Lessons Learned: Summary of Insights From the HERO WEC and Waves to Water Deployments Between 2022 and 2024

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2 East Carolina University, Coastal Studies Institute

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

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Technical Report
NREL/TP-5700-92489
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Suggested Citation
Jenne, Scott, Justin Panzarella, Andrew Simms, Ben McGilton, Alec Schnabel, Mark Murphy, Kyle Swartz, Michael Muglia, Patterson Taylor, and Lindsay Wentzel. 2025. *Lessons Learned: Summary of Insights From the HERO WEC and Waves to Water Deployments Between 2022 and 2024*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5700-92489. https://www.nrel.gov/docs/fy26osti/92489.pdf.

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This work was authored in part by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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List of Acronyms

CSI	Coastal Studies Institute
DAQ	data acquisition
HERO	hydraulic and electric reverse osmosis
NREL	National Renewable Energy Laboratory
PVC	polyvinyl chloride
WEC	wave energy converter
WPTO	Water Power Technologies Office

Executive Summary

In 2020, a team from the National Renewable Energy Laboratory (NREL) partnered with the East Carolina University Coastal Studies Institute to develop a small, modular, wave-powered point absorber desalination prototype. That prototype, known as the hydraulic and electric reverse osmosis (HERO) wave energy converter (WEC), was intended to de-risk the installation activities planned for the Waves to Water Prize (Water Power Technologies Office [WPTO] 2021). The NREL team was given approximately 18 months to design, build, bench test, and deploy the HERO WEC prototype.

The project initiated shortly after the COVID-19 lockdown period; therefore, it was determined that, wherever possible, the design should leverage commercially available off-the-shelf components and simple fabrication techniques to mitigate risks associated with project delays and supply chain limitations. Despite these limitations, the team was able to successfully execute the project.

Since the initial HERO WEC development, it has been used for two in-lab test programs and three ocean deployments. The first in-lab test program (December 2021–January 2022) focused on ensuring that the overall operation of the device occurred as expected and on validating the operation of safety systems such as pressure relief valves or electrical breakers for load mitigation. The second in-lab test program (August 2023–September 2023) was the first time the NREL team leveraged NREL's large-amplitude motion platform to characterize the performance of the HERO WEC (WPTO 2023). Of the three in-water deployments, the first deployment (March 2022) was effectively an installation and recovery practice with no meaningful wave activity during the time that it was installed. The second deployment (August 2022) was a 2-week effort that enabled both the electric and hydraulic configurations of the device to be in the water for approximately 5 days each. This deployment was also the first time that the team had the opportunity to perform a drivetrain swap on the Coastal Studies Institute research vessel. The third deployment (March 2024–April 2024) had to be split into two separate installations due to minor damage incurred from the WEC spinning during the initial installation.

The laboratory data that were collected during the 2023 in-lab test program have been processed, sorted, and made public through the Marine and Hydrokinetic Data Repository (Panzarella 2024). The data collected during the third in-water deployment have also been processed, sorted, and made public through the Marine and Hydrokinetic Data Repository, and both datasets will be used to inform a second iteration of the technology that will be designed for longer deployment timelines.

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1 Wave Energy Converter Overview

The hydraulic and electric reverse osmosis (HERO) wave energy converter (WEC) was initially developed to de-risk the competitor metrics and expected operational challenges of the Waves to Water Prize (Water Power Technologies Office [WPTO] 2021). The HERO WEC is a single-body, fixed-reference point absorber (i.e., a floating buoy directly anchored to the seabed) which supplies power to a reverse osmosis system to desalinate seawater using either an onboard hydraulic pump or electric generator. The buoy is composed of a steel structural frame attached to an approximately 2-meter-diameter octagonal float manufactured from polyvinyl chloride (PVC) fabric, similar to many whitewater raft designs. The WEC is tethered to a 4,000-pound bundled anchor pile on the ocean floor by a taut, 5/16-inch, braided, stainless-steel wire rope (7×19 braid). The wire rope is wrapped around a winch drum that enables the WEC to translate translational heave (up and down) and surge (back and forth) motions into rotational shaft motion. Attached to the winch on one side is a pneumatic spring system that is used to rewind the winch after each wave cycle, and on the other side is a gearbox that drives either a rotary generator (electric configuration) or a rotary pump (hydraulic configuration). More information on the design and test programs conducted with this WEC can be found in the HERO WEC design and experimental data report (Jenne et al. 2024).

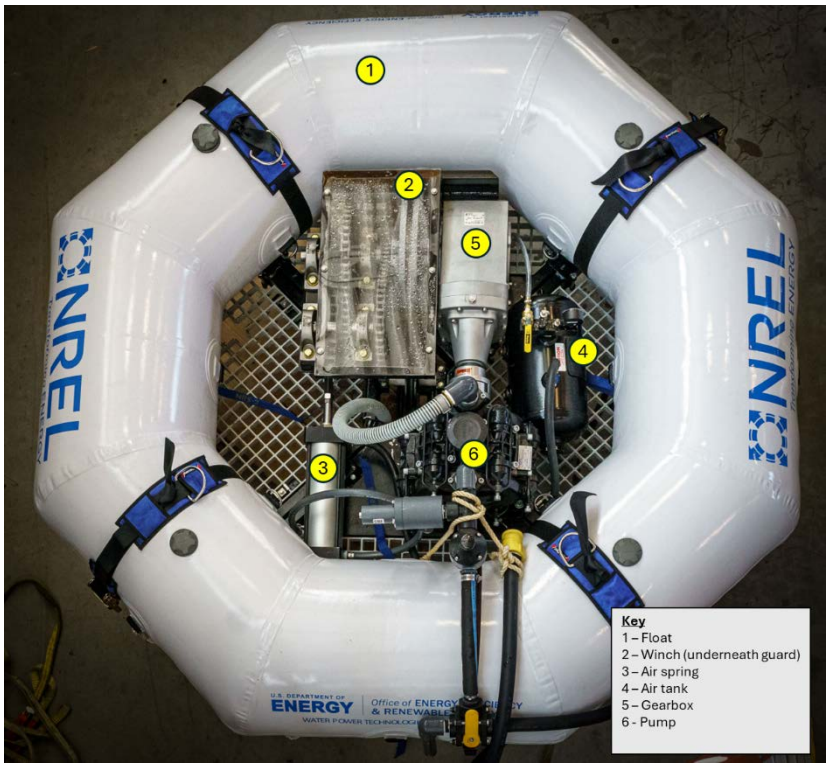

Figure 1. Top-down view of HERO WEC.

Photo by Andrew Simms, NREL

The areas of the Waves to Water Prize that the HERO WEC team prioritized to de-risk during the initial development are as follows:

- **Installation and recovery:** Waves to Water was planned as a timed event (5-day window), and five competitors were awarded during the CREATE Stage of the prize and invited to compete in the final DRINK Stage (WPTO 2021). For this reason, the prize team needed to have a representative technology that could be used prior to the prize to evaluate an installation technique using a pier-mounted crane, a dive team, a bundled-chain-pile anchor, and available small watercraft.
- **A modular WEC:** The HERO WEC needed to represent two different concepts for wave desalination: a WEC that can pump water directly through a desalination system without electricity production and—a more traditional renewable energy approach—a WEC that produces electricity to charge batteries and power an electric pump. Both configurations represent different challenges related to installation, standardized connectors, pier footprint, and personnel safety.
- **Technical requirements evaluation:** Prize competitors were given a set of minimum technical requirements (Table 1) and metrics were developed to measure the success of competitors meeting these requirements. The HERO WEC was used to evaluate the feasibility of these metrics prior to the beginning of the prize.

Table 1. Waves to Water Prize Minimum System Technical Requirements[a]

Minimum System Technical Requirements	
Water Quality	Must be able to produce water with a maximum total-dissolved-solids level of 1,000 milligrams per liter over the competition period. Fluctuations in this level are acceptable as long as the combined average does not exceed 1,000 milligrams per liter.
Produced Volume	At least 400 liters of water are produced during the in-water testing period. If, for any reason, the in-water testing period is less than 5 days, the required produced volume metric will be reduced accordingly.
Shipping Weight	Systems cannot exceed 650 kilograms.
48-Hour Setup	Teams must demonstrate that their systems can be set up within two 10-hour windows.
Battery Storage Capabilities	Batteries are not a requirement of the system; however, no more than 0.5 kilowatt-hours of battery capacity can be included. Once these batteries are discharged, the batteries must ONLY be powered by wave energy.
Other Energy Sources	All energy for desalinating water must come from wave energy. No other renewable sources will be allowed for the primary function of desalination (e.g., tidal, solar, wind). However, other energy sources can be used for ancillary purposes, such as system monitoring and system control.

[a] Table contents from WPTO (2021)

Given the above requirements, available budget, and constraints, two very critical compromises would be made for the HERO WEC that would not be suitable for traditional WEC designs. The first was a reduction in the design life of materials, components, and subsystems. The prize was only a 5-day event; hence, the design team determined it would not be necessary, cost-effective, or feasible to design a WEC to meet the design life requirement typical of most wave energy systems, i.e., greater than 1 year. For certain components on a wave energy system, a 1-year design life can translate to 4–5 million cycles per year. Many of the commercially available, off-the-shelf components that the team evaluated have a design life between 20,000 and 200,000

cycles. For this reason, a minimum design life of approximately 200,000 cycles was determined to be adequate for the de-risking of the Waves to Water Prize.

The second area of compromise, particularly for a research asset, was the decision to eliminate onboard instrumentation. This decision was made with the U.S. Department of Energy Water Power Technologies Office due to two critical factors:

- The WEC was not intended to be a research platform. Given that the primary objective was to provide the installation team with a prototype to practice installation, it was not necessary to collect typical performance or model validation data.
- Given the available budget and project timelines, designing a robust data acquisition (DAQ) system with adequate sampling frequency, onboard storage, and power was not appropriate for this effort.

The on-pier systems (power electronics enclosure and reverse osmosis module) did, however, have a low-power DAQ system to measure reverse osmosis feed flow and pressure as well as voltage and current through the power electronics system. After the Waves to Water Prize was finished in spring 2022, it was determined that the HERO WEC team should retrofit an existing National Renewable Energy Laboratory (NREL)-developed DAQ system to evaluate anchor loads, winch position, and device motion. The team had 3 months to design and build two DAQ systems to integrate into the existing system. The HERO WEC team leveraged an existing system that was under development by the NREL Modular Ocean DAQ (MODAQ) team, known as the "Black Box" DAQ. Two systems were built—one mounted on the WEC that could monitor winch position and location via GPS and a second system mounted on the mooring line to measure anchor loads. Challenges ultimately arose during the installation of this system due to excessive strain on the underwater connector caused by the anti-abrasion protection installed on the cable resulting in loss of connection between this cable and the load cell.

In preparation for the 2024 deployments, the on-pier DAQ system was replaced with NREL's higher-resolution MODAQ, system (NREL 2024). A more robust DAQ was installed on the WEC to replace one of the Black Box units. This system was designed to utilize shore power with a battery backup so that more power-intensive instrumentation could be installed and the system could run for a full 4-to-6-week deployment without battery replacement. This unit was designed with a more accurate GPS and motion tracking system (inertial measurement unit/inertial navigation system), a more robust winch encoder, an air pressure sensor to monitor air spring pressure, and a water pressure and flow sensor to monitor pump output in the hydraulic configuration. The anchor-mounted Black Box was rebuilt with a more robust connection and anti-abrasion protection.

2 Deployment Summaries

To provide further context, a summary of the deployment preparation activities, the three HERO WEC deployments, and the Waves to Water Prize deployment are described below. This section specifically highlights the challenges associated with each deployment, with subsequent sections focusing on lessons learned and design modifications that could prevent these challenges from arising in the future

2.1 Deployment 1—February/March 2022

The primary objective of this deployment was to provide the Coastal Studies Institute (CSI) 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 and then remove the WEC from the water and redeploy it in the electric configuration. To comply with the prize rules, the deployment team utilized a pier-mounted crane for installation. The WEC was shipped to CSI via FedEx, but due to severe weather conditions, it arrived at the institute 3 days late. This delay caused the team to miss the weather window for deployment. However, the NREL team was able to assemble the WEC before returning home. A few weeks later, the NREL team returned to North Carolina to deploy the WEC.

To minimize wasted time, the team used this as an opportunity to practice aspects of the installation process with the pier-mounted crane. During this practice installation, several issues arose, including problems with the rental crane, issues with the divers' dry suits, and a rope becoming tangled in the jet ski. The main lessons learned from this event were the importance of mobilizing and checking all equipment before installation, ensuring that every individual understands their roles and responsibilities clearly, and being prepared for unexpected challenges by having redundant equipment and tools available, as well as the importance of repetitive practice for challenging and unfamiliar installation and recovery efforts.

On the second trip, the team successfully installed the WEC over the side of the pier. Learning from the previous installation, the team developed a more thorough plan before installation day, brought extra equipment and tools to the end of the pier, and ensured that each team member had a well-defined role. However, during this installation, the NREL team overestimated the water depth, and the WEC did not function properly due to incorrect timing on the air spring. This error provided the team with an opportunity to evaluate the feasibility of a recovery and repair effort on the pier. The WEC was successfully recovered, repaired, and reinstalled in about 1.5 hours. At this point, the primary objectives of the first deployment had been met:

- Install a representative WEC using the pier-mounted crane
- Perform a recovery and reinstallation procedure from the pier.

Due to a storm forecast to occur over the following weekend and limited staff availability in the coming weeks, the team decided that the most appropriate action was to recover the device the following morning. This decision was made to eliminate the risk of having to shift the team's focus from the Waves to Water event toward an emergency recovery operation.

2.2 Deployment 2—April 2022 (Waves to Water Prize)

This deployment was a highly ambitious and successful effort despite the weather challenges faced by prize competitors. On the morning of April 3, 2022, a team comprising representatives from CSI, NREL, and the U.S. Department of Energy successfully deployed all four Waves to Water Prize competitors, a feat that will be difficult to replicate considering the challenges of deploying four different wave energy technologies. The deployment was divided into two sets of two activities. The first activity involved installing each WEC, and the second activity, once each WEC was anchored, was to run the cable/hose assembly for each competitor. The cable/hose assemblies were run from each WEC along the ocean bottom and secured to the preinstalled 5/8-inch nylon line by dive teams using premade pads made from approximately 12-inch-long strips of PVC tape. The tape was wrapped around the cable/hose and nylon line, minimizing the motion of each at the bottom. This process was carried out in two sets, with two devices being deployed on the north side of the pier and the other two devices being deployed on the south side. Two cranes, one on each side of the pier, were used to minimize staging and mobilization time. Lessons learned from the first deployment were applied to this deployment, and the installation of each device was successful.

However, in the evening, after all the devices had been installed, an unexpected storm swept through. The storm caused three of the WECs to become detached from their anchors, while the fourth competitor's device dragged its anchor a considerable distance, resulting in damage to its transfer hose. Because this was a prize effort and not a more formal research and development project with significant technical oversight, the team did not sufficiently consider factors like anchor loading and device survivability. The team also determined that the shallow-water, breaking-wave conditions that each competitor experienced fell outside the scenarios modeled in software by the competitors. As a result, it is difficult to determine the root cause of each prototype failure. Nevertheless, the team identified key takeaways that could have helped mitigate some of the challenges faced:

- **COVID-19 constraints:** Due to the challenges faced with COVID-19, previously planned in-person workshops with the competitors, their devices, CSI, and NREL were changed to online meetings. The consequences of this change became apparent when devices arrived days before their planned deployments and last-minute mooring corrections were made by the deployment team.
- **Rigorous design review:** A more rigorous design review may have revealed some failures beforehand, such as issues stemming from the load rating of mooring lines, system end stops, and assumed anchor loads under extreme conditions.
- **Larger safety factors:** During the research and development stage of tech development, it is good practice to use conservative safety factors until the loads and other design conditions are fully understood. However, prize competitions incentivize teams to prioritize winning over creating a most robust or well-rounded product. When evaluation criteria emphasize metrics like simplicity and weight, competitors are more likely to focus on lightweight, simpler designs, often at the expense of structural conservatism and reliability. This trade-off can conflict with best practices for early-stage engineering design.

- **Installation verification check:** Once the WECs were attached, sending a diver down with an underwater camera (e.g., GoPro) to verify all critical connection points may have prevented issues due to mistakes made during installation.

2.3 Deployment 3—August 2022

2.3.1 Mooring Load Data Acquisition System

The third deployment was planned in response to the outcomes of the ocean deployments that occurred in the Waves to Water DRINK Stage. Because the prize competitors operated in the surf zone (i.e., shallow water), linear wave theory would be insufficient to capture all the relevant physics for a WEC. Therefore, the NREL team hypothesized that existing models (e.g., WEC-Sim or other linear-theory-based models) would likely underestimate the anchor loads. Because those models were deemed insufficient in this environment, a better method to identify loads and test this hypothesis was to deploy the HERO WEC in the surf zone and make physical measurements.

The lower-risk option was to deploy the electric system first, as it requires less tether tension than the hydraulic system. To measure these loads, the NREL team utilized the Black Box DAQ system, The system is designed for deep-water in situ measurements and has very low power consumption (approximately 300 milliwatts), allowing it to be operated without an external power supply. 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 DAQ to mitigate abrasion. However, 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.

Three days after the original deployment, the team recovered the WEC and swapped the electric power take-off with the hydraulic power take-off. During the swap, the team inspected the Black Box system to determine if any data had been collected and if the connector was salvageable. Unfortunately, the connector, which experienced high strain, had a damaged conductor pin, requiring significant repair. The NREL team did not have all the necessary equipment for a proper repair on the research vessel; nevertheless, a field splice was attempted using marine epoxy. Although this repair fixed the break, the resistance along one of the conductors was outside of the acceptable range for a reliable reading. Additionally, the hydraulic system did not experience any significant wave action prior to being recovered. Due to these complications, no reliable load measurements were collected during either installation.

Despite the lack of load measurements, reliable winch position observations were made. Using these data, the NREL team was able to translate the winch observations into a motion profile that was later used on NREL's large-amplitude motion platform[1] to replicate the loads that would have been experienced in the lab. With these measurements and those collected from the 2024

[1] For more information on NREL's motion platform, see WPTO (2023).

deployments, the NREL team determined that the linear models can be considered adequate for evaluating anchor loads if the drivetrain is properly calibrated.

2.3.2 Anti-Spin Mooring Challenges

In addition to challenges associated with the DAQ systems, there were challenges associated with the anti-spin mooring system that was installed during this deployment. Although the linear models used to evaluate the device do not account for cross currents or wind loading, these phenomena have been observed frequently at this site. When the team was evaluating potential risks that the system could encounter, they decided that an anti-spin mooring would be necessary to mitigate these risks. The anti-spin mooring system that was deployed in 2022 was a simple Danforth-style anchor attached to the WEC with a 5/8-inch Dyneema line (Figure 2). Although this system was effective at preventing the WEC from spinning, it significantly hindered the motion of the WEC and induced shock loads to the WEC. Within the first day of operation, the D-ring (1,200-pound working load) abraded the nylon strap (2,000-pound working load), and, ultimately, the secondary anchor was disconnected (Figure 3). After this event, the WEC motion was no longer hindered, and there was significantly less shock loading on the system. The WEC did experience some spinning from wave to wave, but the spinning was manageable because the WEC never rotated more than a full rotation in either direction. During the rest of the deployment, the WEC never made a full rotation, and therefore it was determined that the anti-spin anchor was not only unnecessary but ultimately introduced more problems than it mitigated.

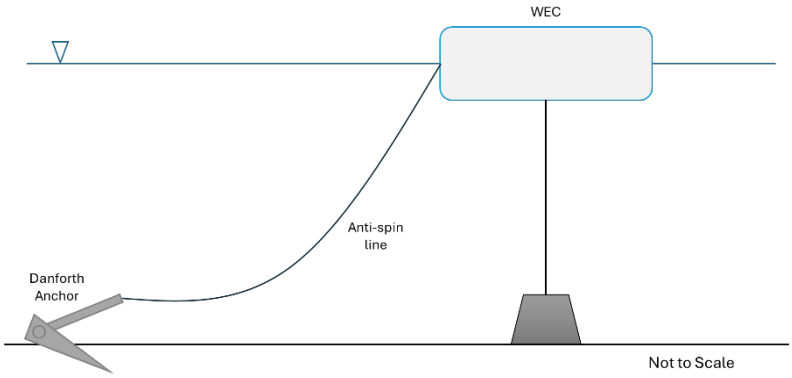

Figure 2. Anti-spin mooring configuration installed in 2022.

Illustration by Scott Jenne, NREL

Figure 3. The D-ring and strap that failed during the 2022 deployment.

Photo by Andrew Simms, NREL

2.4 Deployment 4—March/April 2024

A final deployment was planned for March and April 2024 that would be similar to Deployment 3 but with the hydraulic system being installed first, followed by the electric system. The decision to change the order was made for two primary reasons: to ensure that the hydraulic system would be operational before any potential damage could occur and to provide an opportunity for the North Carolina Renewable Ocean Energy Program and a microgrid developed by the Atlantic Marine Energy Center to connect to the HERO WEC if the desalination objectives were met. Unfortunately, due to complications with this deployment, the Atlantic Marine Energy Center's microgrid could not be connected to the WEC at this time. The 2024 deployment yielded several explicit lessons learned, which are summarized in the following subsections.

2.4.1 Pre-Deployment Preparation

Prior to deploying the HERO WEC, preparations were made to ensure a secure anchoring system and attachment points for the WEC cable and hose at Jennette's Pier, North Carolina. Due to the complex nature of underwater operations in low-visibility, cold water conditions, it is crucial for investigators to simplify or eliminate all unnecessary underwater tasks.

Two weeks before the planned 2024 deployment, a team of divers cleaned the landward, southernmost square cement piling of the pier-end flair. Divers used flat-head shovels, paint scrapers, and 4-inch flat chisels to remove marine growth, preventing chafing and loosening of the straps that secure the cables.

As a result of some of the challenges faced in the Waves to Water Prize (WPTO 2021), the HERO WEC deployments leveraged a larger, 4,000-pound bundle of ship chain, which was prepared as an anchor that consisted of two approximately 8-foot lengths of chain (roughly 2,000

pounds each) arranged in a cross pattern. Each length was tied in an overhand knot using CSI's crane and crowbars, and the bundle was further secured with 1-inch stainless-steel wire rope.

The chain-pile anchor was loaded on the back deck of CSI's research vessel, Miss Caroline, with a dock crane and secured to the deck rail system just behind the vessel's winch (Figure 4) on a plastic pallet.

The unique rail system on the back deck consists of 4×6-inch beams covered with plastic decking, allowing the chain anchor on the plastic pallet to be slid fore and aft on deck with the vessel's winch system. The system enables the anchor to be maneuvered on deck and deployed without lifting, eliminating the dangerous swinging of the heavy pile while offshore. During transit, the pile is secured to the deck as far forward as possible, just aft of the deck winch (Figure 4), to minimize bow pitch, ensuring expedient vessel transit.

Once the vessel neared the deployment site, the Spectra[2] winch line was run through a block on the vessel's A-frame, through another block in a temporary aluminum transom, and around the chain pile. The winch was then used to slide the pile on the plastic pallet aft over the plastic rail surface. Once the pile was near the open transom, the 2×6-inch aluminum transom and block were removed.

The winch line was then secured to two pad eyes in a scissoring mechanism on the rail system. The winch was used to lift the forward end of the scissoring mechanism, allowing the chain pile to slide off the back deck into the water at the deployment site (Figure 4). Using this deployment mechanism reduces the maximum load on the winch line to 2,000 pounds.

[2] Spectra is a type of ultra-high-molecular-weight polyethylene fiber rope, similar to Dyneema rope.

Figure 4. Chain pile sliding off the deck of the Miss Caroline research vessel.

Photo from John McCord, CSI

A stainless-steel chain was run from the chain-pile anchor to a hard plastic marker buoy to mark the anchor location. The stainless-steel marker buoy chain has shackles spaced approximately 1 inch apart that allow for the marker chain to be removed during the WEC deployment or shortened to just below the WEC cable attachment point.

Once the marked chain-pile anchor was in place, a dive team from the pier secured a chain to the base of the cleaned pier piling using a shackle. A 5/8-inch nylon line was then run from the chain pile through the shackle and tightened with a trucker hitch. The nylon line was secured to the pier piling and run through a protective rubber hose to prevent chafing. This nylon line served as a tether during the WEC deployment, securing the power cable and hose to the pier piling and minimizing their movement due to waves and currents.

The power cable and hose were initially towed out to the chain pile by divers using underwater scooters. During later deployments, a pulley system was installed onto a large buoy secured to the chain pile, allowing topside pier support to more easily tow the cable and hose onsite from the pier. Divers then secured the cable and hose to the nylon tether line with PASCO PVC tape.

The cables, hoses, and electric pump were secured to the pier piling from the top pier rail to the strain relief at the bottom using trucker straps. A rope access crew above the waterline and a dive crew below completed this process immediately after the WEC was deployed to minimize damage and wear to the cables and hoses (Figure 5).

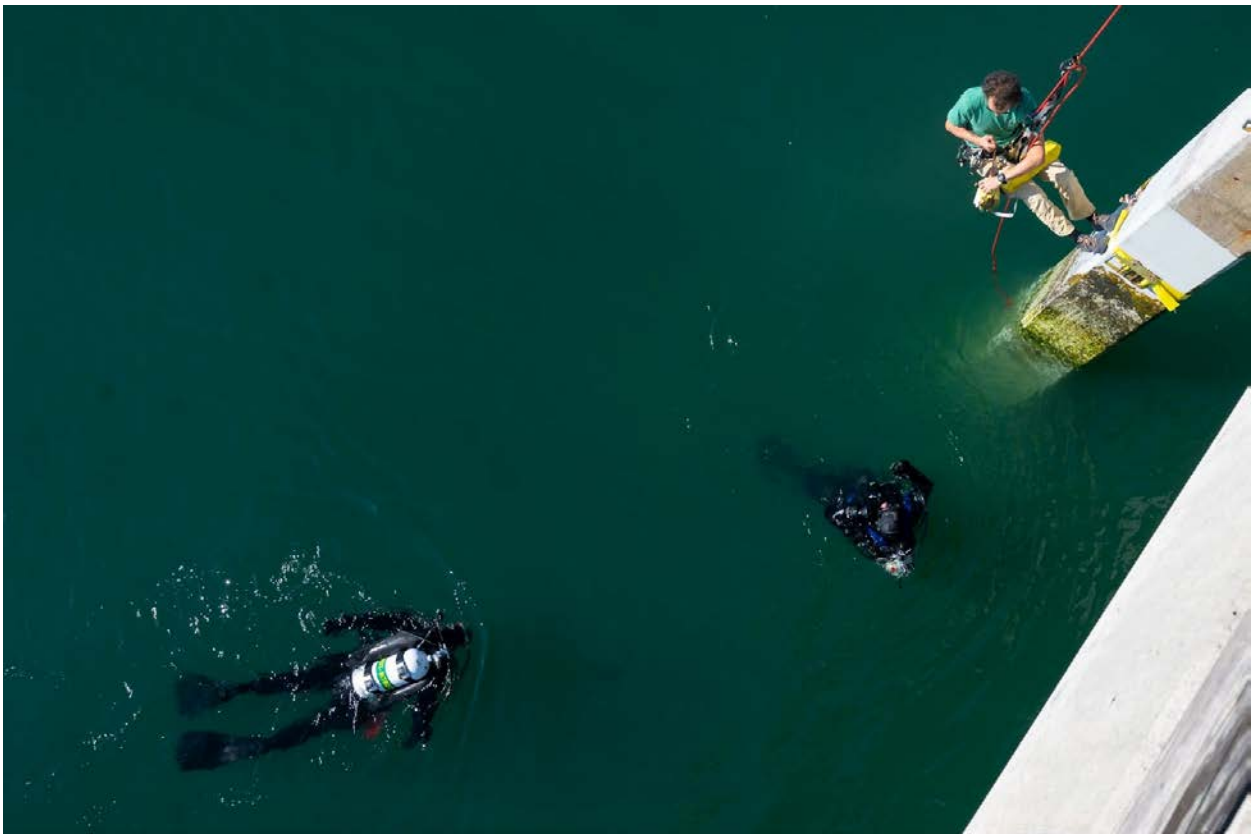

Figure 5. The rope access crew and dive team securing the cables and hose to the pier piling.

Photo from John McCord, CSI

2.4.2 Installation Windows

An attempt was made to install the WEC on March 1—the most probable day for installation during the team's availability. Leading up to that day, the forecast predicted waves of less than 1 foot and calm wind conditions. Although the morning of the deployment was relatively calm, conditions began to degrade swiftly when the research vessel arrived at Jennette's Pier. Despite the conditions being deemed acceptable, they were at the higher end of the team's comfort level. Approximately an hour into the installation attempt, the weather deteriorated further, causing damage to the WEC as it was lifted off the vessel and towed to the site. The damage included a torn D-ring on the float and a cracked PVC fitting on the pump output. The D-ring, not essential for operation, was not repaired. The cracked PVC fitting could have been repaired offshore in calmer conditions but not on this voyage. Thus, the WEC was put back on deck and returned to CSI for repairs. The team made the necessary repairs, and the NREL team returned to Colorado to await another deployment opportunity.

Two weeks later, another window of opportunity presented itself, with 3–4 days of forecasted calm conditions. Under these calm conditions, the team was able to split the installation into two half-days, with the first half-day dedicated to running the hose and the second to installing and commissioning the WEC. With very calm conditions and less pressure on the team to complete all activities in a single day, the installation was completed with no issues. Future design and deployment plans should consider the ability to perform a multistep deployment with independent stages that can be completed during shorter weather windows. This process could

include ensuring mooring and WEC components are properly waterproofed in case of large time gaps between deployment stages.

As underscored by more than two decades of CSI ocean operations, attempting offshore work in suboptimal conditions consistently leads to challenges. Balancing budgets, personnel, and weather is inherently complex. To ensure successful and safe ocean operations, funded projects must prioritize flexibility in their planning to ensure that offshore work can be performed safely (Figure 6). This necessary flexibility should be understood and appreciated by program leaders, project managers, and investigators alike.

Figure 6. Wide-angle view of calm sea state conditions during the HERO WEC hydraulic system deployment on March 14, 2024, at Jennette's Pier, North Carolina.

Photo by Justin Panzarella, NREL

2.4.3 Anti-Spin Anchor Updates

Due to complications from the August 2022 deployment, where the secondary anti-spin anchor limited the WEC's range of motion and subsequently broke free, both the NREL and CSI teams decided to forego its installation for the 2024 hydraulic deployment. Whereas the WEC rotated approximately ±270° during the 2022 deployment without completing a full rotation, the 2024 deployment encountered conditions that caused the WEC to spin beyond this limit, which resulted in the hose and on-buoy DAQ power and data cables wrapping around the winch line (Figure 7), severing them and thus necessitating early WEC recovery. Because of this event, when the electric system was redeployed on April 18, it was installed with a modified version of the anchor system that was deployed in 2022. The CSI team designed this modified anchor system, which consisted of the same Danforth-style anchor. However, the mooring line was broken up into three sections:

- A section of steel chain that was attached to the anchor
- A section of three-strand twisted nylon line with a surface buoy attached

- A final section of chain that leveraged four Shockles™ units in series.[3] A small subsurface buoy was attached to each Shockles section to keep the chain as close to parallel with the seabed as possible.

This modification demonstrated a significant improvement in the WEC range of motion while still preventing the WEC from spinning around the anchor. Figure 8 and Figure 9 show the actual anchor system laid out prior to installation and an illustration of how the system was designed to sit in the water, respectively.

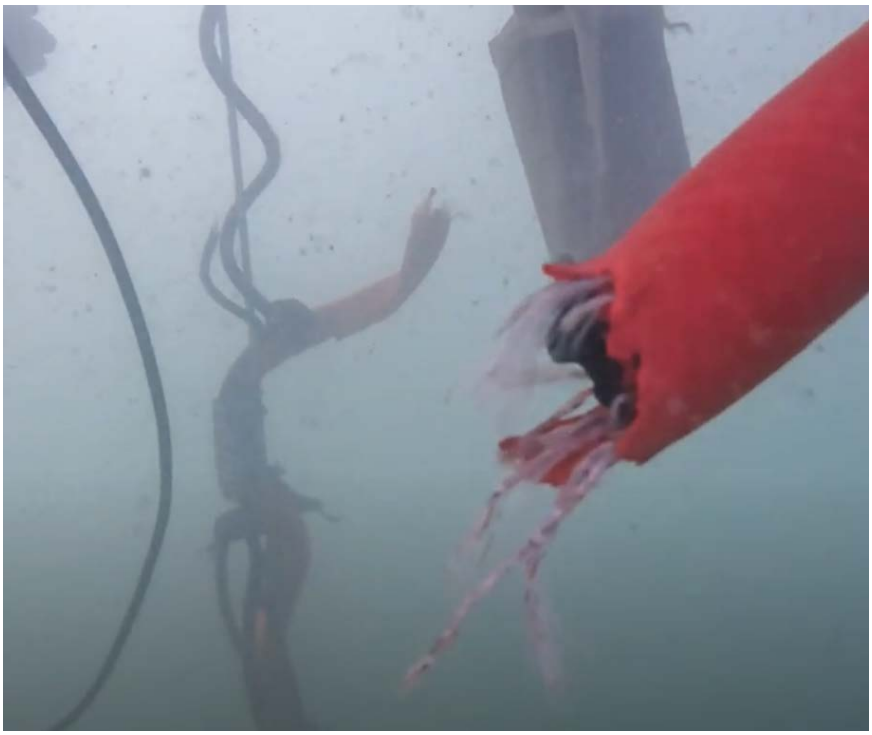

Figure 7. Data cable wrapped around winch line.

Photo from Trip Taylor, CSI

[3] The Shockles system involves a chain-reinforced spring that is used to mitigate shock loading for boats while they are docked. By coupling four in series, the spring stiffness is reduced by a factor of four, and the total range of motion is increased by four.

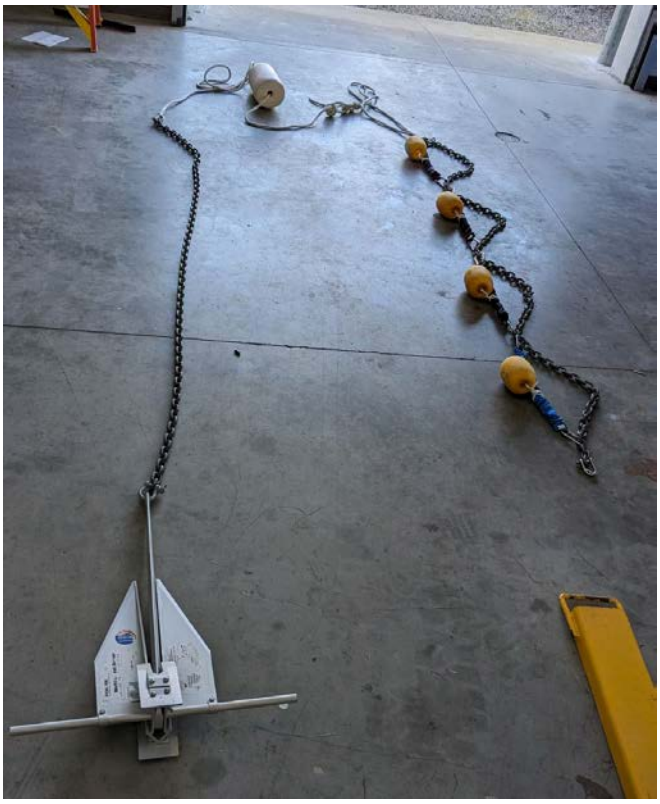

Figure 8. 2024 secondary anchor system, laid out in a CSI facility prior to installation.

Photo by Scott Jenne, NREL

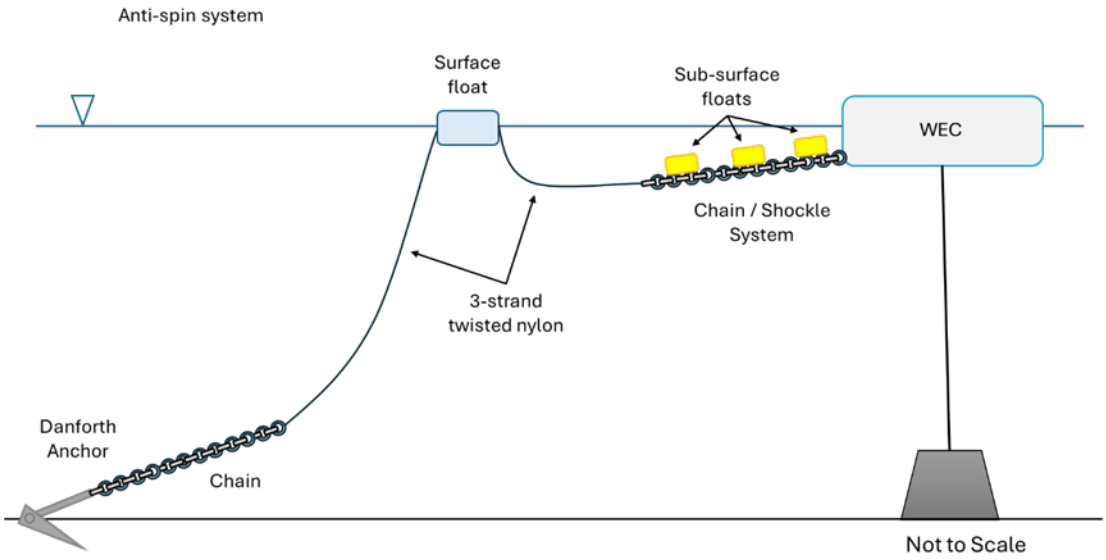

Figure 9. Simplified illustration of how the 2024 anchor system was designed to sit in the water.

Illustration by Scott Jenne, NREL

This modified anchor system was a significant improvement over the design that was deployed in 2022. The new design allowed the WEC to move freely during operation while preventing the WEC from rotating more than approximately ±45°. This anchor system also kept the WEC in

place for approximately 2 weeks during some significant storm events after the primary anchor line failed. The design, while successful, was a proof of concept that the team will likely build upon in future iterations.

2.4.4 Components Hanging in Water Near Wave Energy Converter

During the 2024 deployment, the team noted that the WEC had several components hanging off the side of the float. The hose had a large strain relief loop (Figure 10), and the data and power cables for the on-buoy DAQ were hanging freely from the WEC. Besides the risk of entanglement, as described previously, this also created installation challenges by increasing the number of tasks that needed to be completed on water. A preferred approach would be to create a rigid hose connection on the WEC with a shorter strain relief loop. This would decrease entanglement risks by reducing the free-floating hose length.

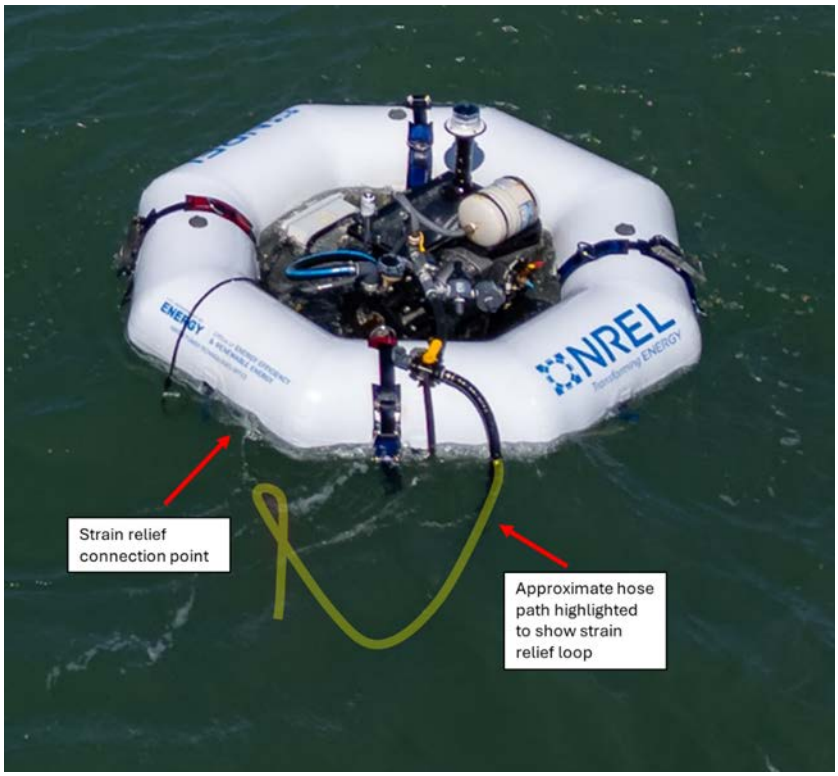

Figure 10. Underwater strain relief loop.

Photo from John McCord, CSI

2.4.5 Underwater Connections

Similar to the components hanging over the side of the WEC, there were several underwater connections that needed to be made to install the device. Each of these connections increases the dive time and complexity of an installation. Although connections such as the anchor shackle may be unavoidable without significant infrastructure and design considerations, reducing the number of hose or electrical connections that need to be made on water is recommended for future designs. All connection points, shackles, rings, harnesses, and strain reliefs need to be fixed properly and double-checked before deployment (Figure 11).

Figure 11. Load cell shackle. The safety wire was inadequate for the loads on the shackle pin, and the shackle nearly disconnected itself.

Photo from Lindsay Wentzel, CSI

2.4.6 Winch Failure

During the electric portion of the 2024 deployment, the WEC broke free from the anchor the night following the installation. There were three main factors that contributed to the winch failure:

- Lack of electrical load
- Limited overall winch line capacity
- Winch line attachment issues.

2.4.6.1 Lack of Electrical Load

The most significant factor that resulted in the winch failure was that the submersible pumps were disconnected. The pumps were intentionally turned off to prevent the batteries from draining overnight before the reverse osmosis membranes and filters could be replaced the next morning because the weather forecast was not promising for power production. Unfortunately, the waves increased in intensity overnight, and the batteries reached a full charge much earlier than anticipated. When the batteries reached 100% charge, there was no longer an electrical load on the generator (i.e., power take-off damping went to near zero). Without a load on the generator, the WEC range of motion increased to the point where the WEC was hitting the end stop. A better solution would have been to either keep the pumps on, have the pumps on a control loop so that they only turn on at a certain state of charge, or integrate some form of a dump load (i.e., dump resistor) to maintain a resistive load on the generator. Future designs will likely integrate a combination of these to reduce the likelihood of such events.

2.4.6.2 Limited Overall Winch Line Capacity

Simply increasing the winch line capacity could have potentially mitigated this problem. The existing winch design can hold approximately 25 feet of winch line. Given the approximately 8–13 feet of water depth, there was likely approximately 11–13 feet of winch capacity left at high tide when the winch failed. After examining the air spring pressure measurements (Figure 12), the team determined that it would not have required a significant increase in winch capacity to prevent that end-stop event. In these conditions, an extra 2–3 feet may have been enough.

However, in more energetic conditions or in conditions where the WEC was drifting in surge, this increase may have only delayed an end-stop event. For this reason, the team does recommend increasing capacity as much as feasible, but increasing winch capacity alone is not considered sufficient to prevent failures.

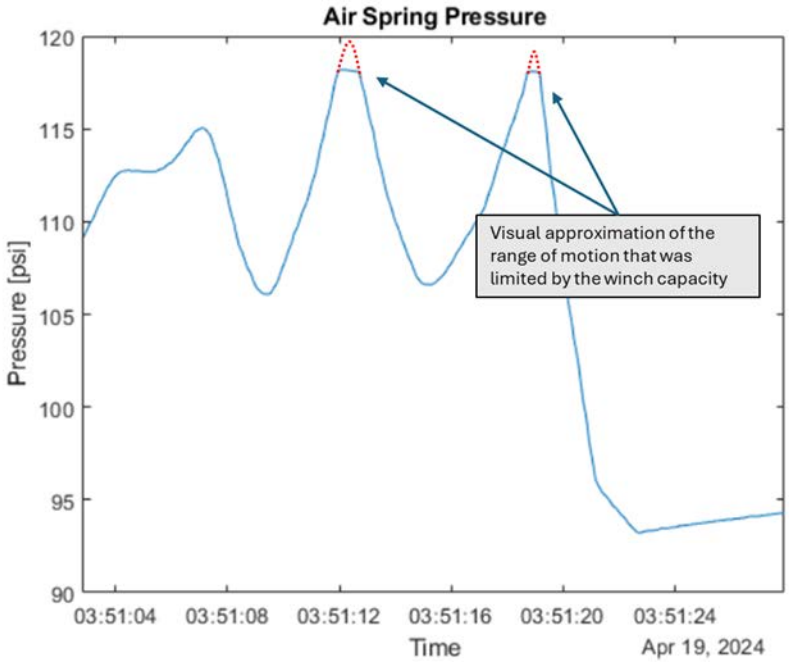

Figure 12. Air spring pressure prior to winch failure, and a visual approximation of the limited range of motion.

Illustration by Scott Jenne, NREL. psi = pounds per square inch.

2.4.6.3 Winch Line Attachment Issues

The last factor that ultimately caused the winch failure was related to how the line was attached to the winch. For the HERO WEC, the winch line is fed through a slot on the side of the winch flange and secured using an aluminum wire rope stop ferrule. The winch and spring return system were also timed to ensure that approximately 1.5–2 wraps of winch line would be wrapped around the winch drum at the end stop. The intent of this design was to make sure that the frictional force between the cable and drum under load would be sufficient to prevent the winch line from being pulled through the ferrule. However, the asymmetric tension profile that the winch experienced (approximately 50-pound recoil and 400-pound pay out) likely allowed the winch line to slip on the drum. This in conjunction with the end-stop events allowed the load to be transferred through the winch line at the point where the winch passes through the flange. This connection point ultimately acted like a shear and cut through the winch line, which can be seen in Figure 13, where the ferrule is clearly still in place and small remnants of the wire rope are lodged in the side of the flange. A preferred method of attachment would be to feed the winch line through the flange with a less aggressive angle and to use multiple rigid connection points along the flange so that, if an end-stop event were to happen again, the winch line would be sufficient to hold the WEC in place without rubbing against any sharp edges.

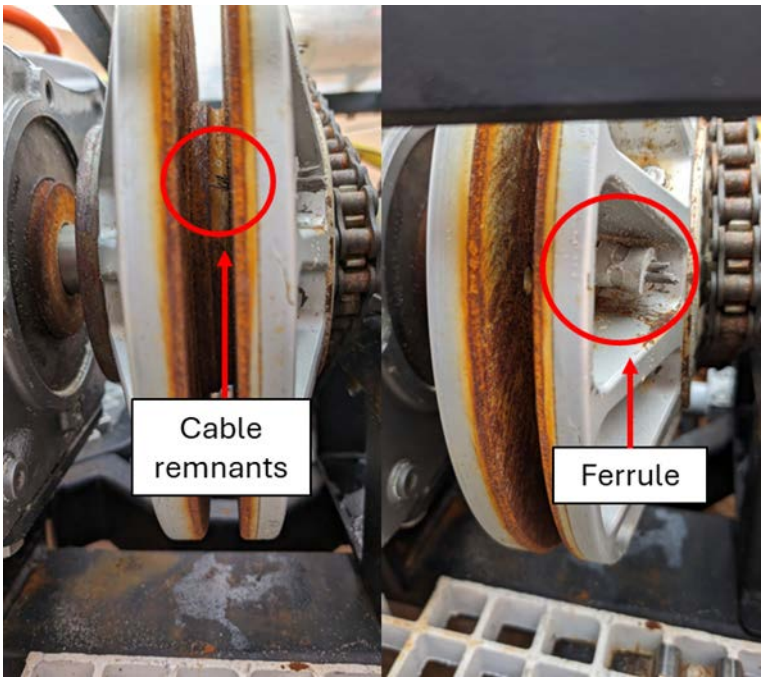

Figure 13. Winch and winch line attachment after WEC recovery.

Photo by Scott Jenne, NREL

It is likely that a modification to any one of these three factors would have reduced the likelihood of failure. However, for future design iterations, the team recommends that all these factors be addressed to increase the probability of success (e.g., maintaining an electrical load, increasing line capacity, and ensuring a more robust connection).

2.4.7 Post-Deployment Efforts

Following the removal of the HERO WEC, several items were recovered from the deployment site by the CSI team. As required by the categorical exclusion from the National Environmental Policy Act, the site was returned to its original state, with all debris removed. These efforts required careful coordination among all teams involved, including divers, the belay team, the pier crew, and the vessel crew.

Trucker straps, which were used to secure the WEC cable and pump to the pier piling, were removed above the water by a belay team. The strain relief was then removed by divers at the base of the pier piling. A 3/8-inch Spectra line was attached to the end of the cable and passed to the Miss Caroline research vessel near the south side of the pier.

The Miss Caroline slowly motored away from the pier toward the chain-pile anchor, applying tension to the buried cable and the 5/8-inch nylon strain relief line. Both were buried in the sand and not visible to divers, so the vessel was used to pull them out. The process required a slow pull to allow the vessel's rocking motion in small waves to help work the cable and line from the sand. Spectra line was used to minimize recoil in case the line parted, ensuring safe operations for the deck crew on the vessel.

A separate operation approximately 1 month later required coordinating a weather window with the Tiki, an 85-foot, 220-ton research vessel, to remove the 4,000-pound anchor (Figure 14).The

anchor pile, no longer attached to the WEC, was marked with a stainless-steel chain and a hard mooring buoy. However, the anchor pile was completely buried, leaving only the marker chain visible at the bottom. The top-ship chain links were buried approximately 1/4-meter beneath the sand, while the bottom links were buried about 3/4-meter beneath the sand bottom (Figure 15).

Figure 14. The Tiki research vessel during the August 2024 recovery operations.

Photo from Susan Dotterer Dixon, CSI

Figure 15. The buried anchor pile with exposed lifting chain and swivel.

Photo from Lindsay Wentzel, CSI

To reduce the pull-out tension required to remove the buried pile, an underwater vacuum system was developed and pretested by the CSI team. That system consisted of two 10-foot sections of 3-inch PVC pipe connected by a rubber sleeve with hose clamps. A 30-gallon air compressor on the vessel was attached to the vacuum system using a 100-foot air hose (Figure 16). A flow valve was installed at the bottom end of the PVC vacuum, allowing divers to regulate airflow during operations.

Figure 16. The compressor (left), underwater vacuum (middle), and flow valve (right).

Photos from Mike Muglia and Lindsay Wentzel, CSI

From the Tiki research vessel, the dive team conducted three dives over approximately 3 hours to excavate the chain pile using the vacuum system (Figure 17). Once the pile was partially exposed, two divers attached separate 2.5-inch-diameter nylon hawser[4] lines to different ship chain links on opposite sides of the pile using anchor knots. The hawsers were then secured to the starboard and port cleats on the vessel's transom (Figure 18).

[4] A hawser line is a thick, heavy rope typically used for towing, mooring, or securing a ship.

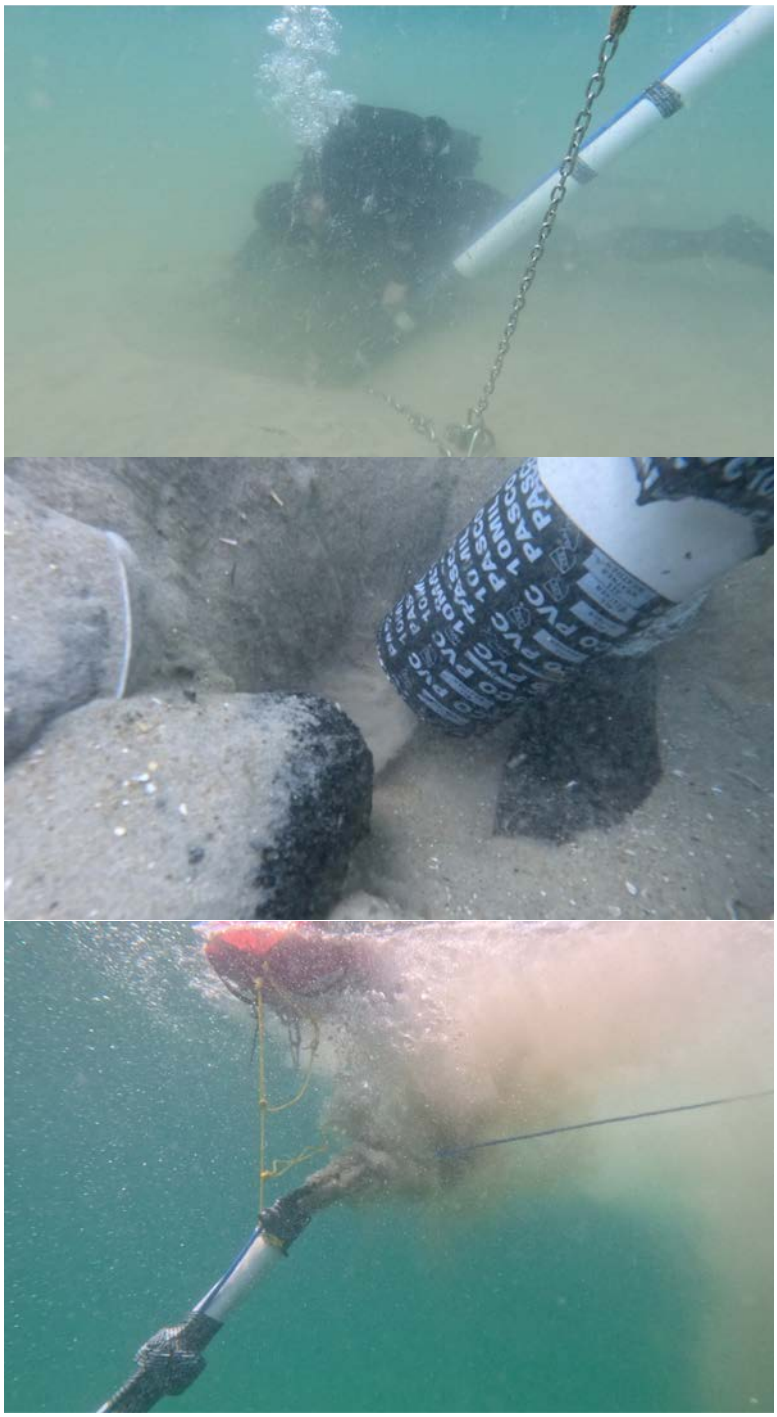

Figure 17. A diver operating the vacuum system (top), the suction power of the system (middle), and the disposal end of the vacuum (bottom).

Photos from Lindsay Wentzel and Trip Taylor, CSI

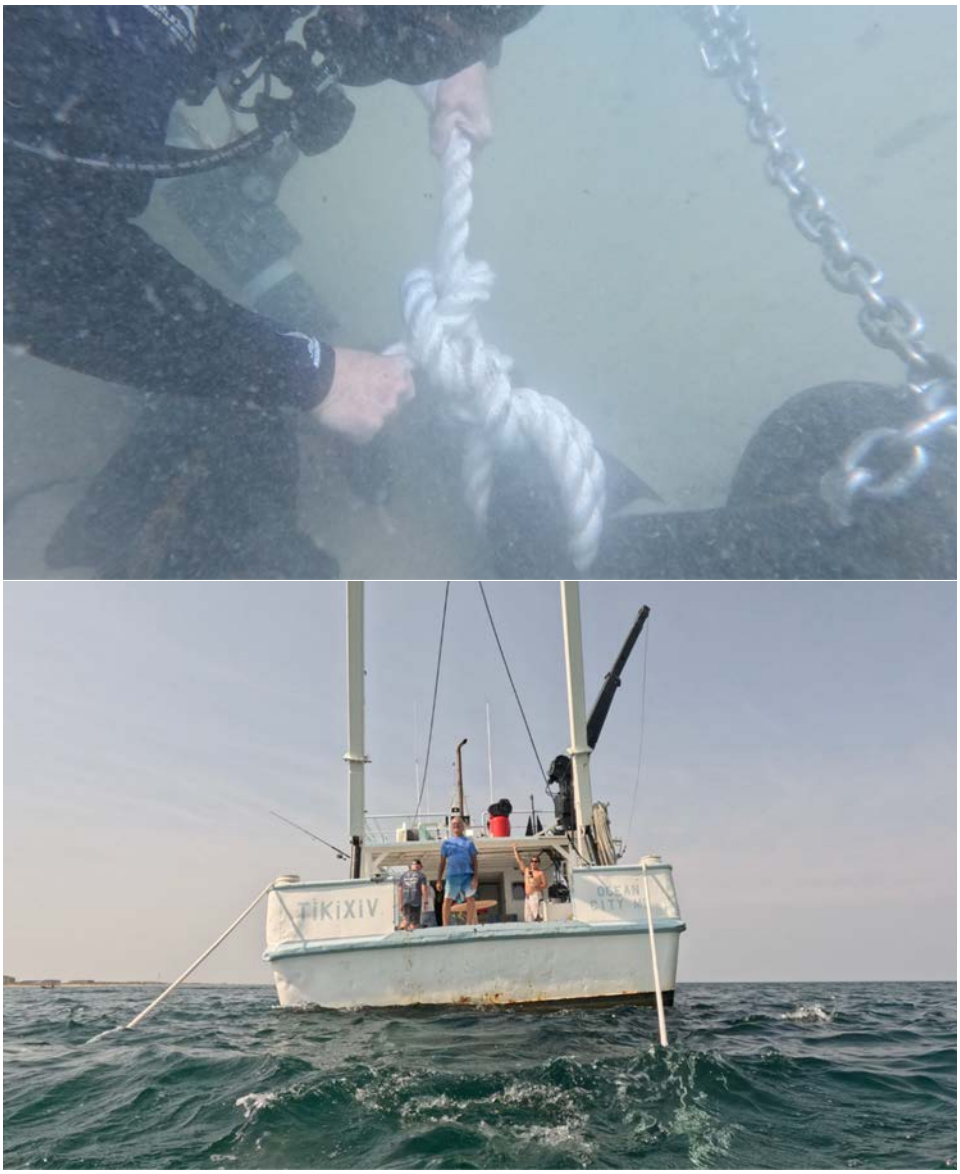

Figure 18. A diver attaching a nylon hawser to the anchor pile (top), and the Tiki research vessel pulling the anchor pile (bottom).

Photos from Lindsay Wentzel and Trip Taylor, CSI

Nylon mooring hawsers were used to provide stretch, allowing the pile to be eased from the sand. A surface marker was also added to the chain pile. The back deck of the vessel was cleared for safety, and the vessel was put in forward gear, with the throttle slowly increased over a period of 15 minutes. The chain pile was gradually pulled from the sand by alternating the vessel's course slowly to port and starboard. It was evident that the pile was free when it moved away from the anchor site with minimal resistance.

The pile was then dragged offshore 100 meters to deeper water away from the pier. Two divers then dove on the chain pile, removed the hawsers, and attached a winch cable running from the deck winch, through a block on the vessel's A-frame, and then to the pile. With the divers back on board, the vessel lifted the chain pile from the ocean floor and placed it on deck (Figure 19).

Figure 19. The anchor pile being lifted from the water.

Photo from Susan Dotterer Dixon, CSI

3 Future WEC Design Considerations

This section aims to distill the lessons learned from the previous deployments into an actionable set of design considerations. The HERO WEC team recommends that future WEC designs consider as many of these as practical to increase the probability of a successful installation.

- **Lift Points:** In addition to designated lift points for known lifting conditions (e.g., crane hoist), provide additional hoisting and rigging point options. Examples of different options might be providing additional D-rings or designing a method to safely lift the device using a forklift. Related to lifting, the design should have numerous ways to safely block the device before and after a lift in different scenarios (e.g., in lab, on a dry dock, or on water).
- **Tow Points:** Similar to providing numerous lift points, WEC designs should include multiple tow points. Every tow point should be evaluated for various load scenarios, with adequate safety factors to ensure personnel and equipment safety during unexpected weather changes that may occur during a deployment.
- **Tie-Off Points:** When practical to do so, all WEC designs should include numerous tie-off points for temporary connections during installation (e.g., work vessel anchoring, attaching tools and equipment to the WEC). Depending on the load rating of the lift and tow points, they may also serve as temporary tie-off points.
- **Safety Handles:** Given the need to have human intervention in the form of installation, commissioning, maintenance, or device retrieval, small WECs should have numerous handles for divers or other support staff to safely grab onto. Providing handles on the sides of a WEC, as well as the top, is preferred if the WEC needs to be boarded during a device intervention.
- **Hose and Electrical Connections:** For any hose, electrical, or other ancillary equipment connections that need to be made, the WEC end should be a rigid connection whenever practical. This rigid connection can prevent unnecessary movement and entanglement when compared to a flexible connection. Ancillary connections should also include adequate strain relief as well as a structural connection in the event the WEC's range of motion exceeds the design conditions so that the ancillary connection is not put under load (Figure 20). Although it may seem trivial, the length of any hose, cable, or ancillary cables should be evaluated prior to on-water installation, and any hose management practices should be validated. During the different HERO WEC deployments, as new instrumentation systems were added, the length and position of individual cables became another challenge that needed to be overcome. In the event that cable lengths cannot be perfectly matched, extra length is best managed on land, where there is a lower chance of entanglement.

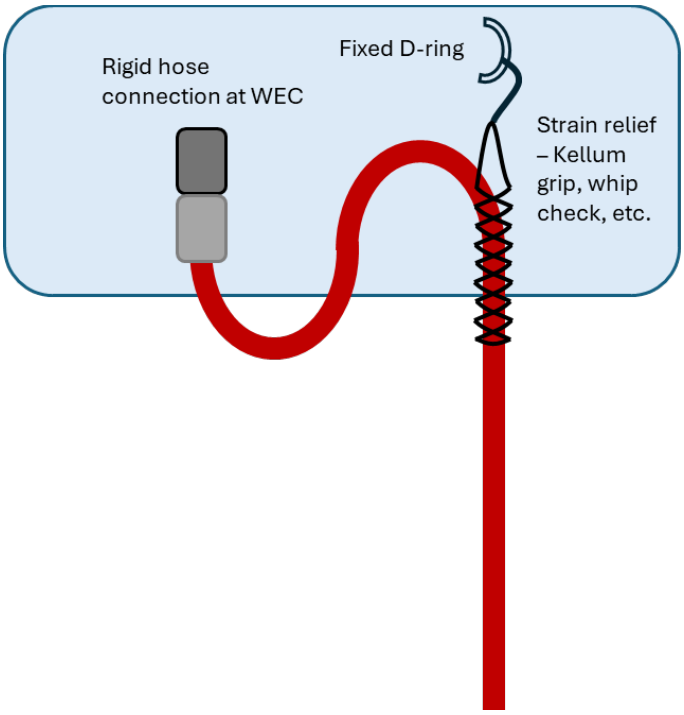

Figure 20. Illustration showing how a rigid hose connection can be implemented to reduce the chance of entanglement.

Illustration by Scott Jenne, NREL

- **Mooring Design:** Mooring systems should be designed to minimize the possibility of entanglement or abrasion with hoses or electrical connections that exist between the WEC and the seabed. Additionally, mooring systems must be designed in a way that results in minimal reduction in the absorbed power at the PTO. Since reductions to primary mooring loads and PTO speed will both result in reduced absorbed power at the PTO, a secondary anchor should apply only the minimum force required to maintain the WEC's orientation. In the case of single body point absorber devices which utilize a single anchor for energy conversion, a secondary anti-spin anchor system is recommended to prevent yaw motion of the device from twisting hose and electrical connections around the primary mooring line. The use of physical springs or catenary moorings (which can act as gravity or buoyancy driven springs) in the secondary mooring system is recommended to reduce the losses due to the mooring.
- **Simpler Commissioning and Decommissioning:** Both commissioning and decommissioning are activities that typically require significant human involvement. To reduce communication mistakes and reduce safety risks, these activities should be as simplified as possible. Easy-to-access levers to release stored energy (e.g., air springs, hydraulic pressure) are preferred as long as they do not introduce additional operational risks (i.e., accidental release during operation). For WECs that have integrated mooring/drivetrain configurations (e.g., HERO WEC winch), as appropriate, consider methods to wind up mooring lines from the surface to avoid entanglement during recovery (e.g., boat props).
- **Instrumentation:** As much as possible, eliminate instrumentation that requires underwater dive support and/or an additional communication line from the surface to the

WEC. For example, instead of directly measuring tension on a winch line, it is better to infer data from a torque measurement on the buoy, as this may provide adequate results with fewer risks. Also, provide "user feedback" for DAQ systems when practical. For example, a simple "on" light and the ability to cycle power on and off from the water if a connection is lost can reduce the risk of not capturing data during an expensive deployment. It should be assumed that once the DAQ system is installed on the WEC, a DAQ recovery will not be possible without recovering the entire WEC.

- **Reducing Personnel Time on Water:** Strive to reduce the time on water and the number of steps needed for installation. If possible, provide a simple list of tasks that can happen in any order rather than a strict order of operations to mitigate unnecessary failures due to personnel stress, communication barriers, or weather challenges.
- **Weather Window Timing:** Plan deployments with weather windows in mind. This recommendation is especially challenging for short deployments, where the probability of calm conditions coinciding with energetic conditions is low. For these types of deployments, flexibility when it comes to personnel and equipment planning is a must.

These general guidelines aim to simplify installation and operation, reduce the risk of failure, and enhance overall efficiency in WEC deployments.

4 Future Test Recommendations

In addition to providing insights into the challenges the NREL team has faced and direct design considerations, the HERO WEC team would also like to provide some input regarding how a test program could be most effective moving forward. One area of improvement that could be employed for wave energy testing in general is to broaden the scope of testing that is performed prior to going to the ocean. To date, most wave energy test programs have been focused on power performance validation or structural evaluation within "expected" wave environments (IEC 2019). What is considered an expected wave condition can vary, and some standards may suggest a particular set of extreme conditions such as a 50- or 100-year wave event. However, one of the potential flaws of this approach is that the test conditions that are evaluated are, in many cases, based on the results of a numerical model. The HERO WEC can serve as an example of where this approach can fall short. For example, the linear theory model (WEC-Sim) that was used to predict the HERO WEC performance and loads did not predict the WEC spinning, which ultimately led to the WEC severing the hydraulic hose in the 2024 hydraulic installation.

As is true with any numerical model, there are several assumptions that need to be made (e.g., simplified joints, 2D wave profiles, lack of cross currents or wind conditions, bathymetry). These assumptions ultimately prevent the existing model from being able to predict certain failure modes. One potential approach to mitigate these challenges would be to drastically increase the time and effort spent modeling the specific conditions above. Depending on the application, this approach may not be practical or even possible given the computational requirements to do so. However, another method might be to evaluate a set of extreme conditions that the models do not predict but represent a set of "worst-case conditions." The latter approach may result in more robust designs that can withstand a larger range of operating conditions. This method would be more akin to how the automotive industry evaluates extreme conditions prior to a vehicle reaching the market. The automotive industry performs a wide variety of tests that consider performance, durability, regulatory compliance, safety, quality, and so on at either the component or system level (Nihal, Bhagwan, and Bhimrao 2022).

One example of a very extreme test, performed by the Swedish auto manufacturer Volvo, involves dropping a car from a height of 30 meters. Håkan Gustafson, a member of Volvo's traffic accident research team, stated that they "hope no one ever needs to experience the most severe accidents, but not all accidents can be avoided" (Neira 2020). In no way is the team suggesting that WECs should be dropped from a crane prior to ocean deployment, but the marine energy industry may benefit from evaluating focused tests that are intended to understand the most extreme and severe conditions that a WEC might experience, ultimately leading to more robust and resilient WEC designs.

This approach echoes historical practices in wind energy, where early wind turbine testing involved destructive tests crucial for risk mitigation. In a 2023 interview, regarding the types of testing performed at the now Flatirons research facility, Sandy Butterfield—a former NREL wind researcher—stated, "The first test was 'Does it [a wind turbine] survive a windstorm?' And at the time, 50% of them didn't" (NREL 2023). These failures eventually led to more focused destructive blade and gearbox testing and were necessary for advancing the wind industry to where it is today.

5 Summary and Key Takeaways

This document outlines specific lessons learned by NREL's HERO WEC team, focusing on in-water deployments, including those from the Waves to Water Prize installations, which feature similar WEC designs. It details various challenges encountered during in-water testing and encompasses logistical hurdles due to weather, anchor and mooring complexities, instrumentation failures, general design insights, and recommendations for expanding the scope of pre-ocean testing.

The ocean presents formidable and unpredictable conditions, underscoring the importance of early considerations such as simplifying installation requirements, enhancing system robustness, and evaluating technology performance beyond expected operational parameters. The authors advocate for transparent sharing of failures and experiences by other technology developers toward collectively advancing the wave energy sector.

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