HERO WEC V1: Design and Experimental Data Collection Efforts

Scott Jenne,[1] Justin Panzarella,[1] Andrew Simms,[1] Michael Muglia,[2] Robert Raye,[1] Casey Nichols,[1] Aidan Bharath,[1] Charles Candon,[1] Alec Schnabel,[1] Ben McGilton,[1] Mark Murphy,[1] and Kyle Swartz[1]

1 National Renewable Energy Laboratory
2 East Carolina University—Coastal Studies Institute

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Technical Report
NREL/TP-5700-91741
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List of Acronyms

ABS	acrylonitrile butadiene styrene
AC	alternating current
Ah	ampere-hour
AHRS	attitude and heading reference system
AWG	American Wire Gauge
BB	BlackBox
CDIP	Coastal Data Information Program
cRIO	Compact Reconfigurable Input/Output
CSI	Coastal Studies Institute
DC	direct current
DOF	degree of freedom
FRP	fiberglass-reinforced plastic
gpm	gallons per minute
HERO WEC	Hydraulic and Electric Reverse Osmosis Wave Energy Converter
in.	inch
kW	kilowatt
LAMP	large-amplitude motion platform
lb	pound
m	meter
M1	MODAQ1
M2	MODAQ2
mm	millimeter
MHKDR	Marine and Hydrokinetic Data Repository
MODAQ	Modular Ocean Data Acquisition
MPPT	maximum power point tracking
NREL	National Renewable Energy Laboratory
OpenEI	Open Energy Information
psi	pounds per square inch
PTO	power take-off
RO	reverse osmosis
TDMS	technical data management system
V	volt
W	watt
WEC	wave energy converter
WPTO	Water Power Technologies Office

Executive Summary

The Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC), funded by the U.S. Department of Energy Water Power Technologies Office, is a research platform aimed at advancing wave-powered desalination by developing and testing a modular, small-scale wave energy converter (WEC) for remote and disaster-response applications. The insights gained from this project will help guide the design and development of larger-scale wave energy devices as well as the integration of marine energy and reverse osmosis desalination. The HERO WEC was initially developed to de-risk the Waves to Water Prize, enabling the staff to practice WEC deployment and recovery, while optimizing installation protocols.

The HERO WEC is a point absorber design that features two primary operational modes: hydraulic and electric. In the hydraulic configuration, the device pumps seawater directly to a land-based reverse osmosis system, whereas in the electric configuration, it provides power to a land-based power electronics subsystem, which is used to operate submersible pumps that then supply seawater to the reverse osmosis subsystem. Extensive laboratory and field testing, including multiple deployments at Jennette's Pier in North Carolina, focused on validating system performance, addressing energy conversion challenges, and understanding some mechanical and operational limits of WECs. In 2023, the team implemented upgrades to improve corrosion resistance, energy conversion efficiency, and data collection based on lessons learned during previous deployments.

Preliminary results demonstrate the feasibility of wave-powered desalination, though challenges remain in making the system viable for long-term deployments in harsh marine environments. Future work will concentrate on refining the power take-off system, lengthening component life, and improving system efficiency. The HERO WEC project contributes valuable insights into wave energy conversion and the practical application of renewable-energy-powered desalination technologies, aiming to advance the broader fields of marine energy and water treatment.

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Background

The National Renewable Energy Laboratory (NREL) Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC) is a culmination of efforts that began with the U.S. Department of Energy Water Power Technologies Office (WPTO) funding their first techno-economic feasibility study of wave-powered desalination in 2016. Over the years, the program's involvement in wave-powered desalination has grown and encompassed numerical model development, detailed simulations, and experimental evaluation of membranes.

Between 2019 and 2022, WPTO sponsored the Waves to Water Prize, which focused on the development of small-scale, modular wave energy converters (WECs) that can desalinate ocean water for disaster response applications. In an effort to de-risk the prize, the NREL team received funding to develop the HERO WEC as a representative technology that could be used to practice installation techniques and evaluate prize metrics. Since the completion of the prize in April 2022, the HERO WEC has been deployed in two different ocean test programs to evaluate a variety of different research objectives.

In FY23, the HERO WEC was upgraded to improve corrosion resistance, reduce losses through an electric conversion system, increase reverse osmosis (RO) system uptime, and increase the data collection quality and robustness. These upgrades were aimed at helping create a better understanding of the challenges associated with small-scale wave-powered desalination.

1 System Overview

The HERO WEC is a modular prototype designed to have either a hydraulic or an electric configuration to evaluate two common energy conversion methods. The WEC consists of five primary subsystems: the WEC, land-based power electronics, the RO system, submersible pumps, and the instrumentation. During operation, the WEC is anchored approximately 250 meters (m) offshore in water that is 2 to 3 m deep. Energy is transferred to a pier that is approximately 100 m away from the WEC through a flexible hose (in the hydraulic configuration) or a power cable (in the electric configuration). In the hydraulic configuration, the hose transfers seawater from the WEC to a land-based RO desalination system at a sufficiently high pressure to operate a Clark-pump-type pressure intensifier and desalinate the water. In the electric configuration, a power cable sends electricity to a land-based power electronics enclosure that converts the electricity from high-voltage alternating current (AC) to low-voltage direct current (DC). The low-voltage DC power is stored in batteries and used to power submersible pumps that are used to supply water to the same RO system. A representation of these two configurations is shown in Figure 1. As an open-source design, additional details in the form of 3D models (SolidWorks assemblies), a bill of materials, numerical models (WEC-Sim), and both laboratory and in-ocean test data are accessible through the HERO WEC Open Energy Information (OpenEI®) page (National Renewable Energy Laboratory 2023b).

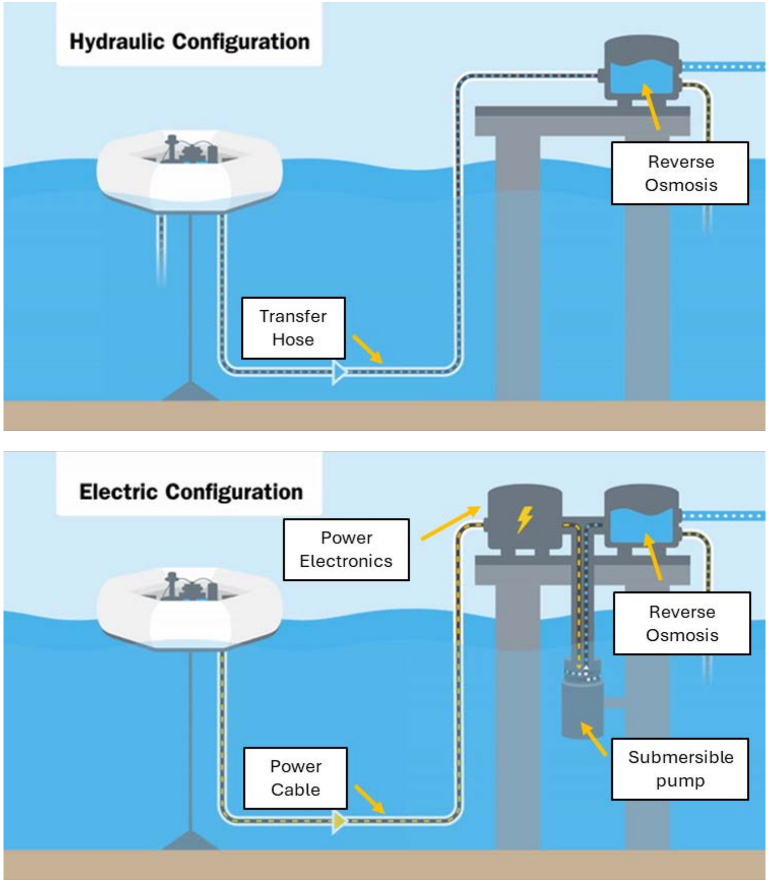

Figure 1. Simple representation of the two HERO WEC configurations

Image by Tara Smith, NREL

1.1 Wave Energy Converter

The WEC (Figure 2) is a single-body point absorber, which means there is a single floating body that is anchored to the seabed. The device converts energy from waves through the relative motion between the floating body and the seabed. Specifically, the HERO WEC was designed for use in shallow water—approximately 2–5 m deep. The primary components are mounted onto a steel frame and translate the relative motion between the HERO WEC and its anchor into useful shaft work using a winch system. The winch translates heave and/or surge motion into rotary motion, which is achieved using a 5/16-inch (in.)-diameter stainless-steel wire rope that is wrapped around the winch and anchored to the seabed. At the surface, on one side of the winch, there is a one-way roller clutch and gearbox. The roller clutch engages as the WEC is moving away from the anchor, and it disengages as the WEC is moving towards the anchor. The gearbox is used to increase the rotational velocity so that the WEC can efficiently drive a pump or an electric generator, depending on the configuration. On the other side of the winch, there is a spring return mechanism that is used to rewind the winch when the one-way clutch is disengaged. These components make up the power take-off (PTO) assembly and are attached to the steel frame—they are described in more detail in the following subsections. The PTO and steel frame are kept afloat by an inflatable octagonal float that is attached to the perimeter of the frame. An image of the assembled WEC in the hydraulic configuration is shown in Figure 3 to visualize the location of these components.

Figure 2. The HERO WEC installed in the ocean, with Jennette's Pier in the background

Photo from John McCord, CSI 74202

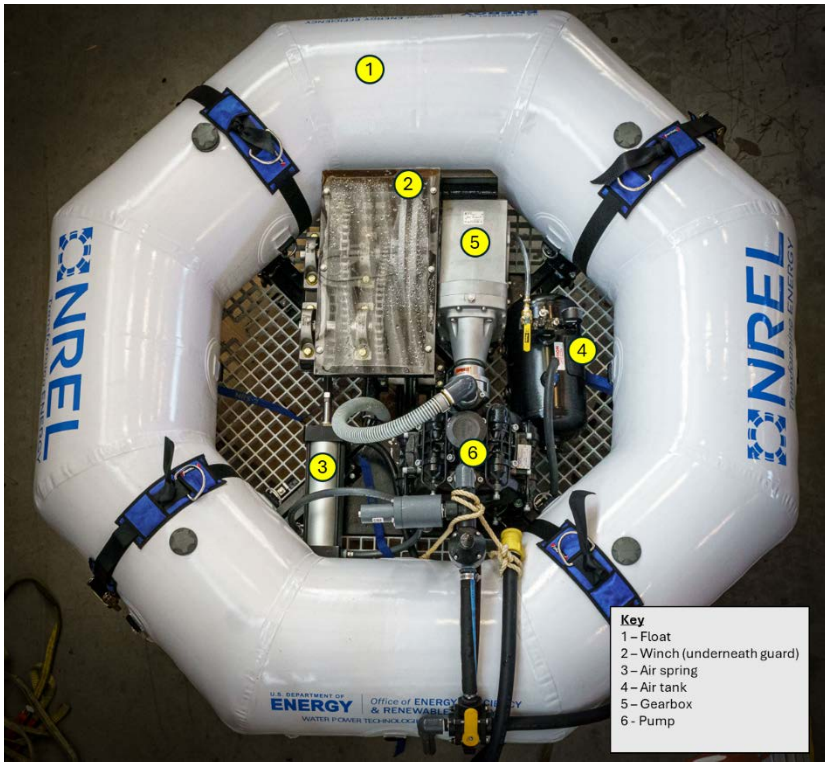

Figure 3. Top-down view of the HERO WEC*,* highlighting key components

Photo by Andrew Simms, NREL

1.1.1 Frame

The HERO WEC frame (Figure 4) was designed as a four-part assembly to meet the shipping requirements of the Waves to Water Prize (U.S Department of Energy 2021). Each quadrant of the frame is assembled from welded 1.5 × 3 in. rectangular tubing and joined with bolted frame clamps. Individual frame quadrants include all necessary mounting features to attach PTO components as well as panels of fiberglass-reinforced plastic (FRP) grating used to prevent debris from entering the WEC and as a safety guard for marine life and divers. At the center of the frame is a cutout, through which the winch line and hydraulic suction hose are routed. The frame features a raised mounting plate to secure the gearbox, flush mounting surfaces for the spring return and pump or generator subframes, and a raised tab to mount the air spring. These mounting surfaces are each made from welded steel plate or C-channel. Each frame quadrant includes two D-rings that are welded to the outer and inner surfaces of the frame perimeter. All eight D-rings are used to attach the float to the frame using 1-in.-wide cam-buckle straps. In addition to the eight cam-buckle straps, there are four additional 2-in,-wide ratchet straps that loop around the float and frame to reduce risk of detachment as well as a location for lift slings during installation and recovery. The FRP grating panels mounted to the frame are supported by 1-1/4-in. 90° low-carbon angle sections that have been welded to the inside of each frame quadrant. The FRP panels are secured to the frame using FRP grating clips and rivet nuts secured to the 90° sections. Multiple smaller components are then mounted directly to the FRP grating panels using the FRP grating clips.

Figure 4. The HERO WEC assembled frame

Photo by Andrew Simms, NREL

1.1.2 Float

The HERO WEC's buoyancy is provided by an inflatable octagonal float (Figure 5). The design consists of eight 18-in.-diameter tube sections built into an octagonal structure. Every two sections are isolated from each other to create four internal chambers. This construction allows the device to maintain buoyancy in the event of a puncture or leak in one of the chambers. The float is secured to the frame by a total of 12 webbing straps. When fully submerged, this float provides approximately 1800 pounds (lb) of gross buoyant force. The float is made from a single-layer polyvinyl chloride fabric that is coated with urethane to improve ultraviolet light resistance and provide additional abrasion resistance. The float is inflated to between 1 and 3 pounds per square inch (psi) to create a semirigid float structure capable of withstanding the force of impact from waves on the device.

Figure 5. Inflatable four-chamber float used to provide buoyancy

Photo by Scott Jenne, NREL

1.1.3 Winch

The winch consists of a winch drum assembly (Figure 6), an anchor cable, a one-way directional clutch (Stieber AL35F2D2), and a return drive shaft. The winch drum is a three-part assembly consisting of a machined core, two flanges attached to the outside of the winch core, and a clutch that mounts to the inside of the machined core (Figure 7). The directional clutch is secured to the inside of the winch drum core using six bolts and drives the input shaft of the gearbox. This directional clutch is configured to transmit power from the winch to the gearbox and disengage as the spring return recoils the winch drum. The WEC end of the anchor cable is attached to one flange of the winch drum using a wire rope stop, and then the cable is wrapped around the drum. The system is designed so that when the spring return has reached the end-stop, there is still at least one full wrap of wire rope around the drum core. This setup is intended to prevent the wire rope from breaking free in extreme wave conditions. The anchor end of the cable is routed over a sheave pulley located at the center of the WEC and then secured to an anchor on the seabed. The sheave pulley is used to align the cable with the winch drum, minimizing side loads on the drum and allowing for neater coiling of the cable. This specific design uses an alternating wrap design to maximize winch capacity while minimizing the distance between the winch and sheave pulley (Figure 8). A return drive shaft is welded to the surface of the drum core opposite the clutch and is mounted on bearings in the spring return system. Sprocket 1 of the spring return system is welded directly to this shaft, connecting the winch drum to the air spring described in section 1.1.5.

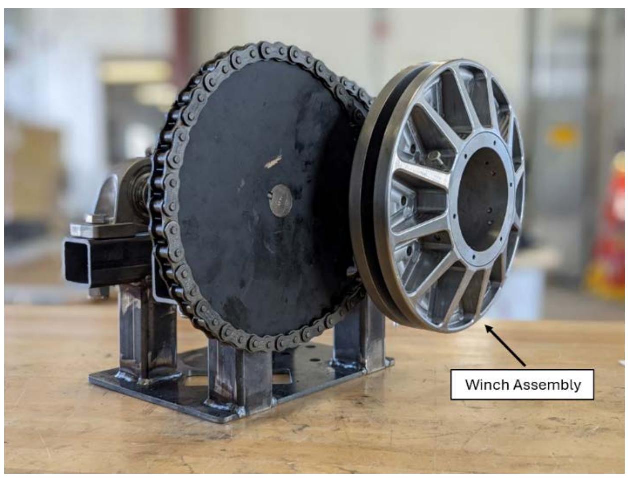

Figure 6. Winch assembly mounted on spring return assembly

Photo by Scott Jenne, NREL

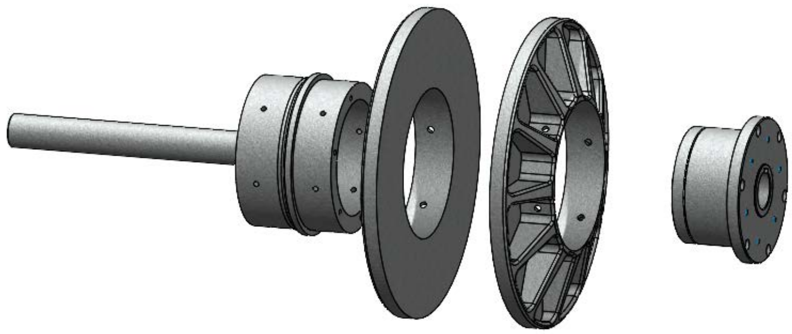

Figure 7. Exploded view of winch and clutch assembly

Image by Jusin Panzarella, NREL

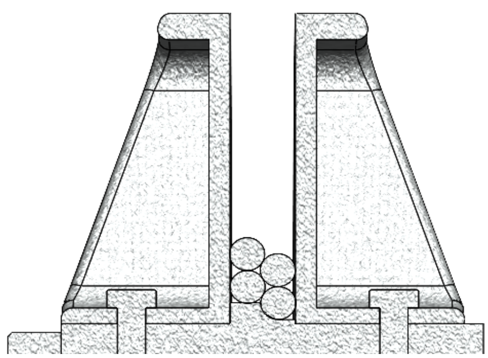

Figure 8. Cross-section view of winch drum with four wraps of cable

Image by Jusin Panzarella, NREL

1.1.4 Gearbox

A gearbox (NORD SK 93 series) is used to translate the low-speed winch motion into a higher rotational speed to drive either a pump or generator. A gearbox with a ratio of 1:11.28 was selected, as that ratio works well for both configurations but is not optimized for either. The selected gearbox design is a helical bevel style, which was chosen in lieu of other perpendicular gearbox configurations (e.g., worm drive) due to its ability to be driven in reverse (i.e., as a speed increaser instead of a speed reducer). This gearbox utilizes bevel gears to transmit power perpendicular to the winch axis, allowing for the PTO and drivetrain to be tightly packaged on the WEC.

The gearbox is bolted to a raised mounting plate on the WEC frame, and a bolt pattern on its casing is used to mount the on-WEC accumulator and spring return guard. In the first iteration of the HERO WEC, the gearbox used a 35-millimeter (mm) keyed input shaft that slid directly into the Stieber AL35F2D2 clutch assembly. Due to challenges with disassembly after numerous cyclical torque inputs, the gearbox was updated in 2023 to an equivalent ratio design that uses a shrink disk input connection at the gearbox. A jaw-type coupling (Lovejoy AL-150) attaches the output shaft of this gearbox to either the pump or generator (Figure 9). Due to the pump utilizing a six-spline PTO shaft, one of the jaw-type couplings was modified to accept a six-spline adapter for the pump. The jaw-type coupler allows for slight angular and parallel misalignment between the gearbox and the pump or generator. The rubber spider within the coupling also provides a small amount of damping in the event of shock loading due to extreme wave conditions. The use of this coupling enables quick installation and removal of the pump and generator, which is desirable for configuration swaps on a boat. A separate jaw-type coupling is fixed to both the pump and generator input shafts, eliminating the need to remove and install the pump/generator side coupling during configuration swaps.

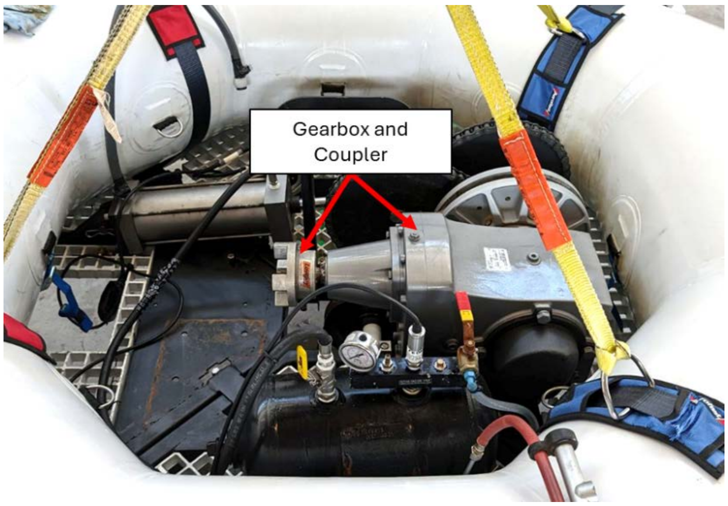

Figure 9. The gearbox and gearbox side of the jaw-type coupling

Photo by Scott Jenne, NREL

1.1.5 Spring Return

The spring return system uses an air-spring assembly to rewind the winch after every passing wave. The air-spring assembly consists of a pneumatic cylinder, a two-stage chain drive assembly, and a 3-gallon air tank. The two-stage chain drive assembly consists of five sprockets (Figure 10), the first four of which make up the two consecutive stages of the chain drive. The two-stage chain drive is used to translate 15 rotations at the winch into approximately 0.75 rotations at the final sprocket due to space constraints within the WEC. Each stage consists of a 10-tooth and a 45-tooth sprocket to reach a 1:4.5 ratio. The two stages combined create a final 1:20.25 drive ratio across the first four sprockets of the system. The fourth and fifth sprockets are welded together and mounted on the primary shaft of the first stage. For this assembly to operate as intended, these sprockets must be "floating" on the main shaft. This "floating" effect is accomplished by mounting sprockets 4 and 5 via needle roller bearings so that they can rotate independent of the primary shaft.

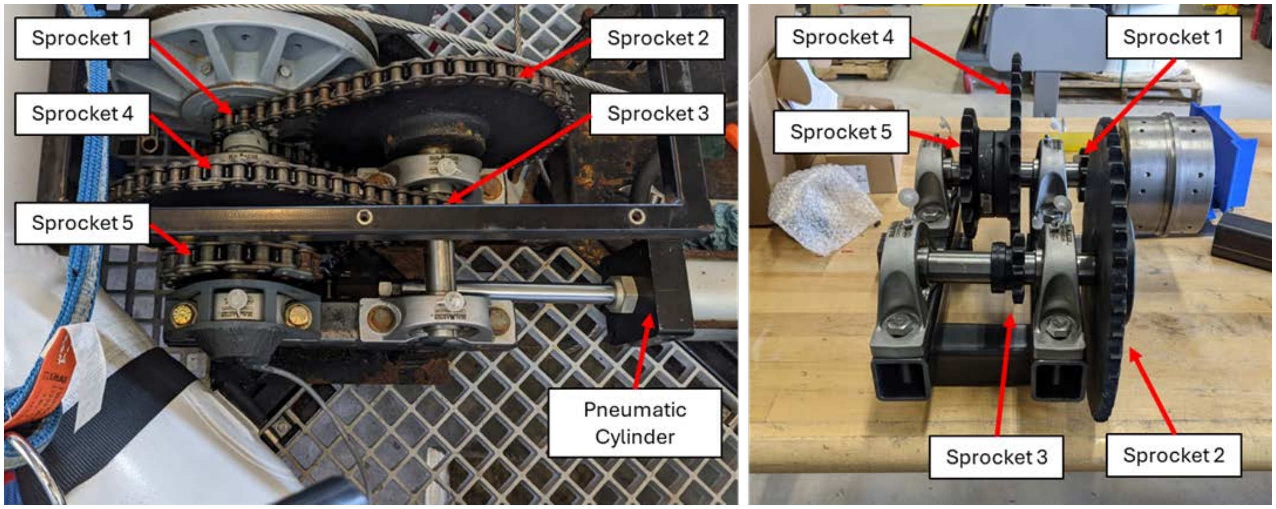

Figure 10. The five sprockets in the spring return assembly

Photo by Scott Jenne, NREL

The two stages of the spring return utilize a closed ANSI-60 chain, while an open section of higher-strength ANSI-80 chain is used to link the fifth sprocket to the pneumatic cylinder. Both shafts in this system are supported by pillow block bearings mounted to a frame made from a welded steel square tube and plate.

The pneumatic cylinder acts as the spring return mechanism. The pneumatic cylinder has a 4-in. bore and is plumbed to a 3-gallon air tank that is charged to 100 psi (Figure 11). Prior to installation of the WEC, the air tank is charged, but the air tank is isolated from the pneumatic cylinder using an in-line ball valve. Once the anchor line has been connected, the in-line ball valve is opened to charge the rod side of the air cylinder and provide approximately 40 lb of anchor line tension. The opposite side of this cylinder is vented to atmosphere using a breather and an elevated air hose. When it is time to uninstall or decommission the WEC, all compressed air is released from the air tank through a discharge valve located on an air manifold above the tank. This process allows safe removal of the WEC and eliminates any concern of stored energy that could harm a diver. The air tank was sized so that there is an approximately 20-psi variance across the total range of motion of the pneumatic cylinder. This relatively small variance in air pressure translates into a nearly constant spring force resulting in approximately 40 lb of anchor line tension under any given wave and less than 10 lb of variance over the entire range of motion.

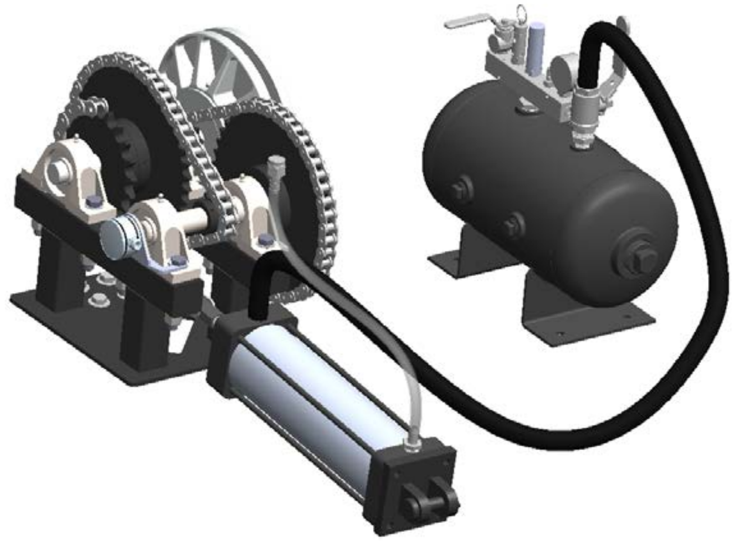

Figure 11. Spring return system with winch drum and air tank

Image by Jusin Panzarella, NREL

1.1.6 Hydraulic Pump

In the hydraulic configuration, a fixed displacement water pump is connected to the output shaft of the gearbox and is used to pump water directly to the RO system with no need for the power electronics assembly. The pump is a Comet BP205 six-piston rotary diaphragm pump with a maximum rated flow rate of 53 gallons per minute (gpm) and a maximum rated pressure of 290 psi. This pump model is an agricultural spray pump designed for a variety of corrosive and abrasive chemicals, giving it reasonable corrosion resistance in seawater. The BP205 is intended for use with a power input of up to 7.5 kilowatts (kW) and shaft speeds between 400 and 550 revolutions per minute (Comet Pumps 2019). This pump intakes seawater through a suction hose routed through the center of the WEC. Particulate is removed from the intake seawater by a 60-mesh (250-micron) stainless-steel strainer attached to the end of this hose. An additional 60-micron filter bag is secured to the outside of the stainless-steel strainer to prevent small sand particles from entering the suction line. A check valve located immediately after this strainer prevents the hose from draining during calm conditions and enables self-priming operation regardless of wave conditions. The input shaft on this pump is a 1-3/8-in. ISO external six-spline coupling. To accommodate this type of input shaft, the Lovejoy coupling used with the pump was modified to include an internal spline coupling. To limit anchor loading and water pressure at the RO system, two pressure relief valves are located at the output of the pump (Figure 12). The first pressure relief valve is used as a control and is set to a cracking pressure of 105 psi. The second pressure relief valve is used as a safety and is set to a cracking pressure of 110 psi. The pressure relief valves at the pump outlet prevent damage to the RO system while providing a passive control system that is able to reduce tension on the anchor line in larger sea states. A 2.1-gallon accumulator precharged to 15 psi is attached to the pump output plumbing to smooth pressure spikes, which helps reduce the maximum winch line tension and smooth the pressure profile seen at the RO inlet. This accumulator is mounted to a steel frame attached to the top of the gearbox and is connected to the hydraulic output plumbing with a flexible water hose.

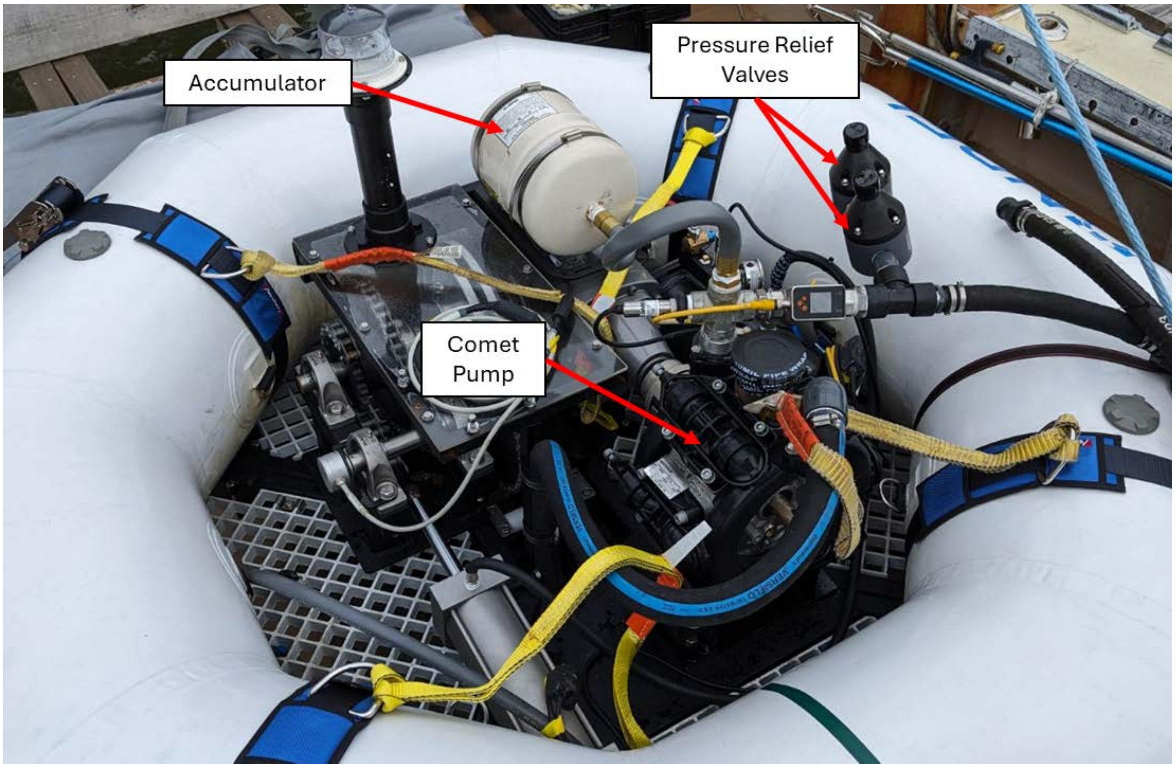

Figure 12. Locations of the pump and pressure relief valves

Photo by Scott Jenne, NREL

1.1.7 Electric Generator

In the electric configuration, a 3-kW three-phase AC generator is used to convert rotational motion of the drivetrain into electrical energy. The generator was custom manufactured by Innotec Power to include a waterproof housing so that the generator could withstand regular submergence. The electricity produced at the generator is then transferred to a land-based power electronics system by 500 feet of connectorized 4-AWG (American Wire Gauge) marine-grade cable. On the WEC side of the cable, the generator is connected using an IP67-rated connector that is coupled to a junction box. The junction box steps up the 10-AWG wire from the generator to the 4-AWG needed to maintain less than a 3% voltage drop across the 500 feet of cable to shore. Typically, the WEC is installed in the ocean before the cable is run; therefore, the generator and junction box are not mounted until after the WEC is connected to the anchor (Figure 13). Similar to the hydraulic configuration, the electric generator is connected to the gearbox via a Lovejoy coupling that is attached to the generator's 24-mm keyed input shaft.

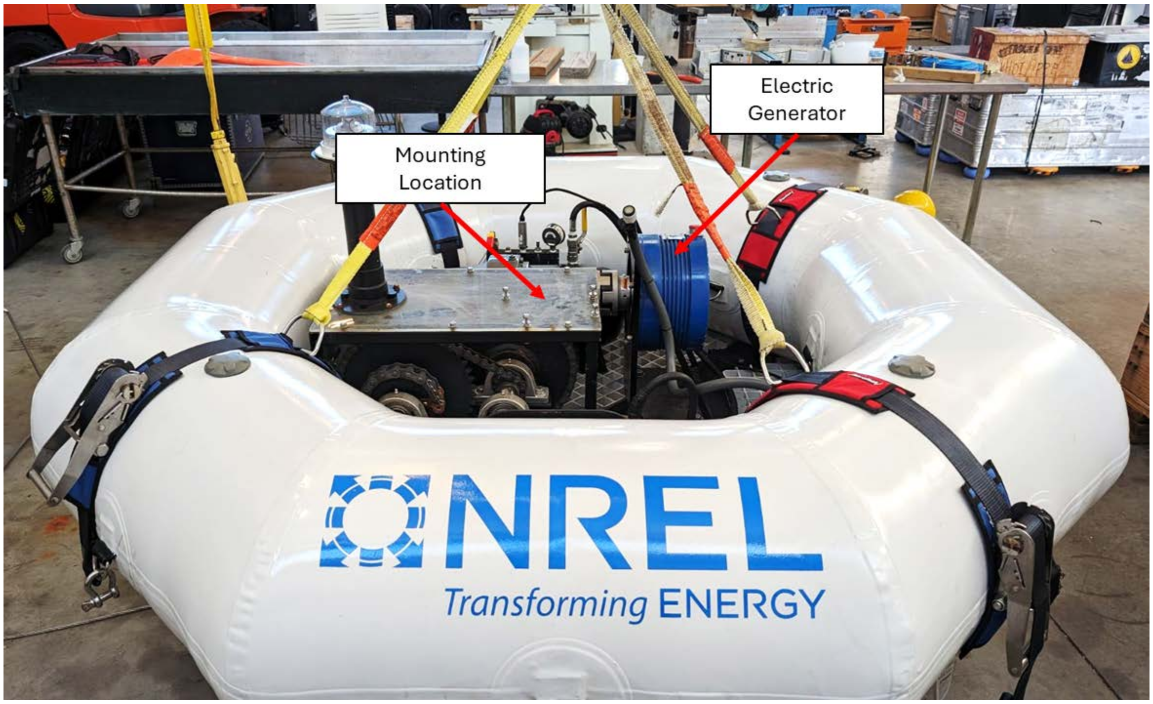

Figure 13. Electric generator and junction box mounting location (junction box not installed)

Photo by Scott Jenne, NREL

1.2 Power Electronics

The HERO WEC power electronics system is used to convert the three-phase AC power output into electricity that can be used to power submersible pumps for the seawater RO system. The power electronics system consists of components housed within five separate land-based enclosures so that low- and high-voltage sources can be isolated. The five enclosures include a rectification enclosure, a charge controller enclosure, a battery enclosure, a pump controller enclosure, and the data acquisition system. A block diagram of the power conversion steps, not including the data acquisition system, is shown in Figure 14.

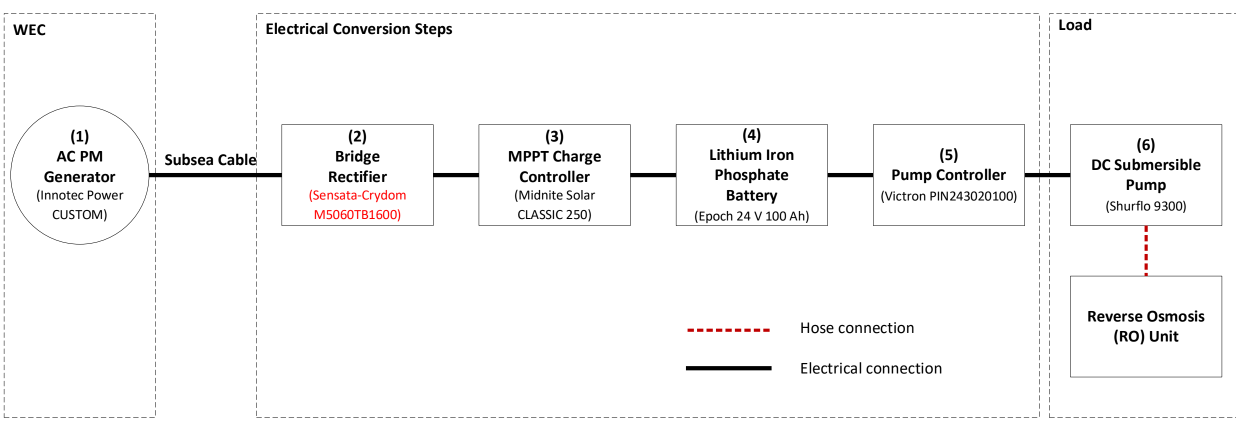

Figure 14. Power electronics conversion block diagram

Image by Alec Schnabel, NREL. PM = permanent magnet; MPPT = maximum power point tracking; V = volt; Ah = ampere-hour.

The first enclosure contains a bridge rectifier to convert high-voltage AC into high-voltage DC and a capacitor to smooth the voltage spikes. This enclosure also includes voltage and current sensors as well as fuses in case of an overcurrent event. The enclosure features a physical disconnect switch allowing the power electronics system to be isolated from the HERO WEC during installation and maintenance.

The second enclosure contains a maximum power point tracking (MPPT)-style MidNite Solar Classic 250 charge controller, which sets its current draw based on the generator output voltage. This component is preprogrammed using a user-defined lookup table. The MPPT-type charge controller used in the power electronics system is intended for solar applications and is only capable of reducing the input voltage (i.e., buck converter), resulting in reduced system performance in calm sea states. The charge controller then outputs 24 volt (V) of DC power that is sent to a bank of land-based batteries.

The third enclosure houses two lithium iron phosphate 12-V DC 100-ampere-hour (Ah) batteries in series (totaling: 24 V DC, 100 Ah). The batteries are Epoch B12100B batteries with an integrated battery management system and a Bluetooth monitoring system (Epoch Batteries 2022) for ease of monitoring in the field. The energy stored in these batteries is sent to a set of submersible pumps powered by two pump controllers.

The fourth enclosure houses the two pump controllers referenced above. Each pump controller (Victron PIN243020100) provides a constant 24-V DC supply to each of the Shurflo 9300 pumps that are used to provide flow for the RO system. The pumps can be disconnected from the land-based power electronics through an external switch. The pumps are controlled via a battery state of charge setpoint that can be adjusted remotely through the NREL Modular Ocean Data Acquisition (MODAQ) system. The pumps can also be manually turned on and off through the MODAQ system. More details on the pumps and the pump housing are given in section 1.4.

The fifth enclosure houses the MODAQ instrumentation system, which is described in more detail in section 1.5.

1.3 Reverse Osmosis System

The HERO WEC RO system (Figure 15) is designed to desalinate seawater by passing it through a Spectra LB400s seawater RO system (Spectra Watermakers 2019). The spectra LB400 system consists of either a single SW30-2540 (LB400) or two SW30-2520 (LB400s) membranes and a Spectra Clark pump. The Clark pump is a combined energy intensifier and energy recovery device that is used to increase the overall system efficiency and reduce the needed input pressure to desalinate seawater. In addition to the Spectra LB400s unit, the NREL team has integrated two stages of cartridge filters. The first stage consists of two 4-1/2-in. × 20-in. 20-micron filters (McMaster P/N 6657T54). The second stage consists of two 4-1/2-in. x 20-in. 2-micron filters (McMaster P/N 6657T42). The two-stage filtration is intended to remove large particles that can either damage the RO system or cause unnecessary maintenance during operation.

This subsystem is used in both the electric and hydraulic configurations; however, it may be bypassed for maintenance with the use of a diverting valve. In the electric configuration, feed flow is supplied to the RO subsystem only when the land-based batteries are above a specified state of charge. The RO subsystem is also frequently bypassed during lab testing to collect data on system performance under low loads.

Prior to the filtration, the RO system utilizes two 4.5-gallon expansion tank accumulators (McMaster PN 4386T6) to smooth the flow in the hydraulic configuration. When the electric configuration is used, these accumulators are not necessary and are isolated using ball valves.

In addition to the Spectra system, accumulators, and prefiltration, the RO system has four flowmeters, two pressure transducers, and two conductivity meters for monitoring. The system also utilizes a three-way ball valve prior to the cartridge filters so that the RO system can be isolated if maintenance needs to be performed while the WEC is operational (e.g., filter or membrane replacement).

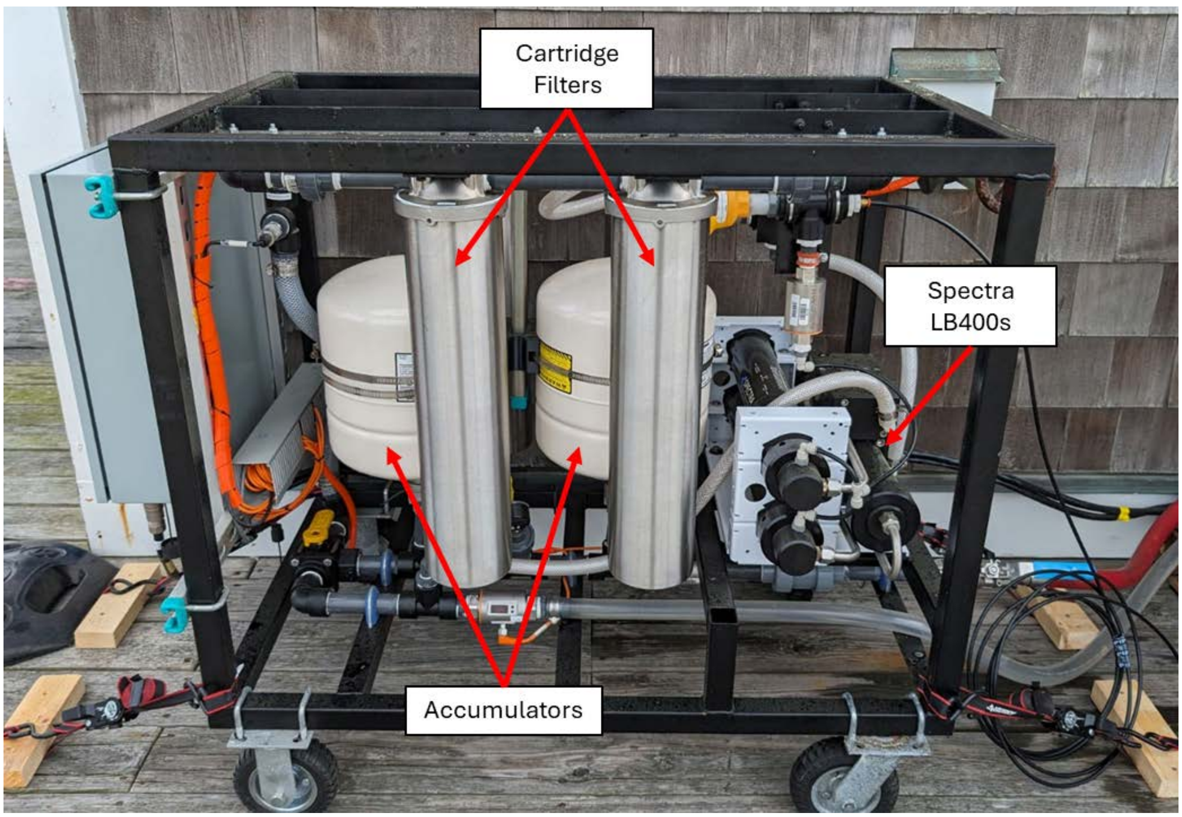

Figure 15. Picture of the RO system highlighting the Spectra LB400s, cartridge filters, and accumulators

Photo by Scott Jenne, NREL

1.4 Submersible Pumps

As described in section 1.2, the power electronics system outputs 24 V DC to power two Shurflo 9300 submersible pumps (Pentair 2015). Each pump is designed to output approximately 1.3 gpm at 100 psi. The RO system is designed to operate at approximately 2.7 gpm at 100 psi; therefore, two pumps were selected to match the flow and pressure requirements. The power stored in the battery bank is sent through two 10-AWG two-wire subsea cables to the pump assembly. The electric pumps are housed inside a custom-built acrylonitrile butadiene styrene (ABS) enclosure so that a single hose could be run to the RO system (Figure 16).

The housing intake provides large particle filtration through panels of 60-micron stainless-steel mesh (Figure 16). This assembly is constructed from 3D-printed ABS parts, two sections of 4-in.-diameter ABS pipe, and two end caps to house the individual pumps. A large 3D-printed intake part is used to hold the two sections of 4-in. pipe, which enclose the pumps and provide a support structure to hold the stainless-steel mesh filter elements. The sections of pipe are adhered to this component using ABS glue, whereas the filter elements are secured to this component by a filter clamp part, which is bolted to the intake and incorporates a track holding a square profile O-ring to clamp the perimeter of each filter element to the intake (Figure 17). Power cables are routed through two submersible cord grips attached to tabs on this part. The output hoses from the pumps are joined at a tee housed within this assembly, and a single output hose is then routed through a hole in the center of the filter clamp, which is sealed by a rubber grommet. The two Shurflo 9300 pumps are each adhered to a 3D-printed mount part that centers the pumps within the pipes and bolts to the 4-in. national pipe taper, or NPT, plugs located at the bottom of each section of pipe to prevent axial movement of the pumps during installation of this assembly. Three flat profile spacer frames are located between the sections of pipe to provide additional support to the assembly. The top and bottom frames feature an extended tab to provide locating surfaces for the ratchet strap, which is used to secure the pump enclosure to a pier during ocean deployments. Two rectangular cutouts through the intake and filter clamp allow a section of nylon webbing to support the pump assembly during installation.

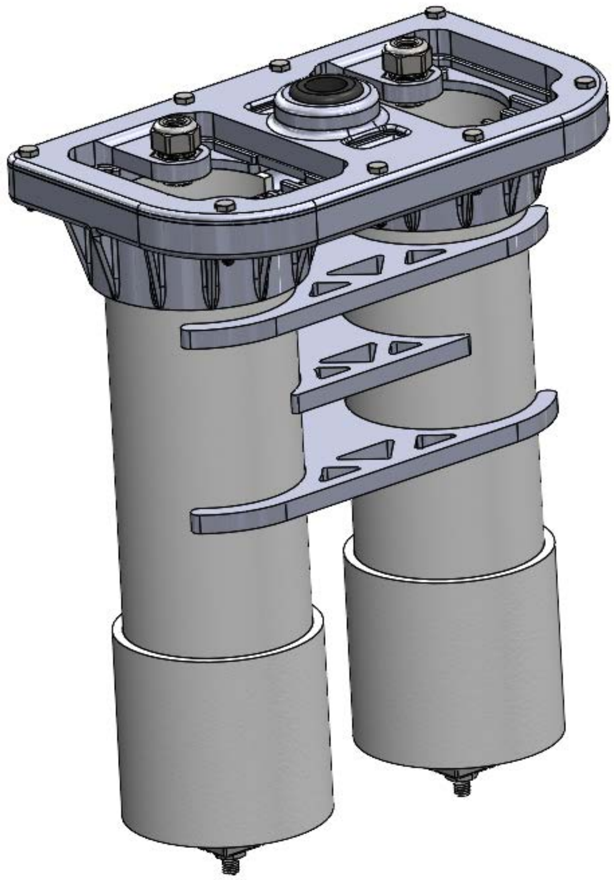

Figure 16. ABS submersible pump enclosure used in the electric configuration

Image by Jusin Panzarella, NREL

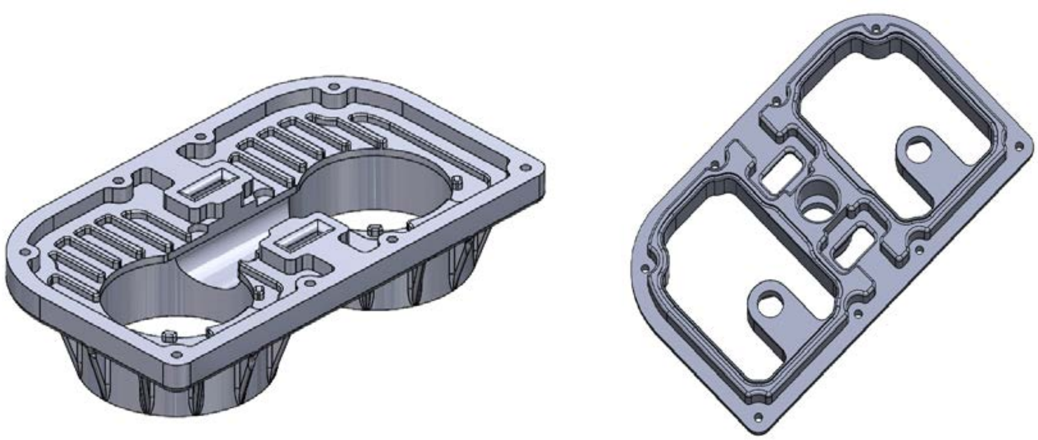

Figure 17. Submersible pump intake part (left) and sealing clamp (right)

Image by Jusin Panzarella, NREL

1.5 Instrumentation

The HERO WEC is instrumented using the MODAQ system from NREL. This system is capable of measuring data at different sample rates from a large number of sensors and is designed to be configurable for collecting data on many types of WECs. The MODAQ system used for HERO WEC is a distributed system with a land-based MODAQ1 (M1) system (Ray, et al. 2024), a smaller on-WEC MODAQ2 (M2) system, and a very small underwater MODAQ BlackBox (BB) system (National Renewable Energy Laboratory 2022).

In its configuration for the HERO WEC, MODAQ features a total of 31 sensors monitoring device performance, in addition to an attitude and heading reference system (AHRS) unit, which outputs data on the device's location and motion using inertial measurement unit and global positioning system capabilities (Table 1). When used on the HERO WEC, MODAQ collects data on five groups of sensors at different sample rates for each group. Data from MODAQ are saved to a technical data management system (TDMS) file for each group every 10 minutes during testing. After testing, the TDMS files are downloaded, sorted, and then processed using Python and MATLAB.

Table 1. HERO WEC Sensors

Tag Name	Description	Subsystem	DAQ[a] IO Modules	Units
Time	DAQ time array starting at zero	MODAQ	All	Unix nanoseconds
PRESS-OS-1001	Hydraulic pump outlet pressure	WEC (Hydraulic)	M2–ADS1115	psi
PRESS-OS-2002	WEC air tank pressure	WEC	M2–ADS1115	psi
POS-OS-1001	Second-stage spring return shaft position	WEC	M2–ADS1115	Degrees
FLOW-OS-1001	Hydraulic pump outlet flow rate	WEC (Hydraulic)	M2–ADS1115	gpm
PRESS-ON-1001	RO system inlet pressure	RO	M1–NI9202	psi
PRESS-ON-1002	Clark pump inlet pressure	RO	M1–NI9202	psi
FLOW-ON-1001	RO inlet flow rate	RO	M1–NI9203	gpm
FLOW-ON-1002	Clark pump inlet flow rate	RO	M1–NI9203	gpm

Tag Name	Description	Subsystem	DAQ[a] IO Modules	Units
FLOW-ON-1003	Brine discharge flow rate	RO	M1–NI9203	gpm
FLOW-ON-1004	Permeate flow rate	RO	M1–NI9203	gpm
CND-ON-1001	RO inlet water conductivity	RO	M1–NI9203	Microsiemens/cm
CND-ON-1002	Permeate conductivity	RO	M1–NI9203	Microsiemens/cm
LC-ST-1001	Anchor load cell	Anchor	[b]	Pound force
PT-ON-1001	Generator phase 1 voltage	WEC (Electric)	M1–NI9239	Volts
PT-ON-1002	Generator phase 2 voltage	WEC (Electric)	M1–NI9239	Volts
PT-ON-1003	Generator phase 3 voltage	WEC (Electric)	M1–NI9239	Volts
CT-ON-1001	Generator phase 1 current	WEC (Electric)	M1–NI9239	Amps
CT-ON-1002	Generator phase 2 current	WEC (Electric)	M1–NI9239	Amps
CT-ON-1003	Generator phase 3 current	WEC (Electric)	M1–NI9239	Amps
PT-ON-2001	Post-rectifier voltage	Power electronics	M1–NI9239	Volts
CT-ON-2001	Post-rectifier current	Power electronics	M1–NI9239	Amps
PT-ON-2002	Charge controller input voltage	Power electronics	M1–NI9202	Volts
CT-ON-2002	Charge controller input current	Power electronics	M1–NI9202	Amps
PT-ON-2003	Charge controller output voltage	Power electronics	M1–NI9209	Volts

Tag Name	Description	Subsystem	DAQ[a] IO Modules	Units
CT-ON-2003	Charge controller output current	Power electronics	M1–NI9202	Amps
PT-ON-2004	Battery voltage	Power electronics	M1–NI9202	Volts
CT-ON-2004	Battery current	Power electronics	M1–NI9239	Amps
PT-ON-2005	Pump controller input voltage	Power electronics	M1–NI9202	Volts
CT-ON-2005	Pump controller input current	Power electronics	M1–NI9292	Amps
PT-ON-2006	Pump 1 voltage	Power electronics	M1–NI9208	Volts
CT-ON-2006	Pump 1 current	Power electronics	M1–NI9202	Amps
PT-ON-2007	Pump 2 voltage	Power electronics	M1–NI9202	Volts
CT-ON-2007	Pump 2 current	Power electronics	M1–NI9202	Amps

[a] Data acquisition.

[b] The loadcell was connected to M1 during large-amplitude motion platform testing and to BB in the field deployment.

1.5.1 MODAQ System

The MODAQ system comprises M1, M2, and BB due to the DAQ scale requirements on each HERO WEC system. This requirement led to a distributed MODAQ design. Due to the number of measurements with a large power consumption and high sampling frequencies within the RO system and power electronics module, a Compact Reconfigurable Input/Output (cRIO) was identified for the land-based M1 system, as there are no power limitations. Also, the system requires the inclusion of a MODAQ Web (National Renewable Energy Laboratory 2023a) interface for live data viewing during deployment, a virtual private network server for remote connection and management, and a global-positioning-system-synchronized master clock for high-precision timestamping. The main controller of the M1 system is a National Instruments cRIO-9049, which includes several IO modules, as described in Table 1. The locations of all sensors across the different sub-systems are also visualized in Figures 18-22.

The M1 system is connected to the on-buoy M2 system through a tether cable that includes wires for RS485 serial communications and a 24-V power supply. The M2 system collects the sensor data on the WEC and sends the data back to M1 through the RS485 communication wires. The main controller of the M2 system is a single-board computer and includes a 40-pin IO header with an Intel x86-64 processor capable of executing the M2 software stack. The system includes two 12-V lithium iron phosphate batteries, which can operate the M2 system for approximately 24 hours. While the tether is connected to the on-WEC M2 system, these batteries are charged, allowing the system to run continuously. If umbilical power is lost, the system will continue to run and will record data locally in bag files (SQLite3 database), which is the binary data file format used by M2. The M2 system collects data from four analog sensors using an ADS1115 I2C connected breakout board.

The anchor loads are measured using a Sensing Systems Tension Link load cell (Sensing Systems Corporation 2022)connected to a BB system. To avoid interference with the HERO WEC mooring system, which is an integral part of the PTO, the BB is self-powered, records its data locally to a microSD card, and is not tethered to the surface float.

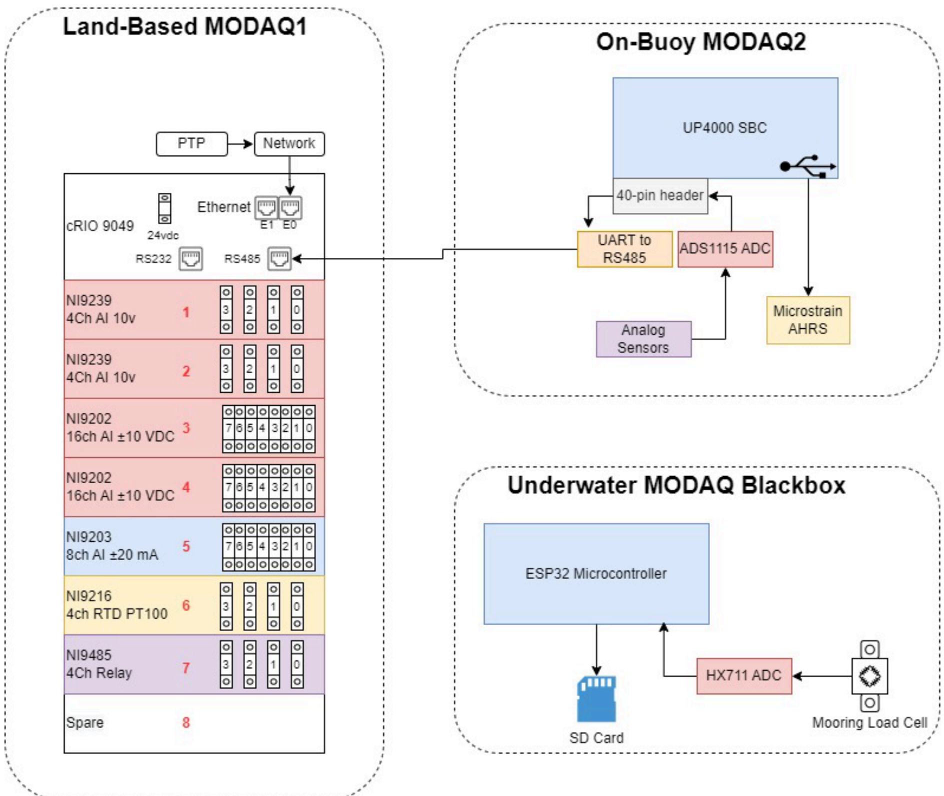

Figure 18. MODAQ system diagram

Image by Rob Raye, NREL

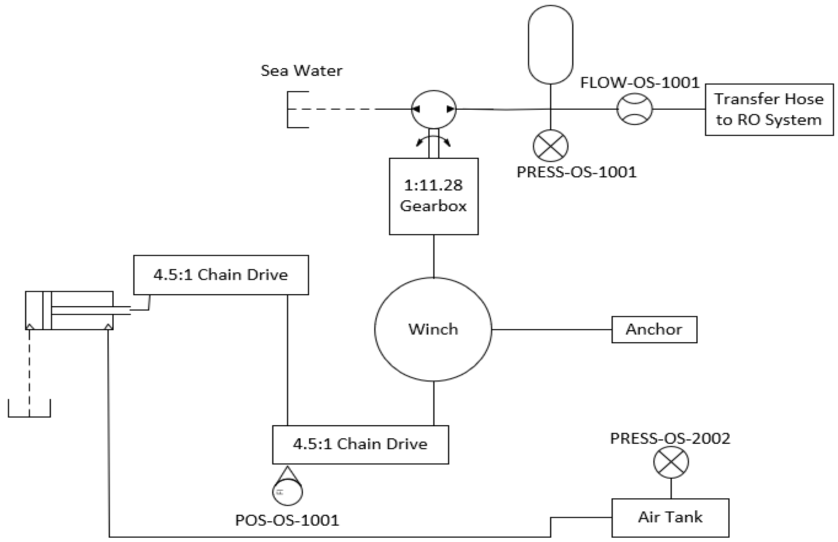

Figure 19. Locations of on-buoy sensors

Image by Justin Panzarella, NREL

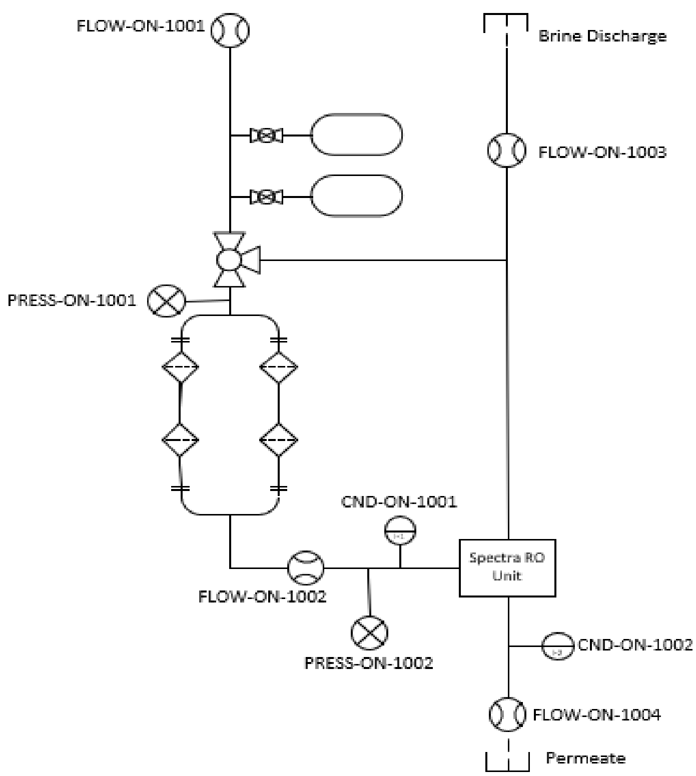

Figure 20. Locations of RO sensors

Image by Justin Panzarella, NREL

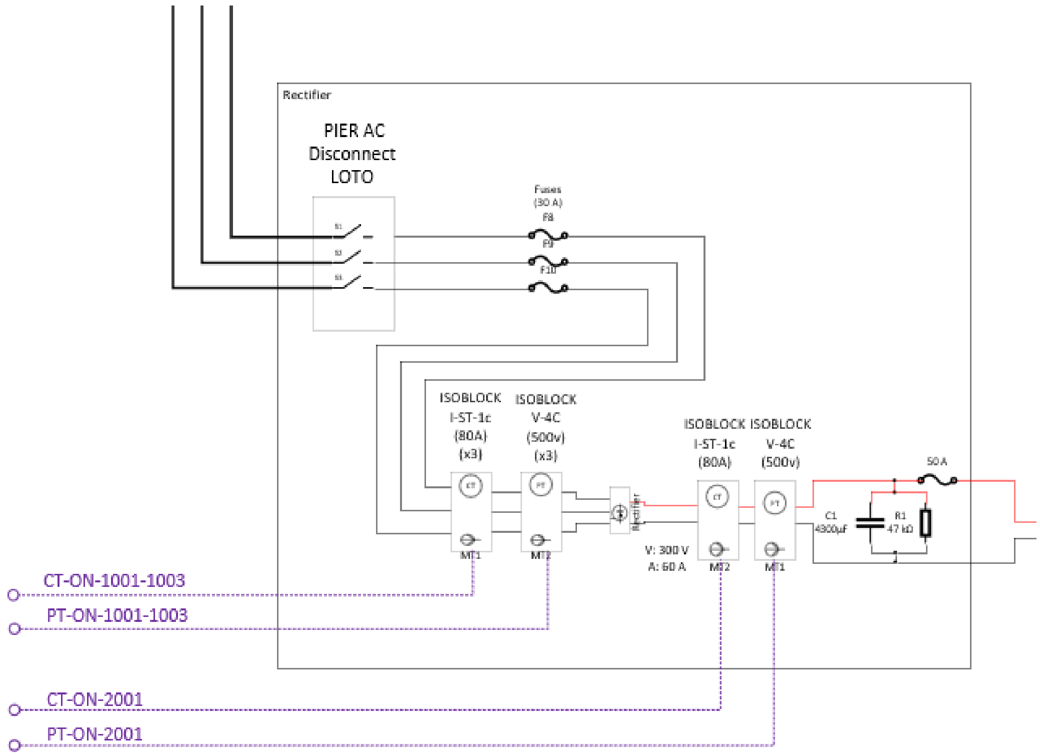

Figure 21. Locations of potential and current transformer sensors used to measure three-phase AC electricity from generator and DC electricity after rectifier

Image by Alec Schnabel, NREL. PT = potential transformer; CT = current transformer.

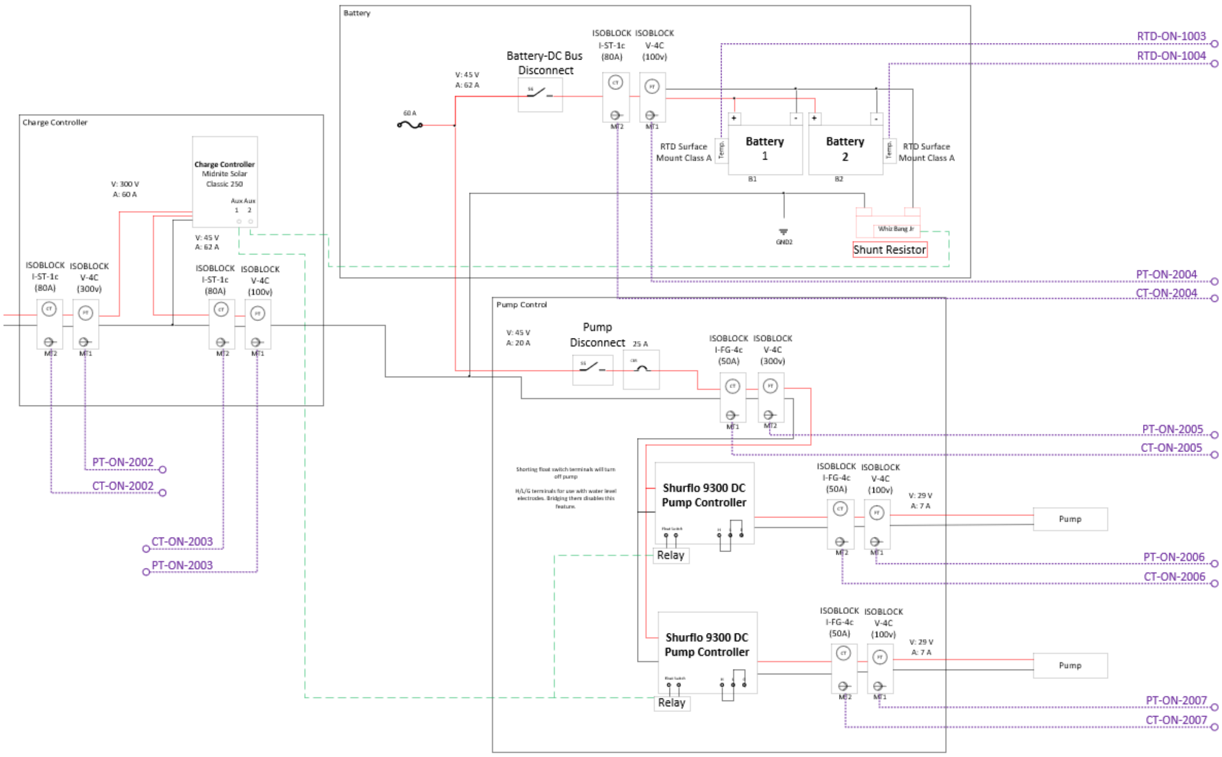

Figure 22. Locations of potential and current transformer sensors after rectifier

Image by Alec Schnabel, NREL. PT = potential transformer; CT = current transformer.

1.6 Prototype Cost

The HERO WEC is a one-off prototype WEC designed to support research efforts that encompass both direct hydraulic to RO and electric conversion to RO desalination. Due to the modular design and additional instrumentation typical of a research asset, the cost of the HERO WEC is significantly greater than that of a WEC that is optimized and mass produced for market consumption. Therefore, the authors do not recommend using the provided HERO WEC cost estimates for traditional techno-economic assessments without modifications or additional assumptions to account for economies of scale and/or potential performance improvements. That being said, it is not unreasonable to use these figures for benchmarking or conservative economic assessments.

The cost breakdown provided in Table 2 has been converted into a format consistent with the U.S. Department of Energy's marine energy system cost breakdown structure. More details and guidance on this cost reporting method can be found on the "MHK Levelized Cost of Energy (LCOE) Guidance and Techno Economic Analysis Materials" page within the Marine and Hydrokinetic Data Repository (MHKDR) (Jenne and Baca 2019). The breakdown provided includes the hardware costs at a "level 3" for the "Marine Energy Converter" category but does not include balance of system, financial costs, or operating expenditures. If more cost details are desired, additional component costs can be found on the HERO WEC wiki page on the "Design & Docs" subpage (Jenne 2023).

The total cost of the HERO WEC, as configured in 2023, in the hydraulic configuration is $51,213.71, and the cost of the system in the electric configuration is $60,671.43. An additional $26,022.76 of instrumentation was used primarily for data collection and public dissemination. The instrumentation cost does not account for the cost of the data acquisition system—only the costs of the sensors due to the large variance in data acquisition costs (Raye, et al. 2024). The costs provided in Table 2 account only for the hardware and do not reflect the cost of system assembly, transportation, installation, or operation.

Table 2. WEC Subsystem Component Costs

Category	Cost in Hydraulic Configuration	Cost in Electric Configuration	Cost of Instrumentation
Structural Assembly	$15,589.32	$15,113.32	$186.00
PTO System	$20,486.12	$26,877.75	$16,955.31
Mooring	$5,307.52	$5,307.52	$3,440.00
RO System	$9,830.75	$12,511.13	$5,441.45
Total	$51,213.71	$60,671.43	$26,022.76

2 Lab Testing and Deployments

2.1 Testing Summary

The HERO WEC has gone through a variety of different testing programs both in-lab and in the ocean at the Jennette's Pier test site in the Outer Banks of North Carolina. Every test program has had a different set of objectives that range from verifying anchor loads, de-risking prize planning efforts, and baselining performance characteristics. Table 3 summarizes the different test programs and the respective objectives.

Table 3. Summary of HERO WEC Test Programs Between 2022 and 2024

Test Program	Lab/Ocean	Location	Objectives	Dates
1	Lab	NREL	Verify system operation and perform safety checks	December 2021–January 2022
2	Ocean	Jennette's Pier	De-risk Waves to Water Prize installation efforts	March 2022
3	Ocean	Jennette's Pier	Quantify anchor loading, perform on-boat PTO swap, and validate laboratory assumptions	August 2022
4	Lab	NREL	Quantify both system performance and numerical model error	August 2023–October 2023
5	Ocean	Jennette's Pier	Quantify system performance at sea	March 2024–April 2024

2.2 Test Program 1: In-Lab System Operation Verification

The first round of testing that was done on the HERO WEC was focused on two primary objectives. The first objective was to make sure the system operated as expected, i.e., the hydraulic system pumped water at the design pressure and flow rates, the electric system was capable of charging a battery bank, and all subsystems operated as expected—such as the spring return. The second was to ensure that the passive safety controls were operational. For the hydraulic configuration, this was a check to confirm that the pressure relief valves were opening at the design point and that there was enough flow capacity to adequately control the anchor loads. For the electric configuration, the testing was done to check that the combination of circuit breakers and the charge controller logic was limiting the current draw, which ultimately regulates anchor loads.

For the first test program, the HERO WEC was secured to an elevated test platform, and the winch line was attached to another pulley driven by a motor drive assembly (Figure 23). This configuration was used to mimic single-degree-of-freedom (DOF) (heave only) motion via sinusoidal wave profiles.

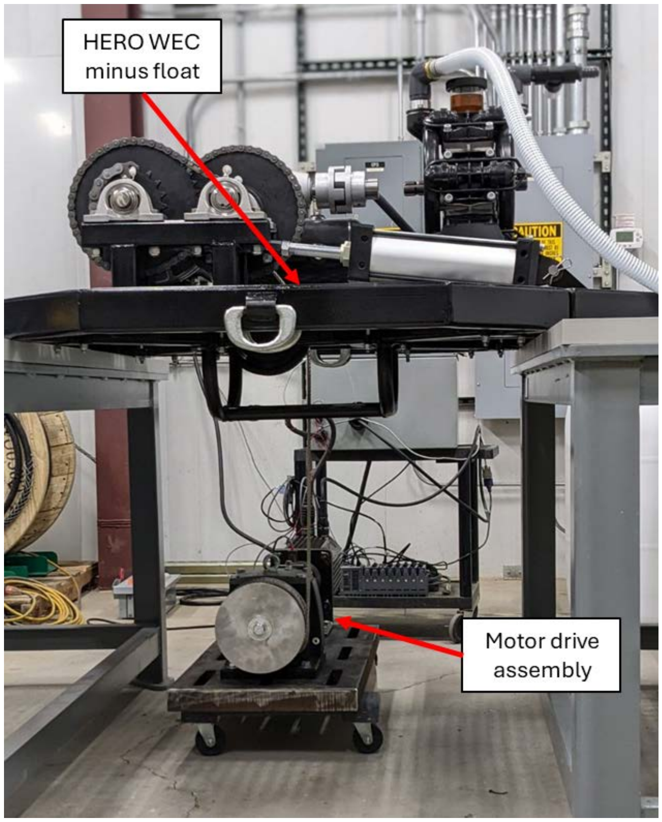

Figure 23. Single-DOF test setup at the NREL Flatirons Campus

Photo by Scott Jenne, NREL

Data for this test program have not been published because a higher-quality dataset was created in 2023 using NREL's large-amplitude motion platform (LAMP) in conjunction with higher-fidelity data. A description of this test program is provided in section 2.5.

2.3 Test Program 2: Waves to Water Prize De-Risking

The primary objective of this installation was to provide the Coastal Studies Institute (CSI) team with an opportunity to install a WEC before the Waves to Water Prize. The original plan was to deploy the hydraulic system for 5 days, then remove the WEC from the water and redeploy it in the electric configuration for another 5 days to replicate the duration of the Waves to Water Prize in each configuration. Due to severe weather conditions, the WEC arrived with the project partner, CSI, 3 days late. This delay caused the NREL and CSI teams to miss the weather window for deployment. However, the NREL team was able to assemble the WEC before returning home. Two weeks later, the NREL team returned to North Carolina to deploy the WEC.

Due to time constraints and a forecasted storm for the following weekend, the team shifted focus and prioritized only the installation and recovery aspects of the installation process (Figure 24) instead of performing the full 5-day test in either configuration. This test program did not result in any significant data collection from the WEC, but it did provide valuable learning opportunities for the prize team and ultimately led to a successful installation of four WECs during the final stage of the Waves to Water Prize.

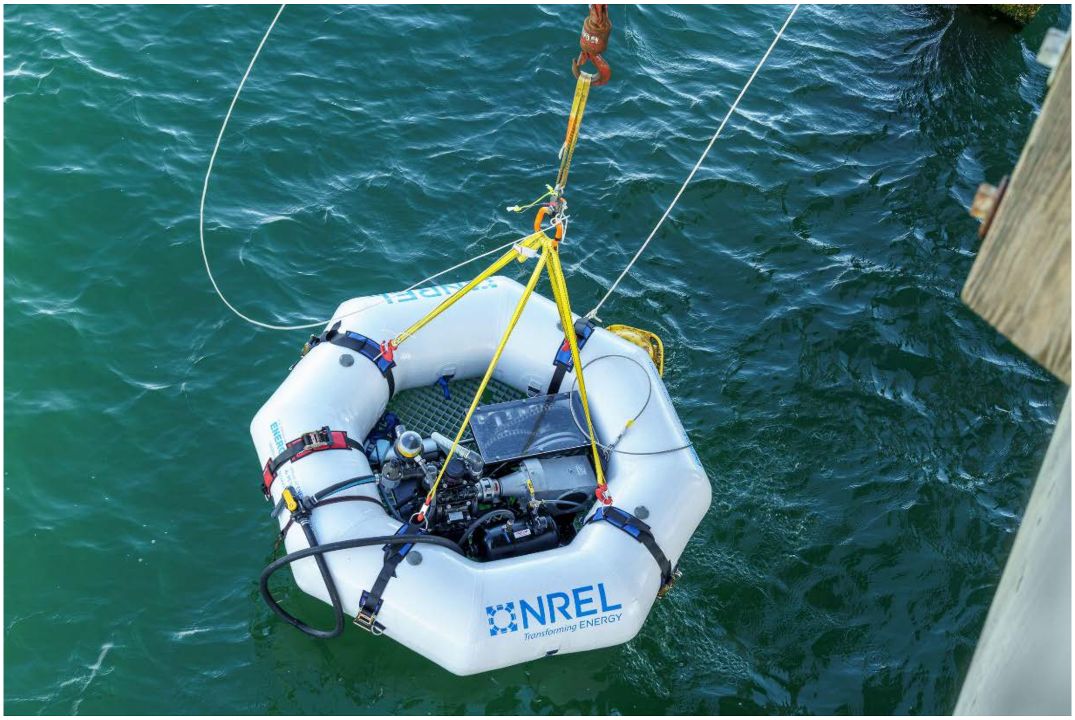

Figure 24. The HERO WEC being lowered over the side of the pier during the Waves to Water Prize practice installation

Photo by Andrew Simms, NREL

2.4 Test Program 3: August 2022 Deployment at Jennette's Pier

The third test program was another in-water deployment at Jennette's Pier that was initiated after the Waves to Water Prize final event in April 2022. Although installation occurred successfully for all the prize competitors, an unexpected storm came in the evening after installation. The storm disconnected three of the competitors' WECs from their anchors, while the fourth team picked up their anchor and damaged their transfer hose. Because the prize competitors' WECs operated near the surf zone, our team hypothesized that existing WEC models (e.g., WEC-Sim or other linear-theory-based models) were underestimating anchor loads. The NREL team determined that the HERO WEC could be used to test this hypothesis. In addition to evaluating anchor loads, the team also used this deployment to understand the feasibility of performing on-water PTO swaps, as well as to collect position data that could be used to evaluate more realistic wave conditions in a lab environment.

To quantify the anchor loads, the NREL team retrofitted the HERO WEC with the BB prototype data acquisition system. BB had been under development at NREL under an existing research effort and was a low-cost data acquisition system initially designed to monitor shock loads and device position. The system is designed for deep water in situ measurements where low power consumption is required—approximately 300 milliwatts—allowing it to be operated for approximately 2 weeks without an additional power source. These attributes made it a suitable option—requiring minimal development time—to evaluate anchor loads without additional data or power cables running to the surface.

During this deployment, chafe protection was installed on the cable from the load cell to the data acquisition system to mitigate abrasion. Unfortunately, the chafe protection put additional strain on the connector, causing it to disconnect during installation. Attempts were made to reconnect the connector underwater, but these were unsuccessful. Later in the deployment, the team was able to recover the WEC and successfully perform an on-boat PTO swap (Figure 25). During the swap, the team attempted to repair the BB data acquisition system, but this was ultimately unsuccessful, preventing the team from meeting the objective of quantifying anchor loads.

Figure 25. NREL and CSI teams performing a PTO swap on the CSI work vessel

Photo from John McCord, CSI 74194

Despite the lack of load measurements, reliable winch position measurements were collected. Using these data, the NREL team was able to translate the winch observations into a motion profile that was used on NREL's motion platform to replicate the loads in the lab. Using these measurements and those collected from the 2024 deployments, they determined that, with proper calibration, linear models are adequate for quantifying anchor loads.

2.5 Test Program 4: LAMP Testing at the NREL Flatirons Campus

The fourth test program was initiated in August 2023 using NREL's Large Amplitude Motion Platform (LAMP) (National Renewable Energy Laboratory 2023c). LAMP is a six-DOF test platform, manufactured by E2M Technologies (E2M Technologies 2024). The platform is capable of replicating wave profiles or device-response motion profiles to validate marine energy device prototypes. In this test program, LAMP was limited to preprogramed one-DOF (heave) and two-DOF (heave and surge) test profiles. Given that these test profiles were preprogrammed and the motion profile is not impacted by the WEC response force, it is more accurate to refer to these tests as "wave response profiles" and not "wave profiles." In simple terms, in order for the HERO WEC to experience a 1-m heave response, a wave with a wave height larger than 1 m would be required. Nonetheless, these preprogrammed motion profiles are still valuable in understanding how the WEC behaves under a variety of conditions and provide a useful dataset for numerical model tuning. The other four DOFs were removed from the test profiles because HERO WEC is a point absorber where most of the power potential comes from heave and surge motion.

2.5.1 Test Setup

The HERO WEC was mounted to the motion platform using an adapter frame. The WEC was secured to the adapter frame at six points on the outside edge of the HERO WEC frame (Figure 26).

Figure 26. HERO WEC and adapter frame being secured to LAMP

Photo by Josh Bauer, NREL 81575

In the lab, the structural floor was used as an anchor point instead of a gravity-based anchor, which is used in ocean installations (Figure 27). The winch line was anchored to the floor with an in-line tension link load cell to measure anchor loads. Because the motion platform is capable of loads that far exceed the design loads of the HERO WEC, a safety pin was installed so that if loads exceeded a threshold, the mooring line would break free before damaging the WEC. The safety pin was also integrated into the LAMP emergency stop circuit so that if it were to break, LAMP would instantly stop, preventing unnecessary damage to the equipment.

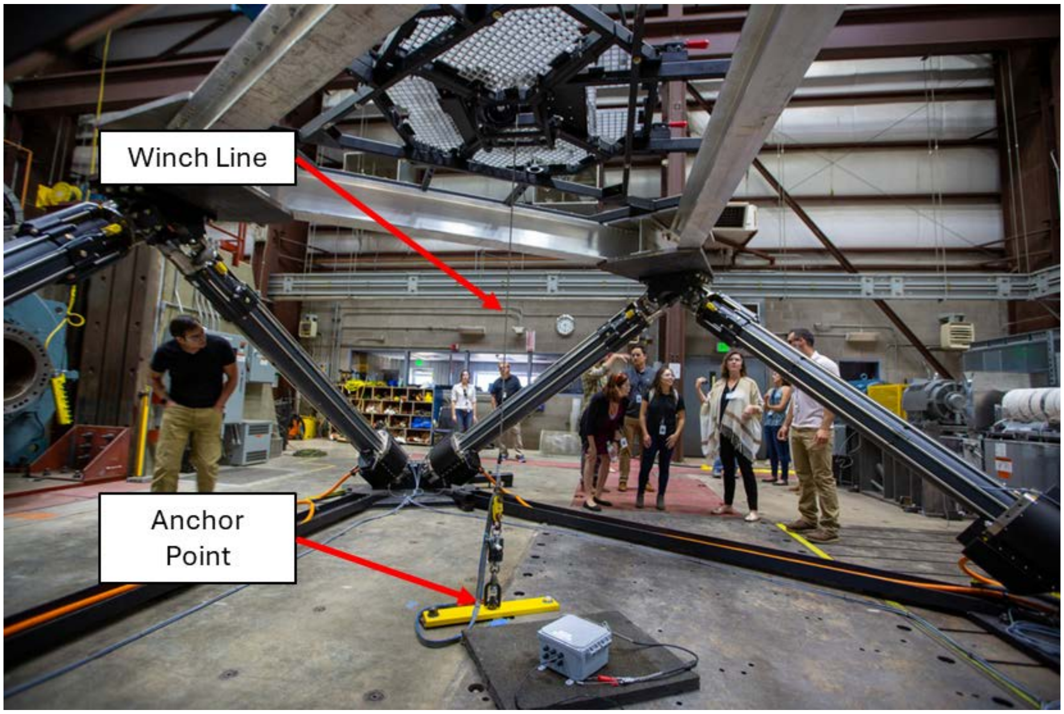

Figure 27. Image of the anchor connection point

Photo by Josh Baurer, NREL 83442

To evaluate the desalination capabilities and provide accurate loads, for both the electric and hydraulic configurations, the full RO module was coupled to the WEC. In the hydraulic configuration, the full 500 feet of transfer hose was plumbed to the WEC, and in the electric configuration, the full 500 feet of cable, submersible pump, and dedicated submersible pump transfer hose was installed in the lab. Given that an RO system will not produce adequate pressure without the appropriate salinity, a tank filled with a solution of sodium chloride and water was used as a feed water source. The solution was approximately 35,000 parts per million of sodium chloride to water and used as a proxy for ocean water. The intake of the hydraulic pump and the electric submersible pump were submerged into the tank, and both the produced clean water (permeate) and rejected brine were plumbed back into the tank to achieve a closed-loop operation. In the hydraulic configuration, both pressure relief valves were also plumbed back to the tank. Renderings of the different tank configurations are shown in Figure 28.

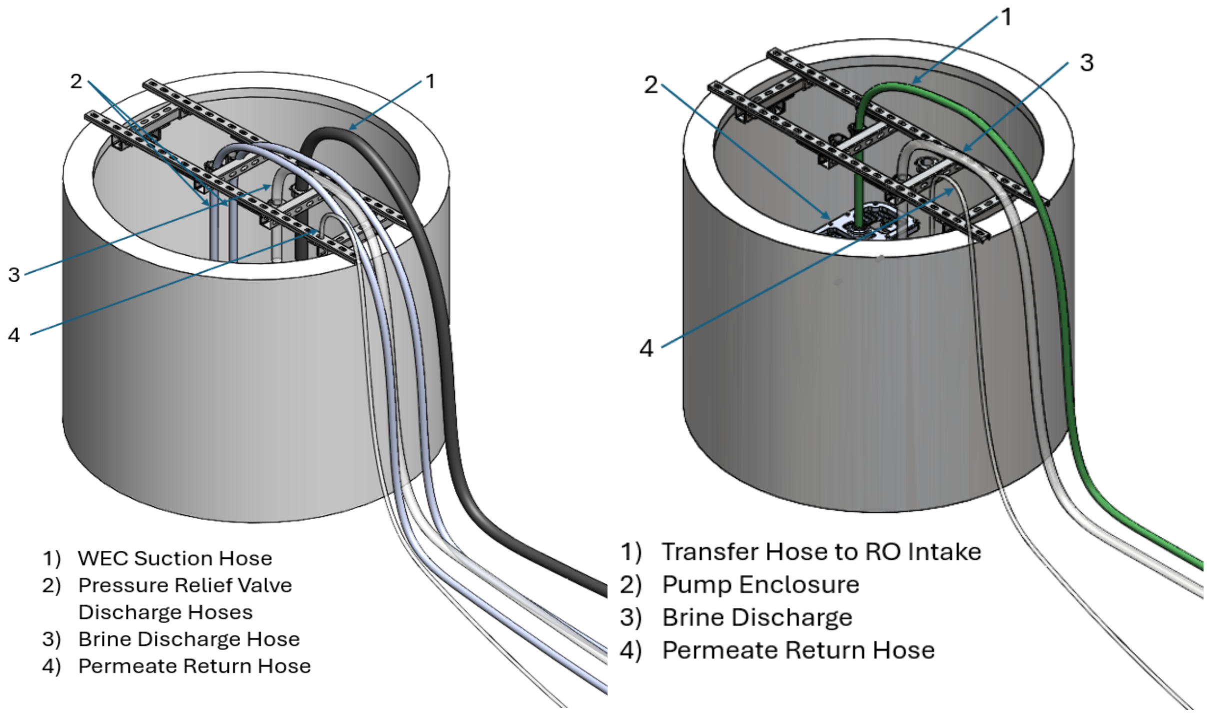

Figure 28. Renderings of the HERO WEC hose routing and seawater tank in both the hydraulic (left) and electric (right) configurations

Image by Justin Panzarella, NREL

Data collection during testing was performed using the data acquisition system described in section 1.5. For lab tests, to eliminate unnecessary battery replacement, MODAQ was used to collect data from the anchor load cell as opposed to the submersible data acquisition system (BB) used during in-water deployments. All the data collected were visualized in real time to a computer located in the LAMP control room and were written to a shared drive for later access and analysis. All the data that have been collected and processed are currently available through MHKDR submission number 520 (Panzarella, et al. 2024).

2.5.2 Test Cases

Tests were conducted with the HERO WEC in three different configurations: drivetrain, hydraulic, and electric. In the drivetrain configuration, the HERO WEC was operated without a pump or generator to collect data on anchor loading used to quantify frictional losses within the drivetrain alone (e.g., gearbox, bearings, and spring return assembly). The wave profiles used in each test case were either two-dimensional heave and surge motion profiles or one-dimensional heave-only motion profiles. Four types of wave cases were used during testing:

- One-DOF (heave) monochromatic wave (i.e., single amplitude and frequency)
- Two-DOF (heave and surge) monochromatic waves
- Two-DOF (heave and surge) multichromatic, or irregular, waves (i.e., varying amplitude and frequency using the Bretschneider spectrum)
- One-DOF (heave) profiles developed from encoder position data collected during the deployment described in section 2.4.

Additional information on the wave profiles used during testing can be found in Table 4, and sample motion profiles are shown in Figure 29.

Table 4. LAMP Test Wave Profiles

Abbreviation	Type	Degrees of Freedom	Number of Wave Sets	Test Length [s [a]]
Heave	Monochromatic	1	3	180
DW[b]	Monochromatic	2	5	1950
IR[c]	Multichromatic	2	1	1950
RW[d]	Translated Encoder Position	1	1	2000

[a] Seconds.
[b] Deep water.
[c] Irregular.
[d] Real world.

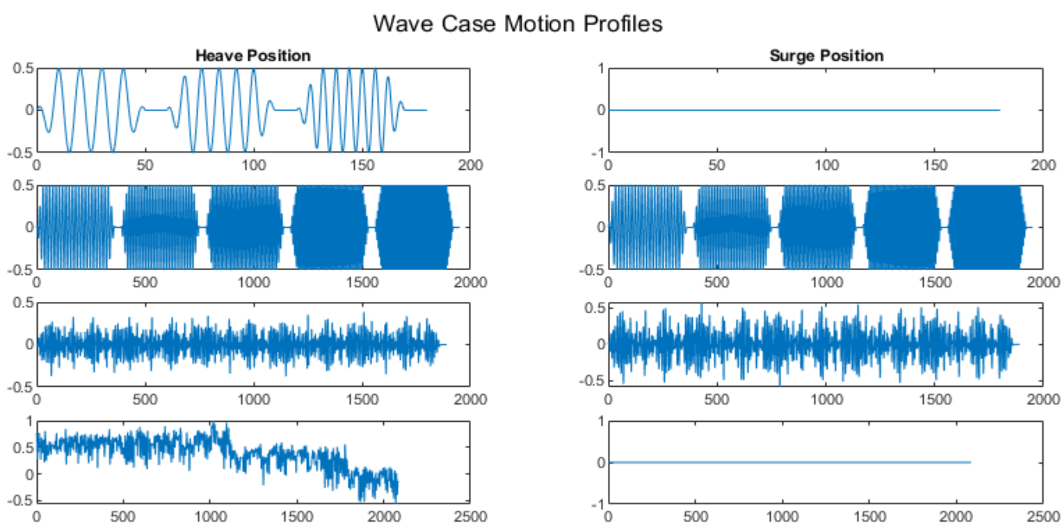

Figure 29. Example heave and surge motion profiles for one-DOF monochromatic sine waves (top), two-DOF sine waves (second from top), two-DOF multichromatic waves (third from top), and one-DOF encoder data profiles (bottom)

Image by Justin Panzarella, NREL

2.5.3 Data Processing

During the test program, raw data from the MODAQ sensor groups were collected in TDMS files that were saved every 10 minutes to manage storage and file size constraints. These files were later processed using Python, which concatenated and merged them into chronological data frames. The data were interpolated to a common set of timestamps and underwent quality control checks, resulting in nine Parquet files per test, each containing raw and interpolated data. Specific Parquet files were used for further analysis, depending on whether hydraulic or electrical cases were being examined, due to the differing sample rate requirements.

To address data collection issues, especially with the anchor load cell, a MATLAB script was employed to read the Parquet files, apply necessary corrections, and incorporate simulated data where needed. Simulink models were iteratively tuned to match the recorded data, allowing accurate calculations across various configurations of the HERO WEC. The MATLAB script was then used to perform power and efficiency calculations, running the Simulink model to produce anchor load cell data where needed. The workspaces output by this script have been uploaded to MKHDR for public access. This repository includes processed data, a test run log indicating where simulated anchor load cell data were used, and additional documentation for use in further analysis. Table 5 summarizes the data that are publicly available on MHKDR from the LAMP test program.

Table 5. Summary of Data That Are Publicly Available From LAMP Test Program

Data Summary

Quantity	Description	Subsystem
Measured Values		
1	Anchor tension measurement	All
1	Encoder measurement for winch position	All
2	Conductivity measurement (RO system inlet and clean water production)	RO system
4	Pressure measurements (1 pump output and 3 points within the RO system)	Hydraulic and RO
5	Flow measurements (1 pump output and 4 points within the RO system)	Hydraulic and RO
8	Current measurements through power electronics enclosure (including DC pump current)	Electric and RO
10	Voltage measurements through power electronics enclosure (including DC pump current)	Electric and RO
Calculated Values		
25	Calculated arrays (e.g., power, efficiency, rotational speed)	All
33	Additional scalar value calculations (e.g., average values, cumulative values, minimum and maximum values)	All

Additional information on the data collection and processing from the LAMP testing and the 2024 in-water deployments can be found in the data descriptions document in the appropriate MHKDR submission accessed from the HERO WEC OpenEI page (National Renewable Energy Laboratory 2023b). These documents include expanded tables and sensor descriptions specific to each test program, along with an overview of the data processing methods and calculations used in each test program.

2.5.4 Simulink Tuning

After the test program was complete, the NREL team used the data to revisit the accuracy of the numerical PTO model for the hydraulic configuration. The electric configuration has not been tuned to the same level of detail given the significantly higher numerical run time required to capture the physics within the power electronics conversion. Tuning the hydraulic model consisted of an iterative process until an adequate agreement was reached across anchor loads, permeate production, and pressure and flow profiles throughout the hydraulic circuit.

For the LAMP tests that were run, the measured winch position was used to calculate a linear velocity profile that could be used as an input for the Simulink model. This method enabled an accurate comparison of experimental measurements and numerical simulation results. The numerical model was tuned progressively, meaning the simplest one-DOF drivetrain cases were tuned first, then the one-DOF hydraulic runs with the RO system bypassed, and finally the full RO system with both monochromatic and multichromatic waves. This approach was used to ensure that if the PTO is modified later (e.g., changing pump size), there would be a reduced risk of compounding error due to losses being accounted improperly. This tuning results in a model that has reasonable agreement across a variety of conditions with some minor variance due to the simplification of the Simulink model (see Figure 30).

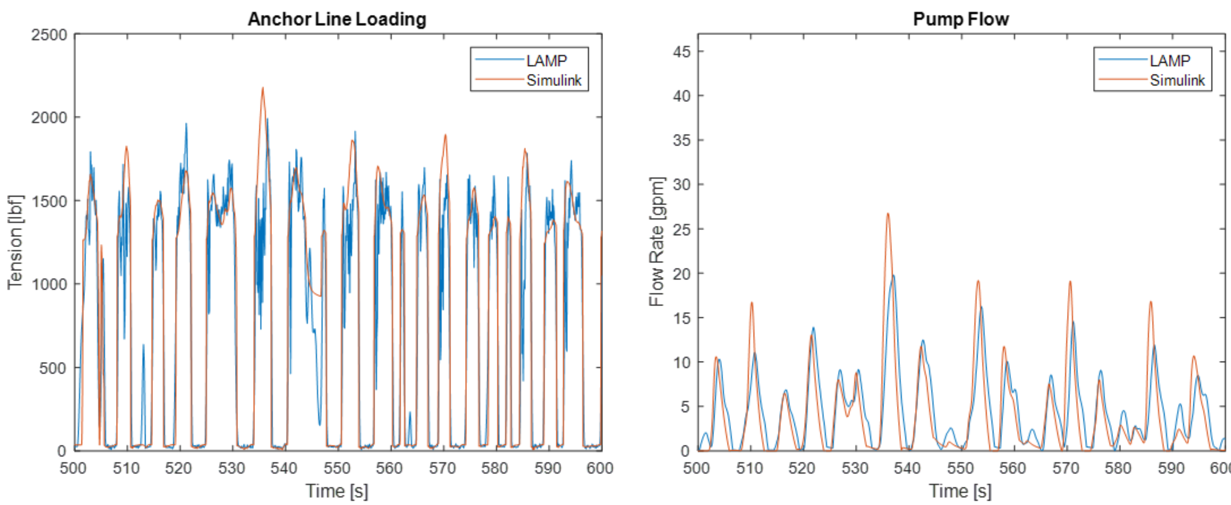

Figure 30. Comparison of the tuned numerical model and the experimental results (left: anchor line tension; right: pump flow)

Image by Justin Panzarella, NREL. lbf = pound-force; s = seconds.

2.5.5 LAMP Test Results

Each set of tests, as described in 2.5.2, had a different set of objectives and therefore was used for different purposes. The monochromatic heave and deep-water cases were collected for model calibration and as a simple set of tests to understand the overall system behavior. The translated encoder position tests were run to understand if the power electronic modifications that were made in 2023 were an improvement over the 2022 deployment. Those modifications include the addition of a capacitor before the charge controller, charge controller tuning curves, and removal of the DC-to-AC conversion after the battery bank. Lastly, the two-DOF multichromatic (i.e., irregular) wave profiles were used to quantify the performance potential of the WEC. As described in section 2.5, these are not direct representations of the wave height and period of the ocean environment because a preprogrammed position input was provided to the test platform. Therefore, the wave height and period that were run represent the WEC response and not the sea state.

The data created from these test profiles have been used to assemble the following performance matrices:

- Absorbed power (Figure 31): This matrix is calculated using the winch tension and linear velocity measured at the WEC for both configurations.
- WEC output power (Figure 32): For the electric configuration, this matrix is calculated using the voltage and current output of the generator. For the hydraulic configuration, it is calculated using the pressure and flow output of the pump.
- Electric DC power (Figure 33): This matrix is calculated using the voltage and current measured after the AC-to-DC rectifier for the electric configuration.
- RO hydraulic input power (Figure 34): This matrix is calculated for the hydraulic configuration using the pressure and flow measured at the inlet of the Clark pump in the RO system (after the accumulators and prefilters).
- RO production (Figure 35): This matrix is measured for the hydraulic configuration only, as the electric configuration runs at steady state off the battery bank.
    - Given that the electric system charges a battery bank and the RO system runs at steady state from the energy stored in the batteries, a matrix was not provided for the electric configuration, as every wave condition would result in the same measurements. Instead, the average power measurements before and after the charge controller are provided.

In addition to the differing operating principles, the DC charge controller used in the electric configuration was a poor match for the voltage profile that is typical of a WEC. For this reason, many of the wave cases were not run because the net power production of the electric system was negative. This outcome was primarily due to two phenomena that were observed during testing. The first is that many of the lower-amplitude wave cases did not produce a voltage at the charge controller input that was high enough to convert into battery storage (32-V DC threshold). Additionally, the charge controller was originally designed for a solar and wind application where large variances in voltage are expected to happen at a much slower rate than for a wave energy application. For those reasons, the charge controller was unable to efficiently convert energy during any of the tests.

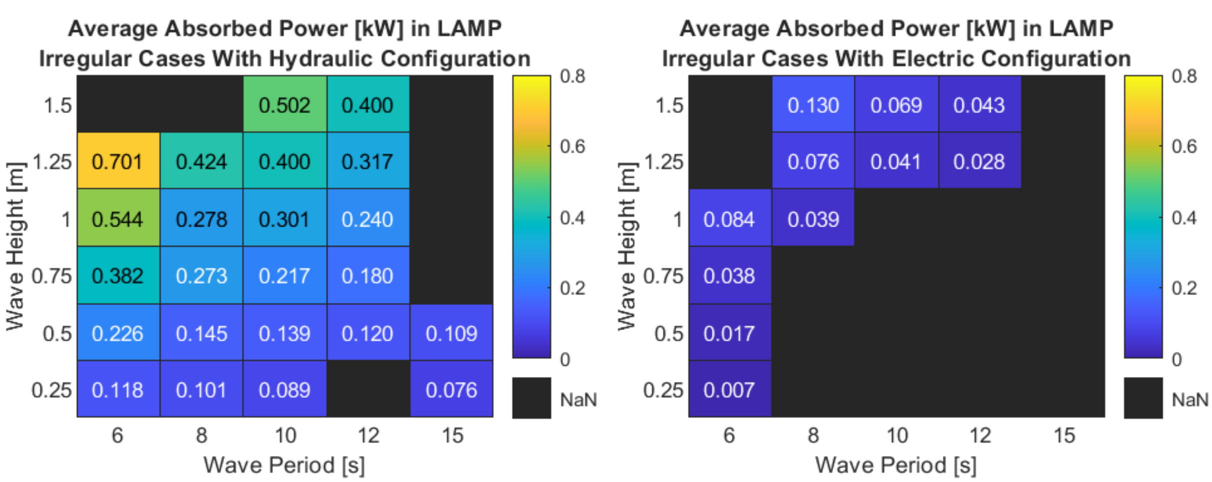

Figure 31. Absorbed power matrix in the hydraulic (left) and electric (right) configurations

Image by Justin Panzarella, NREL. s = seconds.

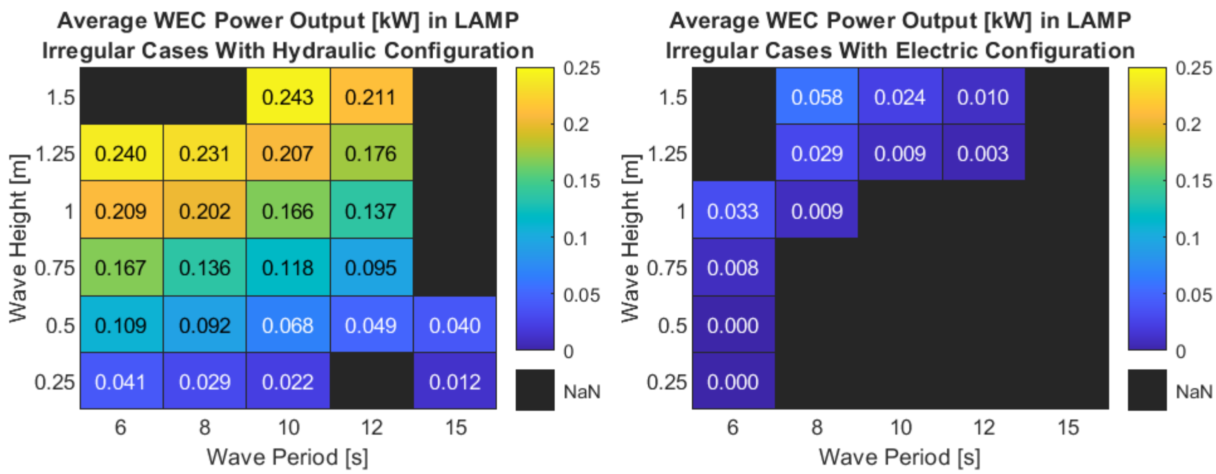

Figure 32. Average WEC power output of the HERO WEC in both PTO configurations with two-dimensional multichromatic wave profiles

Image by Justin Panzarella, NREL. s = seconds.

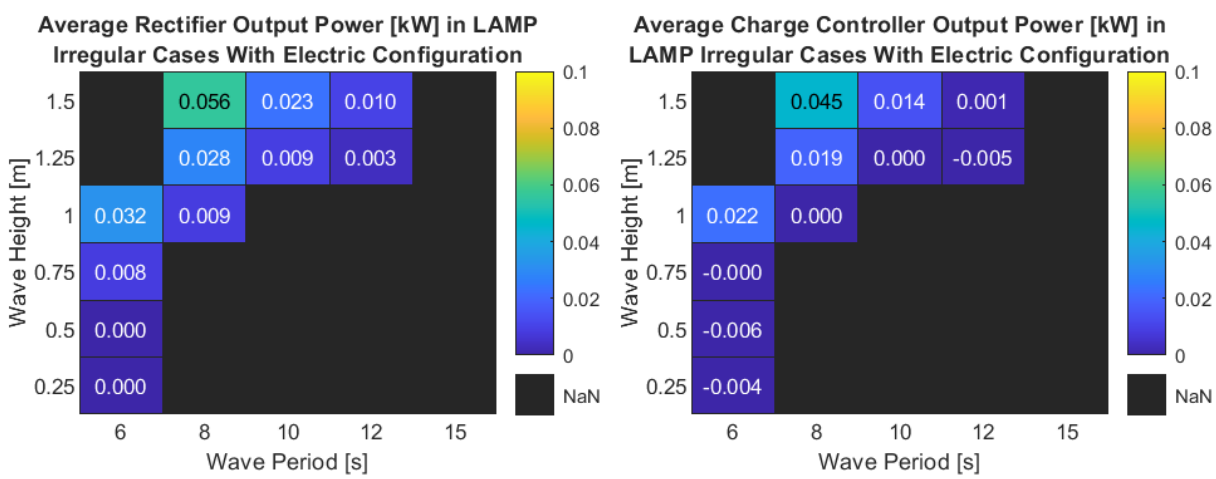

Figure 33. Average electric DC power measured at the rectifier output (left) and charge controller output (right) for the electric configuration

Image by Justin Panzarella, NREL. s = seconds.

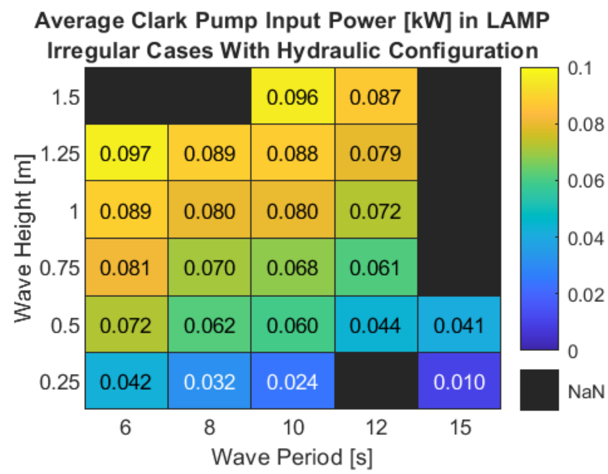

Figure 34. Average hydraulic power at the RO inlet for the hydraulic configuration

Image by Justin Panzarella, NREL. s = seconds.

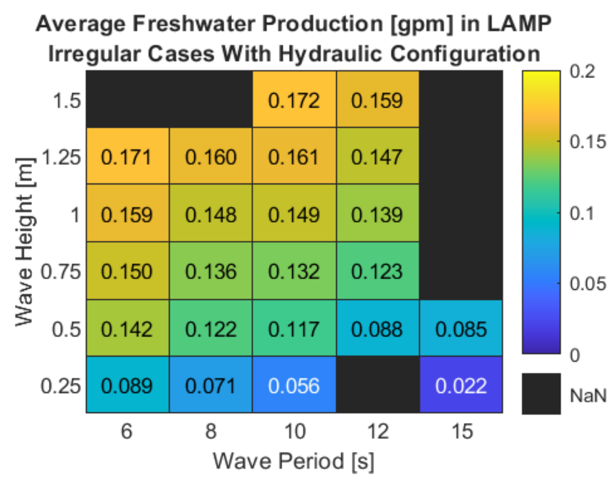

Figure 35. Average Freshwater (permeate) production for the hydraulic configuration

Image by Justin Panzarella, NREL. s = seconds.

The results from LAMP testing show that the hydraulic configuration of the HERO WEC is capable of transmitting more useful power to the land-based RO system than the electric configuration. This outcome is primarily due to the limits of the charge controller and electrical conversion losses, as described in the previous paragraph, and the fact that there are fewer conversion steps. When comparing the two configurations side by side, the hydraulic configuration experiences more mechanical losses in the form of friction at the pump. These losses are apparent when comparing the test cases where the RO system was bypassed. However, the electric configuration also has many more conversion processes than the hydraulic configuration (Figure 36)—the electric configuration has 8 conversion steps after the generator, whereas the hydraulic configuration has only 3 steps after the pump, and of those 3 hydraulic conversion steps, the pressure relief valves do not introduce significant losses into the system until higher energy conditions. Although pumps tend to have a significant reduction in overall efficiency when compared with permanent magnet generators, there are additional losses associated with electric systems that ultimately still require at least a small steady-state pump for desalination applications. Note, however, that one of the largest potential benefits of an electric configuration is the ability to integrate more advanced active control strategies that have the potential to increase power absorption. For this reason, the HERO WEC team will plan to develop a more comparable charge controller in the next few years that can provide a more accurate comparison between the two system configurations.

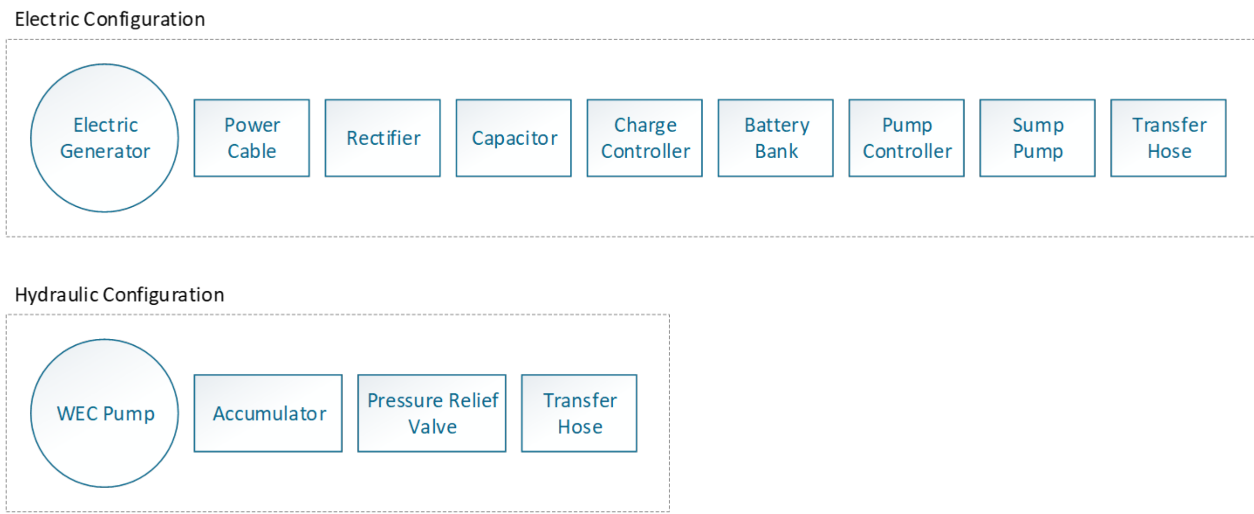

Figure 36. The conversion processes for each system prior to the RO system

Image by Scott Jenne, NREL

In the hydraulic configuration, the RO system was supplied with an average of 10 watts (W) of hydraulic power during the least energetic wave case and just under 100 W during the most energetic wave cases, whereas in the electric configuration, the charge controller output an average DC power of less than 50 W during the most energetic wave case. During LAMP testing, the HERO WEC team also observed that the device consistently absorbed more power in the hydraulic configuration than in the electric configuration for any given wave case. This difference in absorbed power is attributed to the charge controller's relatively slow response time. Within the power electronics system, the charge controller is used to determine the current draw of the system based on the post-rectifier voltage at any given moment. Because the current draw is directly correlated to the torque required to spin the generator input shaft, the winch tension of the device is greatly influenced by the programming of this component. Given that winch tension is a major factor in calculating the device's absorbed power, the instantaneous current draw selected by this component directly impacts the device's instantaneous absorbed power. The team also observed that the average power output of the charge controller was negative under numerous low-energy wave conditions, which was the result of the power draw required to keep the charge controller operating exceeding the useful power output of the component. In these cases, the land-based batteries were discharged to power the charge controller.

2.6 Test Program 5: March/April 2024 Deployment at Jennette's Pier

After testing the upgraded HERO WEC system at the NREL Flatirons Campus, the HERO WEC team deployed the system at Jennette's Pier (Figure 37). At this test site, the HERO WEC was moored to a 4000-lb chain pile in approximately 2–3 m of water. The HERO WEC mooring was approximately 100 m south of the Jennette's Pier research hut, where the land-based systems were located approximately 30 feet above mean sea level.

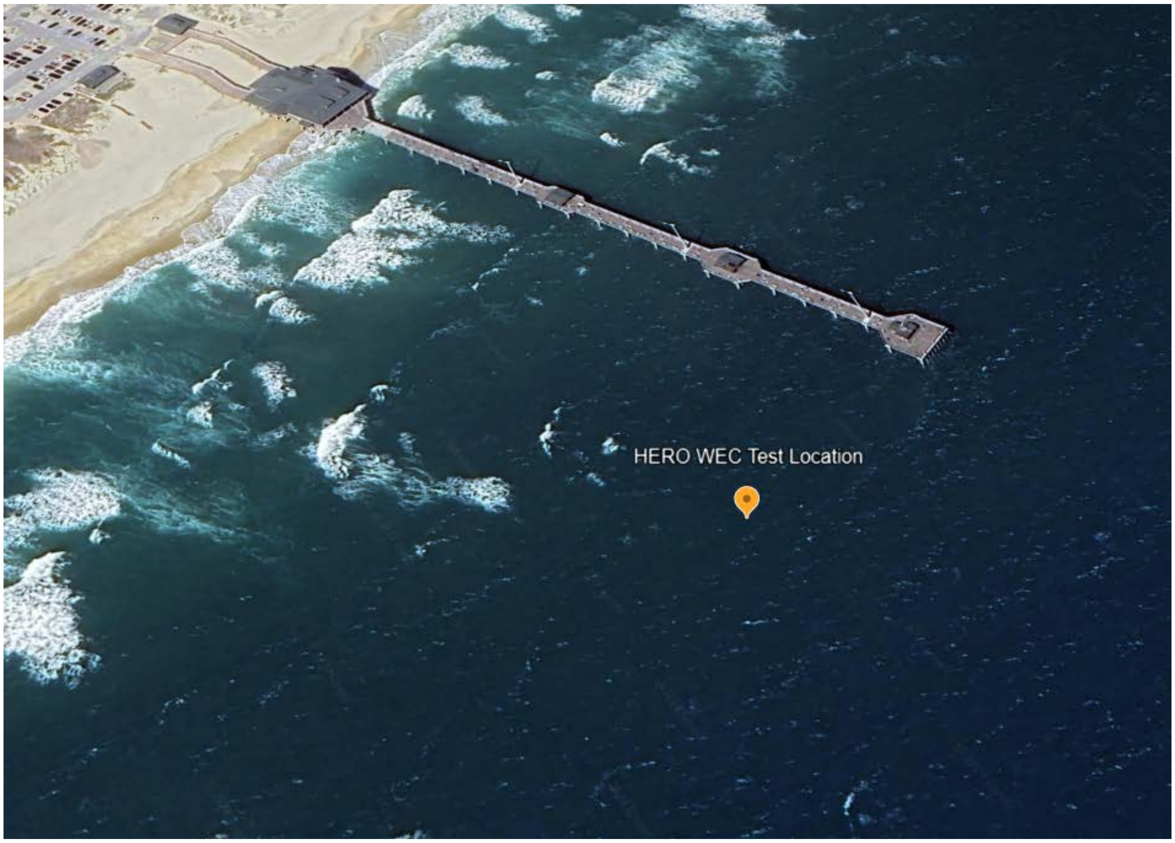

Figure 37. Satellite image of the Jennette's Pier test site

Image from Google Earth

All data from both the hydraulic and electric deployments were processed using a similar method to that used for the data collected on LAMP. In addition to the data collected by the MODAQ system, data wave observations during the deployment were collected from a nearby Coastal Data Information Program (CDIP) buoy #243 (UC San Diego 2024) owned and maintained by CSI to provide accurate sea-state measurements directly offshore of the HERO WEC. The Datawell Waverider buoy is approximately 10 miles directly offshore of the deployment site in approximately 21 m of water, while the HERO WEC was deployed in 2–3 m of water. Therefore, these measurements should inform the range of conditions that the WEC experienced in each deployment despite not being made at the site or the same depth. Data from the electric and hydraulic configuration deployments along with supporting documentation and data processing scripts have been published in MHKDR submissions 551 (Jenne, Panzarella, et al. 2024) and 555 (Jenne, Panzarella, et al. 2024b), respectively. A 5-hour sample of the half-hour summary data for each deployment is shown in Table 6 and Table 7.

Table 6. Sample of Half-Hour Summary Data From Hydraulic Configuration Deployment

Time	Wave Height [m]	Period [seconds]	Absorbed Power [kW]	WEC Output Power [kW]	Permeate Flow Rate [gpm]
3/15/2024 23:00	0.8	11	0.11	0.01	0.00
3/15/2024 23:30	0.8	12	0.13	0.01	0.01
3/16/2024 0:00	0.8	11	0.10	0.01	0.00
3/16/2024 0:30	0.9	5	0.07	0.00	0.00
3/16/2024 1:00	0.9	11	0.10	0.01	0.00
3/16/2024 1:30	0.8	5	0.13	0.01	0.01
3/16/2024 2:00	0.8	11	0.14	0.01	0.01
3/16/2024 2:30	0.8	5	0.15	0.01	0.01
3/16/2024 3:00	0.8	12	0.22	0.01	0.02
3/16/2024 3:30	0.7	11	0.18	0.01	0.01
3/16/2024 4:00	0.7	11	0.20	0.01	0.02

Table 7. Sample of Half-Hour Summary Data From Electric Configuration Deployment

Time[a]	Wave Height [m]	Period [seconds]	Absorbed Power [kW]	WEC Output Power [kW]	Permeate Flow Rate [gpm]
4/18/2024 23:30	0.9	9	0.48	0.05	0.00
4/19/2024 0:00	0.9	11	0.46	0.05	0.00
4/19/2024 0:30	0.9	9	0.49	0.06	0.00
4/19/2024 1:00	1.0	10	0.58	0.07	0.00
4/19/2024 1:30	1.0	10	0.59	0.07	0.00
4/19/2024 2:00	–	–	0.60	0.07	0.00
4/19/2024 2:30	1.0	4	0.73	0.08	0.00
4/19/2024 3:00	1.0	4	0.77	0.09	0.00
4/19/2024 3:30	1.1	9	0.98	0.10	0.00
4/19/2024 4:00	1.1	4	1.05	0.11	0.00
4/19/2024 4:30	1.2	5	1.27	0.15	0.00

[a] The submersible pumps were turned off during this time span, allowing the batteries to charge.

This test program consisted of an individual deployment for each PTO configuration. Over the two deployments, a total of 113 hours of data was collected—94 hours of which was collected in the hydraulic configuration, with the HERO WEC producing a total of 350 gallons of clean water before the transfer hose was cut because of the WEC spinning and twisting the hose around the wire rope. A plot of the clean water (permeate) production during the 6-day deployment versus the measured wave data from CDIP buoy #243 is shown in Figure 38. Due to the wave measurements not coming from the same location as the WEC, variances in wind conditions, changes in tide, and other variables that are not measured, water production does not directly correlate to significant wave height. However, the plot does show a range of production capacity that can be expected.

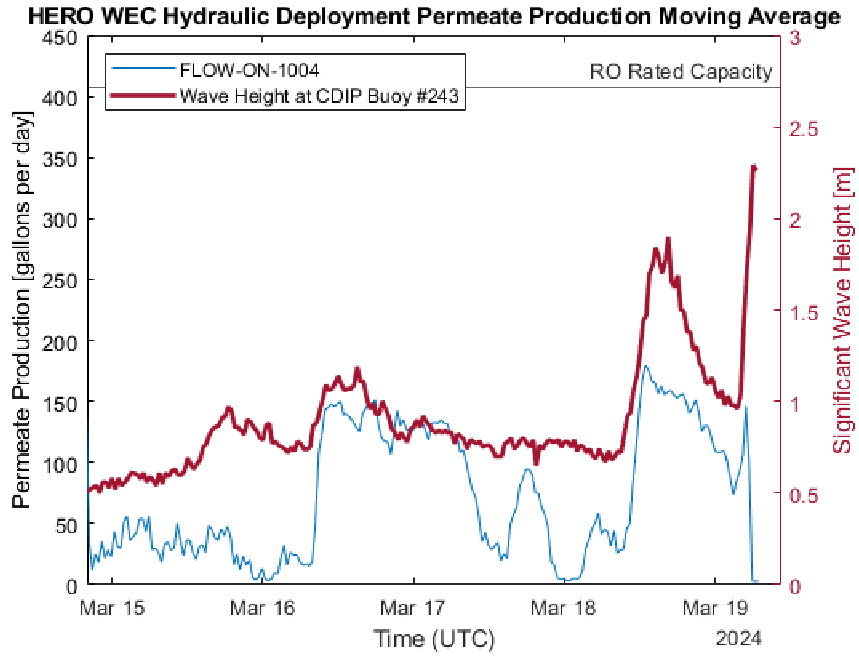

Figure 38. 30-minute moving average of permeate flow rate plotted with 30-minute wave height data from CDIP buoy #243 during the 2024 hydraulic configuration deployment

Image by Justin Panzarella, NREL. UTC = Coordinated Universal Time.

In the electric configuration, 19 hours of continuous data was collected before the system broke free from the anchor. The RO system could not be commissioned on the same day as the WEC installation, so the submersible pumps were turned off overnight to prevent the batteries from discharging. This decision was made due to the prediction of minimal wave conditions overnight. Unfortunately, the wave conditions increased, resulting in the battery system reaching a full state of charge around 2 a.m. ET and ultimately leaving no electric load on the system. This situation caused the PTO loads to be undesirably low for such energetic conditions, resulting in repeated end-stop events that cut the winch line, eventually leaving the WEC inoperable. During the deployment, valuable data on the electrical system were gained during the hours when the batteries were charging. Additionally, valuable data and lessons learned regarding survival strategies for winch-based point absorber WECs were gained from this deployment.

3 Conclusion

Throughout the testing programs, the HERO WEC demonstrated its effectiveness as a proof-of-concept prototype for desalinating seawater in nearshore environments. However, several improvements have been identified to prepare the system for longer-term deployments and operation in more challenging wave environments. During the initial tests, the HERO WEC showed that short-term desalination using a small WEC and RO system is feasible in both direct hydraulic and electric configurations. After addressing the challenges encountered in the first two deployments, the LAMP system was employed to characterize the HERO WEC system, followed by additional in-water testing at Jennette's Pier. The final test at Jennette's Pier confirmed the HERO WEC system's effectiveness in low-energy wave conditions, as well as its ability to function in more energetic sea states. However, the 2024 test validated the need to design a more robust, storm-resistant WEC capable of sustained operation over longer durations. Additional information on the design, laboratory and in-water data, and the SolidWorks assembly files can be found on the HERO WEC website: https://openei.org/wiki/HERO-WEC.

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