Coastal Wave Powered Reverse Osmosis System

University of New Hampshire

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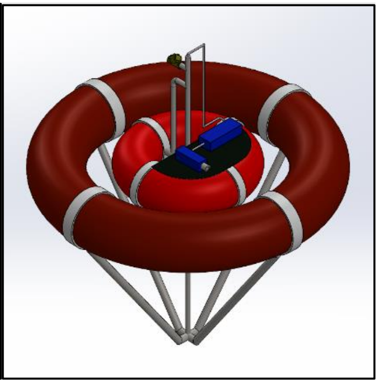
POWERING the BLUE ECONOMY™
Marine Energy Collegiate Competition
U.S. DEPARTMENT OF ENERGY



Student Team

Joseph Camobreco	Co-Lead, Mechanical Engineering	joe.camobreco@unh.edu
Tori Sweet	Co-Lead, Environmental Engineering	tori.sweet@unh.edu
Sam Williams	Environmental Engineering	sam.williams@unh.edu
Alexander Charest	Mechanical Engineering	alexander.charest@unh.edu
Andrew LePage	Ocean Engineering	andrew.lepage@unh.edu
Devan Sack	Civil Engineering	devan.sack@unh.edu
Meaghan Wiggin	Civil Engineering	meaghan.wiggin@unh.edu
Chelsea Kimball	Mechanical Engineering	chelsea.kimball@unh.edu
Brendan Reagan	Business	brendan.reagan@unh.edu

Project Faculty Advisors

Dr. Martin Wosnik: martin.wosnik@unh.edu
Dr. Erin Bell: erin.bell@unh.edu

1. Executive Summary

The 2022 Marine Energy Collegiate Competition focuses on the blue economy and sustaining the world's island populations by supplying them with clean and renewable energy and fresh water. The team from the University of New Hampshire has developed a product that is designed to produce fresh water for remote island and coastal communities with limited access to energy or fresh water. The product is designed for quick deployment and near shore installation in these communities. The product utilizes the heave provided by ocean waves to drive a hydraulic piston. The piston provides pressurized water that is then filtered through a reverse osmosis membrane. The design resembles that of a floating-point absorber wave energy converter. It is moored to the bottom of the ocean with a three-point system to keep sway and drifting to a minimum. The water, once pushed through the membrane, is then pumped back to shore for final purification in the community's cistern or water storage facility. The UNH team's business model plan focused on supplying communities with an inexpensive and easy to install system. The system was sized for the target demographic of small coastal communities. With the UNH design product, communities can get water faster and more reliably compared to traditional reverse osmosis products. The system can provide more water for larger communities by deploying multiple units together, but at the expense of increasing upfront costs. The current design placed in 2.4-meter (8 foot) wave conditions with constant wave action for 12 hours can provide up to about 3000 L of fresh water a day in non-ideal conditions. From calculations and small-scale testing, the product will work reliably and reach the desired pressures needed to operate a reverse osmosis process. This is explained in greater detail in the remainder of the business plan.

2. Concept Overview

The goal of this project is to design an affordable, effective, and reliable system to supply fresh drinking water to remote island communities. Communities that do not have access or consistent access to enough clean drinking water are unhealthy, and unsustainable (CDC, 2014). Importing water is the only option for many, though some have reverse osmosis machines, which require substantial amounts of energy. This energy is costly as well, due to the large quantity and the expense to obtain it for remote communities (Water.org, n.d.). Disaster and disaster recovery areas that have limited access to fresh drinking water would also be subject to similar conditions as these communities. To help mitigate these challenges, the product uses wave energy to generate fresh water. To provide the filtered water, the design uses a round float to drive a piston upward, following the surface level of the waves. The shell of the outside of the piston is moored to the floor, creating a relative motion. The piston then compresses water up and creates pressure for a reverse osmosis (RO) filter system. Once filtered, the water is then pumped to shore using this piston via a hose anchored to the sea floor. The filtered water is then treated and stored on shore in a pre-existing water storage system, or a water storage tank. This product would supplement or provide all the freshwater needs for a community, without the need for electricity or large, high-pressure pumps. This design is simple and can be deployed and undeployed by the community or a contractor. This allows easy maintenance, and low cost of operation with high durability. This product benefits remote communities by generating fresh drinking water using the power of the waves, without the high energy demand of a traditional reverse osmosis machine.

3. Stakeholders

UNH MECC team's design is fit for a variety of marine community settings. But beyond customer diversity there are also other stakeholders within the project. Upon further development, medium scale production would ensue depending on customer discovery and market need. Having the proper suppliers and producers of the UNH Wave Energy Converter (WEC) system would be crucial to scaling the business and growing revenue. Having units ready for response would allow for more potential buyers. The initial users are planned to be remote islands and coastal communities, but after further expansion and R&D, the market could expand to any community with access to waves. That includes, but is not limited to, non-governmental agencies (NGOs), rural communities, military bases, private homes, businesses, and small governments. Once implemented, maintenance is necessary, having staff with the proper tools and training will extend the life of the device and reduce operations costs. A full view of the global market can be seen in section 5. In the next section, a more in-depth analysis of customer needs and resources is completed.

4. Customer Discovery

To better look at the end user and future user of the desalination device, UNH MECC reached out to potential customers for a better understanding of their needs and current practices. Starting with Shoals Marine Laboratory (SML) on Appledore Island, ME, a research station cooperatively operated and maintained by Cornell University and UNH, as a local case study. A second stakeholder type is preexisting water desalination companies. Potential competition is also a group that could be a future partner and buyer; therefore, providing UNH MECC with insight. The team also conducted research with a third type of stakeholder, disaster response and humanitarian aid organizations. These types of groups are also potential users. Lastly, community residents themselves, akin to Appledore Island, the team interviewed a potential community or group of communities that could use such a device.

4.1 Case Study: SHOALS Marine Laboratory (SML), Appledore Island, ME

UNH MECC is fortunate enough to have an island community linked with the home institution. SML is a seasonal teaching and research island laboratory in the Gulf of Maine. To facilitate research and sustainable practice, the current laboratory power system includes solar power, wind power, battery storage, a well, and a land-based RO system. To meet their current water needs, the RO unit is used when needed or when surplus solar is available. In an interview with Shoals Director of Operations, Mike Rosen, UNH MECC learned how a wave powered RO device would fit within the current power/water network. For their current RO system, 5.5 MPa (800 psi) of water pressure is required. But the RO unit does not stand alone and includes a prefiltration and post-chlorination process. Their current well is used frequently during peak season but can only be depleted so low before seawater intrusion could occur. On neighboring islands, communities must pay for water at a home rate plus fuel fees. Drinking water is a defined problem for the islands and Rosen conveyed to the UNH MECC team that there are potential wave-powered RO deployment locations on the northeast side of Appledore Island with preexisting moorings. However, Rosen pointed out that environmental, and social impacts such as local fishermen, and seabed must be considered.

4.2 Current Desalination System Producer: AqSep A/S, Denmark

AqSep is a producer of small-scale desalination systems. Located in Denmark, the private company serves similar customers as UNH MECC's design would. AqSep has cases with isolated islands, rural communities, private homes, commercial settings, and on offshore structures. They produce eight devices ranging in scale and costs vary. AqSep spoke with the UNH MECC team about cost and problems with their systems. In most instances water production costs ended up being around \$0.8 per m^3, but systems ranged from 2.2kWh/ m^3 up to 10.8 kWh/ m^3. Their units can produce up to 22,000 liters of water a day, with examples in rural Asia of 2-3,000 people served per unit. AqSep conveyed that for their clients and customers, there is usually an alternative form of payment, whether that be an NGO, or taking years to pay the investment off. They also conveyed the importance of technical and mechanical simplicity. In rural communities, access to technology does not come easy, so having it run on its own, but simple enough to be maintained, is a significant challenge in this market space.

4.3 NGO and Emergency Response Organizations: Water Mission, SC

Water Mission is a U.S. based NGO that works within the humanitarian sector to provide clean drinking water. They also work in disaster relief situations to provide emergency water access. UNH MECC's design is built for several settings, post-disasters being one of them. The team spoke with engineers at Water Mission to get a better understanding of typical demand and practices on the humanitarian side. Water Mission provides products and services including water pumps, storage, quality tests, treatment systems, and project monitoring. Within their treatment systems, they provide erosion chlorinator, filtration, and reverse osmosis. These systems have been implemented in post-disaster areas. Some examples include refugee camps in Burundi, post-Hurricane Eta in Honduras, and after the recent earthquake in Haiti (August 2018). Their filtration device operates on \$0.14 per m^3 for chemicals and can purify 45 m^3 of water a day. For renewable energy they do provide solar solutions with storage tanks and gravity filtration. An NGO, like Water Mission, is a potential customer that would be the in-between for the wave device and end users.

4.4 Potential Communities

4.4.1 Marshall Islands, Republic of the Marshall Islands

Along with NGOs, and device producers, communities themselves are direct beneficiaries. Isolated and rural communities are UNH MECC’s target market, and in the most need of clean water. In Section 5, Market Feasibility, potential locations are explained and listed. Wave potential is abundant and one of these locations is the Marshall Islands in the center of the Pacific Ocean. In a report about the Ministry of Works, Infrastructure and Utilities, the island of Ebeye has a new desalination plant that can produce up to 1,600 cubic meters per day. The plant averages 520 cubic meters per day for the 9,200 community members. The project is estimated to cost over \$10 million USD and includes saltwater wells and networks for distribution (Saeed, 2020).

4.4.2 Mauritius

A second community interviewed is also a rural island nation. Mauritius is an island in the Indian Ocean, east of Madagascar. It is a large island, with a population of over 1 million, but still fits UNH MECC’s customer profile as they experience extreme weather and water storage issues. UNH MECC contacted Nirkita Seeburn-Sobhun, the senior engineer of the Ministry of Energy and Public Works about the island’s water needs, at the time of this report are still scheduling a call. General data provided showed that even with an intense wet season, water availability is unreliable, even though rural communities may have the infrastructure. Water is around \$0.33 per m^3 for their citizens, but often with low quality.

5. Market Feasibility

While the WEC and RO system is being designed to fit the needs of Appledore Island, it is also imperative to design the system so that it can be implemented in island microgrid communities globally. Potential locations for implementation are island communities in the Caribbean, Southern Australia, the southern tip of South America, the western European coast, and Japan. These locations were chosen due to their similar energy resource as in the Gulf of Maine, as well as dependence on fossil fuels and access to drinking water.

The map in Figure 1 shows the regions of the world that have and do not have access to clean drinking water.

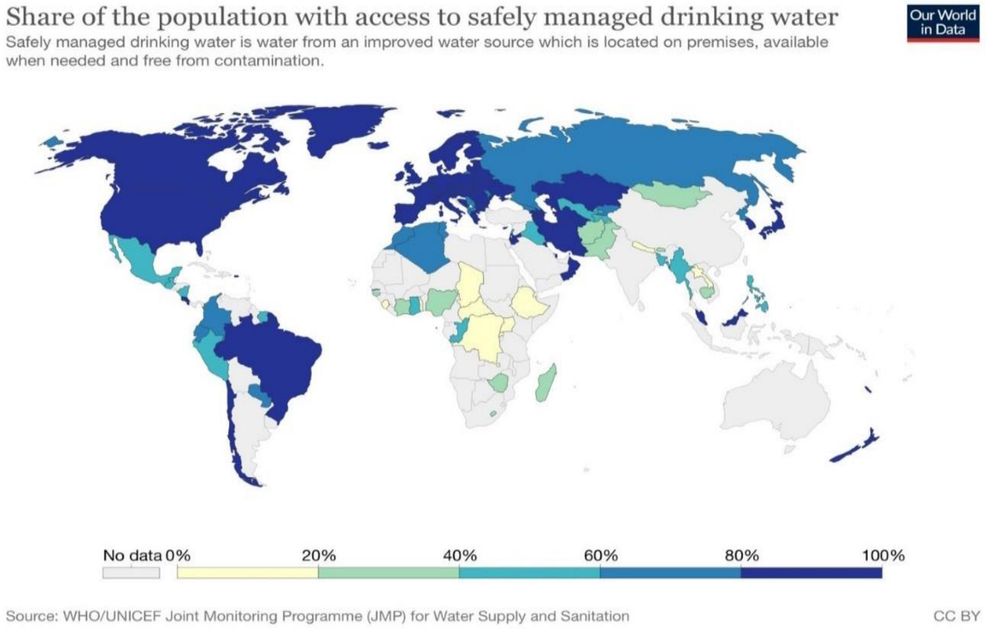


Figure 1: Global access to safe drinking water (WHO/UNICEF, 2022)

Implementation in these markets will not come without challenges, as the RO system placed on a point absorber wave energy converter is a unique design, and there's only a couple other competitors in the market for this specific design. This design enables a bypass of converting the energy produced by the WEC to create clean water, and instead, the pressure created from the waves pumps clean drinking water directly. Island communities closer to the equator, especially in the Gulf of Mexico and the Caribbean, have low wave energy potential throughout most of the year. The annual average wave power values in these areas are increased due to tropical storms and hurricanes, which generate wave power that is too strong to be harnessed by most WECs. Many of these Caribbean communities receive about 1,500 mm (about 60 inches) of annual precipitation for these regions. However, aquifers lacking elevation are more prone to saltwater intrusion, or they may have no aquifer at all. Therefore, many of these tropical island communities heavily rely on outside sources for fresh water.

Markets in the southern hemisphere have relatively large near-coast wave power that is generally steadier than that of markets in the northern hemisphere and along the equator. Thus, communities near the southern coasts of Chile, South Africa, Tasmania, and New Zealand should be explored as potential stakeholders, however there may be fewer microgrid communities that lack a consistent centralized source of drinking water.

Markets in the northern hemisphere, such as northern Europe, Japan, and the northern Atlantic and Pacific coasts of North America, present the closest similarities to the case study location of Appledore Island, in terms of wave power and ocean floor topography. These similarities will allow for the WEC to be integrated easily into these potential markets. Complications arise in these northern markets because the seasonal variation of wave power between winter and summer is the greatest in the northern hemisphere, with higher wave power levels in the winter months (Rosen, M 2021). Potential stakeholders in these regions may be less willing to invest if they cannot be guaranteed stable drinking water production during the summer months, when they are likely to need it most.

Coastal communities that already have some form of renewable energy system in place, whether it be wind, solar, or a combination of both, may benefit from the addition of a WEC and RO system. While there are issues in the seasonal availability of wave energy, it is still more temporally available and persistent in comparison with wind and solar resources. Not only is wave power more predictable than wind or solar power, but it can also fill the gaps in a renewable energy grid. In the markets with the most volatile wave power, potential production is at its peak during the winter months and at its lowest in the summer months, which is the inverse of solar power. In the test location of Appledore Island, the WEC and RO system can be implemented into a microgrid that already has solar and wind power. In the winter months, drinking water can be produced at relatively high rates and can be stored for future use, while wind energy can produce electricity. In the summer months, when wave power is lower, but solar power is higher, wind and solar power can be used to generate electricity and pump stored water throughout the community, while wave power produces lower quantities of drinking water.

5.1 Deployment Location Model

To explore the potential areas of deployment outside of Appledore Island, a model was developed in MATLAB to map monthly average wave heights and locate areas with similar wave heights to the test location. The input data was collected by the National Oceanic and Atmospheric Administration (NOAA) and extracted from the WaveWatch III database (*ERDDAP*, 2022). Appledore Island has a maximum average wave height in January of 2.44 meters, so locations with average wave heights between 2.3 and 2.5 meters were deemed to be within the optimal wave height range. The model can be adjusted to cover any area of the globe during any month by adjusting the parameters of the NOAA dataset. The model was run for each month in the winter of 2021-2022 and June 2022 for North America and East Asia. Based on the modeling results, areas along the coasts of Nova Scotia and British Columbia in Canada, as well as the northern islands of Japan appear to be the most feasible deployment locations. Figure 2 shows monthly average wave height data along the coasts of the United States and Canada between the latitudes of 25 and 60 degrees, with locations within the optimal wave height range overlayed.

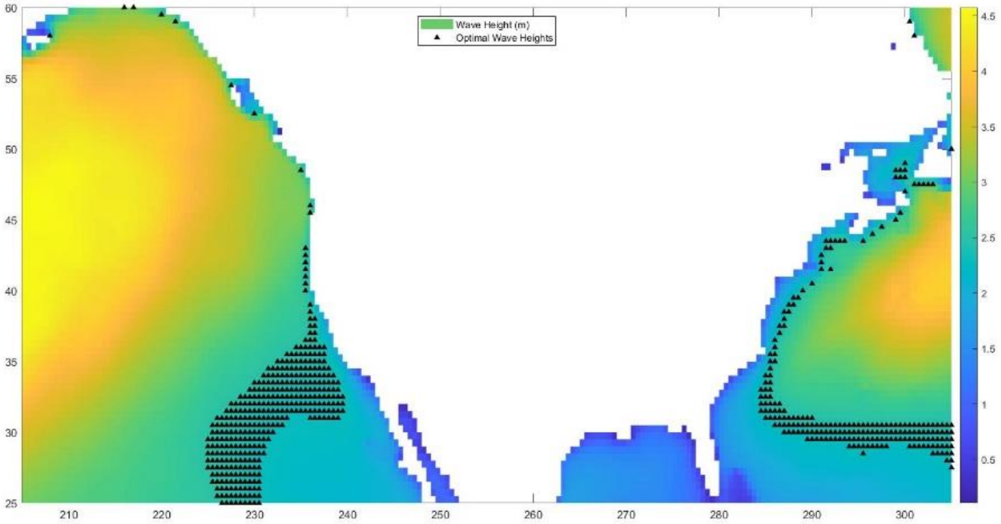


Figure 2: January 2022 monthly average wave heights in North America with optimal wave height locations overlayed

6. Competition

The UNH Coastal Wave Powered RO System (CWPROS) is designed as an easily deployable, low-cost, small-scale solution to make potable water accessible to off the grid coastal communities. The system is like several other emerging prototypes within the wave powered desalination field, but additionally has key attributes that make it an exceptional design.

The CWPROS is designed as a lightweight, small-scale device that is easily deployable. The largest dimension of the system is the outer diameter of the float, which is approximately 3 m (~9 ft). The overall height of the system before being attached to the mooring is approximately 3 m (~9 ft) in its equilibrium position. The heaviest component is 485 kgs, with the entire system weighing 794 kgs.

Table 1. Key Characteristics of CWPROS

Characteristic	**Value**
Outer float diameter	2.74 m
Overall height (at equilibrium)	2.74 m
Heaviest single component	485 kg
Overall system weight	794 kg
Daily Water Production	6.60 m^3

These comparatively small overall dimensions and weights make it feasible for a small group with a limited capability boat to deploy and install the CWPROS. When comparing the CWPROS to other devices currently in development and on the market, one advantage is that it is an all-offshore device with a relatively small size. The Resolute Energy device Wave$_{2O}$ is designed to work with onshore containers that are forty feet long, which takes up valuable space on land and could be difficult for customers to support (Parletta, 2022). The Australian based CETO device utilizes onshore power plants to power their RO devices, which are labor intensive to install and take up space on the land (Engineers, 2022). With the CWPROS device operating entirely offshore without using electricity, its simpler design is advantageous for straightforward deployment.

The environmental impact of installing a CWPROS is low overall, by having a small mooring footprint and low concentration of brine output. Many other similar desalination technologies also have low brine concentrations of 30-35% (Parletta, Oneka, 2022), which is comparable with the CWPROS. This indicates that there are unlikely to be any harmful salinity related effects to local marine flora and fauna when a desalination device is installed. The mooring footprint of the CWPROS has dimensions of approximately 0.09 square meters (1 square foot), utilizing the innovative Halas mooring system design (Project AWARE Foundation, et. al, 2005). A mooring of this size is unlikely to cause severe damage to seafloor habitats, whereas the Resolute Energy Wave$_{2O}$ device has a paddle base which takes up space on the ocean floor of approximately 9.29 m^2 (100 ft^2) (Resolute, 2022). Given that the CWPROS mooring area is significantly less, the environmental impact of its installation will also be reduced.

One significant benefit of the CWPROS is that it is priced at an attainable level for nearly any community. A single device without the additional costs of shipping or installation added in is estimated at $20,000. With an estimated working life of twenty years, and production rate of 3.0 m^3 of potable water per day, the cost per cubic meter is approximately $2.10 USD (calculations in section 12). This price point is slightly above, but still competitive when compared to other similar devices. The Resolute Energy Wave$_{20}$ is estimated to produce one cubic meter of potable water for a cost of $1.25 (Parletta), and the Oneka Technologies desalination solution is estimated to produce the same amount at a cost of $2 (Wave-powered). The CWPROS is 52% reduced in price compared to the Resolute Energy Wave$_{20}$ device, and

70% for the Oneka device. This would make the CWPROS the most affordable option currently available and allow for nearly any coastal community to access potable water without the use of fossil fuels. Additionally, there are no electrical components involved in the system, making maintenance costs low. The yearly estimated maintenance cost for the CWPROS is approximately $250. With its small footprint and overall low weight, shipping costs for the system will also be minimized for customers.

Currently, other similar emerging technologies are self-reported as small-scale systems, however they are not as small scale as the CWPROS. While the CWPROS is modular and has flexible storage options like many of its competitors, its microscale water production performance is notable. A single CWPROS is estimated to produce 3.0 cubic meters of potable water per day (equivalent of 800 gallons per day) under ideal conditions of 8 ft waves, all day. The Resolute Energy Wave$_{20}$ device is reported to produce 500 cubic meters per day (Parletta, 2019), and the CETO device is estimated to create 150 cubic meters of water per day (Engineers Australia, n.d.). Another system currently in development by Oneka Technologies quotes 50 cubic meters per day of water production as the smallest scale device. By offering a device capable of producing potable water for communities of several hundred people at a dramatically reduced cost, the CWPROS fills a market niche for micro-communities in need of clean water.

Table 2. RO Device Cost and Production Comparison

Device	**Cost per cubic meter**	**Cubic meters per day**
UNH CWPROS	$2.10	3.0
Resolute Energy Wave$_{20}$	$1.25	500
Oneka Technologies	$2.00	50
CETO	N/A	150

A wave powered potable water producing device that is affordable for nearly any sized coastal community, has a low environmental impact, and is easily installable is a unique design challenge. The CWPROS meets the requirements for all these aspects in an innovative way by focusing on serving microscale communities. These features of the CWPROS create a competitive edge in the burgeoning wave powered desalination market.

7. Development and Research

Current research has focused on the pressure capabilities of the wave energy converter, and the efficiency of it. This is following the stage approach described in the International Electrotechnical Commission guidelines (IEC, 2018) for a stage 1 device. The design was Froude scaled with a scale factor of 1:8 and then tested in the University of New Hampshire wave tank to assess the pressure-making capabilities as well as the energy conversion efficiency. The full-scale model will use a pressure of 5.5 MPa (800 psi), and so the small-scale model will aim to create a pressure of 690 kPa (100 psi), as pressure scales linearly with scale ratio using Froude scaling, discussed more in the build and test challenge report (Pritchard, 2015).

All measurements were recorded using a digital pressure sensor and Arduino microcontroller. This data was stored on a micro-SD card and later plotted and evaluated using MATLAB. Using the collected pressure data, and the known wave height values, the work done by the pump and the energy that the wave imparted on the pump could be determined. The ratio between these two values represents the efficiency of the system and will allow the team to have a metric to compare future iterations against. This also allows evaluation of expected efficiency and of the simulation used to create it, providing better modelling and test designs before the model is even scaled down and tested. It will also allow for predicted results in various deployment areas.

The wave tank testing of the wave-powered RO scale model was conducted for Stage 1 according to the IEC Technical Specification 62600-103 (IEC, 2018), for the early-stage development of wave energy converters. The main purpose of the testing was to explore initial design choices and to demonstrate that the design has potential. The testing conducted by the UNH team was at Technology Readiness Level (TRL) 1, Proof of Concept, to verify that the wave-powered RO device as designed can operate and pump water under wave excitation as predicted. The TRL 1 testing provided a good basis to be able to move towards TRL 2, Optimization of Design (still within Stage 1).

The wave-powered RO scale model was scaled with Froude-similarity, i.e., the Froude number for the model was kept the same as for the prototype. Froude and Reynolds similarity cannot be achieved at the same time for the same fluid (water); however, it was estimated that the Reynolds number was large enough for our model to not have a significant Reynolds number dependence. The proof-of-concept system used dissimilar geometry to the full-scale model to make construction feasible.

To simulate the small-scale model, Wave Energy Converter Simulation (WEC-Sim) is an open-source software developed by the National Renewable Energy Laboratory (NREL) and National Technology and Engineering Solutions of Sandia, LLC (NTESS). This software focuses on simulating wave energy converters, and the dynamics involved with them. To use WEC-Sim a SolidWorks model of the small-scale model was developed and converted to stereolithography (STL) file format. Then, using Meshmagick, another open-source software, it was converted into a NEMOH file. NEMOH is a Boundary Elements Method code and is one of the accepted file formats for WEC-Sim. Once this file had been converted, it could be run through WEC-Sim. To run the simulation, the mass moment of inertia had to be calculated and entered the simulation code. This was calculated by SolidWorks and used in the simulation.

One of the results of the WEC-Sim study is the net force that the system experiences along the z axis, or heave direction. The net heave force is determined by the software from the interaction of the two bodies. To calculate the net pressure, the net force was divided by the area of the piston. The model was simplified for the simulation, with the float being designed as a simple block with three connecting pipes protruding out of it. The spar was designed as a simple capped pipe in the model. For the buoy mooring, a translational constraint was applied. This constraint does not fix the spar or the buoy but prevents motion that is not in the z direction. The simulation provided results that were very inaccurate for this system. The simulation resulted in only 1.5 kPa being generated, which is almost 10 times less than was observed. The model used in the simulation did not include the addition of ballast, or the mooring configuration, which contributed t the discrepancy. It can be an accurate model, however, if these corrections were applied.

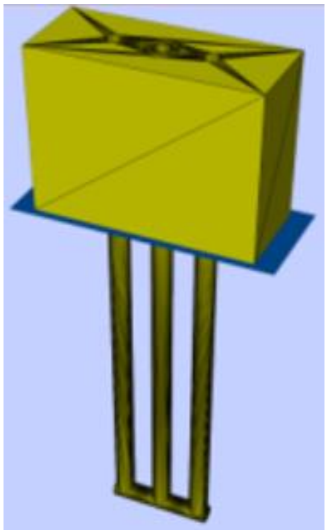


Figure 3: Small-scale model used in WEC-Sim simulation software. Float is shown here above water plane, with the spar below.

The scale model testing also provided opportunities to discover potential problems with the full-scale model during proof-of-concept testing. When first tested, the proof-of-concept model was secured between the carriage and the bottom of the tank, with no other ballast. This set-up can be seen in the image below. The structure connecting the float to the piston head was then unable to draw water into the piston chamber, as the force needed to overcome friction and raise the water into the pump was too great. Ballast had to be added to the piston head structure for it to have enough mass to follow the water level down to draw water in. The pump was also found to be leaking at first, and so a tighter fitting gasket was installed below the pump head to prevent this leaking.

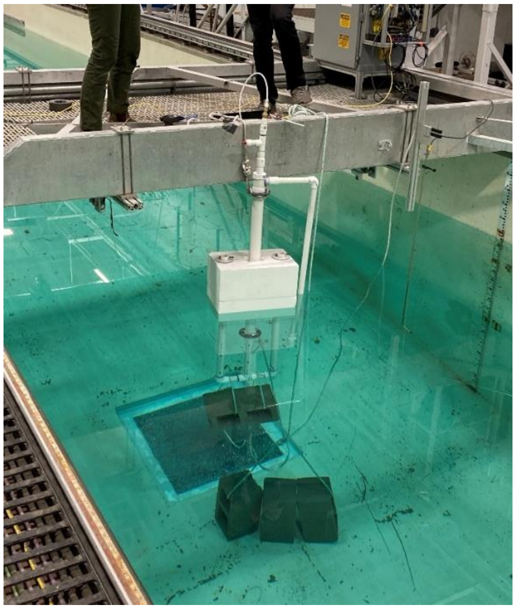


Figure 4: Image of proof-of-concept system attachment to wave tank

The future work includes refining the pump mechanism to reduce friction and increase efficiency, as well as balancing the float buoyancy better to allow it to intake water and compress it. This will be done by performing theoretical calculations and simulations before modifying the small-scale model, to decrease the amount of labor and money spent. When completing these future tasks, the Stage approach outlined in the IEC Technical Specification for early-stage wave energy converter development is to be followed (International Electrotechnical Commission, 2018).

8. Environmental Risk

When designing the wave energy converter desalination system, environmental risk is a key factor to consider. Wave power is one type of renewable energy which means that the energy source is naturally replenished. Using renewable energy, rather than fossil fuels, is one way to lower carbon emissions released into the atmosphere. According to the U.S. Energy Information Administration, renewable energy is only utilized for 12% of the United States primary energy consumption (U.S. Energy Information Administration, 2021). Fossil fuel use is the leading cause of greenhouse gas emissions in the United States; there are opportunities in the United States, as well as world-wide, to harness more energy from renewable energy sources to reduce fossil fuel use. Greenhouse gases are a worldwide concern due to the impact of these pollutants on climate change. Limiting greenhouse gas emissions through renewable energy is an impactful way to combat climate change. Increasing population and urbanization also results in a larger energy demand, creating the need for more energy. A wave energy converter is one way to supply some of this needed energy in a sustainable manner.

Securing the wave energy converter to the sea floor requires the use of a mooring. For this design, the Halas mooring system is utilized as the standard mooring type (Project AWARE Foundation, et. al, 2005). This type of mooring is commonly used for the rocky conditions seen in the Gulf of Maine. The Halas mooring system has little surface area on the seafloor, allowing for there to be minimal sea floor damage. This is especially important in locations where coral reefs are located or other key habitats. While the Gulf of Maine does not contain coral reefs, this system is designed to be deployed in areas where coral must be accounted for. Anchors are one threat to coral reefs because they can tear off chunks of the coral, which harms the coral reef as well as the sea life that uses it as a habitat. Another mooring option that is encouraged for this system is the use of existing moorings in the ocean, if feasible. There are many coastal moorings in the ocean that are not in use, so utilizing these existing structures would eliminate the need to place a new unnatural structure into the ocean. Some existing moorings are not as minimal in size as the Halas system in this design, however these moorings have the potential to act as an artificial marine habitat. Marine structures with a rough surface, such as a fiber reinforced concrete mooring, provide a space where sea life can attach to and create a new artificial coral habitat (Habitat Mooring Systems, n.d.). Since a mooring system is necessary for this design, utilizing one that is small or can act as artificial coral provides an opportunity to minimize the impact on sea life. The surface mounted point absorber wave energy converter requires cabling to attach the device to the mooring, creating the opportunity for marine mammal collisions and entanglement. Collisions and entanglement can harm or kill the marine life involved as well as the wave energy converter and desalination structure. To limit the threat to marine mammals, the design uses the minimum amount of cabling required to secure the system.

Reverse osmosis desalination creates fresh water for consumption, but it also creates brine. Brine is water that contains approximately 70 mg/L of salt and is typically discharged back into the ocean once it goes through the desalination system (Arnal et al., 2005). According to the United Nations, 1.5 liters of brine is discharged per liter of fresh water created. This value may change depending on conditions such as feedwater salinity and local conditions. When brine is discharged directly from the desalination system to the ocean, the salinity of the ocean in that location increases. A high salinity depletes the dissolved oxygen in the water, which may cause harm to benthic organisms. When these benthic organisms are harmed, it impacts the rest of the food chain as well. This was documented in desalination systems where improper brine disposal occurred. High salinity and chemical concentrations in brine can reduce the growth of other marine life, such as sea grasses (Jenkins et al., 2012). Three ways to lessen the environmental impact of brine is to enhance mixing, diffusion, and dilution of the brine in the water column. To increase the amount brine diffusion, the discharge pipe of this desalination system is designed to have a nozzle diffuser at the pipe outlet.

The U.S. Environmental Protection Agency set a salinity limit for brine discharges of ≤ 4 ppt (Jenkins et al., 2012). Some states, such as California, have their own limits on salinity discharges into the ocean. Maine does not have a state limit for salinity, so the EPA limit will be used when monitoring the discharge of the system. Regulations for moorings and deploying marine structures vary by location, so this will need to be considered on a case-by-case basis.

9. Technical Risk

A significant technical risk for the wave energy converter is whether the structure can withstand the forces of severe weather and objects striking it. To ensure that the system can withstand these forces, the design includes as few piping connections as possible. When the proof-of-concept system was initially tested in the wave tank, a leak was found in one of the pipe connections, which resulted in that piece of the system breaking off when durability was tested. The wave size was increased to test durability and the system was allowed to strike the metal carriage structure on the wave tank during this. When this test occurred, the only section of the wave energy converter that could not withstand the external forces was the one pipe connection that had a leak which caused this weakness. An image of the piping striking the metal carriage can be seen below. The pipes for the full-scale design contain only the required amount of piping connections to not add unnecessary risk of leaking. Another management strategy for maintaining strength when there are large external forces on the system is the inclusion of steel rings around the buoy. These steel rings are located where the pipe arms connect to the buoy to ensure that the connections between the pipes and the buoy are secure. The rings also act as support for the buoy to prevent it from warping or breaking.

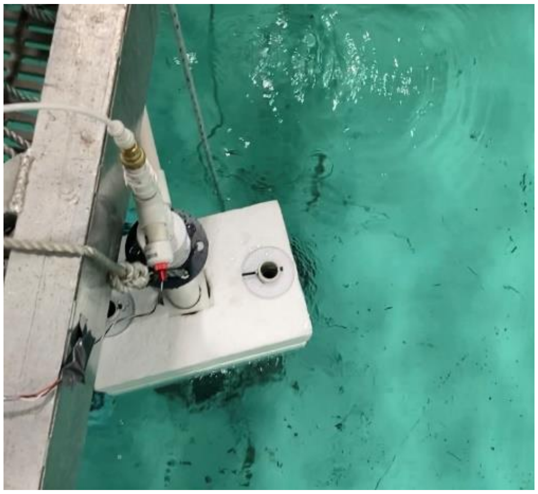


Figure 5: Image of proof-of-concept system striking metal carriage during wave tank testing

A technical risk for the reverse osmosis membrane system is a membrane that is not functioning due to improper pre-treatment. The purpose of pre-treatment for a membrane filter is to remove suspended materials from the water so it does not clog the membrane as the water passes through. To pre-treat the water, micro-filtration will be included before the membrane. Sea water that passes through a membrane system can be corrosive which could cause a problem with piping in the distribution system. To overcome this risk, the pH will be monitored and raised if needed. Another technical risk related to reverse osmosis desalination is the risk of microorganisms in the drinking water after passing through the membrane. A disinfectant, such as chlorine, will be added to the water in the post-treatment process (Collins, 2022).

10. Societal Risk

The use of wave power to harness energy reduces a community's dependence on non-renewable sources of energy, such as fossil fuels. This local source of renewable energy would allow for a community to lessen the vulnerability to rapidly changing fossil fuel prices, e.g., oil. Financial stability in a society would grant an improved quality of life and allow for more money to be allocated to other areas in need of assistance. A major societal risk of non-renewable energy is the greenhouse gases that are released into the atmosphere, resulting in an accelerated level of climate change. Climate change is a major societal concern because it is shown to cause extreme weather events that can be devastating to infrastructure, housing, and the lives of those facing these issues. Using energy from a wave energy converter would not add any greenhouse gases to the atmosphere because there are no emissions released from this system. This would be a direct way for a community to have a role in attempting to slow the impacts of climate change (Bedard, n.d.).

Natural disasters pose a threat to safe drinking water because they can lead to aquifer and well contamination or damage water treatment facilities. Having a small desalination system would create an easily implemented option for providing safe drinking water to communities in need. This reverse osmosis desalination system would aid in natural disaster relief as well as help developing communities who have limited access to clean drinking water. Access to potable water through desalination would improve the health of the community by significantly reducing the risk of water-borne diseases such as cryptosporidium, giardia, and E. coli (Centers for Disease Control and Prevention, 2014). Not only does reliable access to safe drinking water improve a society's health, but it also reduces the amount of time needed to collect water each day where there is not a local source of clean drinking water (Water.org, n.d.).

11. Operation & Maintenance

To deploy the buoy, a vessel will need to tow the device out to the mooring location, and secure it to the mooring with marine grade, heavyweight mooring chain. The system can be set up on the shore and towed out to the mooring location using a boat equipped with midsized engine. While the mooring may need to vary depending upon the deployment location, the Halas mooring system has a low environmental impact. Additionally, a hose will need to be secured along the seafloor to connect the buoy to an onshore freshwater storage system. The system can either be attached to a standard cistern provided with the device or can connect to the community's existing water storage solution. Once the buoy is deployed, it is self-sustaining and requires few additional manual operations. It is capable of pumping fresh water from the ocean to the shore indefinitely with minimal maintenance and repairs.

However, the buoy will cease to function if there are any critical failures. Therefore, the device has been designed so that maintenance may be performed on the buoy while it is deployed. The buoy can be detached from the mooring chain, while the mooring chain is tied to any floating object, so it does not sink to the bottom, and have maintenance performed upon it either on a vessel or onshore. A comprehensive guide to the buoy will be provided so disassembly, maintenance, and reassembly will be straightforward for all customers. A working lifetime of twenty years is estimated for most of the parts, but the device will likely last longer as repairs are made intermittently. A typical part that will need to be checked annually, and potentially replaced as frequently is the reverse osmosis filter. It is likely these should be replaced each year, which has an expected cost of $250. Additional maintenance may include water quality test kits for pH and salinity, which are provided with each device. Water quality tests should be conducted weekly to ensure all parts are functioning as expected and to maintain a high standard of quality for a community's drinking water supply.

12. Financial Analysis

To understand the financial potential of UNH MECC's idea, a revenue outlook was completed, as well as a cost breakdown. A parts list was made using the 1:8 scale as a reference along with currently produced WECs. The components with shipping came to a total of $9,900.

Table 3. Component Costs

Component	Cost
RO Membrane	$250
Parts and Fitting	$3,550
Buoy System	$4,100
Shipping	$2,000
Total	$9,900

To get a capital expenditure cost, O&M cost, and a final unit cost, *Water Journal's* report titled "An Economic Assessment of the Global Potential for Seawater Desalination to 2050" was used. (Gao, 2017). The current capital cost is estimated to be \$20,000 based on other small scale WEC desalination systems, such as Resolute Marine's Wave20. The price will be kept as low as possible to try and make the device easy to acquire. The first step is to calculate the annual amortized capital cost (Ca) using the equation below.

$$Ca = Capital\ Cost \cdot \frac{1 \cdot (1+i)^n}{(1+i)^n - 1}$$

In the above equation, "i" is the annual discount rate and n is the plant life. Following the Water Journal report, "i" was made equal to 8% and n was designated as 20 years. Both values are consistent with the report as well as previous studies. Using the equation for capital cost, a Ca value of \$2,037 per year was calculated. To get to a unit value per m^3 a second equation combines O&M costs with the capital, shown below.

$$Cp = \frac{Ca}{Annual\ Capacity} + C_{O\&M}$$

The equation above uses the Ca value as well as the annual capacity. The annual capacity is calculated using UNH MECC's estimated daily yield of 3.0 m^3 /day or 800 gallons/day. That value is multiplied by 365 to get a very simplified annual capacity. Further estimations on capacity should be done to better understand a full-scale yield. The annual capacity comes out to 1,095 m^3. The O&M costs are calculated using the *Water Journal's* estimations of 0.10 \$US / m^3 for labor, 0.07 \$US / m^3 for chemicals, 0.03 \$US / m^3 for membranes, and 2% of the capital cost as the annual maintenance. Using equation 2, a final unit cost of \$2.10 /m^3 is calculated.

It is likely the cost per volume of water would change as full-scale production could see new obstacles. But, as an estimate in non-ideal conditions, the current value is above but relatively competitive with other systems (see competition section).

13. Technical Report

13.1 Summary for Technical Design

A major portion of remote island communities are without fresh drinking water. A general solution to this is the use of reverse osmosis systems to remove salt and particulate from the water to produce drinkable water for these remote communities. The water produced from reverse osmosis is still considered "hard water" and still needs post process purification before consumed. The UNH MECC system will rely on a four-part reverse osmosis system which will produce "hard water". The "hard water" can then be filtered on land using a myriad of different methods such as chlorine tablets.

These systems can come in multiple different forms, the most common being membrane filters that use very fine membrane to remove particulate. There is also electrodialysis which uses positive and negatively charged plates that separate the cations and anions in salt water which removes salt and particulate, and there are many other forms of reverse osmosis. The UNH team's solution revolves around using a wave energy converted to power a reverse osmosis membrane system. Typically, these systems require large amounts of energy and high pressure. The system is designed to generate the high pressure necessary of around 5.5 MPa (800 psi) to power a single saltwater reverse osmosis membrane. This high pressure is typically obtained using a diesel generator or a connection to the electric grid, which are not usually clean energy. In contrast, the proposed device uses wave energy to power the reverse osmosis process. This energy is clean and renewable, as well as available globally. The designed system operates by using a wave powered linear piston, and a four-stage reverse osmosis filter that can achieve the required pressure of 5.5 MPa (800 psi). Shown below are the different stages of the design.

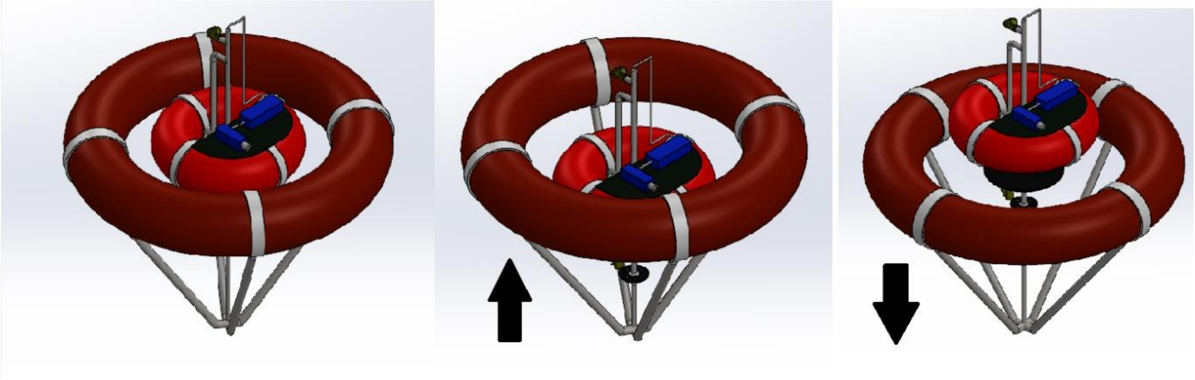


Figure 6: The stages of the wave energy converter pumping water through a reverse osmosis system.

The system consists of two parts: the pumping buoy (outer float) and piston chamber buoy (inner buoy). The piston chamber buoy is moored to the sea floor while the pumping buoy is free to move with the waves. The device starts level with the waterline and when a wave comes and pushes up on the pumping buoy it moves the piston attached to the float up the piston chamber compressing the water inside. Then as waves retract the float creates a back pressure that sucks in more water into the chamber. Then the cycle repeats as more waves come.

Once the water is pushed through the reverse osmosis system the filtered water is then pumped back to shore to be treated and stored for use by the community. It can be easily removed, operated, and maintained. The device also has a small impact on marine life, being roughly the same size as an ocean weather buoy, as well as limiting its damage to the environment by diffusing brine back into the ocean current.

13.2 Manufacturing Overview

For the wave energy converter, UNH will be using 304 stainless steel for the piping system, as well as the piston chamber material. The pipes are standard sizes and are readily available off the shelf. Once acquired, they can be easily and quickly cut to length, as it is a relatively easy material to cut. These will then be joined together by welding the pipe together at the connection points. This will also seal the joints, and prevent any leakage of pressure, and contamination of the filtered water. This will form the structure of the piston shaft, chamber, and piping system. This will also be the material of the substructure connecting the buoy float to the piston shaft.

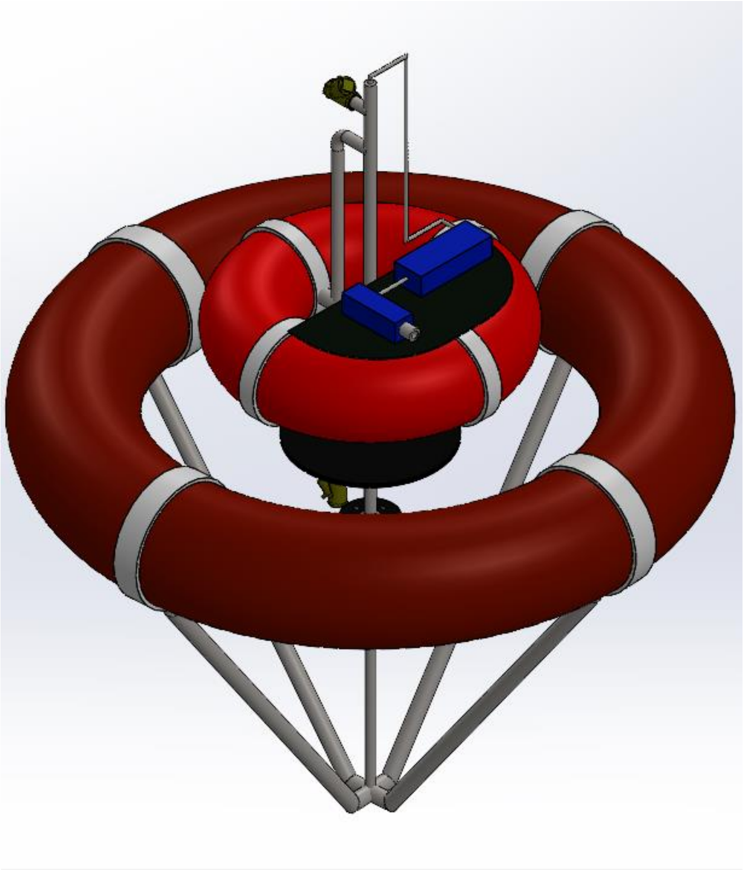


Figure 7: Model of device as viewed in SolidWorks

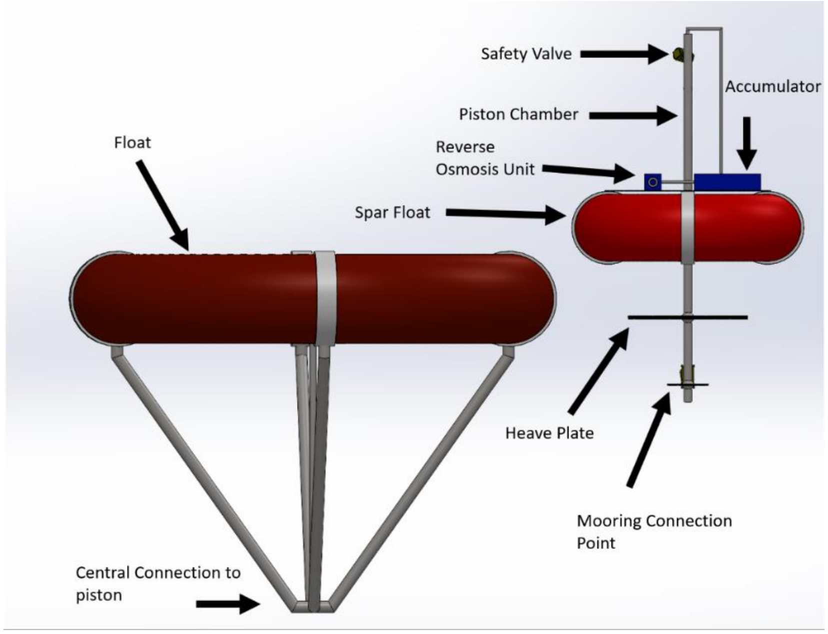


Figure 8: Exploded view of device as viewed in SolidWorks. Major components of buoy labelled.

The buoy will be constructed of polyethylene foam, cast using a mold. The creation of the mold will take a significant portion of the time building the device. The large size of the mold will be the most difficult challenge to creating it, as well as curing time and ensuring an even cast. The substructure will be mounted to the buoy using plates welded to the end of the pipe. These can be seen as the grey bands encircling the float in figures 7 and 8. These plates will be in the mold when the buoy is cast and will then be fixed to it, as the foam will have formed around the plates, thus securing them.

The reverse osmosis system will be an off the shelf multi-stage unit, with four filter phases. These filters can be purchased directly by the consumer and replaced as needed. The filter comes as a complete kit, with the chambers, gaskets and wrenches included. This will allow for fast manufacturing, by merely connecting a piping system to the four-phase unit. This unit will be placed inside a weatherproof, watertight box, however, which will be composed of 304 stainless steel sheet metal walls with a gasketed door with strong latching. This will help protect the reverse osmosis system from the damaging environment, as it will be exposed above the waterline. Any sensors or other equipment added to the system will also be stored in this container for protection.

For typical use cases, the conditions near shore are rocky bottoms. The normal mooring system to be used will be a Halas mooring system. The Halas mooring system uses an anchor cemented into a drilled hole in the bedrock of the sea floor to provide the force. This anchor has an eye hook to which the mooring line is attached. For the hose to bring the filtered water to shore, the typical mooring system will be the Halas system as well. As the conditions near shore depend greatly on the location of installation, these mooring systems may not work. For those situations, a different mooring system would be used that would be well suited for that condition. An example would be Danforth style anchors and heavy chain mooring line for sandy conditions for the buoy (“Mooring Buoy Guide”, 2005). The hose will be moored using helical anchors in the seafloor, as they are cost effective when bought in bulk, and an effective mooring system. An alternative to these would be using an existing mooring system, such as concrete blocks. These blocks can also double as artificial reef structures, benefiting marine life.

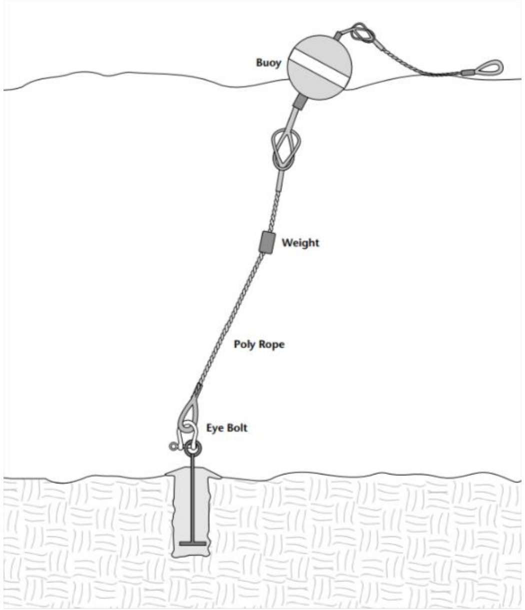


Figure 9: Image of the Halas Mooring System (“Mooring Buoy Guide”, 2005)

Once filtered, the underwater hose will be connected to the output to allow the flow of filtered water to shore to be treated. This piping will be ordered off the shelf from a market supplier. This, along with the mooring for the wave energy converter itself, will be done by a mooring company, as they have the experience, tools, and knowledge to do this. The wastewater from this filtration process, known as brine, is of such a small quantity that it is not regulated. There will be a discharge port on the reverse osmosis filter system, which will return the brine to the ocean. In the interest of the environment, however, a diffuser will be attached to the end of the outlet pipe to reduce any impact on the marine environment. A diffuser is a device that disperses the flow through it and aids in the mixing of the fluids. This outlet will also be located away from the intake, to prevent the filtration of water with a higher salt concentration than the team designed for.

13.3 Mechanical Loads and Analysis

The major mechanical loads on the system will revolve around the pressure generated from the wave forces, as well as the mooring loads. This device is being designed for a pressure of 5.5 MPa (800 psi) in the piston chamber, and the forces that result due to that. The buoy float will be made of cast polyurethane foam in a toroid configuration. The connection of the arms to the buoy is done by encasing a plate within the casting, to fix the arms in the buoy itself. This also prevents any drilling or cutting of the buoy, allowing it to be one continuous structure. The arms are then welded at horizontal connections, which come together to the center and are welded to a central connection. This connection is where the piston shaft is welded as well, in the center of it. The greatest stress concentration is at this location, as the force is all being localized to the piston shaft. The stainless-steel shaft then protrudes upward into the piston chamber, where the water is compressed through the tubing system and the filters, then back to shore via an undersea water pipe.

The buoy float will be made of cast polyurethane foam, as it is durable and low density provides adequate buoyancy force. This will also provide the required force to lift the piston shaft to compress the water to the desired pressures. The foam will also provide some protection from any flotsam that would ram into the wave energy converter, as it would provide a buffer to the central spar, filtration unit and piping.

The connection arms from the buoy float to the piston shaft will be made of 304 stainless steel. This will provide the material with enough strength to withstand the forces and bending moments exerted on it. This will also prevent it from corroding the saltwater environment. This will be fixed to the buoy float using metal plates welded to the end of each arm. The polyurethane will be cast around the plates and the arms to secure them within the buoy with no other processes or hardware needed. The arms will attach to the piston shaft at a central location using a triangular metal piece, made of 304 stainless steel as well. This will provide the surface area and material needed to securely weld the pipes and shaft together.

For the piston shaft, the material will be 304 stainless steel pipes as well and will be welded to the triangular metal piece at the central location. This pipe will be able to handle the forces on it, as the material has a yield strength of 215,116 kPa, and a modulus of elasticity of 193.05 MPa ("AISI Type 304 Stainless Steel"). This is less than the maximum stress that can be applied to the shaft of 156,063 kPa. This was found by dividing the maximum force applied by the cross-sectional area of the pipe ("Barlow's Formula", 2005):

$$\sigma = \frac{F_{max}}{A_{pipe}}$$

The safety factor associated with this is 1.38, which is not a high safety factor, but there are existing safeguards to make this allowable. The buoy cannot provide any more lifting force than when it is fully submerged, which is the maximum force used here. Any sudden upward force would only be due to the buoy being submerged, and the downward force is much less, as it is only the weight of the buoy drawing it down. The shaft will not buckle based on the shaft buckling formula for a shaft fixed at both ends ("Euler's Column Formula", 2012):

$$F = n\frac{\pi^2 EI}{L^2}$$

Where F is the maximum allowable force, n is the end condition factor, E is the modulus of elasticity, I is the moment of inertia, and L is the length of the pipe. Using this equation, the maximum allowable force is 744,566 N, which is much greater than the maximum force the buoy will provide of 44,602 N. This provides a safety factor of 16.69, which shows buckling is of little concern.

Similarly, the mooring force will be less than this, which shows that there is no concern for the connection point to the spar. This is because the mooring force only prevents the buoy from drifting away from the installation location and prevents undue forces on the transport system to shore. The vertical forces applied to it will be less than the force generated by the float, which has been proven to be well within safety tolerances. The horizontal force is minimal, as the use of heavy chain ensures the force will be dominantly in the vertical direction.

At the top of the piston shaft, a 304 stainless steel pipe cap will be welded on to seal the piston shaft, with a bronze bushing impregnated with graphite to provide better wear characteristics and lubrication on the outside of the pipe. An O-ring will also be located just below the bushing to provide a seal against the pressure in the chamber. The piston will then be forced up, compressing the water through the piping system, also made of 304 stainless steel.

If the pressure is increased beyond the designed pressure, it will not exceed 5,861 kPa, as a pressure relief valve will open if the pressure exceeds this value to prevent damaging the equipment. There are also check valves to prevent backflow, located at the intake pipe and the pipe to the pressure accumulator. These check valves are designed and guaranteed by the manufacturers to be rated for 5,516 kPa, which is the operating pressure being designed for. The manufacturers will have also built a factor of safety into the 5,516 kPa safety rating, and so will be suitable for the proposed design.

The piping system is also suitable for the design, as the 304 stainless steel seamless pipes used have a maximum pressure that is less than 5,516 kPa, as found using Barlow's Formula ("Barlow's Formula", 2005):

$$P = 2y\sigma_y\frac{t}{d_o}$$

Where P is the internal pressure at minimum yield, σ_y is the yield strength, t is the wall thickness and d_o is the outside diameter. The pipe being used has a thickness of 6.35 mm, with an outside diameter of 31.75 mm. The yield strength of 304 stainless steel is 215,116 kPa as stated above ("AISI Type 304 Stainless Steel"). This results in a maximum allowable pressure of 86,047 kPa. This is well above the designed operating pressure and gives a factor of safety of 15.60.

The filtration unit is designed by the manufacturer to operate at 5,516 kPa and has a maximum pressure rating of 8,274 kPa. This assembly is rated for pressures well beyond what the designed wave energy converter is possible of generating.

The piping system to shore will be commercially available pipe, and may have a low-pressure rating, as the pressure decreases after the filtration system. This will be purchased and installed by a contractor, as will the mooring system for the pipe and wave energy converter.

13.4 Power Performance

13.4.1 Potential Energy Possible

For the Isle of Shoals, a typical wave height is 1.8 m with a period of 6 seconds, according to the Jeffrey's Ledge buoy data collection. This buoy was used as the data it produces is very similar to the conditions seen at the Isle of Shoals due to its proximity. As such, the potential energy evaluation was done for that size wave. Using the potential energy formula for a wave (Dean, 1992), the energy flux was calculated:

$$F = PEcg = \frac{1}{16}\rho g H^2 \cdot \frac{gT}{4\pi} = \frac{\rho g^2}{64\pi} TH^2$$

Where the PE is the potential energy, g is acceleration due to gravity, T is the period, H is the wave height, and ρ is the density of seawater. The kinetic energy is intentionally neglected, as it is orthogonal to the power take off design for the wave energy converter. This means that any contributions of kinetic energy will be negligeable. The values used were 9.81 m/s^2 for g, and 1,025 kg/m^3 for ρ. The result of this analysis is an estimated power per meter of wave of 9,836 W/m. This is using a regular wave with only the potential energy considered. Given that the buoy diameter of 3 m is the length presented to the incoming waves, the resulting potential power is 29,509 W.

13.4.2 Energy Intake/Efficiency

For most two body wave energy converters, a reasonable efficiency that has been seen is about 60% (Aderinto, 2019). This was used as the assumed efficiency of this wave energy converter, and provided a resulting power take of 17,706 W.

13.4.3 Major and Minor Losses in Pressure

Another source of losses would be pressure losses in the pipes. Most of the plumbing exists on the high-pressure side. The output side is only a uniform hose from the wave energy converter to shore, which, given the flow rate is slow, will result in insignificant losses. These were considered and found to be insignificant. The contraction in diameter from the chamber to the piping system was determined to have a pressure loss of 6.27 kPa, using the contraction formula ("Head Loss", 1992):

$$\Delta P = 12\rho V^2 \left(1 - \frac{A1}{A2}\right)^2$$

ρ is again the water density of 1025 kg/m^3, with V being the velocity through the contraction, with a maximum value of 3.49 m/s given the volumetric flow rate limitation of the filter system. The A values correspond to the areas of the two pipes of 0.002 m^2 for A_1 (51 mm pipe) and $2.87 \cdot 10^{-4}$ m^2 for A_2 (19 mm pipe). The minor losses were calculated using the minor losses equation and table for determining that K_L was 0.49 (Water Flow in Pipes):

$$hL = KL\frac{V^2}{2g}$$

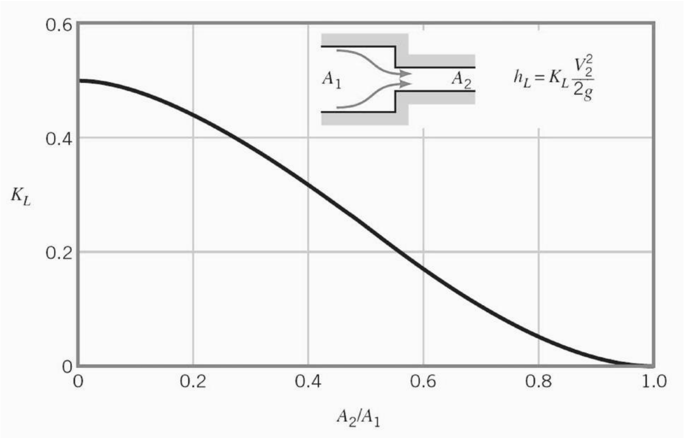


Figure 10: Minor Losses chart for determining K_L

This gave approximately no head loss. The final losses that were considered were the losses in the check valves. Using charts of pressure drop values, the losses were determined to be about 14 kPa for the 19 mm check valve, and less than 7 kPa for the 51 mm check valve, given the two charts ("Pressure Drop Chart Check Valves"):

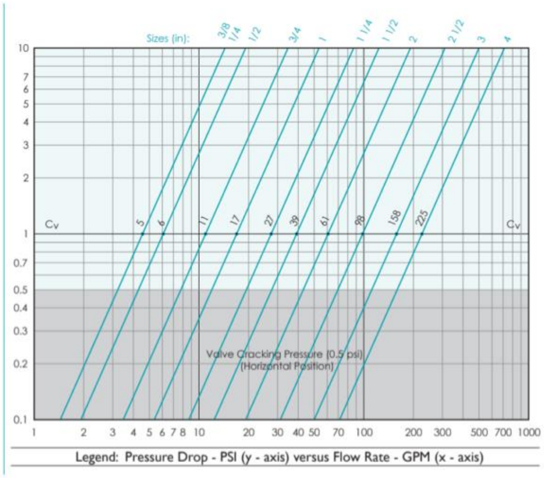


Figure 11: Pressure Drop Chart for Various Flow Rates and Check Valve Sizes

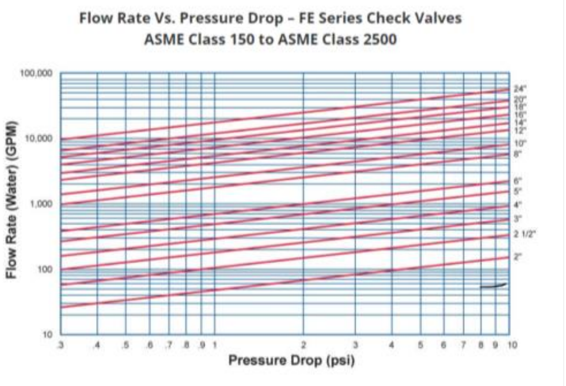


Figure 12: Flow Rate Vs. Pressure Drop

After reviewing these results, the pressure losses were decidedly insignificant compared to the pressures being generated.

13.5 Optimization

When the team was attempting to optimize the design three different systems were discussed at length to find the most optimal system that met the constraints. The UNH team is focused on providing small remote communities and areas suffering from natural disasters with quick access to fresh water. To do this, the system must be small, easily deployed and still produce enough pressurized water to run a reverse osmosis system.

The initial decision matrix focused on deciding the method for harnessing the waves power. The goal is to use a wave energy converter to generate compressed water. The methods the team researched included point absorbers, bottom mounted flap designs, turbine systems, air compression systems, and partial submerged systems. By looking at previously designed systems including the Wave Dragon, Archimedes Swing, Oyster, and the Pelamis the team was able to get some innovative ideas for wave energy converters that work well. The team quickly found that most of these systems either required large upfront costs from the users or required massive installation fees and service costs. By neglecting products with these stipulations, the team chose between three different ideas. The first was a standard point absorber that would be positioned to float on the surface of the ocean, the second was a partial submerged point absorber, and finally was a bottom mounted "flap" design.

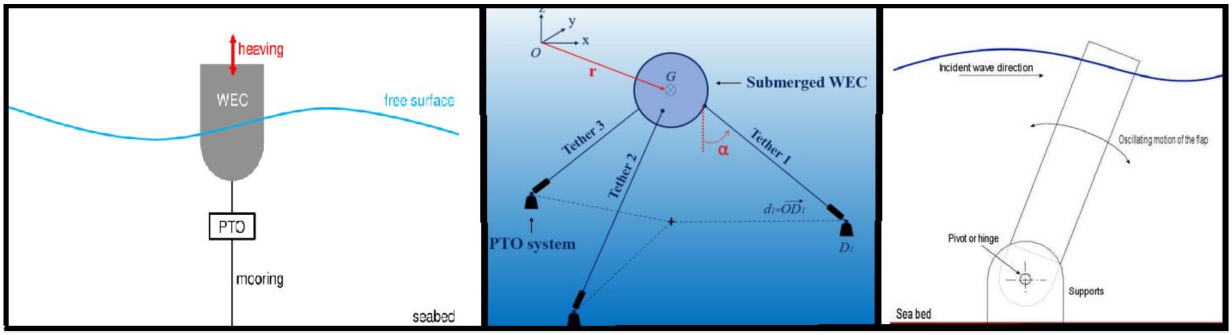


Figure 13: Depicts the three methods the team chose to use as the base of the wave energy system. The first is the surface mounted point absorber, the second is the partially submerged wave energy converter, and the third is the bottom mounted "flap" wave energy

Once the design choices were chosen a decision matrix was used to determine which of the designs was the best choice for the targeted system. The design matrix considered each design along with several pre-determined criteria including area of impact of the system, length of underwater cabling needed, reverse osmosis implementation difficulty, ease of brine removal for the reverse osmosis system, ease of access to the system for service, and overall power generation/freshwater production. The team chose these categories to get a detailed comparison between all the ideas. Since the final system will include a reverse osmosis system attached to the wave energy converted, the UNH team had to make sure that the design could implement such a system, which is why brine removal was considered, and difficulty to implement a reverse osmosis system into the design. From the decision matrix the following results were found.

Table 4: List of Pros and Cons of the three designs

System	Surface mounted point absorber	Partially submerged point absorber	Bottom mounted flap design
Pros	-The brine generated from the reverse osmosis can be put directly back into the sea and dispersed naturally. -The system will make it easier to move in and out of the water. -The power generation is reliable and depending on placement can be very consistent. -Attaching the reverse osmosis system will be easy and can be serviced easily when above water.	-The area of impact is less than the fully floating system and requires less underwater cabling. -The brine generated from the reverse osmosis is dispersed into the current underneath the waves and dispersed naturally.	-This design would have the shortest underwater cables of the three designs. -The power generation from this system is remarkably high and has been tested before. -It would be easy to implement a reverse osmosis device into the system
Cons	-The area of impact of the device along with the underwater cabling. -It will be visible to people on shore and boats will have to navigate around it. -The length of the underwater cabling will be long and expensive to install.	-The power generated from this system is much less than the others but is more consistent using the tidal surges to move up and down. -Implementing the reverse osmosis system would be challenging. -The device would be challenging to implement and service. -Adding multiple mooring lines would also cause issues with sea life and fishing. It would also be a hazard for boats because it wouldn’t be seen from the surface.	-large area of impact on ocean life and the sea floor. -The brine from the reverse osmosis system would have little space to recirculate and could settle on the sea floor. -Device is extremely difficult to implement and require a large upfront cost for divers to install the device. -Service would require a diving team.

After reviewing results from the decision matrix, it was determined that a surface mounted point absorber would be the most ideal to utilize in the design. The decision came down to a floating wave energy converter is the easiest to install and service. The extra underwater cabling and piping costs will be significantly less compared to the costs for diving teams and lead times to set up a submerged wave energy converter, not to mention the service costs involved with an underwater system. The system will also be easier to deploy and move.

The next decision when optimizing the system was the choice of reverse osmosis technology. The decision was between using a traditional membrane system using compressed water or a form of electrodialysis which uses positive and negatively charged plates that separate the anions and cations from the salt water.

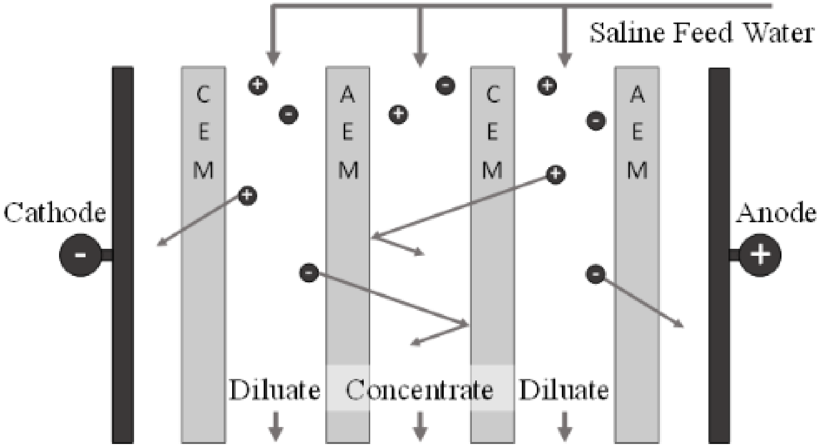


Figure 14: Schematic representation of the electrodialysis (ED) process. ED pulls ions out of the feed water solution by applying an electric potential across a series of alternating anion and cation exchange membranes (Wei He, 2018)

The electrodialysis process is a fairly new technology and requires space and enormous amounts of electricity. The team conducted a similar decision matrix to see which system was thought to be more advantageous for a product. In this decision matrix the group looked at initial costs of the systems, implementation into the design, service, average freshwater production, brine removal, and preexisting technology. By looking at these categories it was found that the focus of the system was ease of access for the user, less upfront costs, and low space requirements. By narrowing down what was desired in the reverse osmosis system the team decided to go with the more reliable and researched membrane system. In conjunction with the UNH team's floating wave energy converter, the membrane system would fit into the design and be easily replaced when a new filter was needed. By having the reverse osmosis system on the buoy, it can be easily taken out and replaced by locals with access to a boat. In the end the decision came to choosing the more reliable system with the most data. In the future, this decision could be further assessed and studied to better determine the best system for the communities being described.

13.6 Environmental Considerations

The Coastal Wave Powered Reverse Osmosis System provides clean infrastructure using the power of the ocean's waves. Although this source of marine renewable energy does not use fossil fuels, studies have shown that factors including size, material, placement, and operation of these systems may have an adverse impact on the marine environment, including sea life and habitats.

Brine, the high salinity discharge result from the reverse osmosis system, is a potential factor of concern to the marine environment. When brine is discharged into the ocean, it will be important to make sure that it does not exceed local regulations, although many places such as Maine do not regulate brine. In large quantities, brine can cut levels of oxygen in seawater, impacting the surrounding plants, shellfish, crabs, and other organisms on the seafloor (Doyle, A., 2019). According to the United Nations, 1.5 liters of brine is discharged per liter of fresh water created. The brine discharge would also need to be released in a manner that allows for mixing and dilution to occur, to not disrupt the existing ecosystem.

Foamed polyurethane is a type of plastic that, when inserted with air, is lightweight, buoyant, and water resistant, making this material an excellent choice to use as a float mechanism for the wave energy converter. However, if not treated correctly, it will break down quickly in the ocean due to the waves and UV radiation from sunlight. This can quickly become a pollutant to the ocean, taking many years to decompose and become toxic microplastics. The buoy system will be carefully treated with a hard plastic covering to prevent any pollution to the ocean (Akester, H. 2019).

Polyvinyl chloride, or PVC, is the plastic polymer that is used for the structure of wave energy converter. This material has high durability and corrosion resistance, with a projected life span of over 100 years. PVC pipe also inhibits the accumulation of biofilm, and better insulates properties and flow capacity than metal pipe. It also has a reduced potential of forming condensation, making it a great material to use for the reverse osmosis system device.

Concrete is a material contributing to most construction projects around the world, where it is the highest consumed product besides water. Its manufacturing process causes about four billion tons of carbon dioxide emissions yearly with evidence from life cycling analyzes of the material (Ramsden, K. 2020). In addition, the use of concrete in seawater is potentially hazardous, where if not properly cured, saltwater entering the pores of the concrete can create corrosion, polluting the surrounding environment, and weaken the durability of the structure (The Constructor, 2018). However, if properly cured and used for an extensive amount of time, concrete and the marine habitat can coexist.

In an investigative study, one concrete beam was placed in two different environments: one in a laboratory, and the other beam immersed in a marine environment (Djelal, C., Long, M., Haddi, A., & Szulc, J., 2020). No damage occurred to the beams during this time. After one year, the two beams were tested in a laboratory bending test. The experiment found that the beam stored in the marine ecosystem bared a loading 32-48% larger before cracking occurred than that in the laboratory. Evidence shows that this may be due to the adaptation of the ecosystem surrounding the concrete beam, acting as a protection barrier to forces acting on the beam. The beam increased stiffness and strength within the marine environment, adding support against damage. This provides evidence that, although the use of concrete increases the life-cycle analysis of the wave energy system, the strength of the concrete mooring to the device will not be compromised over time. Instead, the beam will immerse in the ecosystem, unifying with the environment.

13.7 User Needs

Through market research, design, analysis, and model scale testing, the UNH team has created plans for a successful wave-powered desalination device. But to ensure future success in a full-scale production, the design must meet the user’s needs. Proper functionality in the design means the product is built with the user in mind. In the market feasibility section, a target customer was determined. Those initial customers are rural communities and post-disaster communities that are lacking safe drinking water. In the first case, rural coastal or island communities, a few functions must be met. Firstly, the device cost must be kept low. It is common for the island communities to struggle economically, compared to their mainland counterparts. The UN defined Small Island Developing States SIDS, as a description for these cases. In the financial analysis section, a full-scale model would cost $20,000, with O&M fees starting at a minimum of $250 annually. This cost is low enough for communities to pay with help of an NGO, like AqSep explained, or over installments. A second consideration for rural communities is ease of maintenance. Also conveyed during the interview with AqSep, UNH MECC designed the unit to be simple enough that basic tools and knowledge can do most repairs. That includes, a small enough unit to be worked on with an average size fishing vessel (10 – 15 meters) (United Nations, 2022). Also, the unit will be constructed of basic parts and the RO portion will be an exchangeable membrane for easy replacement. The device must also meet the post-disaster target users. Natural disaster-prone areas are commonly overlapping with SIDS but are not exclusive to them. In the use of emergency water, quick implementation is necessary. Water Mission conveyed this importance and had a fleet of employees but also systems ready. UNH MECC’s design will be small enough to be deployed quickly and even fit on a plane. The device will way around 485.34 kgs and fit into a 4x4x4m volume. The device will be light enough to be put in by a crane at a harbor or ferried out and dripped into place by a medium size fishing vessel or commercial boat. Likewise, if a storm is predicted, a smaller boat will be able to tow it to a safe harbor to ride out the storm.

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