NREL Marine Energy Desalination Research and Development Portfolio

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I. Introduction

THE National Renewable Energy Laboratory (NREL), in collaboration with the U.S. Department of Energy's (DOE's) Water Power Technologies Office (WPTO), has developed a unique R&D approach to advance marine energy desalination. Desalination is a foundational investment within WPTO's Powering the Blue Economy™ portfolio [1], and was the first investment within this portfolio. NREL's marine energy desalination spans techno-economic feasibility studies, numerical modeling, and laboratory testing at the component and subsystem level, as well as development of the Hydraulic and Electric Reverse Osmosis Wave Energy Converter (HERO WEC). This multilayered approach enables an innovative feedback loop where the data and lessons learned from laboratory and field experiments are used to refine modeling tools and analysis techniques, prioritize out-year activities, and refine strategic directions within NREL and across the WPTO portfolio. The primary objective of the NREL-led research is to identify key barriers associated with the commercialization of wave-powered desalination and develop solutions that can be adopted by the marine energy industry. It should be noted, while WPTO's marine energy portfolio includes wave, tidal, ocean current, thermal gradients, and pressure gradients the bulk of the marine energy desalination work has been focused on wave powered desalination. In parallel, these R&D activities can help inform technical assistance and support of industry and academic technologies. These two tracks help build a common solver community approach, while also identifying key stakeholders, government agencies, and other organizations outside of the marine sector that will be necessary for developing a robust industry.

II. Methods

The NREL team's initial involvement in marine-energy-powered desalination started with a techno-economic feasibility study for wave-powered desalination at the municipal water production scale [2]. This study was intended to shed light on whether desalination would be a suitable end use for marine energy given the objectives set out by DOE. Prior to this analysis, WPTO had funded a small number of industry-led wave-powered desalination technologies. However, most of the funding that has been distributed through DOE's Office of Energy Efficiency and Renewable Energy has focused on decarbonizing the electricity grid. For example, DOE's Solar Energy Technologies Office has a target to supply "as much as a terawatt of solar capacity by 2035" to the grid [3]. The Wind Energy Technologies Office has prioritized "providing a full range of grid services, in addition to power" [4]. This emphasis on grid technologies set a precedent for marine energy technologies, which limited the investment opportunities for marine energy technology developers. This was particularly challenging because marine technologies required further development before they could become cost competitive with other renewable technologies in the U.S. grid market. For this reason, WPTO was motivated to understand other markets where energy plays a large role in system economics; these markets could provide near-term development opportunities.

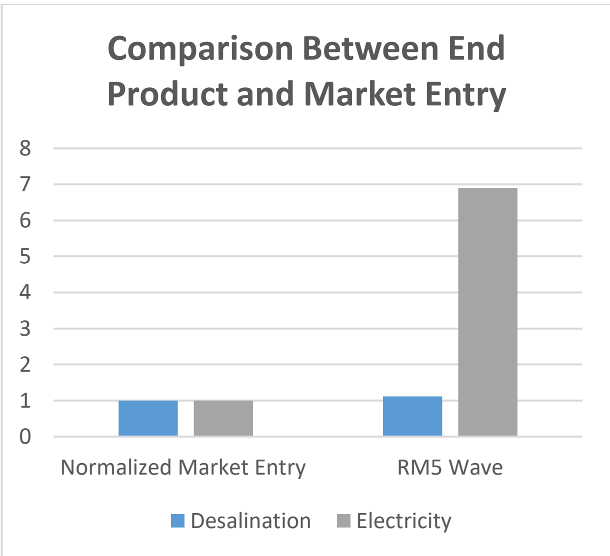

Fig. 1. Early techno-economic results comparing an electricity-producing wave energy array with an array of RM5 WECs designed for large-scale desalination, normalized for each market

Desalination was a strategically valuable opportunity for WPTO to explore due to existing marine energy industry applications, the large energy consumption of desalination plants, and the obvious co-location of the energy resource with the supply-water resource. NREL's initial feasibility analysis leveraged the DOE Reference Model 5 (RM5) wave energy converter, an oscillating surge WEC [5]. RM5 was originally designed for grid applications, but the analysis assumed the electricity generation system would be removed in favour of a reverse osmosis (RO) desalination system. The analysis assumed a California wave resource and an array size equivalent to the output of the Carlsbad desalination facility in San Diego, California [6]. The takeaway from this analysis was that the selling price of electricity from an RM5-like technology producing electricity for the grid would be approximately seven times more expensive than the typical electricity rates [7], but if the same technology was producing desalinated water, the sale price would be less than 1.5 times the current sale price [2]. Fig. 1 compares the normalized results of the grid-connected electricity-producing system and a municipal-scale water-producing system. These results were promising, but there were several assumptions that had not yet been validated. Assumptions about membrane performance, pre-filtration requirements, overall system integration, maintenance, and several other critical design considerations still needed to be de-risked. Nonetheless, the initial analysis demonstrated the value of pursuing desalination as a market opportunity and direct pressurization as a technology pathway.

The lack of validated assumptions represents a significant risk to marine energy technology developers pursuing desalination. To address this, NREL and WPTO have embraced an R&D philosophy intended to uncover showstoppers instead of advocating for a specific technology type. This R&D philosophy is rooted in systems engineering principles namely that any multidisciplinary system should be conceived, designed, and developed as a whole solution [8]. However, given that many of the system inputs for marine energy are still in an early stage of development, an incremental approach is used to focus on areas of high risk. This incremental approach aims to understand specific technical challenges prior to costly system integration. Therefore, this philosophy can be summarized as (1) using systems engineering principles to prioritize challenges and then (2) evaluating risks to determine whether an opportunity should be abandoned, or the next risk should be addressed. An example of how this is used is NREL's project to quantify membrane performance in transient operating conditions.

Fig 2. NREL's RO membrane evaluation experimental setup (image credit: Joe DelNero, NREL)

Membrane performance in transient operation is something that has mostly been ignored by the desalination community. This is largely because most RO plants are run at constant pressure and flow for economic reasons. While this is appropriate for grid-connected RO plants, maintaining steady-state operation is impractical for many renewable-energy-powered RO systems, particularly those powered by wave energy. For this reason, the assumption that the NREL team made was that if membranes could not tolerate large variations in flow and pressure with relatively high frequencies, wave-powered desalination might be a nonstarter due to the high cost of storage. If this assumption was true, R&D dollars would likely be better spent elsewhere. For this reason, NREL fabricated a membrane evaluation system shown in Fig. 2 to characterize membranes in these conditions. Early experiments were promising, and the initial takeaway was that membranes can handle much larger variations in flow and pressure than what membrane manufacturers had recommended [9]. These results suggest not only that commercial RO membranes are suitable for wave energy applications, but also that linear, steady-state models are appropriate for evaluating wave energy converter (WEC)-powered RO designs.

In parallel to membrane R&D, NREL and WPTO launched the Waves to Water Prize (W2W) in 2019 [10]. W2W was a 3-year-long prize effort that incentivized the development of small, modular, wave-powered desalination systems. To de-risk the final event that is shown in Fig. 3, NREL also developed the HERO WEC. Between the technologies that the prize competitors developed and the NREL HERO WEC, numerous technical barriers were highlighted as potential R&D areas, including pre-filtration, energy recovery, power electronics, near-shore installations, maintenance, and device reliability. An unanticipated benefit of developing the HERO WEC was strengthening the collaboration between the WPTO national labs and the prize contestants; lessons learned were shared as each entity worked to solve common challenges. Now that W2W is over, the HERO WEC is being leveraged as an R&D asset that enables NREL and WPTO to systematically focus on these challenges. In August 2022, the HERO WEC was redeployed to establish a baseline for some of the known technical and logistical challenges. To ensure that the knowledge gained from these efforts is not lost, the HERO WEC design, cost details, lab and deployment data, and

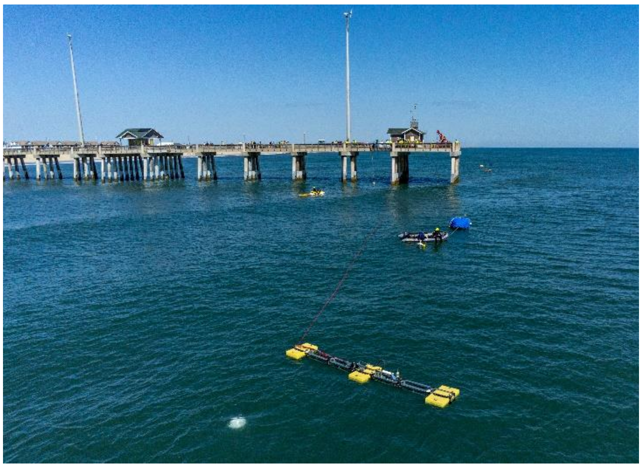

Fig. 3. Two of the W2W competitors' designs being installed at Jennette's Pier in North Carolina, USA (image credit: Josh Bauer, NREL)

any additional learning will be made publicly available on a dedicated website that can be updated as new information becomes available (https://openei.org/wiki/HERO-WEC).

Another key component of NREL's desalination R&D portfolio is implementing numerical models for design decisions, techno-economic analysis, and experimental plans. Developing custom numerical models has been critical for identifying hypotheses and quantifying risks associated with integrating marine energy with desalination technologies. Detailed models enable the team to understand which parameters require assumptions and to quantify the impact of those assumptions on either system performance or economic potential. The Wave Energy Converter Simulator (WEC-Sim) has been used for most of the design and optimization studies that have been performed by NREL due to its ability to model a wide range of WEC and drivetrain technologies [11]. WEC-Sim is an open-source software jointly developed by NREL and Sandia National Laboratories that enables time-domain simulation of the WEC, mooring systems, drivetrain components, controls, and RO system design. Due to the oscillatory and transient nature of WECs, coupling hydrodynamics and drivetrain dynamics is critical for quantifying design changes prior to costly lab experiments and ocean deployments.

III. RESULTS

By coupling all the research areas together—techno-economic analysis, prototype development, and numerical modelling—the team can continuously refine assumptions and provide valuable expertise for existing and future technology developers. This expertise was leveraged to inform WPTO's most recent desalination-focused funding opportunity announcement [12], which aims to fund pre-commercial demonstrations of marine-energy-powered desalination systems. Applicants were encouraged to request support from the NREL HERO WEC team to advance component and system testing with the goal of building upon existing knowledge through technical assistance. This call is intended to bring marine-powered desalination systems one step closer to commercialization by demonstrating technologies in real-world environments. Additionally, NREL and WPTO expect to uncover integration R&D opportunities and technical breakthroughs as new technologies are deployed and data is disseminated.

Looking forward, NREL will continue to work closely with WPTO to prioritize R&D that will reduce technical barriers to commercialization through detailed analyses, simulations, laboratory experiments, and ocean deployments where appropriate. Specifically, the team has targeted the following near-term priorities:

- Continue HERO WEC development with an emphasis on long-term operation and device survivability. This will include more robust laboratory testing on NREL's motion platform which has six degrees of freedom.
- Conduct additional membrane experiments to quantify the impact of oscillatory flow on membrane life and maintenance activities.
- Leverage lessons learned from ocean trials to develop best practices for marine operation of small wave-powered desalination systems.
- Continue to refine techno-economic models that will be used to refine the overall R&D strategy and target industry-led R&D and intellectual property development.

In addition to pursuing the specific tasks above, the NREL team will continue to understand the technology ecosystem and develop strategic partnerships with industry, academia, and community stakeholders that may benefit from the integration of marine-powered desalination.

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