Blue Energy Oregon

Powering Ocean Observation

Wave Energy System for Offshore Data Buoys

Oregon State University

2024

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Executive Summary

Wave energy is a resource of practically endless possibility that is fraught with complex and unforgiving challenges. Numerous studies have predicted that ocean waves could contribute massive amounts of power to the renewable energy transition (Levitan, 2014). The actual industry has long lagged, hindered by the engineering and financial difficulties incurred when working in the open ocean. Expensive testing set-ups, environmental permits, saltwater corrosion, and complicated wave fields have stumped engineers and drowned countless start-ups. Wave power experts commonly agree that "wave energy is where wind energy was three decades ago" (Levitan, 2014). An optimal wave energy design and application has yet to be identified.

While many wave energy developers focus on megawatt-scale projects that can power entire coastal cities, these ambitious undertakings often face substantial cost overruns, posing a significant risk to startups. In contrast, Blue Energy Oregon (BEO) identifies a promising niche in small, offshore wave energy applications. The ocean observation industry, which operates power-intensive sensing equipment in some of the world's most challenging marine environments, presents an ideal opportunity for deployment. Few other renewable resources can operate as reliably in these conditions. BEO will collaborate with the Ocean Observatories Initiative (OOI), which manages these research buoys, to develop a practical and cost-effective power solution. Although the BEO wave energy system provides only 50 watts of power, its six-month operational capacity is enough to sustain OOI's data collection efforts and support crucial scientific research dependent on accurate ocean readings.

Blue Energy Oregon sets the following goals, values, and visions:

Goal: The OOI inshore observation moorings are crippled by power supply inadequacies and rampant biofouling. BEO's wave energy system will provide consistent electricity to all the currently mounted sensors, boost data resolution, and support the addition of new instruments.

Vision: BEO will implement a robust power-take off (PTO) system into each OOI inshore mooring. Installation will be inexpensive and performed during the onshore maintenance phase of OOI's deployment. The PTO system will provide reliable power while mitigating risks.

Value: Oceanographic research is often limited by power supply. OBE will expand the scope and quality of the data collected by OOI sensors. Better data will enable improved scientific research into the complex effects of climate change on ocean resources.

To accomplish these goals BEO has conducted extensive stakeholder outreach to develop a comprehensive, market-research based business plan. Conversations with OOI guided the development of a technical WEC mechanical and electrical design. The design will be further validated through computer simulations and wave lab testing. This report will delve into the outcomes of these tests, pinpointing areas for refinement to be implemented in subsequent testing and design iterations.

1. Business Plan

1.1 Concept Overview

1.1.1 Business Model

Blue Energy Oregon (BEO) is a research and development start-up based out of Corvallis, Oregon, and partnered with Oregon State University (OSU). Funded by Small Business Innovation Research (SBIR) and Business Oregon Grants, OBE will develop a wave energy system that provides power to coastal observation buoys. OBE will collaborate closely with the Ocean Observatories Initiative (OOI) to integrate our wave power system into the OOI inshore observation buoys. Following the deployment of our product into OOI arrays, OBE will explore potential new customers who rely on offshore observation buoys.

1.1.2 Lessons Learned

Last year, our team focused on designing a supplemental power system for the OOI shelf buoys, which are moored at an 80 m depth. These buoys are larger than the inshore buoys and use wind and solar power to partially charge the system. The team designed a WEC that would be moored separately from the buoy. Power would travel between the WEC and buoy via subsurface electrical cables. Anchoring the WEC required three additional mooring lines, which proved to be a critical flaw. Additional moorings incur high costs and long installation times that are far beyond OOI's project scope.

This year, we shifted to focus on the OOI's smaller, inshore moorings. The inshore moorings suffer greater power issues than the shelf moorings, the smaller size is more applicable to a student engineering project, and the biofouling issues present an interesting design issue for the team's chemical and biological engineers. To rectify the previous mooring line issues, the team decided to design a power system that operates using the single, pre-existing, mooring line.

1.2 Stakeholders

Cultivating positive and enduring relationships with involved stakeholders a central BEO objective. The foundation of BEO's market, development, and WEC design stems from extensive conversations with stakeholders, to align our mission with the needs of the greater oceanographic community. Our team prioritized establishing connections with professionals at the forefront of ongoing observation arrays and connecting them back to industry. Outreach played a pivotal role throughout our development process, emphasizing the significance of maintaining open communication channels with our stakeholders.

Oregon State College of Earth, Ocean, and Atmospheric Science

Name/Interview Date: Dr. Jack Barth - 11/09/23
Stakeholder Industry/Affiliation: OSU Oceanography Researcher, OSU OOI and MSI Founder
Discussion: Dr. Jack Barth is a leading physical oceanographer at Oregon State University, and one of the founding members of both the Ocean Observatories Initiative and the Marine Studies Initiative (MSI) at OSU. Dr. Barth's studies the dynamics of the inner ocean shelf. His research is critically dependent on the longevity of OOI and National Data Buoy Center (NDBC) moorings. Adding WEC capabilities to any mooring would enable researchers to install additional sensors and add antibiofouling systems onto submerged instruments. Dr. Barth would love to see the OOI Endurance Array expand along the rest of the Oregon Coast.

Oregon State College of Earth, Ocean, and Atmospheric Science

Name/Interview Date: Dr. Kip Shearman – 11/13/23
Stakeholder Industry/Affiliation: OSU Coastal and Physical Oceanographer
Discussion: Dr. Kipp Shearman is a physical oceanographer at Oregon State University who researches the interaction of fronts with the coastal ocean. Much of Dr. Shearman's research is conducted with observation vessels and gliders. Gliders depend on rechargeable batteries which are notorious for power issues, which can cost thousands of dollars. Dr. Shearman expressed interest in integrating WEC technology with an observation glider to extend its lifetime and suggested that long-term oceanographic projects would be the best market for a small wave energy device.

PacWave

Name/Interview Date: Dr. Burke Hales – 11/17/23
Stakeholder Industry/Affiliation: PacWave Chief Scientist, Wave Power Research and Development, OSU
Discussion: Dr. Burke Hales is the Chief Scientist of PacWave, an open ocean wave energy testing site managed by Oregon State. Dr. Hales discussed the major issues hindering oceanographic research. Cost is paramount, and any wave energy power system must have extensive proof that it is worth the additional expense. Dr. Hales encouraged WEC developers to work with oceanographic research teams seeking to extend the lifetime of their deployment. Dr. Hales also emphasized the importance of designing and testing a WEC for survivability in intense Oregon coastal conditions.

Ocean Observatories Initiative: East Coast Pioneer Array

Name/Interview Date: Dr. Eric Wade – 01/11/23
Stakeholder Industry/Affiliation: Assistant Professor, Department of Coastal Studies at East Carolina University, East Coast OOI
Discussion: Dr. Eric Wade is an ethical consultant for the East Coast branch of OOI and specializes in understanding how deployment impacts the local community. Dr. Wade is working to restore and maintain trust between commercial fishers and OOI by hosting outreach opportunities and using surveys to understand where devices should be deployed to avoid obstructing fishing access. Dr. Wade stressed

that the WEC and mooring system should be marketed to researchers to improve our understanding of the ocean and make data available to everyone to aid in policy and commercial decisions.

Ocean Observatories Initiative: West Coast Endurance Array

Name/Interview Date: Jonathan Fram and Christopher Wingard – 4/24/24
Stakeholder Industry/Affiliation: OSU Physical Oceanographer/OOI Coaster Endurance Array Manager and OOI Senior Instrumentation Technician and Systems Administrator

OOI is a national ocean monitoring project that manages five global ocean sensing arrays. Each array is an extensive, offshore infrastructure system composed of moorings, buoys, linear profilers, and gliders (OOI). These arrays host a combined network of more than 900 sensor instruments that measure the ocean's physical, chemical, and biological properties from the surface to the seafloor (OOI). Data is transmitted to shore and available "open source" to advance scientific knowledge (OOI).

Blue Energy Oregon identified OOI as our primary customer and collaborated closely with OOI's technicians and managers throughout the project. Dr. Jonathan Fram explained the Endurance Array's power limitations. Chris Wingard explained the construction of the inshore submersible buoys, showing our team the instrument platforms, electrical cables, and mooring system. Fram and Wingard both believe that the inshore submersible buoys are particularly well suited for a point-absorber style wave energy system that uses the mooring tension for power. BEO conducted two informational visits to OOI this year that will be consistently referenced throughout the report. We visited OOI five times last year, and those conversations will be referenced as well.

1.3 Market Opportunity

Blue Energy Oregon will partner with the Ocean Observatories Initiative to prototype an integrated Wave Energy Converter (WEC) to supply additional power to the OOI's inshore moorings. Collaborating with OOI technicians will help BEO develop an efficient and pragmatic power solution that is marketable to the greater oceanography industry.

1.3.1 Ocean Monitoring

Ocean monitoring is crucial to understanding global environmental changes. Ocean data can predict weather patterns, natural disasters, water supply, food production, and trade route changes (GOOS, 2021). Characterizing ocean behavior is especially valued in the Pacific Northwest due to the fishing industry. While the endurance array's regions cover less than 5 percent of the ocean's surface, it accounts for a quarter of the global fish catch (OOI: CEA, 2023). More importantly, ocean data helps scientists predict the effects of climate change. As the climate crisis intensifies, so will the need for ocean data. The increasing demand for ocean data is met by federally funded ocean sensing organizations such as OOI, Ocean Networks Canada, and the National Ocean and Atmospheric Administration. These projects use extensive networks of buoys, seafloor nodes, autonomous gliders, and vertical profilers to collect a diverse breadth of data (current, salinity, temperature, etc.) (OOI: CEA, 2023).

1.3.2 Ocean Observatories Initiative

Oregon State University operates and maintains OOI's Endurance Array, a series of moorings that monitor shelf (referencing the continental shelf) variability along the coasts of Oregon and Washington (OOI: CEA, 2023). Each OOI mooring is composed of a surface buoy tethered to a multi-function node (MFN) anchored on the seafloor Washington (OOI: CEA, 2023). Moorings are placed at varying distances from the shore. Submersible inshore moorings sit closest to shore at a water depth of around 25 m Washington (OOI: CEA, 2023). Shelf and offshore moorings sit further from shore at 80 and 500 m water depths, respectively Washington (OOI: CEA, 2023).

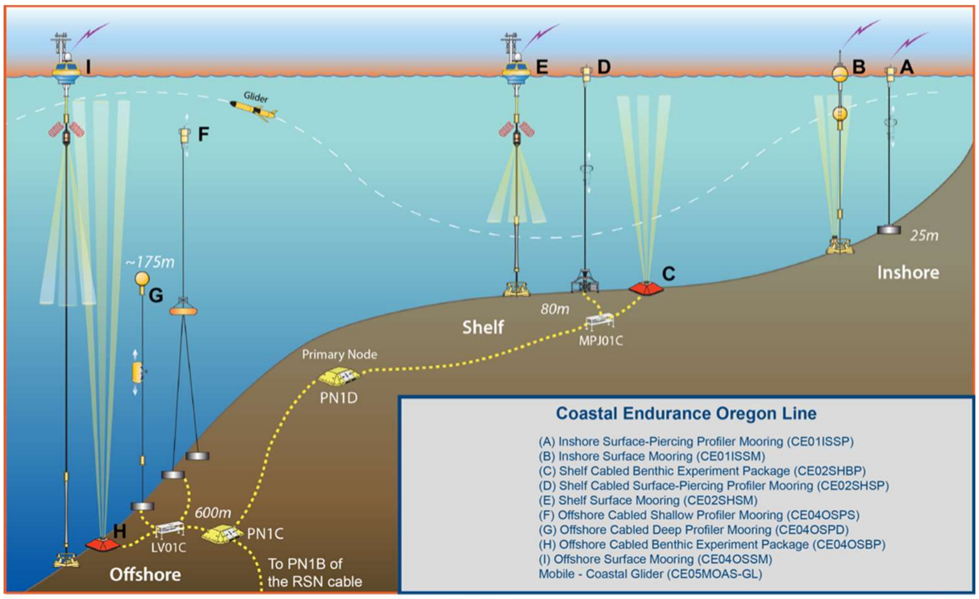


Figure 1.1 Oregon Coastal Endurance Array (OOI: CEA, 2023)

All these systems suffer from inadequate power supply. The large offshore and shelf buoys use solar panels and wind turbines to charge a battery. In the winter, turbines quickly top off the battery in extreme Pacific winds. In the summer, winds are calmer, and power production is limited (Fram, 2023). Instruments run for only twenty minutes every two hours (Wingard, 2023). Data resolution is diminished, and sensitive electronics are damaged by frequently turning instruments off and on (Wingard, 2023).

The smaller, submersible inshore moorings, or model CE01ISSM, perform even worse. Dr. Fram explained that the inshore mooring's battery system supplies only half the necessary power. The limited power supply results in low quality data. On top of this, biofouling grows faster close to shore, and can quickly cripple instruments (Fram, 2023). Dr. Fram and Mr. Wingard summarized that in terms of the inshore moorings, "OOI is simply not meeting its original objectives." The OOI project is in year ten of a thirty-year timeline (Fram, 2023). Scientists are interested in mounting additional sensors, but new, power-hungry instruments are far outside of OOI's current electrical capacity. Dr. Fram believes that an additional power supply could vastly improve the quality and scope of data (Fram, 2023).

Blue Energy Oregon will capitalize on this issue by developing a simple WEC that can be integrated into OOI's Inshore Surface Mooring (CE01ISSM) (OOI: CE01ISSM, 2023). This system will replace the current electrical system, improve data resolution, and minimize the effects of biofouling. The design will maximize power output while minimizing production and installation costs.

1.3.3 OOI Design and Operation Specifications

VWE asked Chris Wingard and Jon Fram to outline their requirements for a WEC designed to provide power to the CE01ISSM inshore buoys.

OOI wants a product that considers real ocean conditions. Biofouling is a consistent issue for OOI buoys. Around every six months buoys and MFNs are retrieved and replaced with a fresh mooring. The old mooring is brough to shore, hosed off, repaired, and recoated with anti-biofouling paint (Wingard, 2023). While this operation is expensive, it is the cheapest way to mitigate damage caused by biofouling. Biofouling is less of an issue in “blue water,” the deep, distant ocean where the large OOI shelf and offshore moorings are deployed (Fram, 2023). Unfortunately, at a 25-meter water depth, biofouling occurs remarkably fast. Basic physics, salinity, and temperature sensors will continue to operate with some fouling, but optical sensors cannot operate with any fouling (Fram, 2023).

While the OOI deployments officially last six months, Dr. Wingard explained that OOI plans for a 210-day deployment (Wingard, 2023). Deployment and retrieval of a buoy takes an entire day, a “ship day”, and costs around $50,000. OOI books ships years in advance, so the dates they can travel out and retrieve a mooring are completely non-adjustable. If the buoy fails due to a power outage, impact, breaking mooring line, or countless other potential disasters, OOI must wait until their next “ship day” to travel out for retrieval. Ship deployments and retrievals compose 30% of OOI’s total budget (Fram, 2024).

Pacific Ocean wave conditions are massive and dangerous in the winter. Due to safety concerns, OOI cannot operate vessels between October and March. Even with cheap and immediate ship access, any deployed device must withstand 6-months of potentially extreme wave conditions before retrieval. There are currently four inshore buoys deployed in the Endurance Array. When OOI retrieves these buoys, they hope they are still 70 to 80% operational (Wingard, 2024).

1.3.4 Power Supply

1,296 primary lithium D-cell batteries power all the instruments onboard each CE01ISSM inshore buoy (Fram, 2023). These batteries are not rechargeable and must be completely replaced after every deployment. The current electrical system only provides only 25 watts during the deployment, half of the power required to successfully operate the instruments (Fram, 2024). 50 watts of power, produced continuously over the entire 210-day deployment, would sufficiently power all instruments, and produce data of an adequate quality (Fram, 2024). Fram and Wingard expressed interest in generating extra power, above the necessary 50 watts. Extra power would enable the mounting of new sensors and instruments, and could also be routed to UV antifouling lights, aiding the quality of optical data. Fram identified 6-months of reliable 100-watt power as a “dream” power supply (Fram, 2024).

Fig. 1.2 210-Day OOI Power Supply Comparison

The batteries for two moorings cost $45,000, with 48.5% overhead. This cost is incurred every six months, resulting in a total cost of around $66,825 per year. BEO aims to develop a rechargeable battery bank powered by a consistent supply of wave energy. This complete electrical system will be more effective and cheaper than the current inshore replaceable battery system.

1.3.5 Competitors

Many buoys today are powered by photovoltaic (PV) solar systems, using batteries to compensate for the periods when the buoy is without sunlight (Wang, 2023) (Meindl, 1996). Wave energy has the potential to power these buoys, but is limited by a lack of research, resulting in a higher net cost of electricity generation, or levelized cost of energy (LCOE), when compared to solar and wind (Meindl, 1996). While developers are actively working to improve wave energy, solar technology remains decades ahead (Foteinis, 2022).

PV solar panels and offshore wind turbines are limited by their source intermittency (Guo, 2023). Wave energy is consistent and could provide a constant power supply to buoys. Ocean waves have a remarkably high energy density, which suggests that wave energy could eventually surpass solar and wind as the primary power supply option for offshore buoys (Kofoed, 2017).

Among the organizations developing commercial WECs, relatively few are designing for smaller-scale applications like buoys. Most WECs are designed and built on scales too large to be cost-effective for powering single buoys (Foteinis, 2022). This narrows the possible competition Blue Energy Oregon will face when marketing our own WEC. Additionally, of the groups that are aiming to power small-scale marine research, very few designs have been proven commercially viable (McLeod, 2022). The company 3newable and the East coast OOI group have produced WEC designs targeted towards buoys operating offshore, but they would require heavy adaptation to operate for inshore buoys. The small-scale WEC from BEO, designed for inshore operation, will therefore be set apart from its competitors.

1.3.6 Future Vision

Blue Energy Oregon has identified three main markets for the company's WEC.

1. Extending the reach of existing OOI operations
2. Scaling the technology to power the Pacific Marine Environmental Laboratory's Tropical Atmosphere Ocean (TAO/TRITON) Array
3. Developing a similar system to TAO/TRITON to monitor changes in Pacific Decadal Oscillation (PDO).

OOI is interested in extending the Endurance Array geographically to the Columbia River Plume and the greater California current along the western United States (Barth, 2023). The current array only captures data for the middle of the Columbia River Plume, and a single point in an eastern boundary current that stretches from north Washington to Baja California. River sediment transport helps contain harmful algal blooms (HABS) by increasing the turbidity of the water column. Furthermore, NOAA models using the plume can accurately predict if a future bloom could compromise a fishery (NCCOS, 2013). Understanding these dynamics further could bolster Oregon fisheries and make them more resilient to the increasing frequency of HABS in the past 15 years. Looking further south, critical ecological boundaries in the California Current could be analyzed as ecological regime shifts along the current form some of the most productive fisheries in the world (NOAA: California Current Region). Exact locations highlighted to improve the study of the plume are depicted in Figure 1.4 while Figure 1.3 depicts the future expanded OOI array.

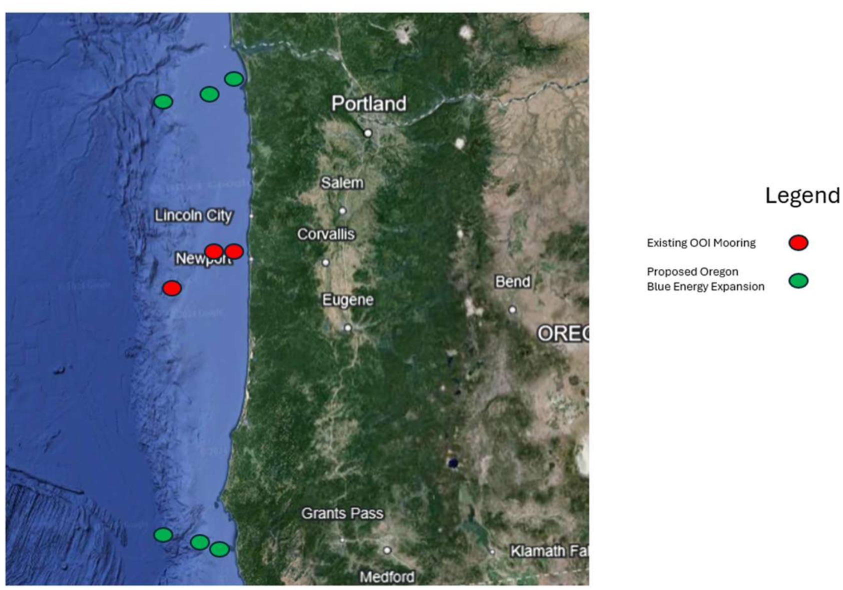


Figure 1.3 Expanded Oregon Range

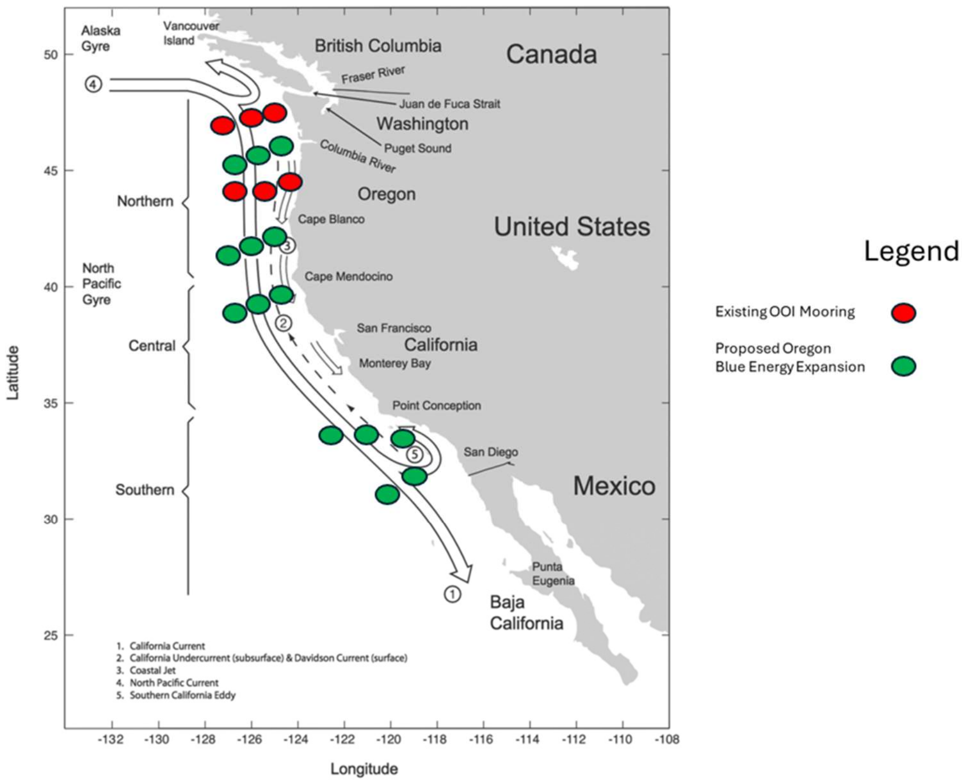


Figure 1.4 Modified map of California Current with extensions to the Endurance Array marked in green (Mauzole, et.al, 2020)

The Tropical Ocean Global Atmosphere Program (TOGA) is a multi-ocean observation system and a key part of the World Climate Research Program (WCRP), a global effort to understand the Earth's climate and how it changes annually. This array consists of the Tropical Atmosphere Ocean (TAO/TRITON) array in the equatorial Pacific Ocean, the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) array in the equatorial Atlantic Ocean, and the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) array in the equatorial Indian Ocean. These three arrays are responsible for monitoring changes in sea surface temperatures and weather that signal important events like El Nino and La Nina in the Pacific (sea surface warming/cooling that drives global climate patterns), the Atlantic hurricane season, and the Indian monsoon season. These systems have wide-reaching consequences for millions of people worldwide in agriculture, fishery management, water management, and transportation. The array currently uses rudimentary buoys with single-use batteries that provide hourly measurements via Iridium satellite while high-resolution data can only be collected once the buoy is recovered (NOAA: Mooring) The entire TOGA array is slated to be updated in the coming years to increase both deployment time and data clarity, additional onboard power generation can create opportunities for both.

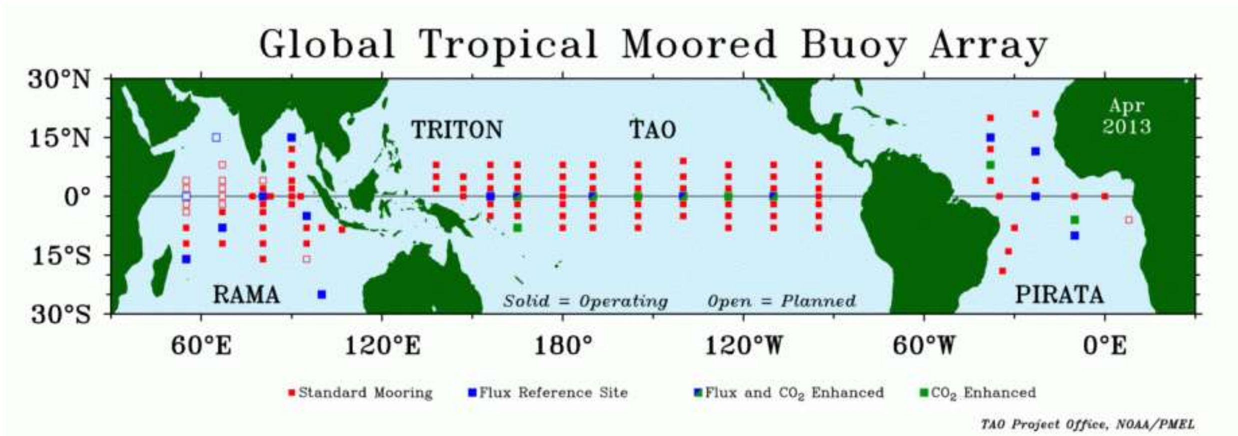


Figure 1.5 Full reach network, with TAO/TRITON, RAMA, and PIRATA arrays highlighted (climatedataguide.edu)

Lastly, a critical region of the ocean that has gone largely unmonitored is the Pacific and the effects of decadal oscillation, a process in which the entire North Pacific basin swings between warm and cold periods like the more well-known El Nino/La Nina oscillation in the South Pacific. These oscillations take roughly ten years to form and can have wide-reaching consequences when combined with surface temperature anomalies, as seen with the blight of sea star wasting disease (climatedataguide.edu). The only active long-term surveying operation is Station Papa off the coast of Alaska which is a collection of submerged moorings and gliders rather than a full cabled array (OOI: Papa, 2015). This lacks both the range of TAO/TRITON and the variety of data that existing OOI cabled arrays can obtain. Fully electrifying this system and connecting it back to the shore would improve the global understanding of PDO and the larger North Pacific gyre. Figure 1.6 shows a possible configuration of a PDO array.

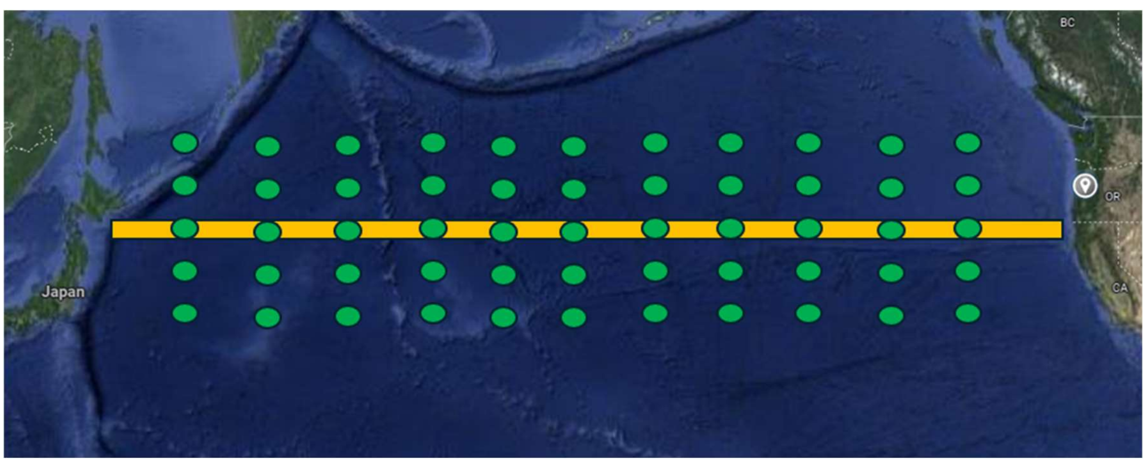


Figure 1.6 PDO array design to mimic TAO/TRITON in the equatorial Pacific

1.4 Development and Operations

Blue Energy Oregon has a five-stage development strategy that outlines key advancements in both business and engineering. Our strategy aligns with the nine general technology readiness levels (TRLs) (Heilman, 2014) to ensure the project stays on track to receive SBIR funding (DOE: SBIR/STTR, 2023).

Table 1.1.

	Business Developments	Engineering Developments
Stage 1: Proof of Concept Year: 0 TRLs: 1-4	**Qualification and Application for SBIR Phase I Funding:** Meet all eligibility criteria for SBIR Phase I funding and prepare a strong application outlining project goals, potential impact, and feasibility. **Blue Economy Relationships:** Cultivate relationships with key stakeholders such as Oregon State University (OSU), Ocean Observatories Initiative (OOI), PacWave, and other prominent figures within the Oregon marine energy community.	**Basic Principles:** Research and collaboration with OOI to determine basic system requirements and power generation needs. **Technology Conceptualized:** Select WEC archetype and generate concept based on design requirements, complete initial CAD model. **Characteristic Proof of Concept:** Perform load analysis to validate the feasibility of the proposed WEC technology under real-world conditions. Identify potential challenges and refine the technical design. **Simulation:** Characterize CE01ISSM behavior in WEC-Sim and determine if proposed WEC meets power requirements
Stage 2: Model Validation Year: 1 TRLs: 5-6 SBIR Phase I	**Grant Utilization:** Model development and validation expenses, property, and personnel to support prototype development. **Blue Economy Relationships:** Throughout testing, leverage the expertise, resources, and industry insights offered by partners such as HWRL and OOI to ensure accurate and useful test results.	**Scale Model WEC:** Select model components, assemble model sub-systems, integrate sub-systems into complete, functioning model. **Wave Basin Testing:** Validate model WEC in the directional wave basin at HWRL, use wave data to accurately represent operational environment. **Biofouling Team:** Continue testing and development of optimal anti-biofouling technology.
Stage 3: Prototype validation Years: 2-3 TRLs: 7-9 SBIR Phase II	**SBIR Phase II Funding:** Prototype development and validation expenses, custom full-size components for production. **Commercialization Prep:** Reach out to other ocean observation groups to gain insights and facilitate future collaboration opportunities. **System Support:** Develop comprehensive deployment and maintenance plan.	**Design Re-Evaluation:** Compare all testing results, adjust WEC design as necessary for ocean conditions. **Full Scale Prototype:** Select components, develop full scale prototype. **Open Ocean Testing:** Long term, open-ocean validation of BEO WEC System integrated with CE01ISSM in PacWave facilities. **Reliability in WEC-Sim:** Iterative, accurate simulations to fully characterize final WEC reliability in varying environments.

STAGE 4: MARKET INTRODUCTION Years: 4-5 SBIR Phase IIB	**Initial Release:** Deploy initial iterations of CE01ISSM with the fully integrated BEO WEC System. **Company Growth:** With the successful release of BEO's WEC System, looking into other potential partners in ocean observation.	**Deployment:** Work closely with OOI for a smooth integration, installation, and deployment process. **Finetuning:** Reassess and adjust all processes and documentation based on customer feedback and initial outcomes. **Replication:** Continue creation, installation, and deployment of WEC System.
STAGE 5: LOOKING FORWARD Years: 6+	**Continuous Improvement:** Improve existing product and business practices and marketplace opportunities. Invest time and money into exploring. **System Support:** Explore contract technicians to support installations and maintenance as production increases. **Expanding Horizons:** Overall business growth through exploration of potential partners outside of ocean observation.	**R&D:** Work closely with other companies to help develop custom solutions to their offshore energy problems. **Data:** Gather and use operation data to optimize and alter systems for maximum power generation. **Advancing Technology** Optimize existing technology, improve anti-biofouling methods, modification modular. **New Technology:** Explore and design new WEC technology and archetypes to progress BEO and the marine energy industry.

1.4.1 Solution and Pricing

BEO's Solution

Blue Energy Oregon's wave energy solution attaches to any operational CE01ISSM buoy without modification. The wave energy converter uses wave motion and mooring line tension to generate power. OOI's expensive and wasteful battery system is replaced by BEO's rechargeable battery bank. The rechargeable battery bank receives, and stores wave generated electricity, and provides 50W power during the entire 210-day deployment. This power sufficiently operates all instruments mounted on the mooring, extending "up time," improving data resolution, and mitigating damage caused by constantly powering sensors on and off. When using a BEO wave energy system, OOI can improve their inshore data collection at a fraction of the previous cost.

The BEO WEC system is lightweight yet robust. The complete BEO system weighs 660, and OOI's original disposable battery bank weighs around 110 lbs. (Fram Email, 2023). OOI already has added 200 pounds of lead ballast to some inshore buoys. Dr. Fram deemed the increased weight acceptable.

By leveraging existing attachment hardware on the CE01ISSM weldment, BEO provides a seamless and cost-effective installation. To mitigate the risk of damage associated with the buildup of unwanted biological growth, the WEC housing (Figure 2.6) is coated with an anti-biofouling paint developed by BEO's biofouling team. For further details about technical design specifications, see Section 2.2 "Technical Design: Concept."

Table 1.2 Comparing the Existing OOI power supply to BEO's WEC system.

Electrical System	Power [Watts]	%Operational Power	Cap Ex	Annual Op Ex	5-Year Cost (10 deployments)	Weight
Existing OOI	**25**	**50%**	**$66,825**	**$66,825**	**$334,125**	**110 lbs.**
Proposed BEO	**50**	**100%**	**$25,000**	**$2,000**	**$30,000**	**660 lbs.**

Pricing

BEO sells a package that includes a complete wave energy mechanical system, installation of the system onto the inshore buoy, and a rechargeable battery bank for a price of $25,000. This cost covers installation and the routine maintenance after a system completes its first 210-day deployment. BEO believes this is an appropriate price for the attachment due to the cost of production and the engineering labor expense. By not including maintenance in the price, BEO provides client companies with the opportunity to train their own technicians to care for and maintain the WEC package. This would be more cost-effective for our customers to provide and train their own technicians. This WEC attachment is a great investment because it provides the chance to maintain the body layout of the inshore buoy while still providing power to the necessary instruments.

Installation and Maintenance

Initial WEC installation and maintenance is performed by BEO engineers and technicians to ensure product success and consistency. Following each 210-day deployment, regular maintenance is conducted to guarantee smooth operation and the longevity of WEC. This maintenance is carried out on land after OOI retrieves their CE01ISSM buoy and can be performed by either a BEO technician or a partner technician who has completed the required training programs. After the first maintenance session, BEO offers regular maintenance services priced at $2,000 per year per mooring. This service encompasses all necessary parts, travel, and labor for two routine maintenance procedures for a single WEC. Once appropriate procedures are established and documented, BEO plans to offer training to customer technicians at low cost so they can conduct installations and maintenance internally.

The WEC system is designed with safeguards to maintain full operational capabilities for its deployment, minimizing the need for non-routine maintenance. If the WEC System needs to be serviced during its 210 -days at sea, BEO will work with OOI to assess the situation and decide how to proceed depending on the risks and damages.

1.4.2 Risks and Permitting

Risks

There are many environmental and human safety risks associated with marine energy devices. Environmental risks include the physical damage and stress that can be caused by a WEC detaching from the mooring system or the overall system breaking. If any part of the WEC system detaches, it can cause serious damage to the surrounding marine ecosystems. Marine devices detaching from the mooring, results in the body free floating. A collision with a buoy or vessel is expensive and dangerous.

Another risk associated with marine energy devices is the anthropologic sound projected into the ocean. Anthropogenic sound, or noise generated by humans, can be created through different aspects of the WEC, like the mooring line chains colliding or the sound of metallic parts rubbing together. WEC noise can produce a frequency range of up to 4 kHz, which has the potential to mask fish communication sounds which range from 100 Hz to 1 kHz (G. Buscaino, 2019). Masking fish noises can cause behavioral and physiological problems and can eventually lead to the damage of vital functions like reproduction, communication, and predator detection. It is important to acknowledge that while physical collision is a crucial risk, sound pollution is an increasing issue in the ocean environment today.

Permitting

In addition to constructing a wave energy converter, it is important to consider the significant regulatory implications associated with its placement in the designated energy-generating site. To gain permission to place a WEC into the ocean, there are many licenses, permits, and compliances that either must be obtained or followed before being allowed to place the system into the water and start generating power. While there are many different laws and regulations, the most important license is the Federal Hydroelectric License from the Federal Energy Regulatory Commission (FERC). There are also the site leases from the Bureau of Ocean Energy Management (BOEM) and the nationwide and navigation permits from the U.S. Army Corps of Engineers (USACE) and U.S. Coast Guard (USCG). Along with filing for a license, the company producing and implementing a WEC must follow a list of compliances that all focus on maintaining the safety and health of the surrounding marine and avian ecosystems. After the permits and compliances then follow the state and local acts and permits that must be followed or submitted. *Table 1* shows all the necessary regulatory aspects.

Table 1.3 Required regulatory aspects of WEC implementation on a national, state, and local level (Lehmann et al., 2017)

Permits	Compliances	State	Local
Research Lease or Site Lease (Bureau of Ocean Energy Management (BOEM))	National Environmental Policy Act (NEPA)	Site Lease: (Department of State Land (DSL))	Local Land Use Compatibility Statement
Hydroelectric License (Federal Energy Regulatory Commission (FERC))	Endangered Species Act	Coastal Zone Management Act Consistency (Department of Land Conservation and Development (DLCD))	Conditional Use Permit

Nationwide Permit #52 (United States Army Corps of Engineers (USACE))	Marine Mammal Protection Act	Water Quality Certification (Department of Environmental Quality (DEQ))	
Private Aids to Navigation Permit (United States Coast Guard (USCG))	Essential Fish Habitat	Removal- Fill Permit (DSL)	
	Migratory Bird Treaty	Easements for Cables in Territorial Seas (DSL / DLCD)	
	National Historic Preservation Act	Ocean Shore Alteration Permit (Oregon Parks and Recreation (OPRD))	
		Water Right (Water Resources Department (WRD))	

Hydroelectric License

The hydroelectric license is one of the most important regulatory actions required before WEC deployment and is required for any electrical system that uses water as a kinetic power source. This means that both hydroelectric dams and marine energy devices, like wave energy converters and tidal energy converters, are required to obtain this license. The supplementary acts that must be followed within this document are NEPA, Clean Water Act, Endangered Species Act, National Historic Preservation Act, and Coastal Zone Management Act (CZMA), Essential Fish Habitat Act (also known as Magnuson-Stevens Fishery Conservation and Management Act), the Migratory Bird Treaty Act of 1918, and the Marine Mammal Protection Act (Buscaino, 2019). To be approved, the project in question must follow all these regulations, in addition to submitting an Environmental Impacts Statement for approval by public comment.

1.4.3 Financial and Benefits Analysis

The financial expenses of operating and maintaining Blue Energy Oregon are shown below in the four tables. These charts detail the specific expenses that are included in BEO, including the price per unit made, maintenance, company overhead, and the development costs.

Table 1.4. The one-time expenses for the construction of one WEC package.

Cogs: One-time Expenses (per unit)	
Expense	**Amount**
Frame	$ 170.00
Housing	$ 100.00
Batteries	$ 10,710.00
Water Proofing	$ 1,000.00
PTO	**$ 3,002.11**
Generator	$ 120.80
Spring	$ 166.67
1 in shaft	$ 28.39
1.5 in shaft	$ 97.82
2 in sprocket	$ 19.00
3 in sprocket	$ 58.20
6 in sprocket	$ 82.33
Spring spool	$ 15.70
Main spool	$ 75.00
1 in bearings	$ 414.96
1.5 in bearings	$ 1,433.76
Shaft collar	$ 106.71
Belts	$ 100.00
Roller chain	$ 30.00
Damping springs	$ 130.08
Wire End	$ 122.69
Labor	**$ 5,000.00**
Assembly Labor	$ 5,000.00
Installation Labor	$ 100.00
Total	**$ 20,082.11**

The cogs table contains the one-time expenses incurred by BEO required to build a single WEC package. The table is broken into two parts: PTO system components and the labor costs to construct a single unit. Each part is listed along with the associated price. The assembly labor includes the price for a team of engineers to construct the WEC package. The cogs table directly influences the price to the customer, serving as the main factor contributing to the final cost of the WEC system.

Table 1.5. Expenses associated with maintenance and product support per WEC unit.

Routine Maintenance Cost	
Expense	**Amount per visit**
Technician Labor	$ 480.00
Equipment	$ 400.00
Travel Costs	$ 50.00
Total per unit	**$ 930.00**
Total Annually	**$ 1,860.00**

By performing routine maintenance on land, BEO avoids the expenses involved in offshore maintenance. However, should the WEC need to be serviced at sea, BEO must have the resources available to send a technician out to the WEC site. The product support table, shown above, details the expenses for routine maintenance on land. If the need for maintenance at sea arises, the expenses would increase in travel costs and technician labor. The reason these sections would increase is due to the cost of the boat rental to the WEC site. Also, it would be expected that the technician would be working longer so their labor costs would increase.

Table 1.6. The overhead annual expenses for the BEO company, including the total salary expenses.

Overhead (annual)		
Expense	**$**	**162,800.00**
Software Licenses	$	40,800.00
Insurance	$	51,700.00
Building Rent, Maintenance, Cleaning etc.	$	55,300.00
Training and Continuing Education	$	15,000.00
Personnel	**$**	**1,095,000.00**
Admin/Management	$	330,000.00
Marketing	$	120,000.00
Finanace/Legal Team	$	195,000.00
Engineers	$	450,000.00
Total	**$**	**1,257,800.00**

The overhead costs include the annual expenses that are necessary to maintain BEO as a functioning company. The overhead table includes a wide range of expenses like the building rental and software licenses like Microsoft office, computational programs, and CAD modeling software. The table also includes the total salary cost for each group of employees. BEO would initially have two administrative staff and two management staff; their estimated salary would be $85,000 for administrative and $80,000 for management. The marketing salary would be $60,000 for two employees, while the finance team would have three staff members with the salary of $65,000. Lastly the engineering team would have six engineers with a salary of $75,000. These expenses are crucial as they provide an estimated breakdown of cost to startup and operate a marine energy company.

Table 1.7. The development expenses table includes prototyping, testing, and equipment costs.

Development: R & D, operating labor, prototyping etc.	
Expense	**Amount**
PTO Model Materials Cost	$ 525.00
Hull Model Materials Cost	$ 470.00
Electrical Model Materials Cost	$ 143.00
Design+Assembly Labor	$ 7,960.00
Wave Lab Testing Facility	$ 11,000.00
Testing Engineer Labor	$ 6,330.00
Prototype Materials Cost	$ 2,700.00
Open Ocean Testing	$ 15,000.00
Systems Integration with OOI	$ 25,000.00
Equipment	$ 20,000.00
Total	**$ 89,128.00**

The development table includes the expenses of the prototyping, testing, and design process. The table includes all the costs for the model that was tested in the build and test report. For the testing, the table includes the prices for testing in the O.H. Hinsdale Wave Research Laboratory and the open ocean test with PacWave. The systems integration with OOI is the expense of testing and installing the WEC package on their inshore buoy. Lastly, the equipment cost includes the machine shop basics like tools and machinery, as well as more specific machines like 3D printers.

2. Technical Design

2.1 Design Overview

Blue Energy Oregon established the following criteria to guide the technical design of a wave energy system for the OOI inshore buoys.

1. BEO's wave energy system must efficiently and reliably produce at least 50 Watts of power throughout the entire 210-day OOI deployment. BEO will aim for a power production over 50 watts, as extra power would result in a more reliable electrical system, allow mounting of new instruments, and extend the buoy's deployment time.
2. The BEO wave energy system must be completely reliable in Pacific Ocean conditions. Biofouling, corrosion, and storm wave conditions will be considered in all aspects of design.
3. BEO prioritizes the customer in all aspects of design. The BEO wave energy system must be extremely easy to install onto the operating OOI inshore moorings. Cost should be minimized, and onshore maintenance of the device should be able to be easily performed during the bi-yearly retrievals.

Extensive conversations with OOI technicians help BEO generate a precise list of customer requirements and buoy specifications. Wave conditions at the deployment site were evaluated seasonally and modeled for testing. A diverse set of concept ideas were weighed before a final mechanical and electrical system design was chosen and polished. This design was evaluated and optimized using computer simulations.

2.1.1 Inshore Buoy Overview

The inshore CE01ISSM buoys are moored at a 25 m water depth. The foam buoy is 1.5 m in diameter. An aluminum frame runs through the buoy, called the “weldment.” This frame supports several instrument clusters, houses the buoy electrical and battery system, and includes a metal structure for deployment and retrieval. Instruments are mounted 2 m above the water's surface, on top of the buoy, and 1.5 m below the buoy (Fram Email, 2023). This creates an even weight distribution and a relatively high center of gravity ().

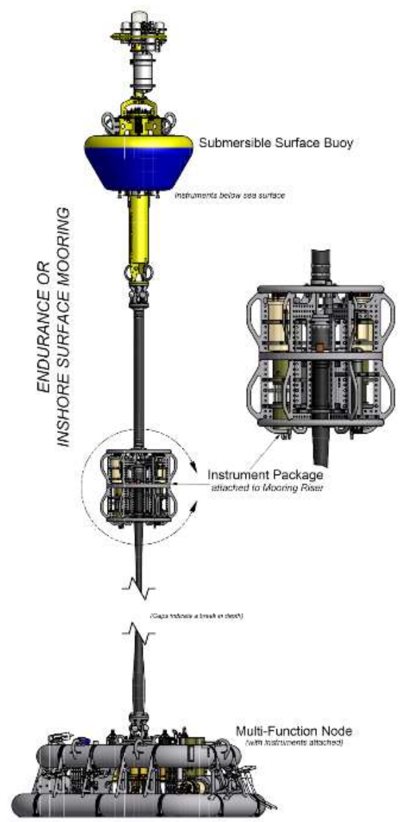


Figure 2.1 Inshore buoy diagram

Hanging 5 m below the buoy is a metal frame that supports a package of instruments. This frame is called the “Near Surface Instrument Frame” of NSIF. The NSIF is attached to the buoy with chain enclosed in rubber tubing. Dr. Wingard explained that the chain hose is remarkably stiff, which helps keep the NSIF from rising and colliding with the buoy (Wingard, 2024). A steel, multi-directional joint attaches the chain to the bottom of the buoy and allows the buoy to rotate relative to the mooring.

The system is moored to a heavy stainless-steel anchor that rests on the sea floor, called the “Multi-Function Node” or MFN. Additional instruments are mounted to the MFN. A taut, 15 m elastic cable connects the NSIF to the MFN. These cables are designed by WHOI and engineered by EOM Offshore. Dr. Fram explained that the inshore buoys are top-heavy, and without the taught mooring line the buoys are liable to tip (Fram, 2024). The mooring lines are designed to allow the buoy to follow waves in calm seas, but in storm conditions the cable stiffens, and the buoy submerges.

Adding extra weight to the CE01ISSM inshore buoy is not a concern for OOI. Dr. Fram and Dr. Wingard explained that they had already added 200 pounds of lead ballast to the bottom of the weldment to stabilize the buoy and reduce its buoyancy. A wave energy system would ideally replace some of the heavy batteries, so we will target a wave energy system that weighs less than 600 pounds, including the rechargeable batteries.

The batteries are stacked inside the boy's frame. Instruments are connected to the battery package by simple electrical cables that travel up to the weldment and down the mooring line to the MFN. A wave energy system would simply be "plugged in" to those cables.

2.1.2 Ocean Conditions

A regular wave is a sinusoidal wave with a constant amplitude, wavelength, and period. Real sea states have an irregular, or random, wave form. The most common way to characterize ocean waves is using a wave spectrum, or spectral density. A random wave spectrum is defined by significant wave height (SWH) and a peak period (PP). Significant wave height is equal to the "average of the highest one-third of the waves, as measured from the trough to the crest of the waves (NDBC, 1996). The sea state is the general condition of the surface of the water at a certain time and location concerning wind waves and swell. Wave spectral density is the distribution of energy in the frequency domain (energy per unit frequency) (Aubrey, 2024). Another attribute of waves is the direction in which the wave energy is concentrated. While non-directional waves, also referred to as isotropic waves, propagate uniformly in all directions, directional/angled waves are those in which the energy is concentrated in a specific direction. Multidirectional waves exhibit characteristics of both directional and non-directional waves and amplitude and period vary depending on direction without having a dominant direction of propagation.

The wavefield experienced by the Endurance Array is, as Dr. Fram called it, "complicated" (Fram, 2022). He shared that another company had previously approached them with a WEC system for their buoys and that this device has failed because they had underestimated the complexity of the ocean environment (Fram, 2022). Throughout the design process, BEO used historical data collected by the National Data Buoy Center (NDBC), data collected from the OOI Endurance Array, and model wave data from the Water Power Technologies Office (WPTO) Wave Hindcast Dataset to

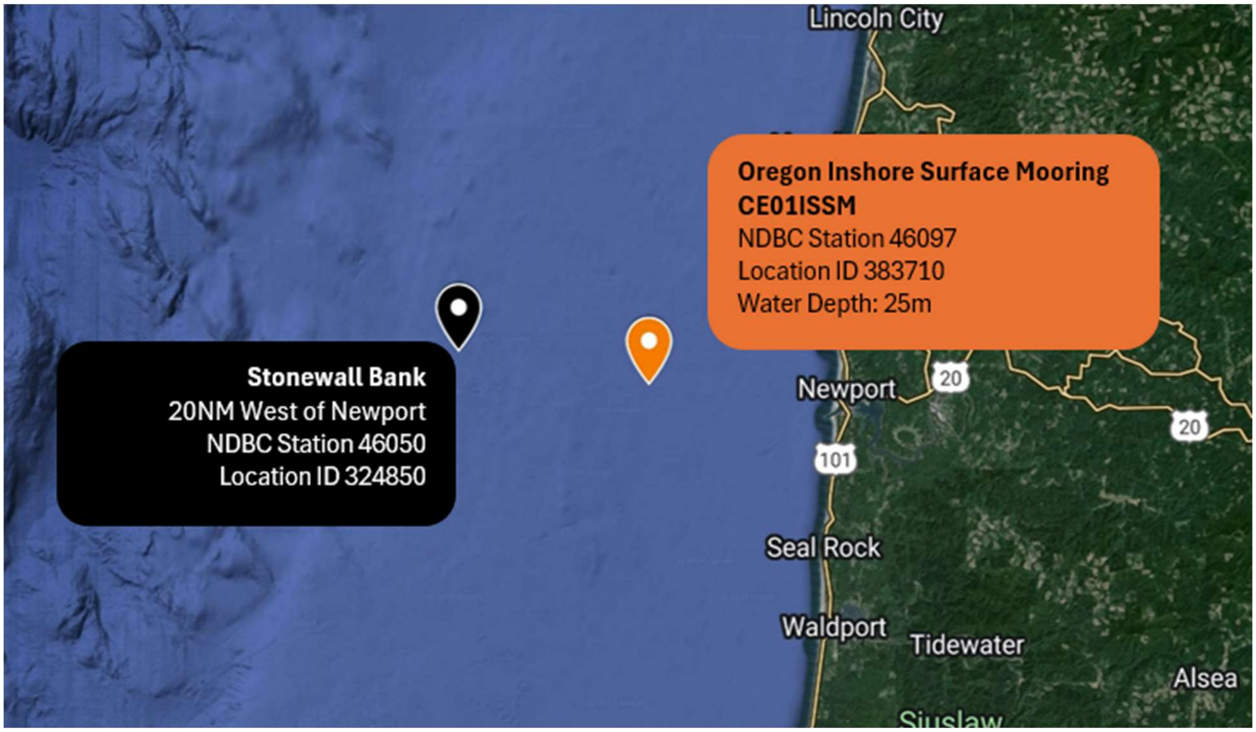


Figure 2.2. Location of the CE01ISSM buoy and the Station 46050 Buoy for reference

Table 2.1. The significant wave height and peak period depending on the season.

Season	Significant Wave Height	Peak Period
Winter	2.37	13.33
Spring	1.66	11.01
Summer	1.55	9.1
Fall	1.86	11.01
Annual Avg.	**1.86**	**11.12**

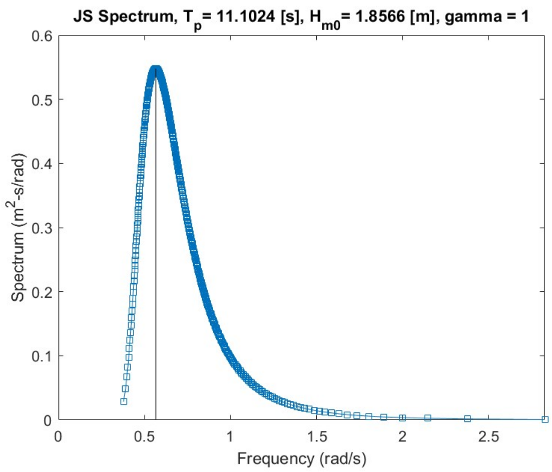


Figure 2.3. Average Annual JONSWAP Spectrum

2.2 Concept

2.2.1 Concept Selection

OOI specified that the WEC design must connect directly to OOI's single pre-existing mooring line. Multiple mooring lines allow a WEC to be oriented into the predominant wave direction but require additional permitting and costs. A single mooring line constrains the WEC to collect power unidirectionally. Two general WEC archetypes can accomplish this task: a point absorber and a rotating mass. Several variations of these archetypes were considered. BEO needed a simple design that could be easily integrated into the inshore buoy with minimal modifications, and efficiently use the buoy's natural motion to produce power.

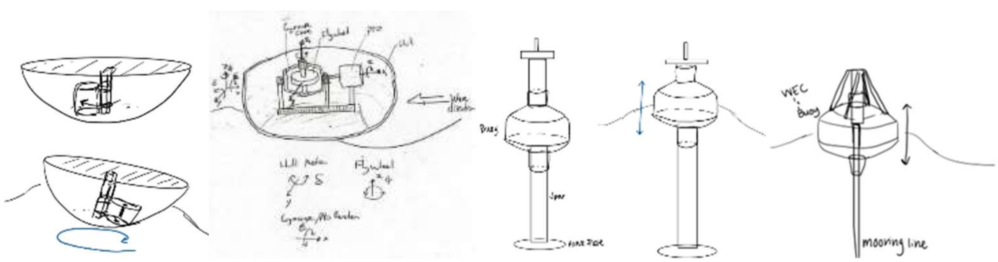


Figure 2.4. Initial Concept Sketches, from Left to Right: Inertial gyroscope, Rotating mass gyroscope, Two Body Point Absorber, Single Body Point Absorber

A single body point absorber was chosen as the final design archetype. A rotating mass WEC presents a design complexity far outside the scope of a student project, plus the inshore buoy surface area is too small to support an easily installable rotating mass system. Single-body point absorbers are simple to construct, can be mounted in-line with the mooring below the buoy hull, and exhibit excellent power efficiency. A single body point absorber comprises a floating mass anchored to the seafloor. The oscillation of waves exerts tension on a cable, and the power take-off system transfers the tension into rotational motion using a cable and spool attachment.

2.2.2 Concept Overview

A metal attachment structure is welded to the bottom of the weldment. This metal attachment structure includes holes which bolt to the multi-directional joint. Electrical cabling runs through a hole in the middle of the metal attachment structure, through the multi-directional joint, and into the chain-hose that extends to the NSIF. BEO will take advantage of this metal attachment structure by designing a WEC that bolts directly through the pre-existing bolt holes. Electrical lines exiting the WEC can either plug directly into a cable running down the weldment, or into cabling contained in the chain-hose that leads to the NSIF. The metal attachment structure and simple cable plug-ins are pictured below.

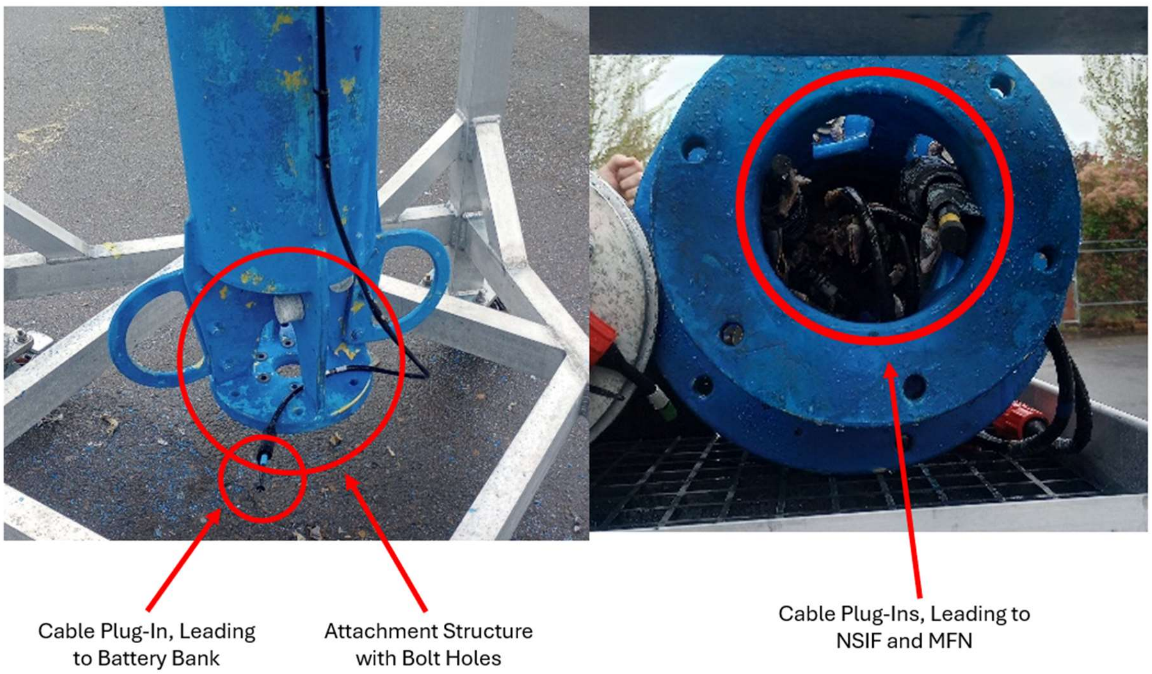


Figure 2.5. The cable and mooring connection on the OOI inshore buoy

The BEO WEC uses mooring line tension to produce power. OOI's steel rotating joint that attached the mooring line to the buoy will be replaced. The BEO WEC will attach the mooring line to a small belt that is wound around the PTO spool. Attaching the mooring line to a relatively small and fragile belt introduces serious risks. Pacific storms will induce occasional snap load tensions in the mooring line, which would almost certainly break the belt or PTO spool. A broken belt or PTO spool would sever the mooring from the buoy, and the inshore buoy would float unconstrained in the open ocean.

To address this risk, BEO designed a frame travel system for our WEC. The mooring line is mounted inside a frame, with the PTO-belt directly attached to the top of the mooring line. Within the frame, the mooring line can smoothly slide up and down along stainless-steel rails. This movement allows the belt to spool in and out of the PTO. The frame stands at 1.75 m in height, providing nearly 6 ft of travel capability. This specific travel distance was selected for two primary reasons. Firstly, at 1.75 m, the system can effectively follow the majority of waves from peak to trough without encountering travel limitations, as the average annual significant wave height stands at 1.87 m. Additionally, the 1.75 m distance mitigates the risk of collision with the NSIF, which lies submerged 5 m below the buoy. The high stiffness of the cable hose connecting the NSIF to the mooring keeps the NSIF directly below the buoy which aids power conversion.

Snap loads still pose a risk to this design, as a large wave could aggressively slam the mooring line into both ends of the frame. To mitigate this risk, BEO installed soft stops on the top and bottom of the WEC frame. Each soft stop consists of several springs supporting a thick rubber pad. When the mooring line hits the top or bottom of its travel, momentum is absorbed by the pad and springs. The elastic mooring line also contributes to limiting snap loading. When waves are extreme, the mooring line will collide with the bottom soft stop, and the resulting tension will pull the buoy under the ocean's surface, as intended in the original OOI design.

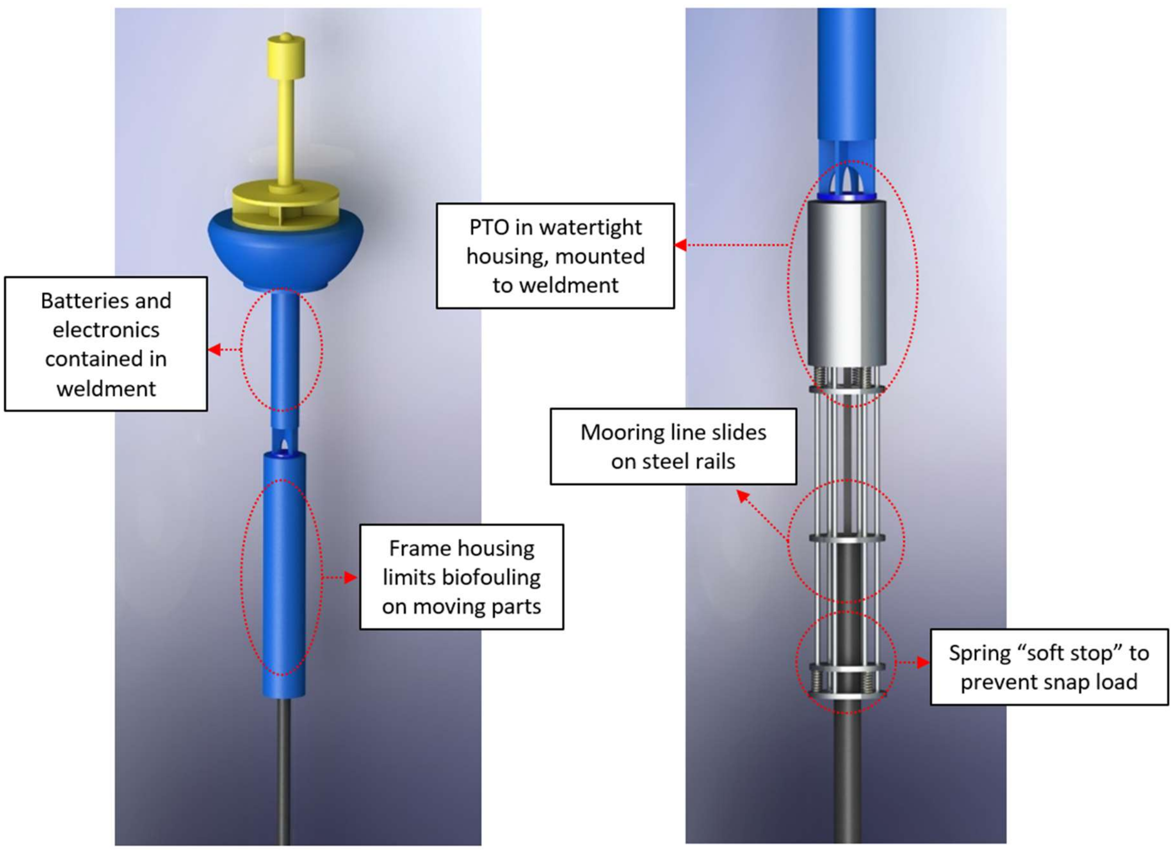


Figure 2.6*2*. BEO WEC System installed on OOI Inshore Buoy

The power take-off system will be completely submerged during the entire buoy deployment. This means that adequate waterproofing and antifouling are paramount to reliable operation. There are two holes in the PTO compartment that need to be sealed. The first is at the bottom where the belt attaches to the spool. This hole will be sealed with a flexible waterproof membrane made of vulcanized natural rubber and stockinette fabric, similar to a drysuit (figure 2.7). The second hole is at the top of the PTO compartment where the power cord passes through. This hole will be sealed with an O-ring system and oil barrier. Over the course of each deployment, the seals will degrade due to saltwater corrosion and friction from the sliding belt. The constant motion of the belt will deter biofouling organisms (Fram, 2024). When the device is brought to shore for maintenance both seals will be completely replaced. BEO identified water seals based on the assumption of replacement.

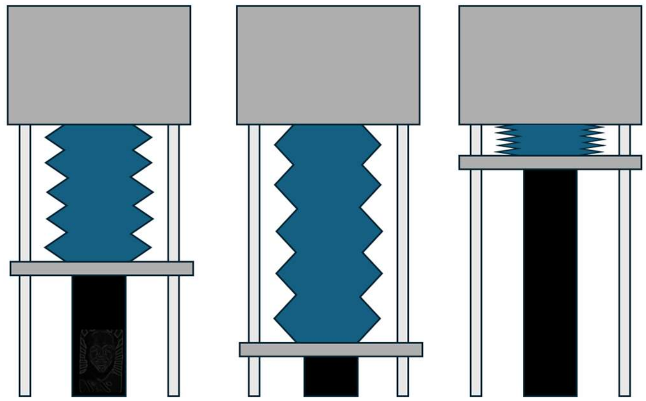


Figure 2.7. Waterproofing system for the PTO belt

2.2.3 Power Take-off

The proposed PTO produces an alternating current. Since there is no ratcheting mechanism, this design opts to rectify the produced power electronically rather than mechanically. This alternating mechanical power is transferred to the generator in the following way (see *Figure 2.8* for an annotated diagram):

1. The mooring line is attached to a belt wound on a spool.
2. The spool is attached to a rotary shaft.
3. This shaft connects to a secondary shaft through a chain drive.
4. The second shaft contains a spool attached by a belt to a compression spring.
5. The second shaft also connects to a generator shaft through a chain drive.

As the buoy moves up, increased tension in the mooring line causes the spool to unwind. This spins the primary shaft, which in turn spins the secondary shaft. The belt attached to the secondary shaft causes the spring to compress. The chain drive attached to the secondary shaft causes the generator shaft to spin.

As the buoy moves down, the spring decompresses. This causes the spool to rewind, resetting the system for the next upstroke. The entire PTO concept is visualized below in *Figure 2.8*.

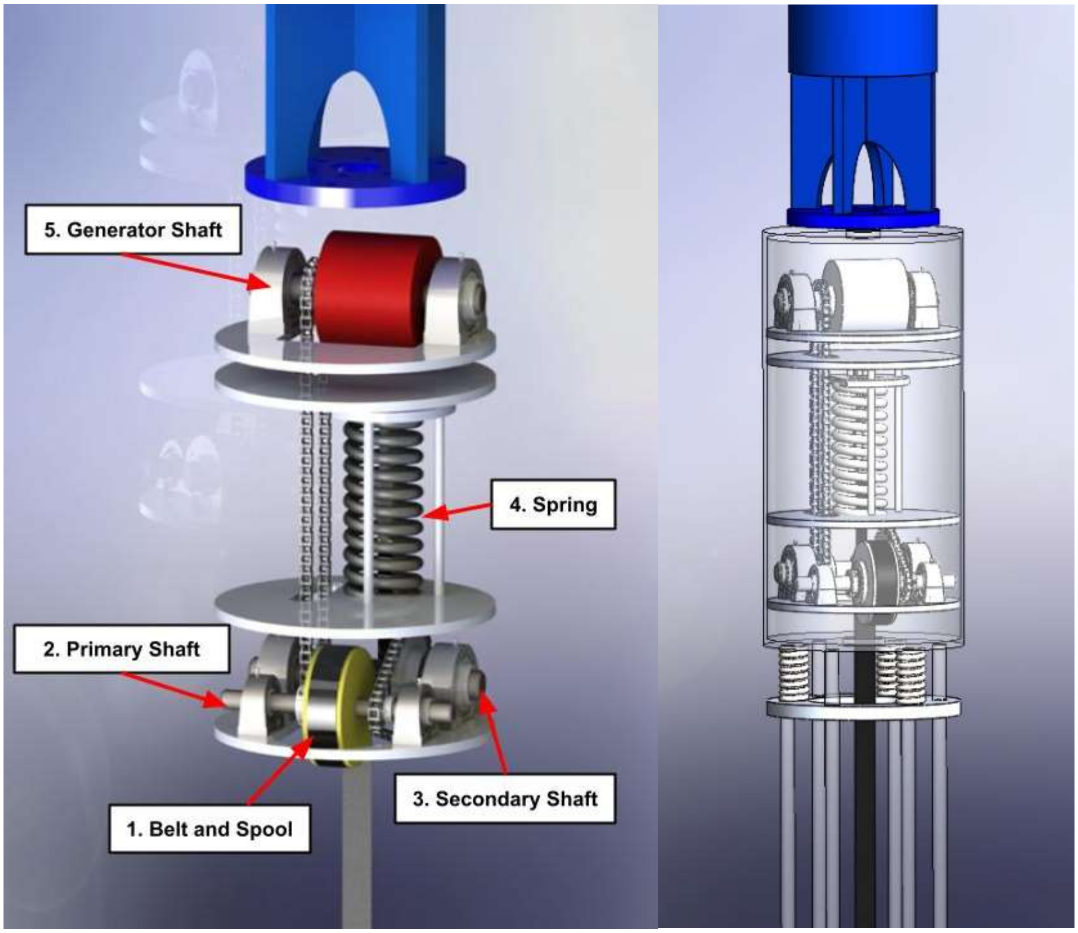


Figure 2.8. Diagram of PTO components (left) and assembly (right)

2.2.4 Electrical System

Computer simulations estimated a conservative average mechanical input power of 35 W (§2.4.3). The prototype generator must be able to sustain a 35 W input and fit inside of the PTO frame. A 100 W capable generator fits both requirements. Waterproof 100 W generators are used in wind energy, such as the NE-100 W. To meet electrical load requirements, BEO designed a hybrid solution that pairs the wave energy converter with a rechargeable battery pack. The system can make up the difference between required power and WEC produced power. In this design, the batteries are fully charged at the beginning of the deployment. During the 210-day deployment, the WEC supplements power, reducing the size and cost of the battery. Battery sizing for three different load cases is provided. Costs are based on the Department of Energy's estimated Electric Vehicle Battery pack cost of $153 per kWh (DOE, 2023).

Table 2.2. Power Requirements and Battery Comparison

Net Power Target	50W	75W	100W
Average Power Supplied by Battery (50W pull – 35W WEC input)	15W	40W	65W
Energy Required for 210 day deployment	75.6kWh	201.6kWh	327.6kWh
Pack Level Battery Cost Estimate	$10,710	$28,764	$46,818

Power delivery, load management, and safety must also be considered in the electrical system. Power delivery to the sensing equipment is already built into the OOI inshore buoy in the form of a 48V electrical bus that connects all the onboard sensing and communication equipment. Load management is included in the inshore buoy's control system. BEO's system must supply a steady 48 volts on the main power bus in all possible power production conditions. To do this, a transformer, converter, over current protection, battery management system, and onboard battery charger are specified.

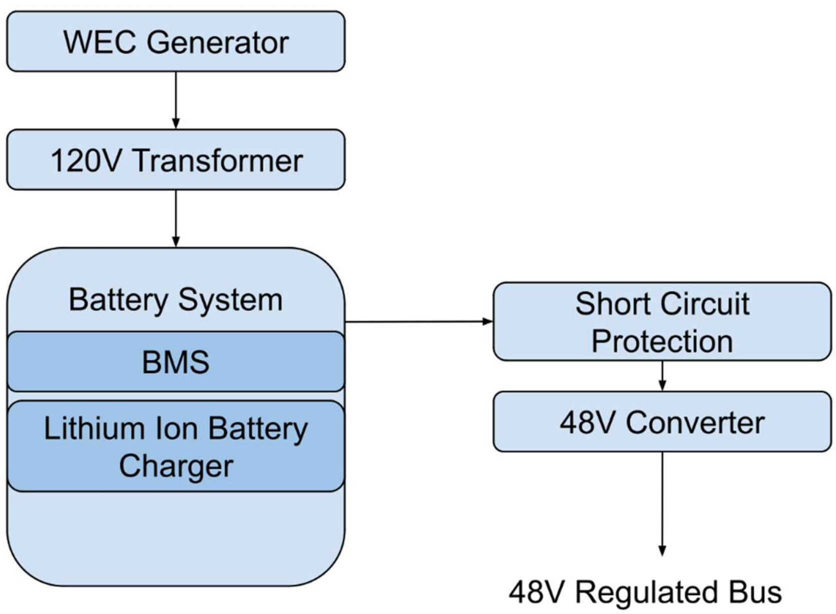


Figure 2.9. Electrical System Diagram

The AC voltage from the generator is increased to 120V to minimize power losses and create a supply voltage that works with common off the shelf electrical components. This voltage travels to the battery system. The battery system has an onboard converter responsible for charging the battery, maintaining the pack's health, and controlling the rate of charging. Power is pulled through a high side fuse and 48V step down converter to supply the main electrical bus.

2.2.5 Total Wave Energy System Weight

Table 2.3. Weight of WEC components

Component	BEO Weight
PTO Mechanical System	200 lbs.
Generator	6.5 lbs.
Rechargeable Batteries	240 lbs.
WEC Frame and Housing	150 lbs.
Total	**600 lbs.**

2.2.6 Survivability and Safety

In the case that the WEC system breaks or experiences storm conditions, there will be an integrated survivability system. If the spool that generates power snaps the buoy will continue to operate and take ocean measurements. In this case, the instruments can continue to use the electricity that was generated and stored in the rechargeable batteries. Once the stored electricity runs out, then the instruments will stop taking measurements and the system will operate a nonelectrical ocean buoy. While this is not the most power efficient method, allowing the instruments to use the stored energy allows for a safe way in case the power generation breaks. The system is designed to ensure safety of the buoy and if the WEC package breaks, the OOI buoy will operate as it currently does when their battery pack runs out. With this safety condition, OOI will not be disadvantaged because it is similar to their current situation with drained batteries.

In the case of survivability, the BEO WEC will be integrated with a system that will be triggered when wave conditions are too intense for the buoy to generate electricity safely. Our team decided that a significant wave height above 4 m waves, which is level 6 on the Beaufort Wind Scale, would be considered as intense storm conditions (NDBC, Station 46050). Once the buoy experiences these conditions, the survivability system will be triggered so that the buoy would become entirely subsurface. This submerged depth will be decided by the water depth, 25 m, and the height of the entire full-scale model, 3.88 m. To ensure a safe submergence, underwater floats would inflate on the mooring line which would cause the buoyancy point to change. The change in buoyancy would cause the whole buoy system to be submerged underwater, which is a safer condition since it is not as intense as above surface. Submergence would not only protect the WEC system but also the integrity of the instruments, which are already designed by OOI to be safe in subsurface conditions.

2.3 WEC-Sim

2.3.1 Objective

Computer simulation of marine energy devices serves three primary objectives: modeling a system's physical behavior, optimizing parameters, and predicting performance. BEO will use WEC-Sim, an open-source marine energy simulation software developed by the National Labs, to simulate the OOI inshore buoy with an attached point-absorber PTO.

We set four objectives for our WEC-sim experiments.

1. Understand how the system behaves in a variety of ocean conditions. How do the NSIF and elastic stretch hose affect the device's motion, and the PTO's power production?
2. Provide accurate estimations for mooring line tension and buoy displacement that can be applied to a PTO design.
3. Optimize the PTO damping value using a power production comparison.
4. Evaluate the WEC system's power production.

2.3.2 WEC-Sim Approximations

Before adding a PTO, the OOI Inshore Surface Mooring is simulated in its current state. Several important components of the Inshore Surface Mooring affect hydrodynamic behavior and need to be modeled. These components include the distributed instrument packages, the NSIF, and the 15 m elastic mooring cable.

Buoy Weight Distribution

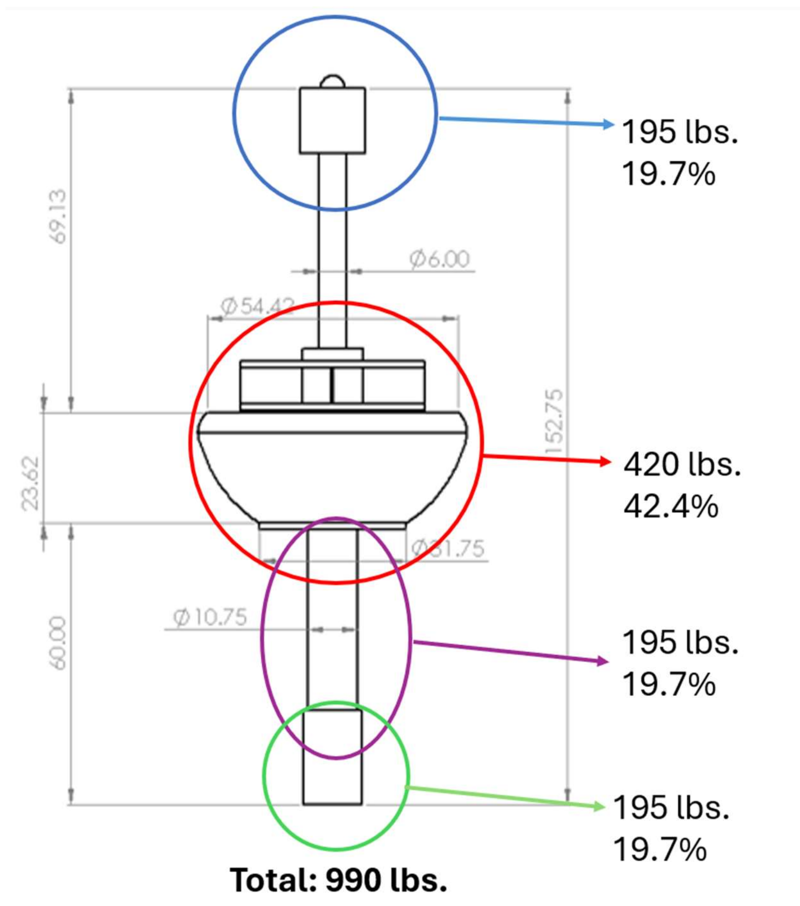


Figure 2.10. Weight distribution of OOI buoy

The total weight and moments of inertia of the buoy must be accurately represented in the WEC-Sim model. The WEC is divided into the following sections: top sensors and electronics package are shown in blue, the weldment foam and central electronics are shown in red, the batteries and bottom sensors are shown in purple, and the ballast/ universal mooring joint are shown in green.

Near Surface Instrument Frame

The NSIF is negatively buoyant and has a mass of 200 kg. While the NSIF's negative buoyancy will have some effect, the NSIF is modelled in WEC-Sim as neutrally buoyant for simplicity. Thus, the modeled NSIF acts as a neutrally buoyant hydrodynamic body. These simplifications attempt to represent a system that more closely resembles a single body point absorber. In a full-scale deployment this could be achieved by attaching a foam block to the NSIF.

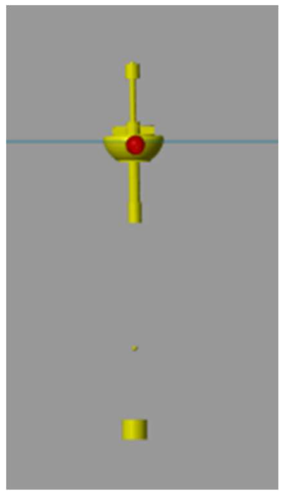


Figure 2.11. WEC-Sim motion body explorer of OOI Buoy and NSIF system

Elastic Mooring

This stretch hose is designed to avoid snap loading in the mooring line, prevent tipping in heavy waves, and allow the inshore buoy to submerge in extreme sea states. The non-linear curve is designed to help the observation buoy survive storm conditions.

It is critical to correctly model the elasticity of the inshore mooring line. The WEC's power production relies on mooring tension, and a stretching mooring line will absorb energy that could otherwise contribute to power production. To model the line, we first contacted David Aubrey, CEO of "EOM Offshore" the company that manufactures the OOI mooring lines. Aubrey explained that the hose is designed with non-linear tension-elongation curve, pictured below.

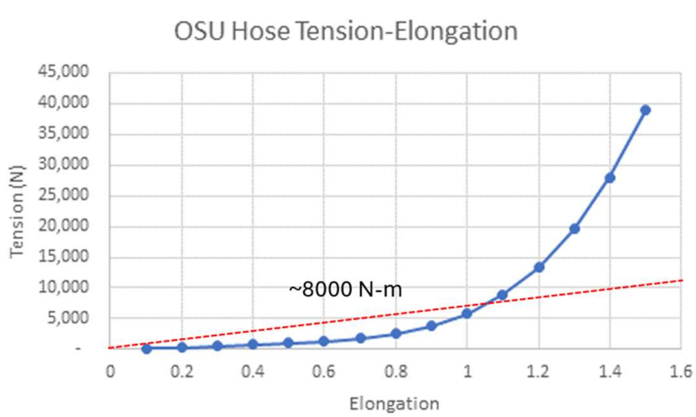


Figure 2.12: Non-Linear EM Stretch Hose Tension-Elongation Curve (WEC-Sim, n.d.)

To simplify the model a constant 8000 N/m stiffness is used. In future work, the team will attempt to use data points on the Tension-Elongation curve to accurately represent changes in stiffness for varying elongations. If changes to OOI's mooring is possible, BEO plans to test a stiffer mooring in attempt to generate more power than when using the current EM stretch hose.

2.3.3 RAO Results

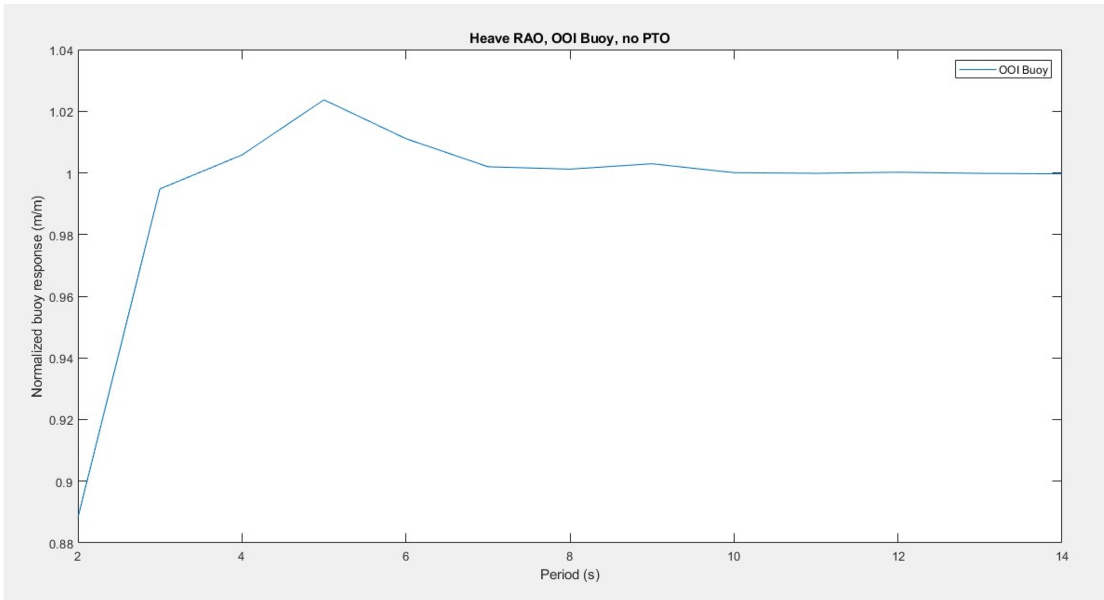


Figure 2.13. RAO plot of OOI buoy without PTO

The first stage of WEC modeling is to characterize hydrodynamic behavior. Response Amplitude Operator (RAO) plots are used in marine engineering to visualize and understand wave body interactions. These tests are done at constant wave height and a range of frequencies. Certain frequencies will cause the buoy to move with greater amplitude than the wave height. In WEC design, buoy geometry is optimized to maximize response amplitude at the most common frequency observed at the deployment location. In the build and test report, the team will attempt to validate the model by comparing the WEC-Sim produced RAO and the scaled test RAO.

2.3.4 Damping Comparison

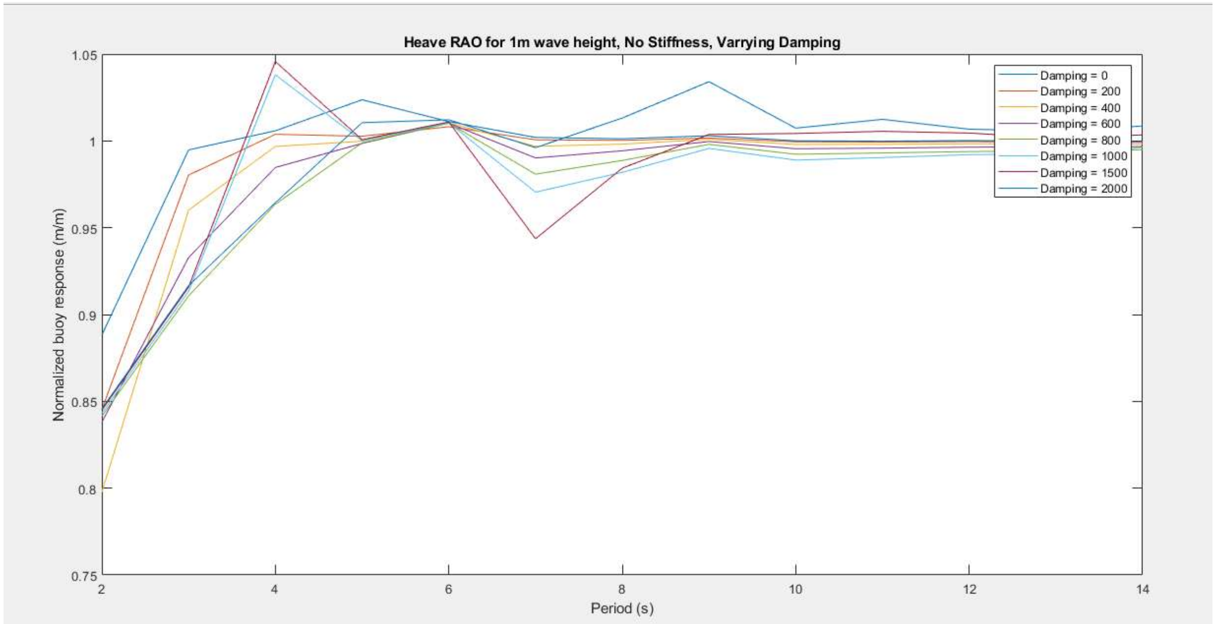


Figure 2.14. Damping Effects on buoy Response

The BEO WEC mainly captures power from heave motion. A range of PTO damping values are simulated to compare the effect of damping values on buoy heave response (*Figure 2.14*). PTO damping appears to have little impact on heave response. However, the peak response at 0.2 Hz, or a 5 second period (*Figure 2.14*) does not align with the long wave periods typical along the Oregon Coast (the average annual wave period is 11 seconds). In future modeling and design cycles, BEO will attempt to optimize buoy geometry so that the peak heave response occurs during higher wave periods.

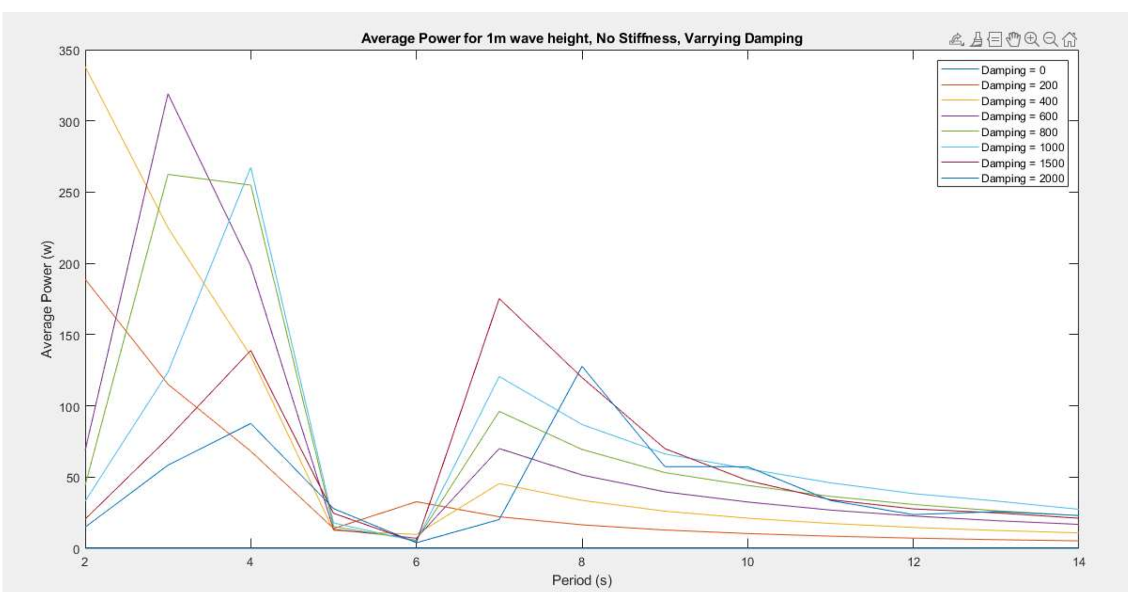


Figure 2.15: Damping Effects on Power Production regular waves

Next, BEO investigated the PTO power output for a range of wave periods and damping values. Average power output (*Figure 2.15*) is at a maximum at a smaller period than the RAO peak (*Figure 2.13*). This means that the WEC motion is not optimized for the wave conditions seen at deployment. However, 50 watts of power are produced in the 8 to 12 second period range, which gives our WEC design feasibility. The model shows instability at a 6 second period (*Figure 2.14*). When viewed in the "Simulation Mechanics Explorer," (a WEC-Sim software attachment that produces a visual of the device moving), at 6 seconds the buoy oscillates in a tipping motion instead of heaving. We expect that this behavior could be a minor resonance frequency induced by the mooring and PTO springs to draw. BEO will investigate this odd hydrodynamic behavior further in future reports.

2.3.5 Power Production

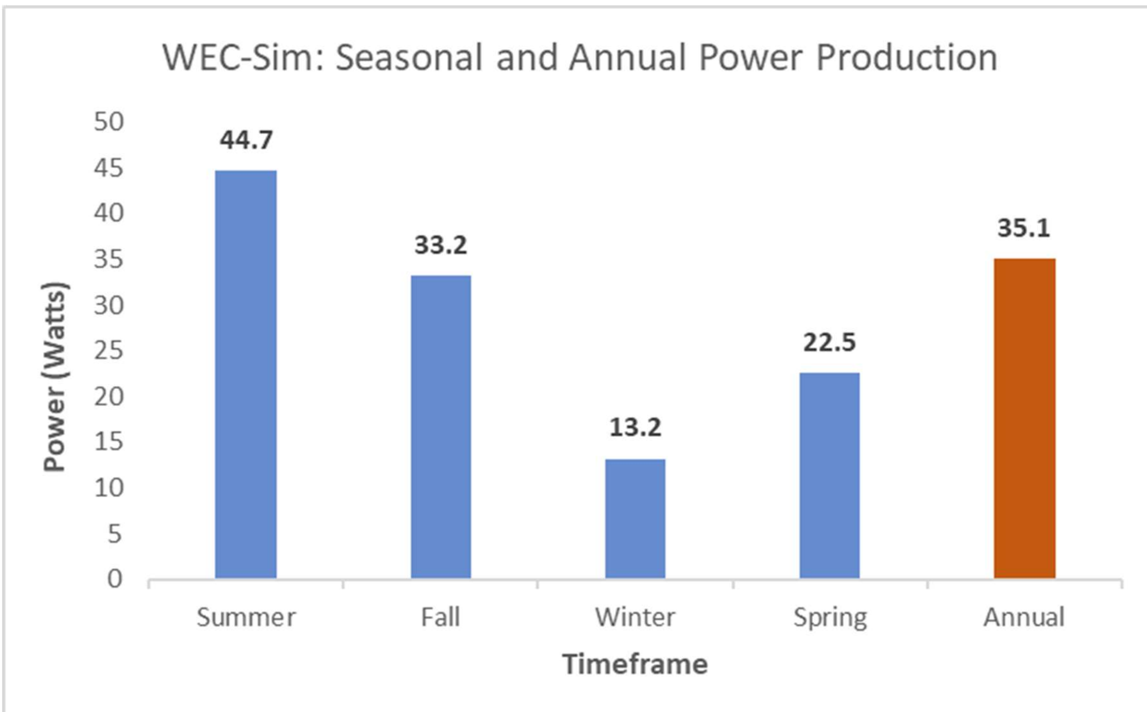


Figure 2.16: Assessment of seasonal power production

Finally, the team ran 4, 20-minute simulations for seasonal wave spectra. The power is averaged in postprocessing and shown above (*Figure 2.16*). When finding wave spectra, buoys group data in 20 minute intervals. Thus, simulations of 20 minutes accurately represent sea states and are adequate for finding average power production. A surprising result is higher power production in summer than in winter. This could be from errors in the model, and PTO optimization for smaller wave conditions seen in summer. The team should further investigate these results.

3. Build and Test

While computer simulation provides estimations of the buoy's physical behavior and power production, the next step in developing a system is to build and test a replica model of the proposed WEC Concept.

BEO constructed a PTO for viability testing in the O.H. Hinsdale Wave Basin. A 1/4 scaling factor was used to scale the buoy and waves. Two foam hull shapes were tested to assess how altering the hull geometry could impact device performance. A variety of irregular and regular wave experiments produced RAO and power data. This data was compared to computer simulation plots and actual Pacific Ocean wave conditions. BEO used these results to evaluate performance and identify design changes to be implemented in future testing cycles.

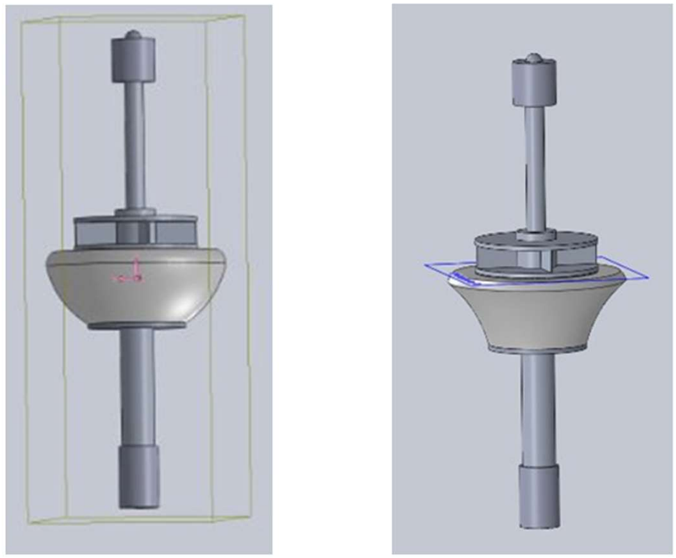
3.1 Scaling for Test

Early in the development process, BEO set out to determine an appropriate factor by which to scale the entire system down to accurately represent the OOI buoy and conditions within the wave lab basin. The team first attempted to determine a scaling factor based on depth. Using the CE01ISSM mooring depth of 25 m and the wave basin depth of 1.36 m, the resulting scaling factor is 0.054. A model of this scale would have a maximum outer diameter of 3 in making it unrealistic to develop a PTO system for a buoy of this size. Relying heavily on input and guidance from our faculty advisors, the team took a different approach to scaling the WEC System. After determining the smallest practical footprint for out PTO design (number), a scaling factor of ¼ was chosen because the resulting model Buoy is large enough to house the PTO system.

With a scaling factor determined, BEO continued with the build process and generated a test plan that detailed the types and sizes of waves we intended to run in the Wave lab. Upon discussing the plan with HWRL directors Dr. Tim Maddox and Dr. Pedro Lomonaco, we became aware of an oversight in our scaling approach. The waves we had proposed, having been scaled using a Froude scaling factor of ¼, were only accurate for a depth of 6.25 m. Because the depth of the basin is 1.36 m, additional scaling, or distortion, was performed on the wave data to accurately represent the velocity profile of the waves at a depth of 1.36 m. Using the shallow water wave approximation for wave velocity, we related the orbital velocities at the scaled depth (6.25 m) and the test depth (1.36 m) to determine the distortion factor required to adjust the periods of the waves during testing.

3.2 Build

3.2.1 Buoy Design and Fabrication



OOI Buoy (A): The currently operating OOI hull design

Experimental Buoy (B): The currently operating OOI hull design

Figure 3.1 3D rendering of the basic geometry of experimental (B) and OOI buoys (A).

BEO tested two different float shapes in the wave basin. The wave basin was reserved for five days, providing the team with ample time to perform additional tests. We decided to experiment with an alternative foam full geometry. The "OOI buoy," (Figure 3.1.A) is the current, deployed, and operating OOI float design. It is convex and solid. The "Experimental Buoy," (Figure 3.1.B) is an alternative float designed by BEO. It is concave, and includes four through holes to decrease buoyancy. Testing an different geometry will inform BEO if altercations to the foam buoy could potentially increase power production.

Each float was cast with marine foam. The foam exterior was spray painted yellow and coated with fiberglass resin. A replica weldment was created by securing PVC pipe in the center of each of the foam floats. Bolts at the bottom of the weldment allow mounting of weights to represent the weight of an attached wave energy system. The PTO and additional lead weights secured to the hull top surface using threaded rods inserted into the hull and secured with resin.

Figure 3.2 Mold Casting the Hull Shapes

3.3.2 Power Take Off System

The model PTO was constructed with t-slot aluminum bars. The spring cage accommodates a variety of spring sizes, so spring stiffness can easily be adjusted during testing. The generator and encoder were mounted with sheet metal, and a spool was 3D printed.

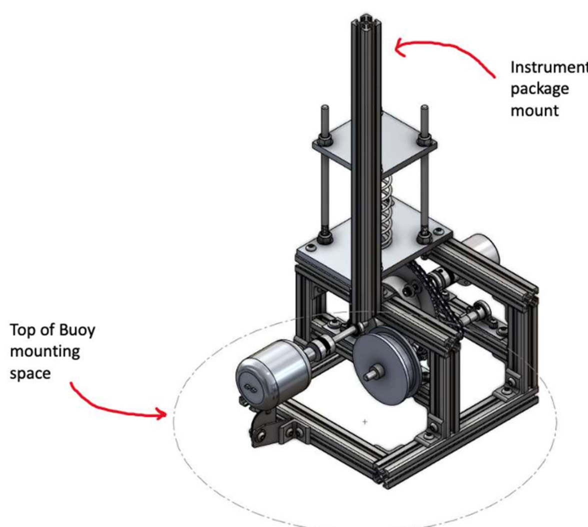


Figure 3.3 3D rendering of proposed power generation concept.

One major discrepancy between the model WEC and the full scale WEC system is how it is mounted to the OOI Buoy. While BEO's full scale WEC system mounts to the bottom of the mooring weldment, mounting the model PTO this way was not feasible due to depth constraints of the wave basin and the complexities it would introduce to the build, waterproofing, and setup, and processes. Dr. Bryson explained that the PTO system isn't subject to the same scaling restraints as the rest of the WEC. If the environment, the model device was built larger and mounted to the top of the buoy (Bryson).

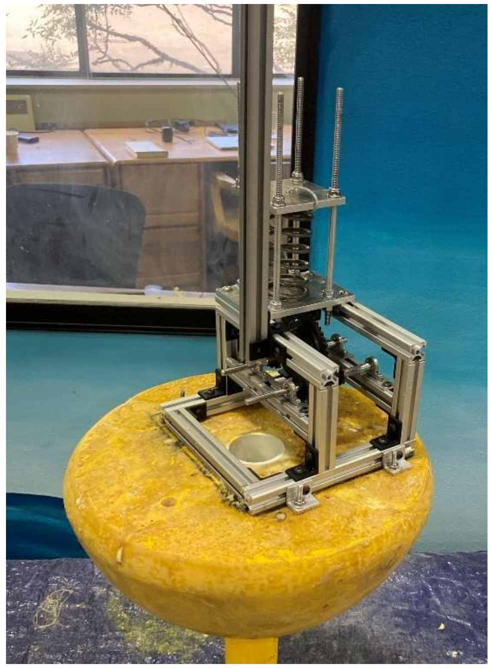


Figure 3.4 PTO frame assembled and mounted.

3.2.3 Mechanical Loading and Failure Analysis

BEO conducted a basic stress analysis of the test-scale PTO. The primary forces the PTO experiences are tension on the spool, and mass reactionary normal forces. Figure 3.5 shows a free body diagram of the model PTO, and table 3.1 lists the calculated force values.

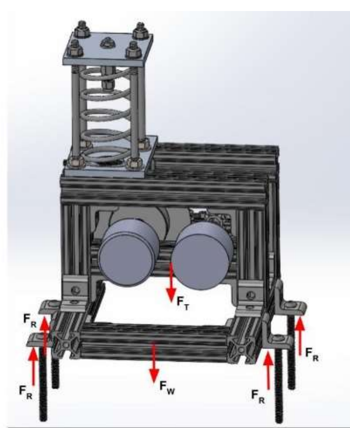


Figure 3.5 External PTO forces. FT represents the tension force on the spool, FW represents the PTO weight, and FR represents the normal force.

Table 3.1 Maximum external forces acting on the PTO in an upright position.

Force	Value (N)
Tension on spool (F_T)	111.21
Weight (F_W)	23.58
Normal (F_R)	134.78

The main potential failure point is the spool shaft. A standard stress analysis with an idealized shaft model was used to estimate static and fatigue factor of safety for the shaft. The results clearly demonstrate that the shaft can handle all operational stresses and is safe for testing.

Table 3.2. Stress and fatigue analysis results for the lower torque shaft.

Value	Result
Static factor of safety	2.1
Fatigue factor of safety	2.5
Cycles to fatigue failure	38×10^9

Similar calculations were performed for the other PTO components. All factors of safety were above 2.

The PTO performed exceptionally during testing. As predicted by the stress analysis, all the components withstood both standard and storm conditions. Based on these results, BEO felt justified using the same factor of safety when selecting full-scale PTO components.

3.2.4 Electrical System

Efficiently operating and converting WEC power is complex. Water poses a risk of short circuits, and the relatively low RPM of the generator results in low input voltages. This can lead to higher internal power losses. A carefully designed electrical system is crucial to obtain real-time encoder data and electrical generation.

Generator

For the model PTO system, we chose to use an off-the-shelf, AC bike dynamo light generator. This dynamo is designed for the comparatively low RPM of a bike tire and has internal magnetic flux characteristics tuned for power generation. The dynamo also boasts water-resistance, a corrosion resistant aluminum construction, and a small footprint, making it well-suited for our test environment.

Encoder

A “Taiss/AB 2 phase Incremental Rotary Encoder” with 360 pulses per revolution (P/R) was directly mounted to the generating shaft to measure shaft velocity on board the test WEC. This encoder operates across a wide DC voltage range from 5 to 24 V and provides a good balance of cost and precision. The maximum mechanical speed of the encoder is 6300 R/min.

Controller

The controller serves as a crucial interface between converter sensors, an encoder, and an acquisition device for data storage. It addresses challenges such as differing logic levels among components by employing bidirectional logic level shifters. Additionally, the controller was customized to meet low-power requirements, utilizing a stripped-down version of an STM32 family controller, the STM32F103C8, featuring a 32-bit Cortex-M3 CPU core with a 72 MHz frequency, ensuring adequate processing capability without necessitating advanced design techniques.

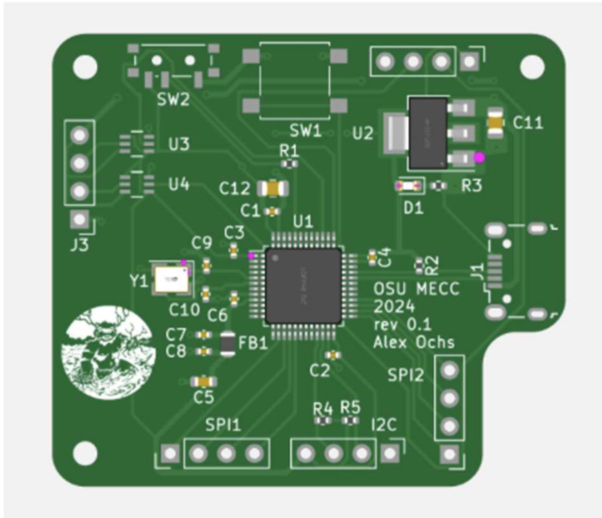


Figure 3.6 Manufacturers rendering of the converter board, with switches and logic level shifters depopulated. These were added manually before installation.

Converter

The converter transforms alternating current (AC) from the generator into direct current (DC) to power the controller and other components. It features through-hole components, including a current shunt IC (HCPL-7520-000E) with a 10 mΩ shunt and an AC voltmeter with minimized gain handle peak voltage spikes of up to 40 V.

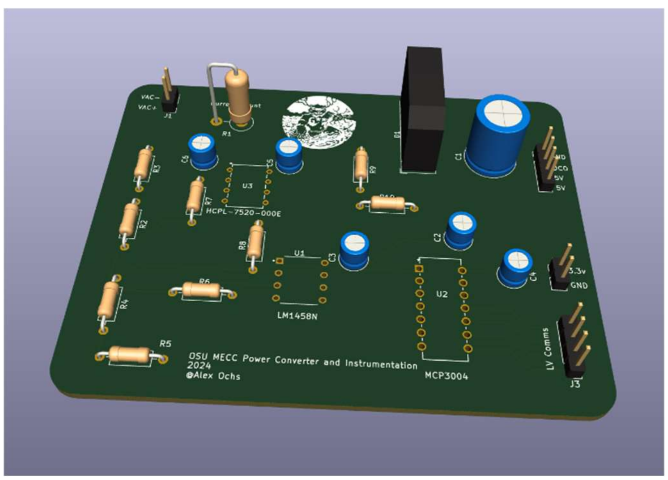


Figure 3.7 Converter board rendering with current amplifier, differential amplifier, and ADC depopulated. These were added manually before installation.

The analog-to-digital converter (ADC) operates with a 3.3 V reference voltage and 10-bit precision in single-ended mode. The converter employs a full-bridge rectifier and a 1000 uF capacitor to maintain power supply during wave-generating periods.

Waterproofing

Heat shrink tubing and dielectric silicone grease were used on all exposed wire connections to provide insulation and protection against water ingress. Dielectric grease was applied to all screws and shaft inlets, and the components were further sealed by wrapping them in polyethylene sheeting. To further protect the electronic components, an organic polymer spray coating was deposited on all circuit boards and exposed wires. This coating acts as a barrier against moisture and helps prevent corrosion.

One of the main challenges encountered was the encoder not being inherently waterproof or water-resistant. While the motor and encoder are nominally positioned above the waterline, they could become submerged during the mooring process or in the event of an overtopping wave. The application of dielectric grease aimed to mitigate this risk. The generator, while "water resistant" is a single pole output generator, meaning that the frame is used as one of its terminal outputs. This required careful consideration during the waterproofing process to ensure proper insulation and prevent short circuits.

3.3 Test

3.3.1 Test Setup

To anchor the buoy in the wave basin, 45 kg fishing line wound around the PTO spool is threaded through a hole in the foam buoy, and out through the bottom of the PVC weldment. A carabiner attached to the end of the line connects to the mooring spring. When moored, the entire line is under tension, and the PTO spring is pre-tensioned to around half of its total compression. This means that at the crest of waves the PTO spring approaches its maximum compression, and at wave troughs the PTO spring decompresses towards its neutral length.

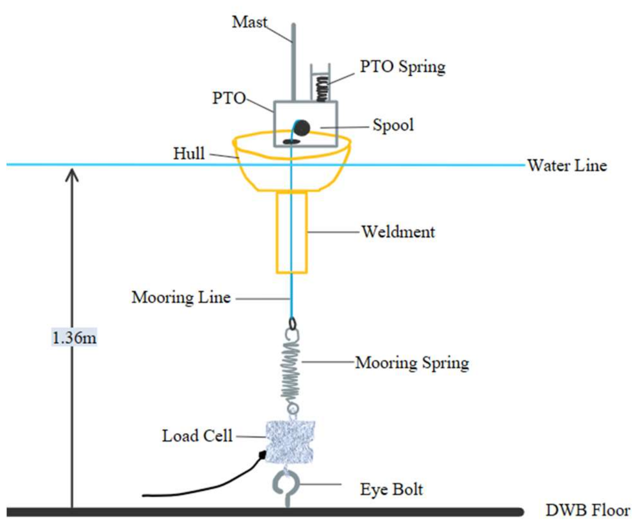


Figure 3.8 Diagram of WEC testing setup in DWB

To ensure that the wave lab results are as accurate as possible, lead weights mounted to the test-scale device mimic the weight distribution of OOI's full scale moorings. The team found that the marine foam float was surprisingly dense. The weight of the float, combined with the large PTO results in a weight distribution disproportionately concentrated near the float. Lead weights mounted high on the test-scale buoy represent the sensor weight at the top of the OOI weldment. Weights mounted to the base of our model represent the OOI batteries, sensors, and ballast. While our weight distribution is not perfectly accurate, we still were able to model the high center of gravity of the OOI system, and the weight distributed along the entire length of the weldment.

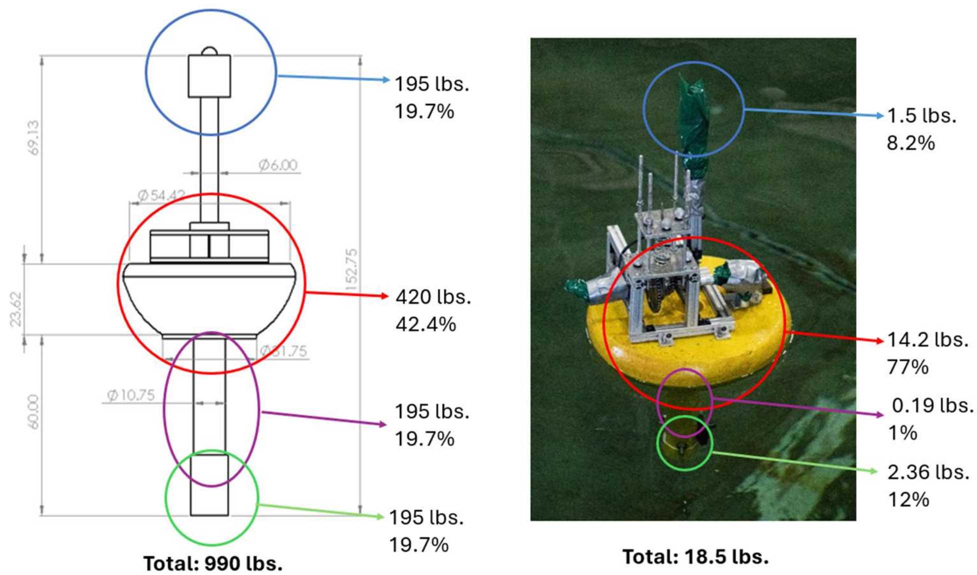


Figure 3.9 Comparison of technical drawing and testing model

3.3.2 Instruments

A “Qualisys” motion capture system was used to record the motion of the buoy in the DWB. Small, above-water Qualisys markers were strategically placed in different locations on the WEC using double-sided adhesive. This configuration of markers fully defines the body of the WEC based on the predefined wave basin origin. After being calibrated, the Qualisys cameras recorded the three-dimensional motion of each marker as we tested the device in different wave conditions.

Figure 3.10 Qualisys marker locations.

The load cell connected between the eye bolt and the mooring spring measures the force on the mooring line. This load cell was placed and calibrated by the wave lab technicians and is connected to the HWRL data acquisition system (DAQ) to ensure that it is in sync with the rest of the sensors. Wave gauges were positioned around the WEC deployment area to measure and record the observed water levels during testing. An onboard optical rotary encoder was used to track the generator's shaft speed, which could be used to verify mechanical displacement and account for any abnormalities in displacement resulting from the mooring spring and not the PTO.

3.3.3 Methods

The WEC was first subjected to regular waves with a constant wave height and varying periods, for five minutes each. Data collected from these tests was used to generate RAO plots to compare to the RAO plots from WEC-Sim and to characterize the periods at which peak power generation occurs. Afterwards, the wavemaker generated an irregular white noise spectrum where waves of varying periods are superimposed upon one another and run simultaneously. The data from that test, after being processed using a Fast Fourier Transform (FFT), will confirm the peak frequency of the WEC.

To approximate the actual sea states experienced by the CE01ISSM Buoy, WPTO Hindcast model data for the buoy's longitude and latitude (44.639 N 124.304 W) was used to define the irregular wave spectra in the wave lab (NDBC, Station 46097). Using MATLAB, mean, maximum, and modal significant wave height, and peak period data for each month from 2000 to 2010 were generated, then exported to Excel for scaling using Froude scaling and a scaling factor of $\lambda = 0.25$ for the prototype model. Wave periods were adjusted once more to account for the discrepancy between scaled depth, 6.25 m, and the wave basin depth of 1.36 m. Subsequently, all data was processed through a MATLAB script to ensure that desired waves could be generated in the DWB by the wavemaker without exceeding any displacement or acceleration limits of the system.

The HWRL irregular waves can be generated using the Pierson Moskowitz spectrum (PM) or the Joint North Sea Wave Observation Project Spectrum (JONSWAP). The PM spectrum was used for all irregular wave tests because it is simple, widely used, and assumes a fully developed sea state meaning the wind has been blowing steadily over a considerable distance and duration (*Ocean-Wave-Spectra*.

Considering that the WEC exclusively generates power in the heave direction, the influence of wave direction or angle on device power output is minimal. Therefore, directional, or angled waves were of lower priority during the wave lab testing period.

Table 3.3 Wave lab testing conditions for each trial.

Test No.	Type of test	Scaled Wave period(T)/Peak period (Tp) [s]	Wave Lab Depth Adjusted Wave period(T)/Peak period (Tp) [s]	Wave height (H) or SWH (Hs) [m]	Angle (deg)	Time (min)
1	Spring Adjustments	3, 4, 5, 6	1.40, 1.86, 2.33, 2.80	0.15	0	20 (5 ea.)
2	RAO regular waves with PTO	3, 4, 5, 6	1.40, 1.86, 2.33, 2.56, 2.80, 3.26	0.15	0	30 (5 ea.)
3	RAO white noise (irregular)	3, 4, 5, 6	1.40, 1.86, 2.33, 2.80	0.1	0	20
4	Irregular Spectra PM(Hmax when T=6)	6	2.8	0.15	0	20
5	Irregular Spectra PM (Hmax when T=5)	5	2.33	0.15	0	20
6	Irregular Spectra PM (Hmax when T=3)	3	1.4	0.15	0	20
7	Multi Direction Spectra (PM, Hmax when T=6)	6	1.4	0.15	15	20
8	Multi Direction Spectra (PM, Hmax when T=5)	5	2.33	0.15	15	20
9	Multi Direction Spectra (PM, Hmax when T=3)	3	2.8	0.15	15	20
10	RAO Regular Waves Around Peak Response	5.8, 6.2, 6.4, 7.3	2.7, 2.9, 3.0, 3.4	0.15	0	20 (5 ea.)
11	Irregular Spectra PM Idealized		Peak Period Chosen from RAO: 2.7	0.2	0	20
12	Buoy 2 RAO Regular Waves w/ PTO		1.40, 1.86, 2.33, 2.56, 2.80, 3.0, 3.26	0.15	0	(5 ea.)
13	Buoy 2 RAO White Noise w/ PTO		1.40, 1.86, 2.33, 2.80	0.15	0	20
17	Buoy 2 Extreme Sea States		3.5	0.34	0	20

Figure 3.11 BEO testing in the Hinsdale wave laboratory

3.4 Test Results and Data

3.4.1 Regular Waves

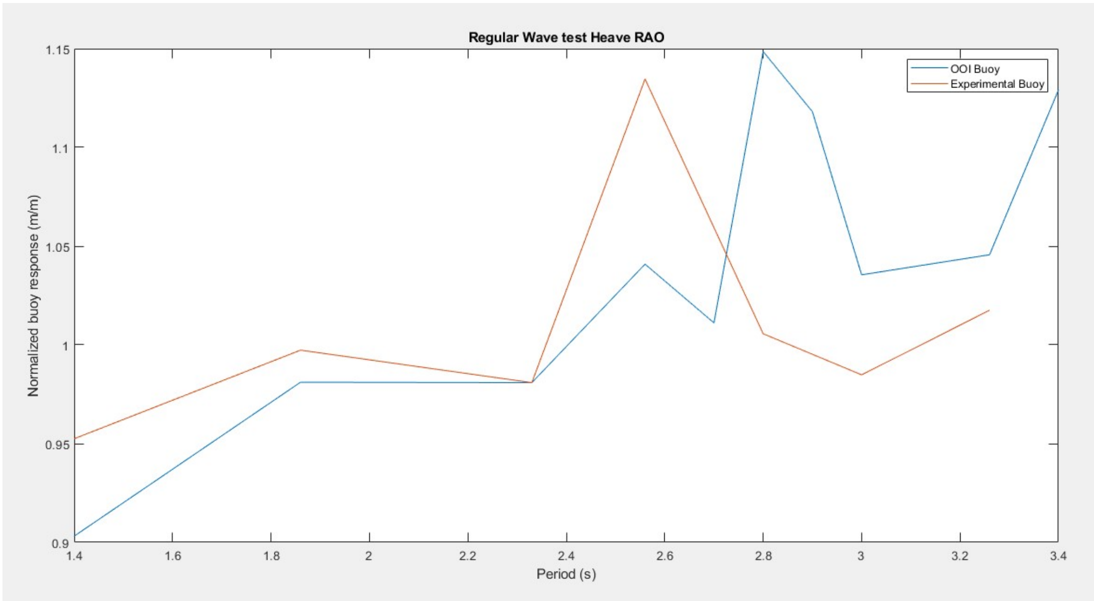


Figure 3.12 Experimental Heave RAO plot for regular waves

The team produced two response amplitude operator (RAO) plots as shown above. The scaled OOI buoy shows a peak response at a period higher period than the experimental buoy shape. The team will keep the current OOI float shape, as a peak response at higher periods will better match the operating wave conditions. Keeping OOI's float will avoid massive expenses.

3.4.2 White Noise Test

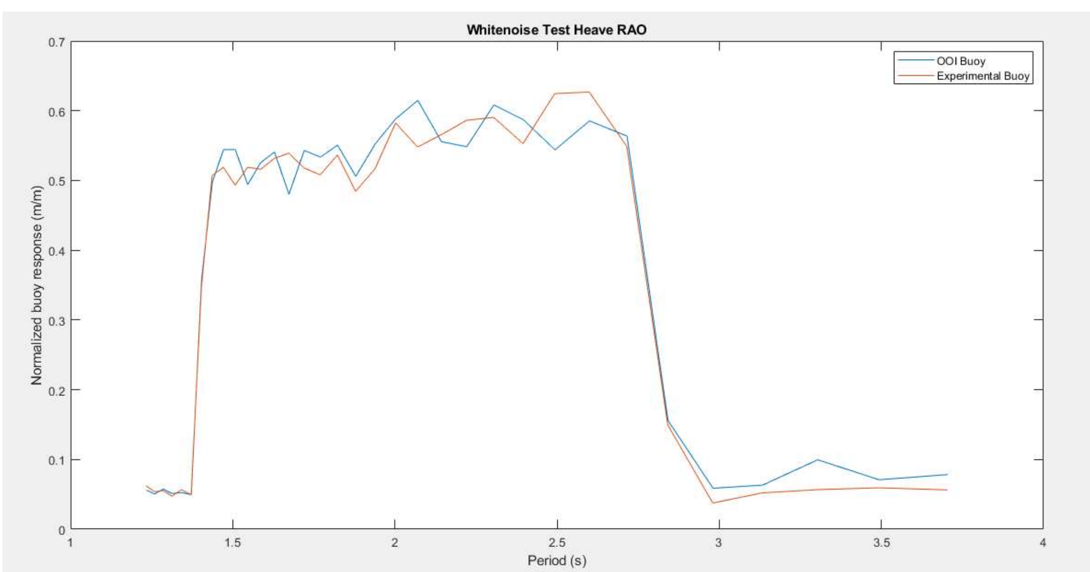


Figure 3.13. Experimental Heave RAO for white noise test

Next the team performed a white noise test. The white noise test consists of 0.10 m waves with randomly produced periods ranging between 1.4 and 2.8 seconds. This test was used to validate the RAO plots and more closely mimic a random range of wave conditions. The white noise test plots show a more realistic normalized response amplitude, as unpredictable real ocean conditions typically neutralize extra heave motion. The white noise plots do not clearly validate a similar large peak response as the regular wave RAO tests.

3.5 Conclusions

3.5.1 Conclusions from test data

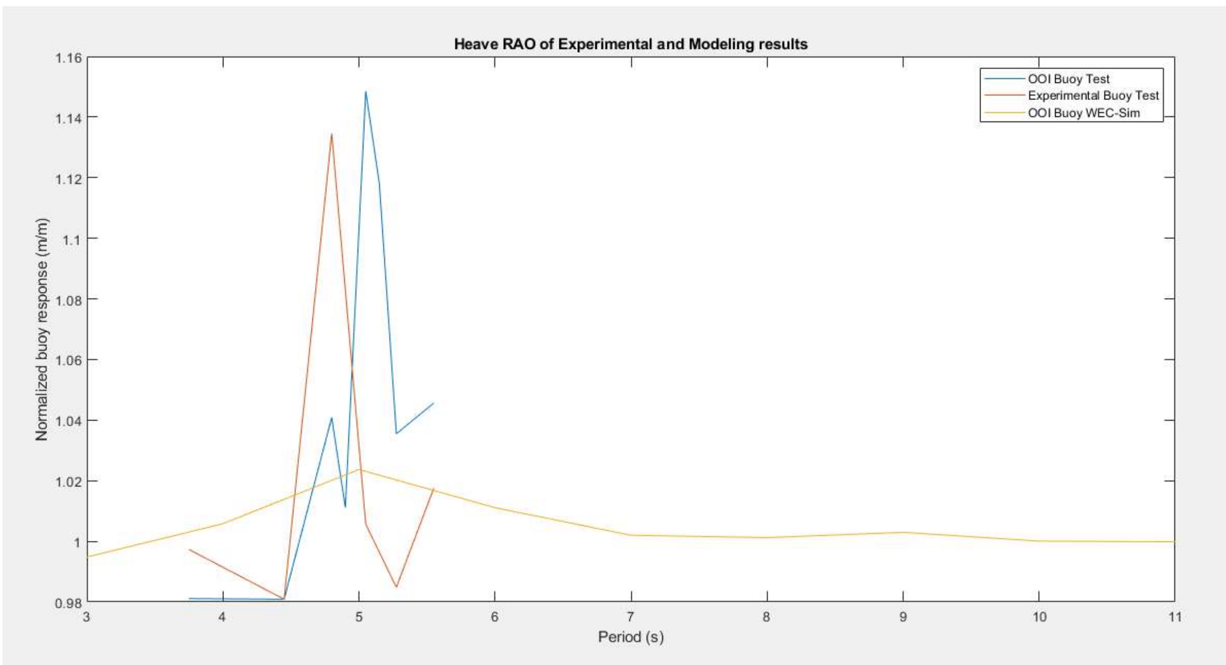


Figure 3.14. RAO Comparison of Modeling and Scaled Test Results

There were many challenges during testing related to scaling. This led to testing a narrower and smaller range of wave periods than expected. After testing and further conversations with HWRL staff the team concluded that using the wavelength to buoy diameter ratio is most relevant for scaling a mostly surface following WEC. While wave orbital shape and velocities need to be considered, they are most important when simulating submersible WEC's. The figure above shows the WEC-Sim RAO results overlayed on the testing RAO scaled up to full using wavelength to buoy diameter ratio. The test RAO and WEC-Sim RAO have similar peak responses at 5 second periods however white noise tests show this needs to be further investigated.

These tests have shown that BEO should not focus on designing a hull shape to optimize buoy response. Any optimization should be done through active PTO control systems. The next DWB testing should investigate a more accurate weight distribution and observe more motion characteristics like pitch, roll and surge. Going forward the team will implement the following tests:

- Benchtop PTO damping and stiffness testing to optimize power production.
- Investigate heave plate on the NSIF to test power production.
- Develop a safety system to account for device failure during storm conditions. Options include submerging the WEC and decoupling the PTO system.

BEO is looking forward to improving and developing our system into a functional and innovative solution in the marine energy sector.

3.5.2 Lessons Learned

Reflecting on our recent project, we've learned several crucial lessons that will shape our approach in future endeavors. Firstly, engaging with all stakeholders early and consistently, particularly our advisors, proved instrumental in fostering collaboration and idea-sharing. Additionally, we learned the hard way about the importance of meticulous waterproofing—quadruple-checking and waterproofing all components is non-negotiable to ensure system reliability. Another key takeaway was the necessity of planning for data processing before testing. This oversight resulted in unnecessary delays and complexity in interpreting results. Moving forward, a clear post-processing data plan will streamline our analysis and understanding.

Time management also surfaced as a significant factor. Allocating ample time for building the Power Take-Off (PTO) and electrical system with qualitative visual validation is essential for success. Moreover, earlier coordination with the test facility and obtaining necessary information in advance could have enabled us to improve data collection and analysis by connecting our onboard sensors to the wave lab (DAQ) system. These lessons underscore the importance of communication, attention to detail, proactive planning, and time management in our future projects.

3.6 Anti-Biofouling Technology

From client conversations and outreach to the greater blue energy sector, BEO has identified biofouling as a primary concern in the industry. BEO performed a series of experiments to address biofouling on the team’s WEC to improve the longevity of the WEC and to make biofouling technology more eco-friendly.

3.6.1 Background

Biofouling is defined as the unwanted settlement of aquatic organisms on any surface. Fouling is separated into two types: micro and macrofouling. Microfouling is unwanted algae or bacterial growth on a device. Macrofouling is the unwanted settlement of large community-building organisms like barnacles, seaweed, and soft corals. Both processes reduce the efficiency of a submerged design’s moving components, degrade key support structures, and reduce the accuracy of readings from submerged sensors. Biofouling is a key challenge for long-term WEC installations as it increases the repair time of a WEC, decreases the overall deployment time, and limits where the technology can be used. An advanced biofouling stage on an OOI mooring recovery is shown below.

Figure 3.15 Inshore buoy post-recovery.

Two types of antifouling coatings are used commercially to resist biofouling: ablative and hard. Ablative materials flake off when an organism attaches to prevent them from growing further. A hard coating repels or kills an organism before it can settle on the surface. Hard coatings have historically depended on copper-based paints to function. Copper is an effective toxicant as it disrupts the growth of algae and the early life stages of shelled organisms. Overuse of copper-based paint has led to the EPA banning its use in Washington and California, with select municipalities citing the effect of high copper concentrations paired with increasing ocean acidification creating steep declines in fishery health (Leal, 2018).

Oregon is at high risk of ocean acidification due to CO2-rich waters from seasonal upwelling along a major eastern boundary combined with increasing anthropogenic (human-caused) CO2 emissions. Newport and the nearby Heceta Shelf are key assets to many commercial fishing industries that bring in $588 million annually to Oregon's economy (ODFW, 2019). For these reasons, OOI has specified that no copper-based coatings can be used on the mooring and requires that any new coating/prevention method be relatively eco-friendly and affordable. OOI's current ablative method uses a mix of barium sulfate and zinc oxide to allow for a month-long deployment of its inshore buoy. OOI has specified that adding additional deployment time to the inshore buoy is dependent on the WEC's power generation and the device's ability to resist/eliminate biofouling. Therefore, OBE has investigated numerous antifouling base materials and undercoats in order to lengthen the buoy's deployment time.

3.6.2 Method Selection

To meet OOI's antifouling demands for their buoy, an in-depth literature review process was performed to select a base material and several undercoats for testing. OOI stated that the largest threat to mooring performance was the macrofouling of gooseneck barnacles (Pollicipes polymerus). OOI reports that up to 100 additional pounds of organic matter can attach to the mooring throughout a deployment, with *P. polymerus* making up the majority of the biomass. *P. polymerus* attaches by first secreting a "testing" chemical to gauge if a surface is habitable before an organic cement is used to attach to the surface. This testing process leaves areas of compromised antifouling agents called "cryptid footprints" that chemically signal other animals to attach, further weakening the coating (Liang, 2019). OOI only uses one ablative coat to combat this form of fouling. This method becomes ineffective due to the buildup of cryptic footprints and the physical detachment of the coating without any additional undercoat. Figure 3.16 depicts the progressive biofouling process on a submerged surface.

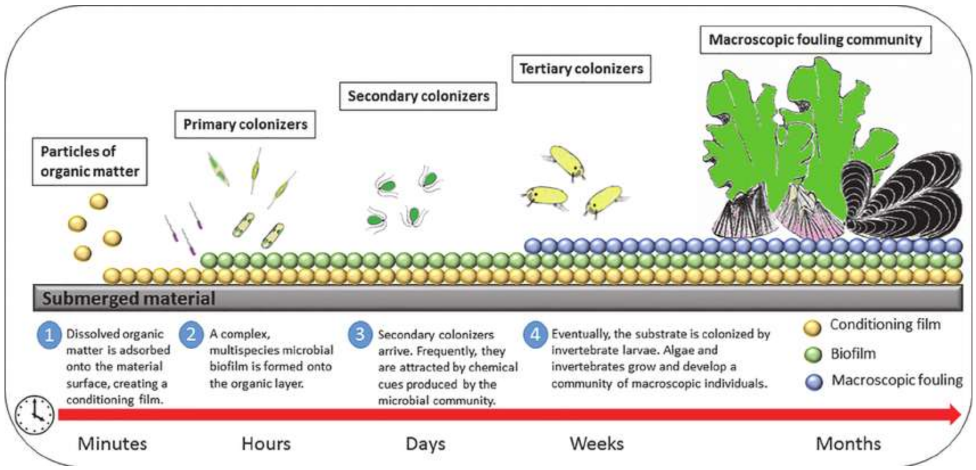


Figure 3.16 Biofouling progression from Martín-Rodríguez et.al highlighting the succession of more complex organisms throughout a deployment.

Blue Energy Oregon's biofouling team focused on exploring different combinations of physical and chemical methods to repel *P.polymerus* for the protection of the WEC. Physical methods depend on disrupting the adhesion of an organism by altering the surface conditions of a material or using the existing properties of a material to resist fouling while the goal of chemical antifouling is to disrupt key attachment methods or to kill biofouling organisms on contact. The binding method of *P. polymerus* was investigated to determine an optimal physical and chemical antifouling to test. *P. polymerus* uses a combination of glycoproteins (a protein with a carbohydrate attached to it) to create a settlement-inducing protein complex (SIPC) (Liang, 2019). The mechanics of the SIPC are not fully understood by the scientific community so multiple different methods were proposed.

First, a base material was selected. The success of a physical antifouling method depends on whether the base material is hydrophobic or hydrophilic. Hydrophobic materials move water away from key attachment points but require additional chemical antifouling to fully function. They are low-cost and well-documented, with OOI using high-density polyurethane foam (HDPE) as the main body of the mooring. Hydrophilic materials are a new approach to antifouling that prevents adhesion by making the material waterlogged on the microscopic level. This prevents organic cement from forming or the physical attachment of organisms to the WEC (Qiu, 2022). Hydrophilic antifouling is still in the experimental stages of development, high cost, and requires nanoscopic precision that our team is not trained in. For these reasons, HDPE foam was selected for the WEC body.

Next, a suspension method for the chemical antifouling was investigated. Soy wax was selected as it is a low-cost plant-based option and has additional hydrophobic properties from a mix of long-chain fatty acids and alcohols. Natural degradation of the material produces non-toxic byproducts, and the coating lasts for six months when exposed to outdoor conditions. This meets the current deployment schedule of OOI and is an eco-friendly option for the client. If the mooring deployment time increases because of WEC power generation, a longer-lasting option will need to be used. Spar-urethane is a popular plastic-based sealant due to its durable nature and low cost. Both coatings were tested alone and with a chemical additive to compare resistance to biofouling.

Lastly, a chemical agent was selected. Titanium dioxide (TiO_2) is an additive in mineral-based sunscreen due to its high reflectivity and non-existent skin reactivity. As an antifouling agent, TiO_2 impacts an organism's ability to absorb free electrons from the environment to catalyze key reactions like photosynthesis in algae or ion uptake in shelled organisms (Yi, 2023) Several recent studies have shown that concentrations of TiO_2 as low as .05% have been successful at repelling biofouling organisms when applied as a dried paste (Kamei, 2016). The main issue studies cited with TiO_2 was that the coating began to be compromised after 20 days. To the team's understanding, no study has been conducted by suspending TiO_2 particles in a simple coating method, most are dependent on nano-scale adhesion to complex surfaces or nitric acid-bound coatings. TiO_2 is commercially available as a powder and requires no additional permitting to obtain. Reinforcing a TiO_2 powder coating using either soy wax or polyurethane would create an eco-friendly hard coating for OOI. Sealing the entire system in OOI's current ablative coating is likely to produce the best results for the exterior of the WEC. Interior antifouling management was outside the scope of this project but would be regulated using intermittent UVC exposure (Hunsucker, 2019). Figure 3.17 depicts the entire proposed antifouling system to be tested.

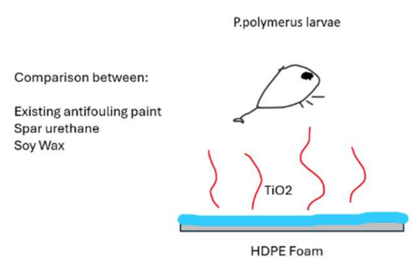


Figure 3.17 Rough design of antifouling system focused on repelling *P.polymerus*

3.6.3 Experimental Design

Five sets of two HPDE foam slabs were prepared for a thirty-day emersion study in Yaquina Bay following the Florida Tech Center for Biofouling and Corrosion Control short-term submersion study protocol (Wanka, 2023) Two slabs were covered on a .05% solution of wax and TiO_2, two with a .05% solution of spar-urethane and TiO_2, two with antifouling paint and .05% solution of wax and TiO_2, two with antifouling paint and a .05% solution of spar-urethane and TiO_2, and two controls. Each slab was then weighted and then secured to a manifold. Weights and rope were used to ensure the manifold was held underwater at two feet deep. Photos were taken every 10 days to document changes to the material. On the final day, all samples were weighed and scraped to determine what species were present. Final weights were computed in Excel to create a bar graph and perform an ANOVA between all samples at the 0.05 confidence level.

3.6.4 Results

Primary fouling organisms were found to be microfoulers like diatoms and bacteria through visual inspection, however the exact species could not be determined. Final samples are shown in Figure 3.18 with microscopy of wax scraping in Figure 3.19. Total mass change across samples varied slightly (1-10 g) with the control sample having the greatest range between tests seen in Figures 3.20 and 3.21. Single-factor ANOVA showed no overall significance between groups (Table 3.5).

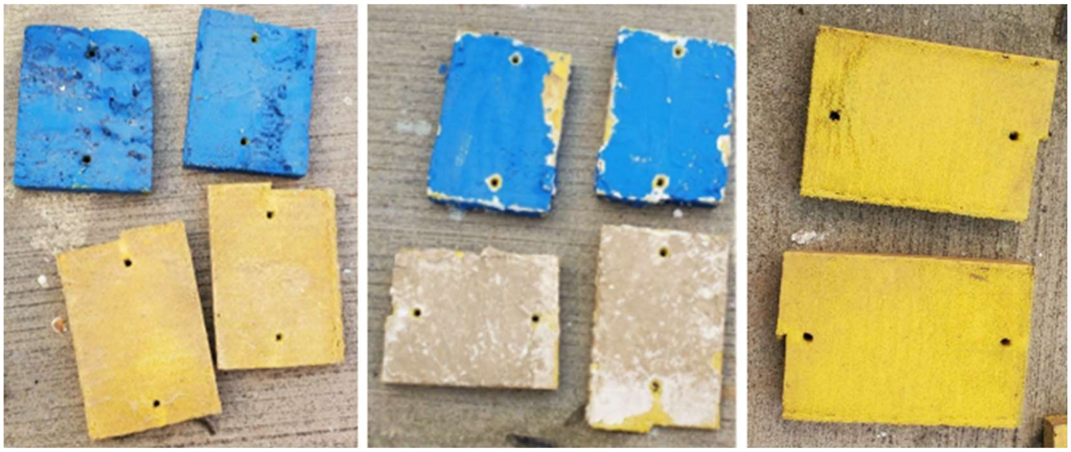


Figure 3.18 Spar urethane, wax, and control samples 1 week after removal. All wax samples showed excessive material loss during the emersion process.

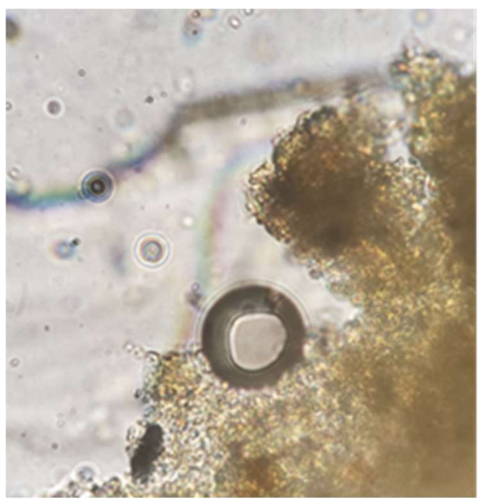


Figure 3.19 100X magnification of wax biofouling. Mass is composed of chain-forming diatoms and unknown biofilm-forming bacteria. Both are key microfouling organisms in estuarian environments during the winter.

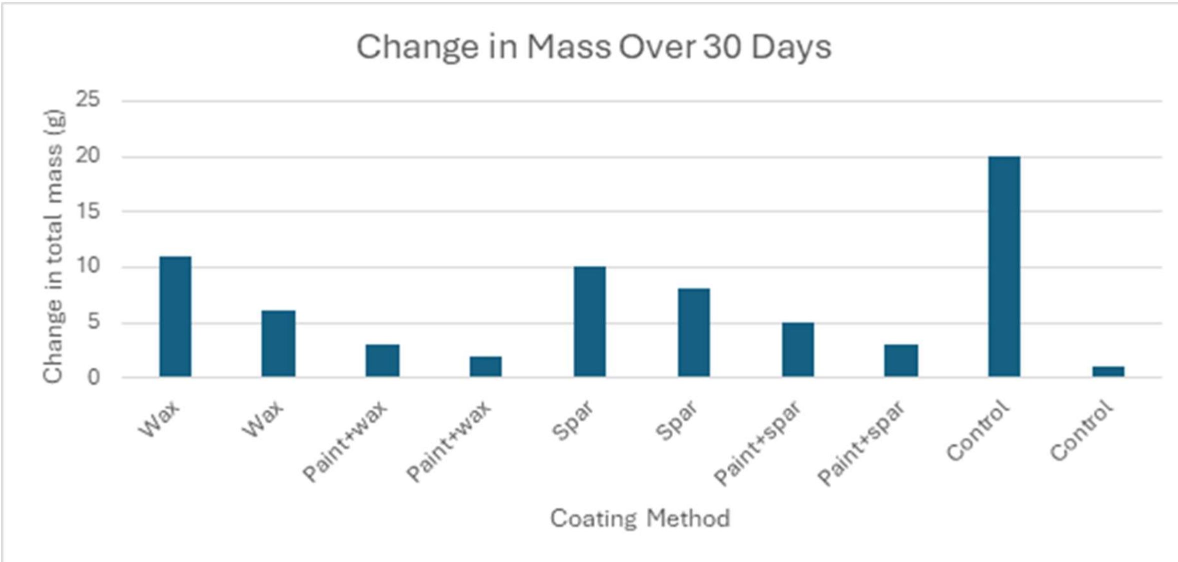


Figure 3.20 Change in sample mass after 30-day emersion study in Yaquina Bay. All samples were allowed to dry for a week after removal from the bay.

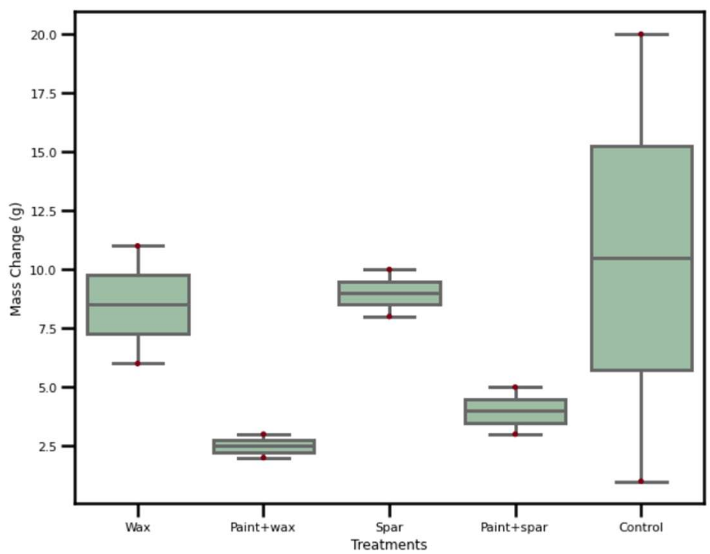


Figure 3.21 Boxplot results for all samples.

Table 3.4 ANOVA results for all samples.

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	95.4	4	23.85	0.603797	0.677363	5.192168
Within Groups	197.5	5	39.5			
Total	292.9	9				

3.6.5 Discussion and Conclusion

Overall, there was no significant difference between coating methods. Several issues may contribute to these results, with the team identifying low winter estuarian production and coating durability as the main culprits. Estuarian production is tied to both river inflow and oceanic inputs. Oregon experiences a strong downwelling season in the winter which could prevent nutrients like nitrate and phosphorus from entering the estuary to promote primary production or the growth of macrofouling organisms. Additionally, Oregon and the majority of the Pacific Northwest are amid a strong El Nino year, reducing riverine output into the estuary and further limiting nutrient availability.

Wax visually performed worst overall, with the coating cracking and accumulating large amounts of bacterial biofilm and diatoms. Heterotrophic bacteria are common in estuaries due to high carbon input from rivers (Anderson, 2022). In addition, several microbes in the gut microbiome of zooplankton can break down wax, including polyurethane wax, into usable nutrients. (Benson, 1975). This makes accurate comparisons difficult as any accumulated biomass may be actively removed by microbes. Spar urethane performed best in terms of coating durability with no observable loss of material over the 30-day deployment. Additional tests must be performed to determine the effect of wax/spar TiO_2 suspension methods. A longer deployment during the peak upwelling season (June to September) with more replicates would increase the rate of fouling on all materials and provide more statistical power for analysis. For BEO, TiO_2 is a promising solution to the harm done by traditional antifouling methods and deserves to be investigated further to support the company's future WEC program.

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