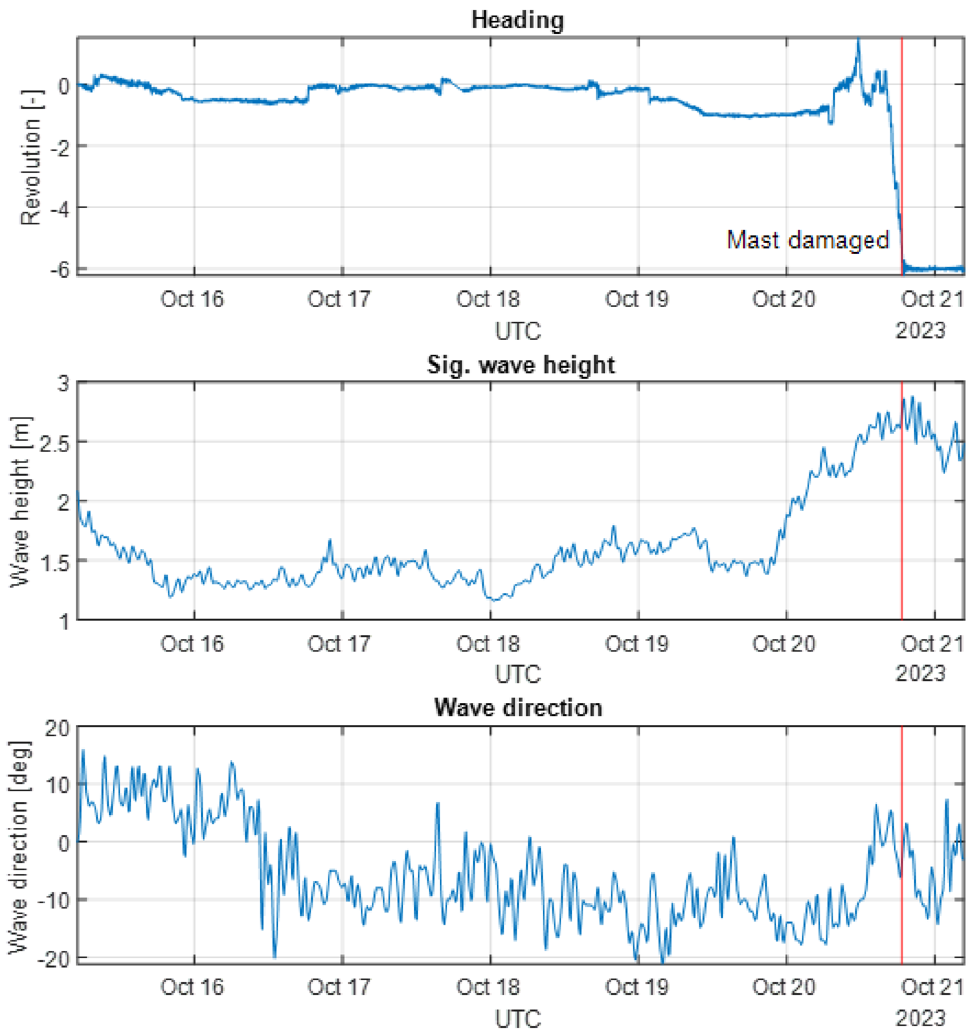


Figure 77 - AOPS yaw stability

Hydrodynamic modeling for a heavier nacelle showed reasonable agreement between the simulated and observed motion in other degrees of freedom.

12 MODEL VALIDATION

12.1 Performance Model Validation

The observed total mechanical power was compared with both design target model and as a deployed model (Figure 78). The blue circle is the observed 10 minutes average total mechanical power when both PTOs are on. The blue dot is the observed 10 minutes average total mechanical power when only fore PTO is on. The solid red line is 30 minutes average total mechanical power using the model with target system mass and stable power electronics. The red shaded area is the total mechanical power using the model with adjusted system mass (11.2.1.4) and approximated unstable power electronics behavior. The upper and lower bound of the shaded area is the maximum and minimum of 10 minutes average over 60 minutes of modelled data.

For all the sea states during the test period, the observed total mechanical power was within the modelled predicted range. However, in larger sea states where significant wave height was greater than 2 meters, it appears that the model underestimated fore performance while it overestimated aft performance (Figure 79 and Figure 80, respectively). The two conflicting errors nearly cancel when added together, which explains why the sum of the performance of the two PTOs is within the error bounds despite the individual PTOs falling just outside of the bands. .

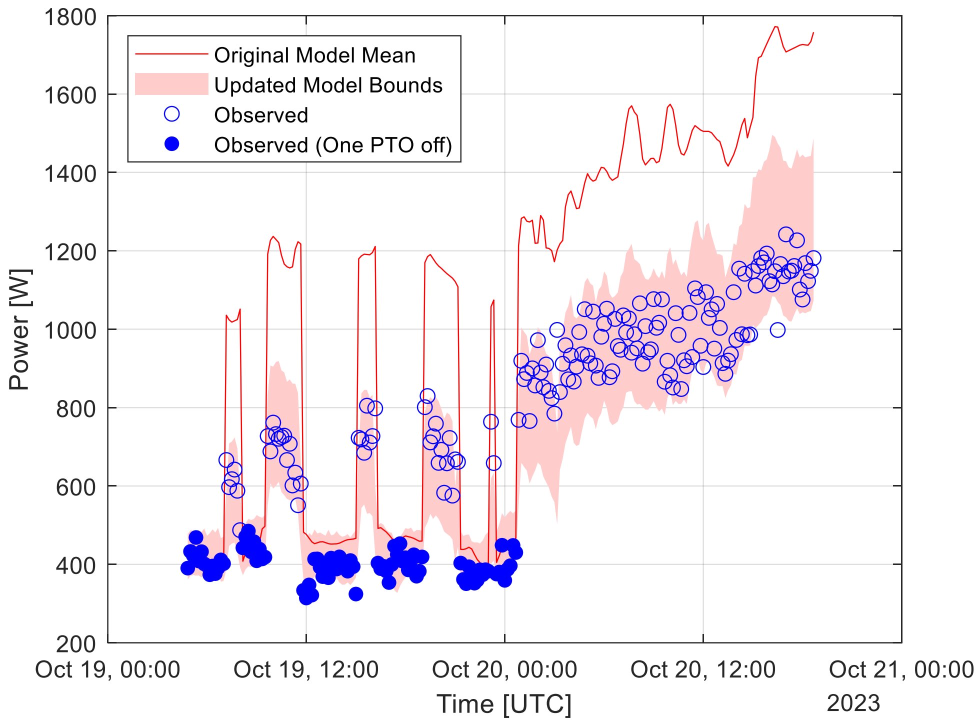


Figure 78 - Model validation of total mechanical power capture.

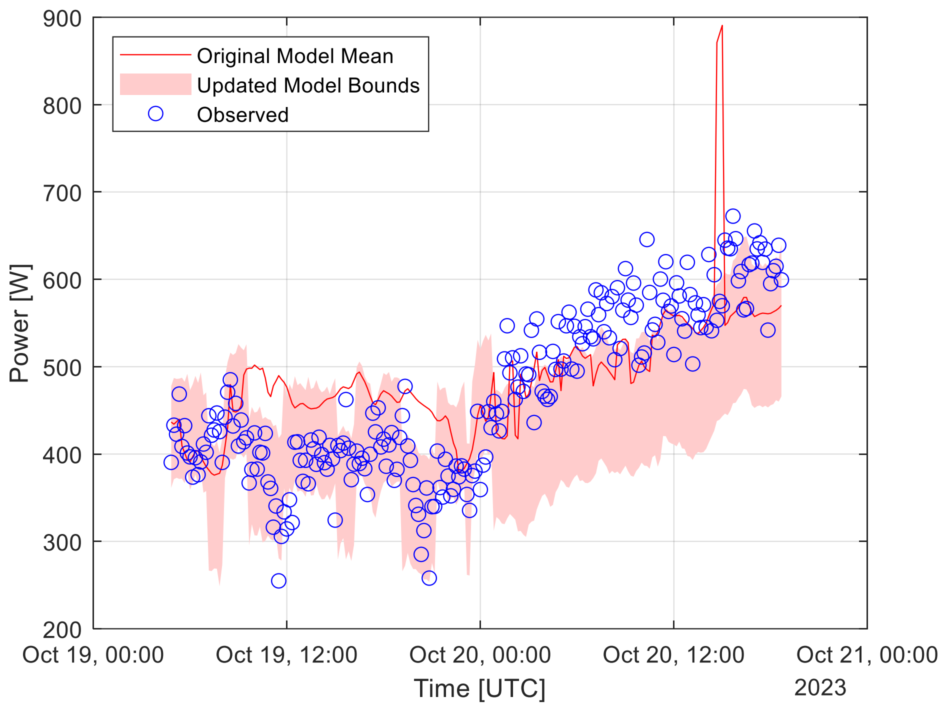


Figure 79 - Model validation of fore mechanical power capture.

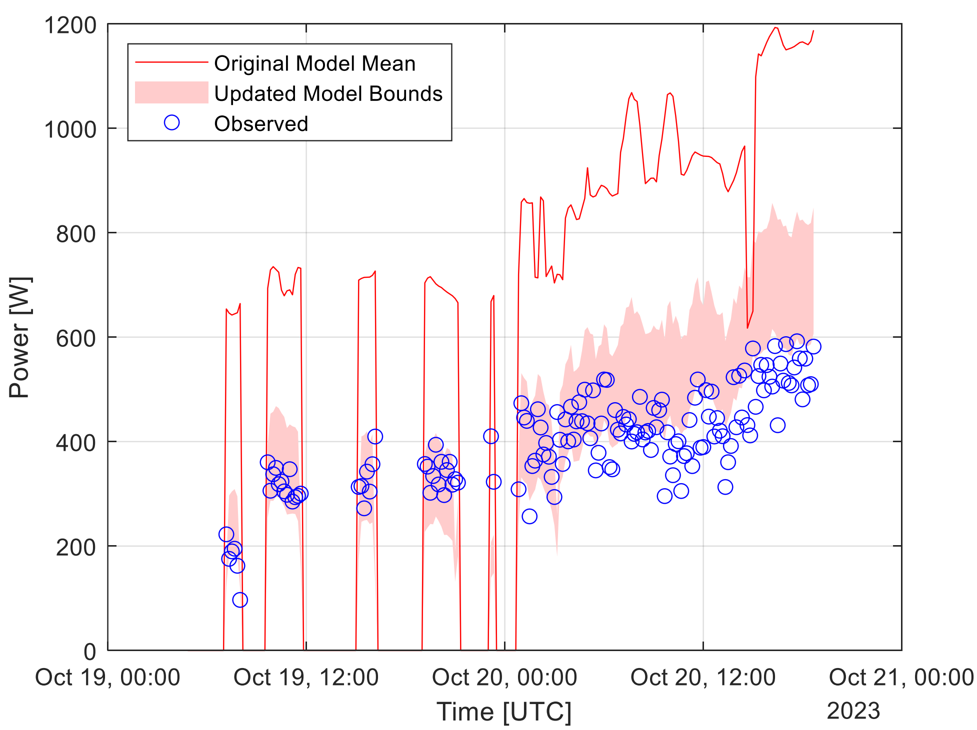


Figure 80 - Model validation of aft mechanical power capture.

Modeling showed reasonable bounds for device performance at each conversion stage, as evidenced by data collected during the deployment (Figure 81, Figure 82, Figure 83). However, as shown in Figure 83, PE output was consistently over-predicted in the higher-energy condition; this is caused by instabilities in the power electronics that were difficult to capture in simulation.

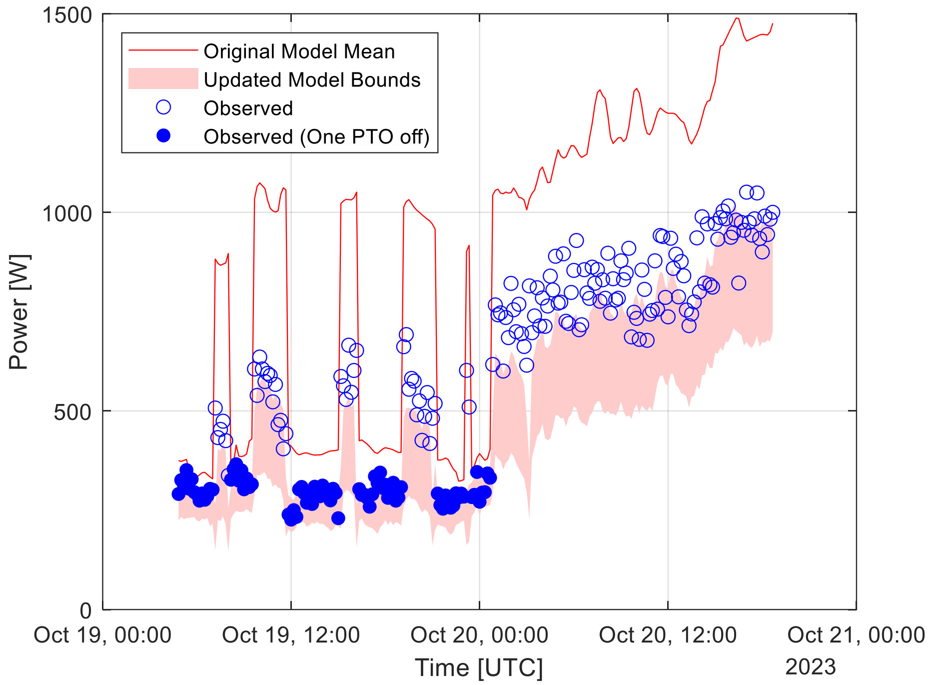


Figure 81 - Model validation of mechanical power delivered to generator.

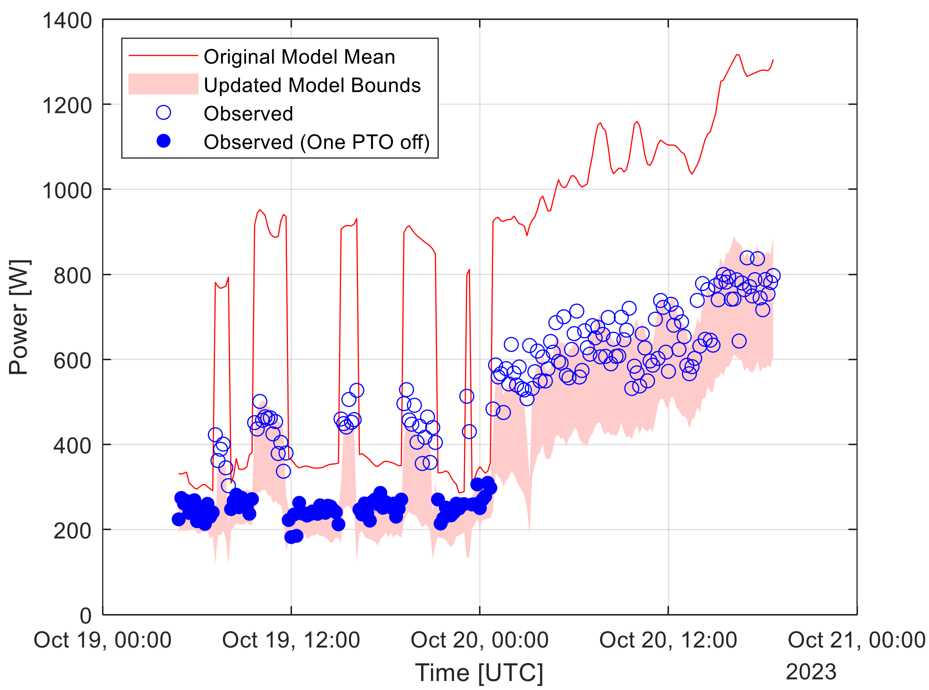


Figure 82 - Model validation of electrical power delivered to power electronics.

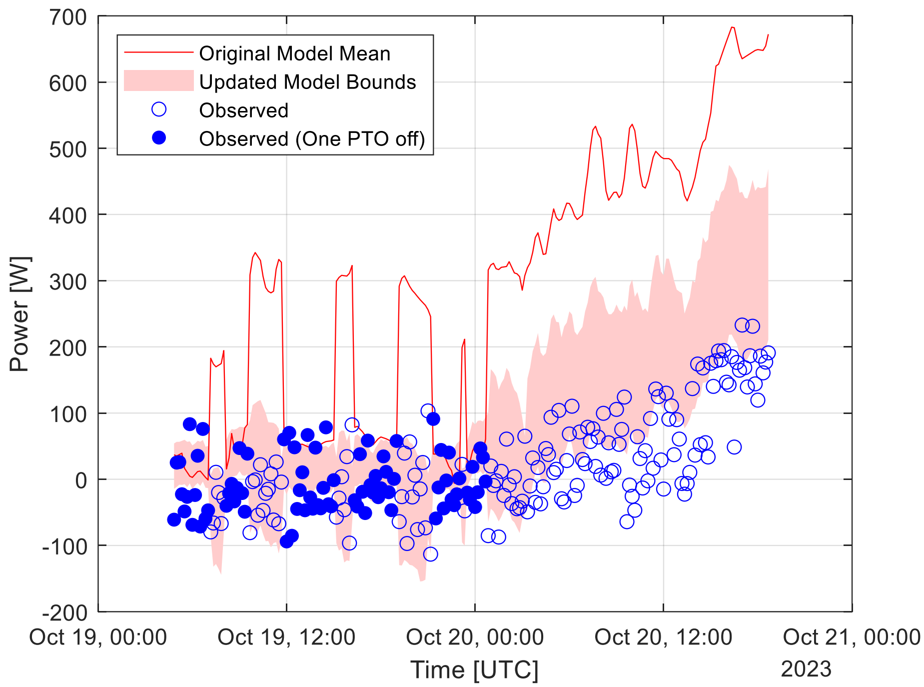


Figure 83 - Model validation of power delivered from power electronics.

12.2 Thermal Model Validation

The thermal model used for validation was based on the largest sea state observed during the trial period, which occurred at 10/20/23 22:30 UTC and consisted of a significant wave height of 2.5 m and an energy period of 9.0 s. A top-down view of the temperature distribution is presented in Figure 84. Note the labeled numbers indicate enclosure numbers inside the nacelle.

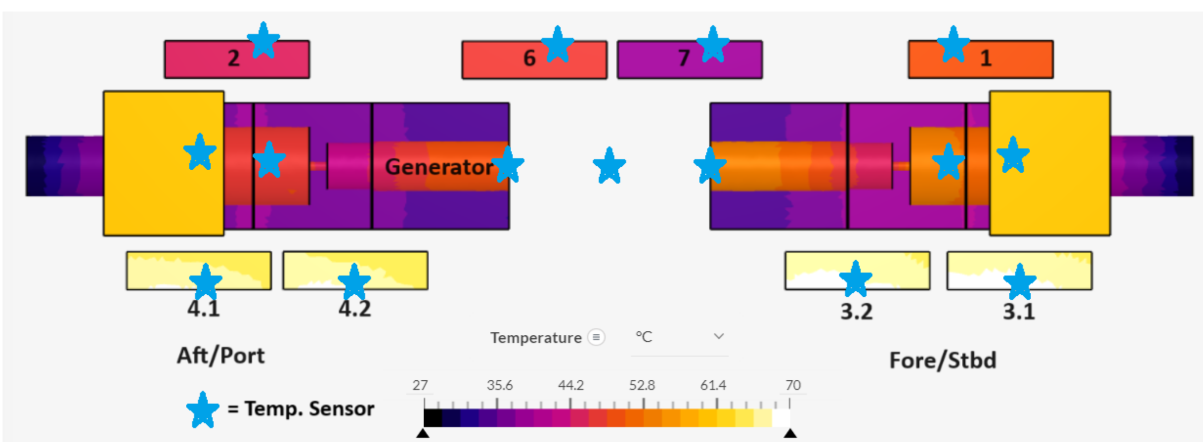


Figure 84 - Top-down view of the temperature distribution in the thermal model used for validation.

A comparison of the expected heat generation from hydrodynamic modeling and observed heat generation is shown in Figure 85. Note that there were no sensors to capture the actual power loss from the battery charger (located in enclosure 7). With the exception of the aft generator, losses were generally lower than simulated results. The anomalous aft generator observation can be explained by pointing to limitations in the hydrodynamic simulation software, which regularly over-predicts speeds on the aft side and under-predicts speeds on the fore side. Because generator efficiency is closely tied to this speed, the respective losses were likewise affected.

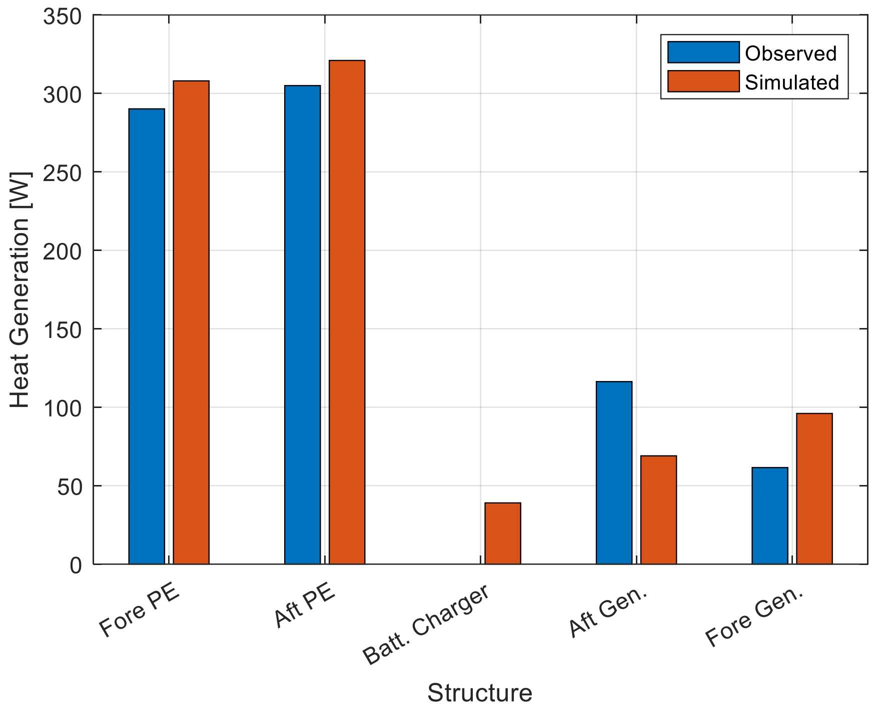


Figure 85 - Observed and expected heat generation in several systems.

Figure 86 shows both the simulated and observed temperatures. The thermal model consistently over-predicted the actual temperatures seen in the sea trial, despite the higher power losses in the aft generator during deployment. A discussion of possible sources of uncertainty follows the figure.

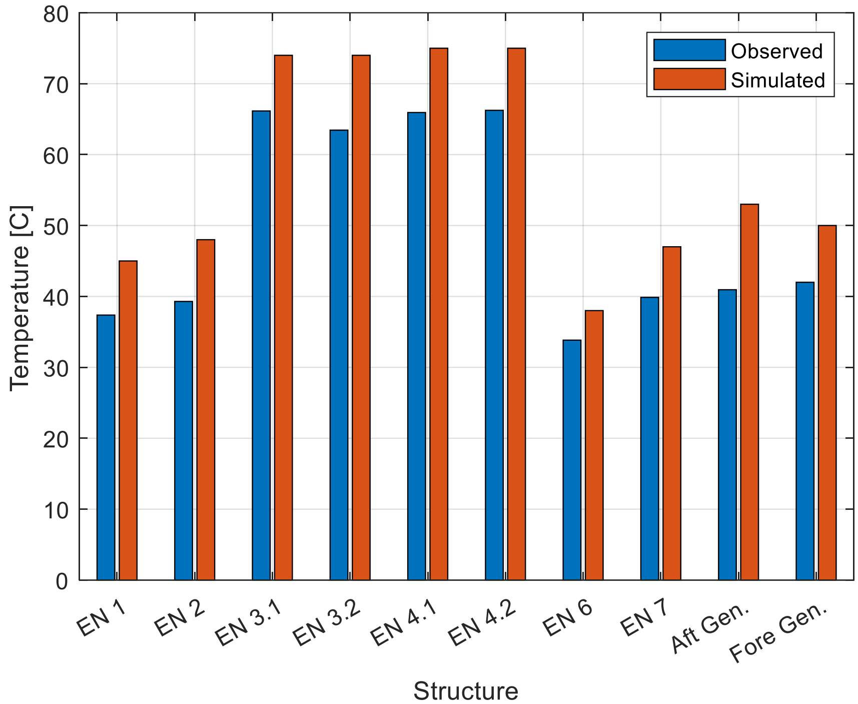


Figure 86 - Observed and simulated structure temperatures.

Potential sources of uncertainty in the thermal model include:

- Steady state assumption: The thermal model assumed thermal equilibrium had been reached. With a minimal amount of trial data, it is difficult to determine whether the system actually obtained equilibrium.
- Sensor placement: It is difficult to compare a point-measurement from a sensor to a 3-dimensional model. Small variations in sensor placement can capture unexpected temperature variations (e.g., wall temperature vs air temperature near the wall).
- Computer-aided design (CAD) simplification: The intensity of computational fluid dynamics (CFD) modeling necessitates finding a balance between accuracy and computation time. CAD is drastically simplified to minimize the model's computational requirements, but it is challenging to know what elements can be removed without sacrificing accuracy.
- Natural convection modeling: Natural convection is the dominant method of heat transfer in the SeaRAY system. Natural convection, especially in enclosed spaces, is a difficult phenomenon to accurately model. Because of the large thermal- and velocity-gradients near walls, the system becomes very dependent on mesh design and solver parameters. Current and future trial data will be used to more effectively tune the model.

With these limitations in thermal modeling noted, it is important to keep the purpose of the model in focus. In this design, thermal simulation is performed as a preventative measure to avoid component overheating. Highly accurate simulations, although helpful, are not necessary to identify hot spots or other problem areas. In addition, the conservative approach taken ensures that actual temperatures are unlikely to exceed model results. For these reasons, the error between measured and modeled temperatures were deemed reasonable and helpful to the design process.

13 CONCLUSIONS

The Project successfully designed, delivered, and tested a prototype low-power WPS aimed at lowering the total cost of ownership and providing robust, new capabilities for customers in the maritime environment. The top-level requirements were all achieved to various degrees as outlined below, except for power delivery to assets. More in-depth explanation follows:

- Average energy generation above 1 kW per year: Achieved
- Low-mass/high power to weight ratio (as light as possible while still being able to produce target average energy generation): Achieved
- Rapidly deployable in less than 1 day: Achieved
- System fits within standard ocean container(s): Achieved
- Minimal assembly work dockside: Achieved
- Able to use smaller, lightly manned vessels: Achieved
- Mooring, data, and communications combined into one line: Achieved
- Fully-integrated energy storage: Achieved
- Capable of delivering continuous power as required: Suboptimal
- Designed for Hawai'i's Wave Energy Test Site (WETS): Achieved

The system was shipped and delivered to the deployment location on a 45-foot flat rack – an industry first for a WPS with kW-scale generation capacity and a major feature for delivering future commercial units around the world.

The deployment of the SeaRAY AOPS took less than 1 day. When the barge arrived to the deployment site, all equipment was in the water in less than an hour. Although a larger vessel of convenience (the barge) was used for the deployment, the C-Power team was able to recover the system in a towed configuration using a tug boat, indicating the capability of the system to be deployed and recovered with smaller, lightly manned vessels. The single combined power, data, and mooring line was noted as one of the key features that helped streamline deployment and recovery.

The planned deployment was intended to be six months at WETS. Four weeks of operation were achieved. During the four weeks, the device was in small to moderate wave climates and all data was collected, stored, and processed for model validation.

Although the in-water testing period was minimized due to the damage sustained, the data collected during the deployment is invaluable to improve the design of the SeaRAY going forward. Using the updated as-built system model validated by dynamometer and demonstration data, an average annual generator output power of 1168W is expected at WETS. This exceeds the target metric of 1000W average.

Additionally, although the subsea assets were not able to be tested during the SeaRAY AOPS in-water operation, the onshore integration testing and validation played a critical role in demonstrating system functionality. These tests confirmed the capability of the system to provide consistent power flow and enable bidirectional communications, validating key performance metrics and ensuring readiness for future deployments supporting customer assets. Alternatively, the mooring load cell that was attached to the top of the SBU could be considered an asset as it connected into the SBU the same way an asset would, receiving power and transmitting data bidirectionally that was recorded in the cloud. Power electronic performance was suboptimal due to higher than expected hotel loads and control loop instability. Corrections for these issues have been identified and will be addressed in future deployments.

13.1 Techno-Economic Metrics

The techno-economic metrics of the SeaRAY AOPS were evaluated through this Project (Table 2). Both the baseline and target numbers for each metric were established at the beginning of the Project. A couple of factors impacting the techno-economic outcomes of this Project are outlined below:

- The large constant load of the DC-DC converters (600 W), and the instability issues, decreased the overall efficiency of the energy conversion chain which drastically reduced power capture from estimations. This inefficiency decreased the power to weight ratio (PWR) capable of this size of a device. As this technology progresses, the efficiencies should see significant gains and the PWR will go up.
- A factor for a higher levelized cost of energy was the high cost of building a first-of-its-kind prototype which raised the build costs higher than expected.
- The ballasted waterline of the system while in operation was not at the target, decreasing power capture efficiency.

Table 2 - Techno-Economic Metrics for as built SeaRAY

Metric	Unit	Baseline	Target	SeaRAY (DOE reference site*)	SeaRAY (WETS)
Levelized cost of energy (LCOE)	$/watt-hour(Wh)	0.324	0.048	0.126	0.110
Annual energy production (AEP)	kWh/year	629	2139	3527	4049
Power to weight ratio (PWR)	W/kg	0.061	0.111	0.041	0.047
Peak to average power ratio		40.7	24.0	43.3	41.1

13.2 Lessons Learned

Several lessons were learned through this Project that are critical in inform SeaRAY technology development, future marine operations, and best practices moving forward. Table 3 provides a summary of these lessons learned.

Table 3 - Lessons Learned Summary Table

What worked	**What it proves**
Asset demonstration	The seafloor battery powered and communicated with a simulated asset (mooring line load cell). Onshore integration of both the AUV and seafloor sensor indicated the ability of the SeaRAY AOPS to integrate with external assets.
Controlled power consumption	Once started, SeaRAY adjusted its power consumption based on the wave activity.
Cellular connection	Simple connection enabled two-way communication.

Data collection system	Collected and transmitted data on SeaRAY performance for online, real time performance monitoring.
Fiber Optic cable	Enables high band width data communication (required for ROVs and similar).
No end stops	Float arms can travel past each other, ensuring durability and continuous power generation.
Power electronics	Converted wave energy to usable electricity to power the SeaRAY and stored energy in the nacelle batteries.
Single mooring line	Enables quick deployment and reduced structural loading.
Watertight integrity	During the deployment and before the mast broke off, no water entered the nacelle.
What we learned	**Impact on future design and activities**
Bilge	Bilge system needs to be able to pump water out faster than water can enter through a damaged line. When the air intake was upside down in the water, water was able to enter through the valve the incorrect direction and at a rate equal to or greater than what was being pumped out because the two lines were the same diameter. Route air inlet inside mast for further protection. Use stainless steel piping instead of PVC. Have redundant valves where possible to eliminate single failure point. Redundancy is needed in control of air and water movement.
Bridle	Investigate bridle line material and end terminations to increase durability. Lines will be better controlled in future deployments to avoid snags during heave plate submergence process.
Bridle line pre stretch	Validation of bridle lines for length and stiffness will help ensure proper characteristics are installed on device.
Crane lifts	Understanding static vs. dynamic loading capabilities is crucial to informing marine operations. Avoiding at-sea lifts where possible can streamline deployment and broaden vessel options.
Foam in buoyancy modules	Foam used for buoyancy modules should occupy the full volume required for desired buoyancy without voids and must be appropriately rated for pressure expected at operational depth.
Heave plate ballasting	Create two chambers in heave plate to control how the heave plate moves from the surface to under the WPS.

Mast	Stronger mast structure with all cables routed internal to the mast for a more robust design. Signage to deter boat docking.
Model validation	C-Power will continue to refine and update models with data collected during the future deployments.
Power Electronics Stability	Future power electronics controls will use a fixed input current/voltage ratio for a given dampening command as well as faster control loop to address the instability issue and achieve the target profile.
Redundancy of critical systems	Redundant recovery lines, battery operated equipment (lights), communications, and dewatering alternatives will all be pursued.
Reserved buoyancy	Ensuring the device staying on the surface if a compartment of the nacelle gets flooded is critical to maintaining positive buoyancy
Solar panels	Solar panels need to be ruggedize and marinized for varying metocean conditions.
Surveillance	Install surveillance cameras onshore and/or on nacelle for all projects during deployments.
Thimbles	Thimbles will be changed to stainless steel and tubular shaped, rather than galvanized steel and C-shaped. Covers will also be considered to be added on the eyes for further protection.
Towable	Towing the surface unit in for recovery was a significant achievement for future deployment and recovery operations. Considerations given to design of next-generation WPS and heave plate to make them easier to tow.
Vessel availability	Find multiple vessel options that meet the requirements rather than just one.

13.3 Project Impact on Future Work

The Project impacts on future work cannot be overstated. The Project fundamentally shaped C-Power's plans for the SeaRAY product line and provided critical information, learning, and experience that has already been and will continue to be used to refine system design, improve IO&M, and ultimately more efficiently meet AOPS commercial use case requirements.

In addition to the improvements outlined in Table 2 above, C-Power is pursuing further demonstration of the SeaRAY AOPS at WETS through DE-EE0007347. The goal is to incorporate subsystem upgrades and extend the in-water testing period of the prototype beyond what was achieved through this Project.