The Design, Fabrication, and Test Program for NREL's Wave-Powered Desalination System

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Keywords—**Deployment, Desalination, Wave Energy**

I. INTRODUCTION

STARTING in 2018, the U.S. Department of Energy's Water Power Technologies Office (WPTO), initiated the development of a prize competition as a foundational investment of Powering the Blue Economy™ [1], The prize encouraged the development of small, modular, cost-competitive wave-powered desalination systems. The National Renewable Energy Laboratory (NREL) was tasked with managing the prize, known as the Waves to Water Prize (W2W), and providing technical input based on prior desalination research performed at the lab. NREL partnered with the Coastal Studies Institute (CSI) and Jennette's Pier in North Carolina for their expertise in deploying research articles at the Jennette's Pier research facility. The prize consisted of five stages that included high-level concept proposals, numerical modelling, site-specific design, subsystem prototyping, and a final ocean demonstration. Due to the logistical risks of installing numerous prototypes in the ocean at the same time, NREL was tasked with designing and building a test article to de-risk the final event.

The test article design needed to represent the technologies expected in the final stage of the prize. This meant that the design was expected to follow the same rules as the competitors, providing CSI with an opportunity to practice installations and develop a final logistics plan prior to the final event.

After concluding the W2W event in April 2022, the NREL test article was redeployed in August 2022 to better understand the challenges of anchoring wave energy converters (WECs) in shallow water conditions with breaking waves.

II. METHODS

A. Design Objectives and Constraints

The NREL team worked with WPTO to define a set of design objectives for the test article, recognizing the challenges of both the competition deployment and the broader wave energy community. The primary objective was to provide an opportunity for the installation team to practice installing a device that produces electricity and pumps water. This was driven by the differing challenges associated with deploying an electrical cable versus a water hose. The prototype needed to utilize the same anchor design that was provided to the teams. It also needed to conform to the size and weight limits that were required for transportation from the CSI facility, mobilization down the pier, and a safe crane lift over the side of the pier. The NREL design was also expected to follow the same technical requirements that were defined in the W2W rules document [2]. For reference, the minimum system technical requirements are listed in Table 1.

TABLE I
MINIMUM SYSTEM TECHNICAL REQUIREMENTS

Category	Description
Water Quality	Must be able to produce water with a maximum total dissolved solids level of 1,000 mg/L over the competition period. Fluctuations in this level are acceptable as long as the combined average does not exceed 1,000 mg/L.
Produced Volume	At least 400 L of water are produced during the in-water testing period. If, for any reason, the in-water testing is less than 5 days, the required produced volume metric will be reduced accordingly.
Shipping Weight	Systems cannot exceed 650 kg.
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 kWh 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.

Two key requirements for the test article were (1) the capability to produce electricity to power a desalination unit and (2) the capability to desalinate seawater hydraulically (i.e., without producing electricity). To achieve these dual capabilities, the NREL team proposed a modular design called the Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC). The HERO WEC was designed so that the drivetrain and the desalination unit were common between both configurations, eliminating the need for two unique designs. This modular approach was chosen to reduce fabrication and testing time as well as cost. In the electric configuration, the drivetrain drives a three-phase alternating current (AC) rotary electric generator that sends electricity to the nearby pier. The three-phase power is rectified into direct current (DC) and converted using a maximum point position tracking (MPPT) DC charge controller. The charge controller charges a 24V DC battery bank and is sent to an inverter to power a 110V AC submersible pump. The submersible pump provides the required flow and pressure to the RO unit. In the hydraulic configuration, the drivetrain drives a rotary pump that pumps water directly to the reverse osmosis (RO) unit without any electronics or active controls. To maintain an acceptable level of pressure and flow at the RO intake, an accumulator bank is installed on the RO intake when operating in the hydraulic configuration.

The HERO WEC was designed to use the same chain pile anchor (approx. 900 kg) and fit into the same shipping crate [3] as the prize teams. Due to electrical safety requirements, the power electronics enclosure was unable to fit into the crate and was shipped separately in an outdoor rated enclosure. The rest of the HERO WEC components—WEC, RO system, electric generator, and spare parts—were designed to fit into the shipping crate. Because the NREL system was not intended to compete with prize competitors' systems, the design was based on known state-of-the-art technology and avoided "advanced" WEC designs (e.g., active control strategies, shape-changing geometries, embedded power take off concepts, or any other design that had not been previously demonstrated and documented in the literature).

B. *Design Process*

Once the design objectives were defined and agreed upon with WPTO, the team developed a series of conceptual designs based on technologies with proven hydrodynamics compatible with shallow water wave environments. The team performed initial analysis on a single-body point absorber, two-body point absorber, oscillating surge WEC (OSWEC), and attenuator [4]. Due to the sandy site conditions and the risk of critical component burial, OSWECs were determined to be too high-risk, despite potential performance advantages [5]. The single-body point absorber was selected as the lowest-risk design based on the available time, available funding, and similarity to the designs being proposed by prize competitors.

The conceptual design that was selected consisted of a toroidal float, a winch to translate linear motion into rotary motion, and a spring return. The Wave Energy Converter Simulator (WEC-Sim) [6] was used for initial design studies to estimate a toroidal float size that wouldn't move the 900-kg (2,000-lb) anchor. WEC-Sim was also used to evaluate whether to extract power in a single direction or in both positive and negative heave directions. It was determined that extracting power in the positive heave direction would provide more power and would require a significantly smaller spring constant; in addition, it would be easier to find off-the-shelf components that would be compatible with the design. Due to time constraints, WEC-Sim simulations were evaluated with a simplified linear damper and spring in place of a more realistic drivetrain. The WEC-Sim model outputs were used to provide the ideal range of force and velocity for a drivetrain design envelope.

C. *Final Design*

The final HERO WEC design consists of three major subsystems: the WEC, the power electronics, and the RO system. The power electronics subsystem was not used in the hydraulic configuration but was a significant portion of the overall system design and fabrication process.

The WEC consists of the following subsystems:

- *Frame* – Steel construction that can be reduced to four quadrants for ease of shipping.
- *Float* - An inflatable octagonal float fabricated from polyvinyl chloride (PVC) coated fabric with a urethane coating.
- *Winch* – A custom-designed winch that translates linear motion into rotary motion.
- *Spring Return* – The spring return leverages a two-stage, 20:1 chain reduction to translate rotary motion into a compact liner pneumatic cylinder that can be tuned to different spring rates and isolated during installation and retrieval.
- *Clutch* – The output of the winch is then attached to a one-way clutch so that the winch can recoil after each wave cycle.
- *Gearbox* – An 11.28:1 gearbox is used to increase the speed of the winch and drive either the rotary pump or rotary generator.
- *Rotary Pump* – An off-the-shelf diaphragm-style pump that was designed for spraying agricultural pesticides and fertilizer.
- *Rotary Generator* – Custom-manufactured permanent magnet three-phase generator.

An image of the final design that was deployed by the NREL and CSI team is shown in Fig. 1.

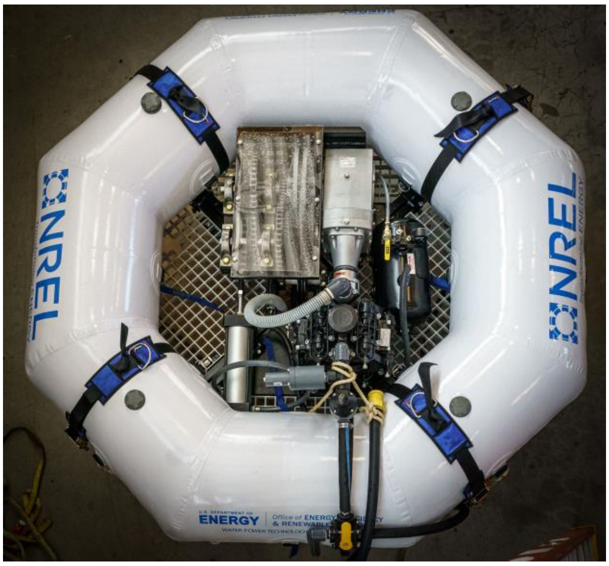

Fig. 1. A top-down view of the HERO WEC, in the hydraulic configuration, prior to its deployment at the test site in North Carolina, USA (image credit: Andrew Simms, NREL)

The power electronics subsystem is used to convert the electricity from the generator into a more stable electricity source that can be used to power the pump feeding the RO system. The electrical system consists of the following subcomponents:

- *Power Cable* – The system utilizes a 500-ft marine-grade cable with four 4-AWG (American Wire Gauge) conductors to transfer power from the generator to a pier nearby.
- *Rectifier* – This component translates the three-phase AC signal into a DC signal.
- *Charge Controller* – The charge controller is an MPPT-style controller that converts a 32V–250V DC input into a 24V DC output. The charge controller uses a preprogrammed voltage-current curve to determine the current draw given a voltage input.
- *Battery Bank* – The system uses a 24V DC 80-amp-hour lead-acid battery pack. This rating is above the allowable 0.5-kWh rating described in the W2W rules. Initially, a 20-amp-hour battery pack was used; however, the starting amps required for the submersible pump were too high to maintain consistent operation. Because one of the objectives of this system was to validate measurement techniques, it was determined that this would be an appropriate area to deviate from the competitor rules.
- *Inverter* – An inverter converts the 24V DC battery power into 110V AC to run a submersible effluent pump.
- *Submersible Pump* – The submersible pump with an induction motor supplies the RO system with approximately 22 L/min (6 gal/min) at 620 kPa (90 psi).

A large portion of the losses come from the numerous conversion steps in this process. In 2023, the system was upgraded with a permanent magnet DC pump to replace the AC pump. This significantly reduced the starting amperage and running amps required. It also eliminated the inverter and associated losses. A smaller RO system reduced the pump size requirement and increased the operating time. A diagram of the electrical conversion steps and a picture of the final power electronics enclosure are shown in Fig. 2 and Fig. 3, respectively.

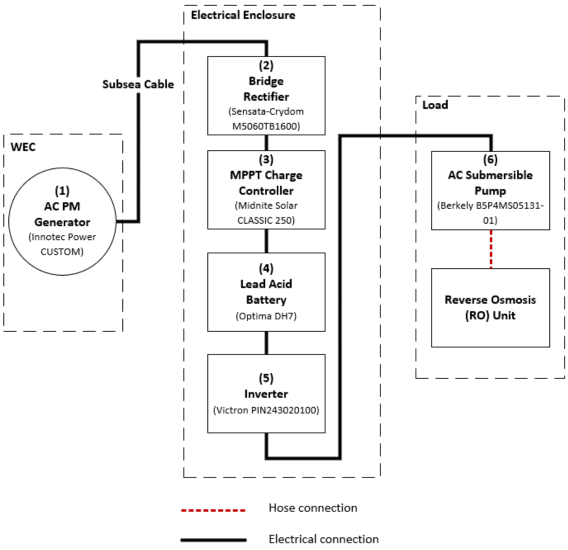

Fig. 2. A diagram of the electric conversion processes incorporated into the HERO WEC electrical design.

Fig. 3. A picture of the final power electronics enclosure that was deployed in North Carolina, USA, in 2022 (image credit: Andrew Simms, NREL)

The RO system that was deployed in 2022 consists of two off-the-shelf Spectra LB 400 water makers [7], a relatively small 8-L (2.1-gal) accumulator to smooth the pressure and flow into the system and diverting valves and instrumentation. The Spectra LB 400 units were selected for their fully integrated energy recovery system. This increases the overall system efficiency and reduces the required feed pressure to approximately 550–690 kPa (80–100 psig). For comparison, a system without energy recovery would require feed pressures of approximately 5,550–6,690 kPa (800–1,000 psig). In the electric configuration, the accumulator was removed because the pump runs at a constant pressure and flow, whereas the hydraulic configuration fluctuates with the passing of each wave. Further analysis in 2023 suggested that removing one of the spectra units and increasing the capacity of the accumulator volume would increase the system availability and increase the overall water production by ensuring that a larger percentage of the deployment would be above the required pressure to push water through the RO membranes. An image of the RO system that was used in 2022 is shown in Fig. 4.

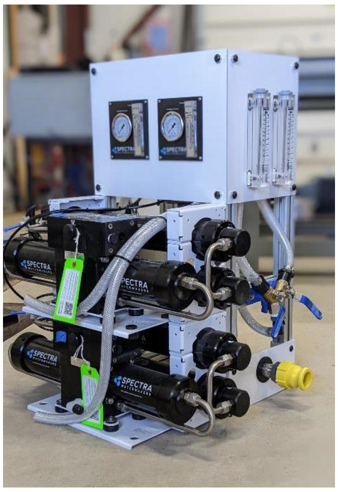

Fig. 4. A picture of the RO system that was deployed in North Carolina, USA, in 2022 (image credit: Scott Jenne, NREL)

D. *Lab Testing*

Prior to deploying the HERO WEC in North Carolina, the NREL team performed shakedown tests at NREL's Flatirons Campus in Boulder, Colorado. These tests focused on ensuring that the HERO WEC's safety checks operated as expected and provided information that could be used for future design iterations. The experimental setup consisted of a simple motor drive attached to a gearbox and a winch. This system was directly coupled to the winch on the WEC and was used to mimic a sinusoidal wave input at the winch. An image of the temporary test setup is shown in Fig. 5.

Fig. 5. Image of the laboratory test setup that was built to verify system operation of the HERO WEC (image credit: Scott Jenne, NREL)

The primary objective for the hydraulic configuration test plan was to ensure that buoyant loads were under the threshold to move the chain pile anchor. The system utilizes a pressure relief valve at the output of the pump, which dumps to the atmosphere. This mechanism ensures the device will not pick up the anchor in a storm or extreme weather conditions. The electric configuration limits the anchor force by limiting the allowable current draw at the MPPT controller. This limits the amount of reaction torque that can be provided at the generator significantly below the 900-kg (2,000-lbf) threshold. In addition to the current limiting function, an electric breaker is installed so that an overcurrent event will trip the breaker and the generator will spin with no current draw. In the laboratory tests that were performed, the electrical configuration was continuously under the threshold required to move the anchor. The hydraulic configuration did have momentary spikes that exceeded this threshold. Due to these results, a secondary pressure relief valve was added to the system prior to deployment to ensure that the system pressure could be maintained during extreme events.

In addition to verifying anchor loads, the laboratory tests were used to tune the MPPT controller prior to deployment and ensure the data acquisition system was working properly. Fig. 6 shows a comparison of the anchor loads from the two configurations when run with a sinusoidal wave condition representative of a heave response that is approximately 1.5 m with a 7-s period. This response represents the response that would be expected in a wave condition with a wave height of approximately 3 m and a period of 7 s. Given that the WEC was deployed in water that is between 2-3 m deep, this would be above the upper limit the device would experience before breaking waves occur.

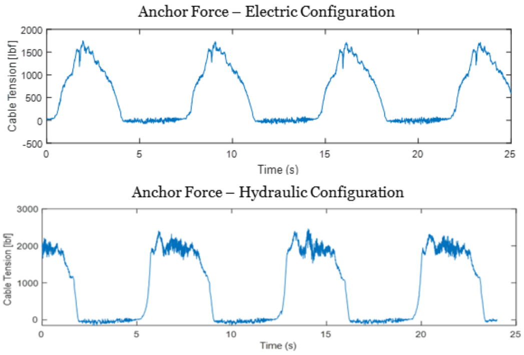

Fig. 6. An example comparison of the anchor force that was measured at NREL's facility.

III. RESULTS

The HERO WEC was deployed two different times in 2022. The first deployment was predominantly focused on understanding installation logistics during calm conditions and therefore did not capture performance data. The second deployment occurred in August 2022 and consisted of two weeklong efforts. The team deployed the electric configuration first, and the device successfully produced water in week one. Because it was the first deployment in which the device was exposed to ocean wave conditions, a large portion of the day was spent tuning the MPPT controller to maximize production. After the wave conditions subsided to a condition safe for on-water operations, the WEC was recovered by NREL and CSI to replace the electric generator with the hydraulic pump. The following day, the hydraulic hose was connected to the RO system. Unfortunately, for the remainder of the deployment window, wave conditions were too calm for water production, and the WEC was recovered and shipped back to NREL. Fig. 7 shows the electrical power of the HERO WEC at the DC bus during the deployment window. There is a section of data that appears to be missing on August 17; at this time, the power electronics system was disconnected for troubleshooting, so there was no power production at the point of measurement.

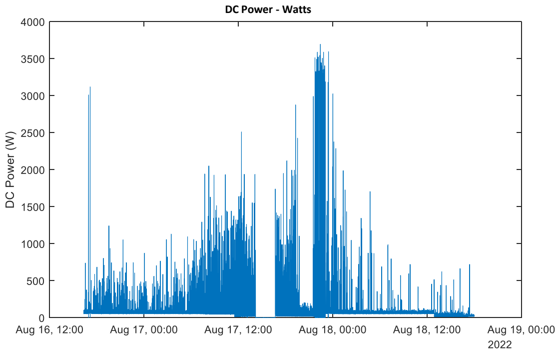

Fig. 7. Electrical power delivered to the DC bus during the deployment window for the electric configuration.

IV. DISCUSSION & CONCLUSION

The HERO WEC is the first wave energy converter that NREL has designed, fabricated, and deployed. It is a valuable research tool for NREL, WPTO, and the broader marine energy community to understand the challenges associated with wave-energy-powered desalination and small wave energy systems. It also provided essential ocean learning experiences for the team while developing strong collaborations between colleagues. As of 2023, the NREL team has upgraded subsystems and components based on lessons learned and refined modelling efforts with the intent to deploy the device again with the CSI team in November 2023. The lessons learned and data collected from these deployments and laboratory experiments will directly inform WPTO's future research strategy. In addition to the direct impact the prototype will have on the WPTO strategy, the design details, modelling results, and data collected in the lab and at sea will be made available on the publicly accessible HERO WEC website (https://openei.org/wiki/HERO-WEC).

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