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A Novel Portable Wave-Driven Desalination System for Emergencies and Remote Coastal Communities

David Ding[1], Jia Mi[#], Xian Wu[#] and Lei Zuo[#]

[1]Episcopal Academy, USA
[#]Advisor

ABSTRACT

With 40% of humanity living in coastal areas, ensuring reliable access to freshwater is crucial to enhance the resilience of these coastal communities during emergencies, such as natural disasters, and to sustain remote coastal areas with limited water infrastructure. This study proposes a novel design for a portable wave-driven reverse osmosis desalination device to provide water in these applications with minimal carbon footprint. The device utilizes a point absorber wave energy converter and a hydraulic power take-off system to drive reverse osmosis desalination. The device is highly portable, weighing under 30 pounds, and the water produced is convenient to collect due to its near-shore operation. Additionally, the device leverages near-shore infrastructure to achieve relative motion, without requiring mooring. The proposed system's power and water output are modeled and device parameters are tuned in a hydrodynamic simulation conducted in MATLAB. This is validated with preliminary calculation results. It is found that the device can effectively drive desalination in any wave condition. Additionally, a techno-economic analysis examines economic feasibility. Results indicate that, on average, the device can produce 91-121.4 liters per day, enough to support the daily water usage of 6-8 individuals or the drinking needs of 25-33 individuals. At 10,000-unit production, the device's capital cost of $163 and Levelized Cost of Water of $0.011/L make it highly affordable. Thus, analysis results demonstrate the novel device's feasibility and significant potential in the intended applications.

Introduction

About 40 percent of the world's population lives within 100 kilometers of the coast (United Nations, n.d). Many of these coastal communities must be prepared for water scarcity during emergencies such as water contamination and natural disasters. One such example is when Hurricane Harvey hit Texas in 2017, shutting down 50 municipal water systems in the state and causing numerous hospitalizations and deaths caused by unsanitary drinking water (US EPA, 2020). Additionally, many remote or isolated coastal communities, like coastal Alaska, smaller Hawaiian Islands, and the Virgin Islands in the U.S. (US Department of Energy, 2019), are even more vulnerable to water scarcity because they have more limited water infrastructure and resources (US Department of Energy, 2019). Thus, reverse osmosis (RO) desalination, the process of removing salts and contaminants from ocean water by filtering it through semi-permeable membranes at high pressures, poses as a promising source of potable water for these communities. Specifically, small-scale, portable RO desalination systems that can be quickly and cheaply deployed in any location are optimal for coastal community resilience and water supply. In emergencies, rapid and reliable access to fresh drinking water is critical, and small, portable desalination devices, which can be quickly deployed, improve the resiliency of coastal communities against these situations. Additionally, as larger-scale water infrastructure or desalination are infeasible due to geography, small-scale desalination can provide the water supply for isolated remote coastal communities.

Currently, almost all (99%) of global desalination production is powered by fossil fuels, necessitating a shift to renewable energy in the industry for sustainability and environmental protection (Thi, et al., 2021).

With an energy density five times greater than wind and ten times greater than solar, wave energy, or energy harvested from waves, is an ideal renewable energy source for small-scale portable desalination as it is the most space-efficient (CorPower, 2024). Additionally, in coastal or island communities, wave energy is often more practical and reliable than other sources like diesel or wind (US Department of Energy, 2019).

Small-scale portable wave-powered desalination has not been widely adopted. There has been innovation through competitions like the DOE-sponsored Waves To Water Challenge (American-Made Challenges, n.d.), in which the goal was to develop a small, modular, wave-powered desalination system. Existing designs (Mi, et al, 2021; NREL, n.d.), however, are limited in addressing emergencies and remote coastal communities for at least three reasons. Firstly, most existing designs require mooring, or anchoring, systems. However, there is often neither the time nor resources for divers to fix a mooring system to the seafloor in emergencies. Second, it is challenging to collect and transport generated freshwater from these systems as they are placed far from shore. Lastly, almost all existing devices are still quite large in size and weight; the Waves to Water challenge requirements stipulated that the designs fit in a 1m x 1m x 1m shipping container and weigh under 1430 pounds. This makes the devices difficult to transport and deploy.

This paper proposes a novel portable wave-driven desalination system to aid in freshwater production in emergencies and isolated remote coastal communities. The design eliminates the use of any mooring systems, making it easier and more reliable for emergency situation use. Also, it is lightweight (under 25 pounds) and portable, making it easy to deploy in emergencies and remote coastal communities. The device is deployed near-shore so the issue of transporting generated water is mitigated.

Design Concept

The intended applications of the device to generate potable water in emergencies and remote coastal communities create several design constraints: the performance requirement of producing enough fresh water for a typical family, weight, and size limits for portability, and no mooring systems. Additionally, the device should be affordable for widespread access.

A novel design I developed to meet these constraints is shown in Figure 2. A point absorber wave energy converter (WEC), a floating body that captures wave energy through heave, is chosen due to its simplicity and portable nature. For the device, a buoy, shown in Figure 2, is utilized for the WEC. Additionally, a hydraulic Power Take-Off (PTO), which converts the point absorber's motion into a reciprocating motion for desalination, is chosen. The PTO drives a lever that is connected to a piston pump. The pump pressurizes and feeds ocean water into an RO membrane for desalination.

The PTO system, shown in Figures 2 and 3 uses a rotating chainwheel-and-arm mechanism with a counterweight to transmit the heave motion of a buoy to drive the lever of a hydraulic pump that pressurizes water for reverse osmosis. The PTO is bidirectional; as shown in Figure 3, when the buoy rises in the wave crest, the counterweight drags down the slack in the chain, spinning the chainwheel and driving the lever. when the buoy falls in the wave trough, it drags down the chain, similarly driving the lever. Since the PTO converts the buoy's motion into rotational motion, the high variability of ocean wave height does not affect its ability to power the pump. Additionally, the counterweight and chain mechanism of the PTO also allows for self-adjustment to tidal fluctuations as the counterweight reaches equilibrium with the buoy at any buoy height. The PTO only drives the lever downward, the small upward force for pulling the lever back up is supplied by an elastic band.

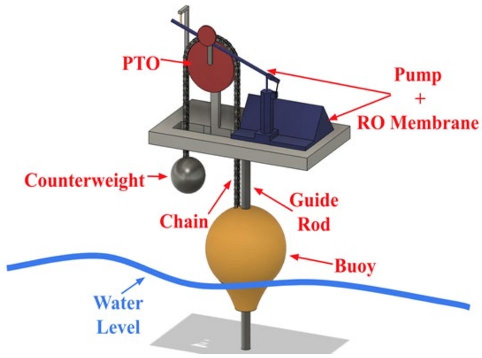

Figure 2. 3D Model of Design

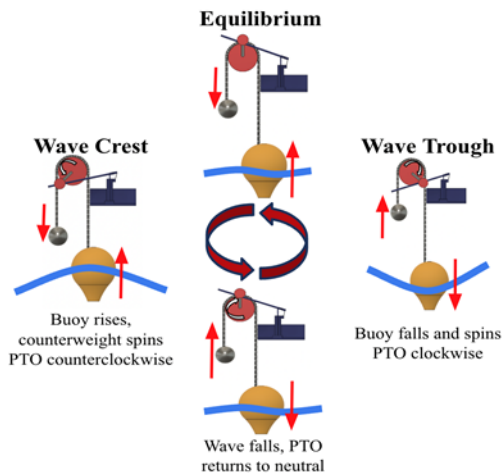

Figure 3. Bidirectional Movement in the System

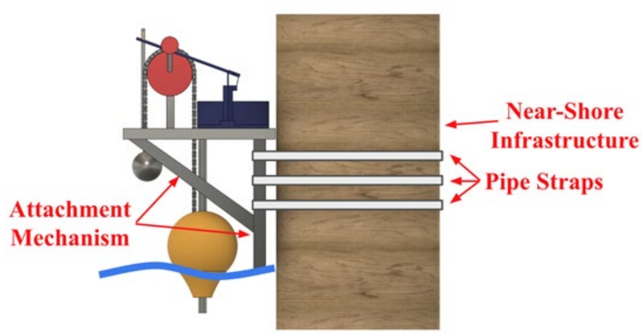

Figure 4. Attachment Mechanism

To secure relative motion between the buoy and the main body of the device, which is essential for wave energy harvesting, a mounting mechanism shown in Figure 4 is used to attach the device to near-shore infrastructure, such as a supporting beam of a pier, jetty, or other structure. This attachment is used instead of a mooring system. Additionally, since the device leverages near-shore infrastructure, it is thus deployed very near-shore, allowing water generated by the device to be collected easily.

This novel design addresses the issues and design constraints mentioned above. The device weighs approximately 30 pounds and can fit in a 63 cm x 25.4 cm x 25.4 cm box, meaning it can be easily transported by a person. It should be noted that significant weight is conserved by utilizing inflatable buoys for the WEC and counterweight that are filled with water at the time of deployment, as the WEC and counterweight need to be quite heavy to drive the PTO.

Simulation and Techno-Economic Results & Discussion

This section explains methodology, and reports and interprets analytical results from preliminary calculations, hydrodynamic simulation, and techno-economic analysis on the proposed design.

Preliminary Calculations

Data Collection

The data inputted into preliminary calculations and hydrodynamic simulation is taken from the National Buoy Data Center data buoy at Bethany Beach, DE (NDBC, n.d.). The data from the buoy is collected from 1/1/23 to 12/31/23. Since multiple measurements are taken each day, this results in over 17,000 data points gathered, ensuring unbiased estimates. The data is displayed in Table 1. Specifically, measurements of Significant Wave Height (WVHT), which is the height of the highest third of waves, and Dominant Wave Period (DPD), which is the frequency band that corresponds with the highest energy wave and closely matches the energy period (National Data Buoy Center, 2009), are taken to use as wave amplitude and period inputs. Importantly, the average wave condition across 2023 was a WVHT of 0.9m and 9s DPD. Bethany Beach's buoy was chosen due to its proximity to shore and ability to collect the needed wave data.

Table 1. Probabilities of Wave Conditions

					DPD					
WVHT	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
0.3					0.1%	0.1%	0.2%	0.5%	0.1%	0.2%
0.4	0.1%	0.1%		0.3%	1.6%	1.2%	0.9%	1.1%	0.5%	1.2%
0.5	0.5%	0.7%	0.2%	0.8%	3.0%	1.8%	1.6%	2.6%	1.1%	2.3%
0.6	0.6%	0.7%	0.7%	1.5%	2.0%	1.4%	1.6%	2.9%	1.6%	2.7%
0.7	0.9%	1.2%	1.4%	1.8%	2.1%	1.2%	1.5%	3.1%	1.2%	2.6%
0.8	0.9%	1.1%	1.1%	1.5%	1.5%	1.1%	1.2%	2.3%	0.9%	1.7%
0.9	0.7%	0.8%	0.7%	0.8%	0.9%	0.7%	0.7%	1.2%	0.5%	1.1%
1	0.3%	0.6%	0.5%	0.7%	0.9%	0.4%	0.4%	0.8%	0.4%	0.9%
1.1	0.1%	0.5%	0.5%	0.4%	1.0%	0.3%	0.3%	0.5%	0.2%	0.5%
1.2	0.1%	0.4%	0.2%	0.2%	0.7%	0.3%	0.2%	0.3%	0.1%	0.4%
1.3		0.4%	0.2%	0.2%	0.5%	0.3%	0.2%	0.2%	0.1%	0.2%
1.4		0.3%	0.2%	0.1%	0.4%	0.1%	0.2%	0.2%	0.1%	0.1%
1.5		0.1%	0.2%	0.1%	0.3%	0.1%	0.1%	0.1%		0.1%
1.6		0.1%	0.3%	0.1%	0.2%	0.1%	0.1%	0.1%		0.1%
1.7		0.1%	0.2%	0.1%	0.1%	0.1%		0.1%		
1.8			0.2%	0.1%	0.1%					
1.9			0.2%	0.1%	0.1%					
2			0.2%	0.1%						

2.1			0.1%	0.2%						
2.2				0.1%	0.1%					
2.3				0.2%	0.3%					

Minimum Force Needed to Power The Pump

By utilizing specifications for the RO module, the force (F) needed to power the pump is calculated:

$$F = P \cdot SA \qquad (1)$$

P is the pressure of the feed water (62.5 bar) and SA represents the area of the pump piston (SA=6.6*10^{-5} m^2 based on pump measurements). Based on Equation 1 and an average mechanical advantage of 0.22 from the lever, the force required from the PTO is 90.75N.

Minimum Power outputs

Using the National Buoy Data Center wave data, specifically Significant Wave Height (H) and Dominant Wave Period (t), the minimum power output (P) from the PTO necessary to reach the pump's 62.5 bar optimal pressure is calculated. It should be noted that if the PTO power output does not reach the minimum value outputted from the equations, desalination still occurs, but at suboptimal pressure.

$$P = W/T \qquad (2)$$

$$W = F \cdot X \qquad (3)$$

$$X = (4H/2\pi r) \cdot 4r/2 = 4H/\pi \qquad (4)$$

The equation for x comes from the fact that the buoy moves 4H in one wave. This means that the PTO rotates (4H/2πr) times, where r is the radius of the PTO. Thus, the lever moves (4*H/2πr)*4r since it moves twice the diameter in one rotation. However, the PTO only supplies downward force, meaning it only does work along half this distance, so we divide by 2, yielding the final equation. This last principle also means that the PTO does not do work over all of the wave period. Here, we estimate that the PTO does work for two thirds of the period:

$$T = 2T/3 \qquad (5)$$

Additionally, utilizing the volume of the piston pump (V), the daily feed rate of the device can be estimated based on the number of pumps each day:

$$R = (V \cdot 86400 \cdot 4 \cdot H)/2\pi rt \qquad (6)$$

Based on an average wave condition of 1.1m WVHT and 8s DPD, Equations 2, 3, and 4 are utilized to calculate the minimum power output of the PTO in this condition, which is 23.8 watts. The minimum power outputs across 190 possible wave conditions with DPD ranging from 4-13 and WVHT ranging from 0.5 to 2.3 are also calculated and shown in Table 2. Based on Equation 6, the daily feed rate to the pump in the average wave condition is 505L

Table 2. Preliminary Calculations for Minimum PTO Power Outputs (watts) in Various Wave Conditions

	DPD									
WVHT	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
0.5	21.7	17.3	14.4	12.4	10.8	9.6	8.7	7.9	7.2	6.7
0.6	26.0	20.8	17.3	14.9	13.0	11.6	10.4	9.5	8.7	8.0
0.7	30.3	24.3	20.2	17.3	15.2	13.5	12.1	11.0	10.1	9.3
0.8	34.7	27.7	23.1	19.8	17.3	15.4	13.9	12.6	11.6	10.7
0.9	39.0	31.2	26.0	22.3	19.5	17.3	15.6	14.2	13.0	12.0
1.0	43.3	34.7	28.9	24.8	21.7	19.3	17.3	15.8	14.4	13.3
1.1	47.7	38.1	31.8	27.2	23.8	21.2	19.1	17.3	15.9	14.7
1.2	52.0	41.6	34.7	29.7	26.0	23.1	20.8	18.9	17.3	16.0
1.3	56.3	45.1	37.6	32.2	28.2	25.0	22.5	20.5	18.8	17.3

1.4	60.7	48.5	40.4	34.7	30.3	27.0	24.3	22.1	20.2	18.7
1.5	65.0	52.0	43.3	37.1	32.5	28.9	26.0	23.6	21.7	20.0
1.6	69.3	55.5	46.2	39.6	34.7	30.8	27.7	25.2	23.1	21.3
1.7	73.7	58.9	49.1	42.1	36.8	32.7	29.5	26.8	24.6	22.7
1.8	78.0	62.4	52.0	44.6	39.0	34.7	31.2	28.4	26.0	24.0
1.9	82.3	65.9	54.9	47.0	41.2	36.6	32.9	29.9	27.4	25.3
2.0	86.7	69.3	57.8	49.5	43.3	38.5	34.7	31.5	28.9	26.7
2.1	182.0	72.8	60.7	52.0	45.5	40.4	36.4	33.1	30.3	28.0
2.2	190.7	76.3	63.6	54.5	47.7	42.4	38.1	34.7	31.8	29.3
2.3	199.3	79.7	66.4	57.0	49.8	44.3	39.9	36.2	33.2	30.7

Minimum Masses of the Counterweight and Buoy

Knowing the force needed to power the pump also allows for the calculation of the necessary masses of the buoy and counterweight. Since the counterweight supplies the downward force on the PTO during the crest of the wave, when there is slack in the chain from the buoy rising, the force of gravity on the counterweight must be sufficient to power the lever, which can be specified as:

$$Cg \cdot 0.75 > F \quad (7)$$

C is the mass of the counterweight and g=9.8, the acceleration due to gravity. A scale factor of 75% is included to account for friction.

Similarly, the mass of the buoy must overcome the force required to drive the lever and the mass of the counterweight in the trough of the wave. Thus:

$$Bg \cdot 0.75 > Cg + F \quad (8)$$

Additionally, based on Equations 7 and 8, the minimum masses of the counterweight and buoy are 12.3 kg and 28.8 kg, respectively. The Polyform CC-3 buoy has a volume of around 48L, so it can hold the 28.8L of water required to reach this weight requirement, and similarly for the counterweight with a smaller buoy.

Hydrodynamic Simulation

To estimate total water output, hydrodynamic simulation on the buoy is done using a MATLAB script similar to the WEC-Sim software (Yu, et al., 2014). Also, the device parameters of the buoy mass and the PTO damping coefficient are tuned to find the optimal parameter. The MATLAB script uses a time-domain radiation-and-diffraction numerical model to solve for the system dynamics of the buoy in regular wave conditions by solving Cummins' Equation, a differential equation describing the motion of floating bodies:

$$(m + m_\infty)\ddot{x} = -\int_{-\infty}^{t} K(t-\tau)x(\tau)d\tau - F_{hs} + F_e + F_v + F_{ext} \quad (9)$$

m is the mass matrix and m_∞ is the added mass matrix. X is the displacement vector. K is the radiation impulse response function. The integral term represents the convolution integral. F_{hs}, F_e, F_v, and F_{ext} represent restoring force, wave excitation force, viscous damping force, and external forces, respectively (Yu, et al., 2014). Here, F_{ext} is the PTO's force, which is assumed to be linear with respect to velocity. The buoy selected for simulation is a commercial buoy, Polyform CC-3, which was estimated to provide enough power for the PTO and has a center through-hole for the guide rod. The buoy's geometry is inputted into the commercial Boundary Element Method package, ANSYS AQWA, which calculates hydrodynamic parameters such as the response amplitude operator, added mass, and radiation damping. Figure 5 depicts the results for added mass and radiation damping of the buoy from ANSYS AQWA.

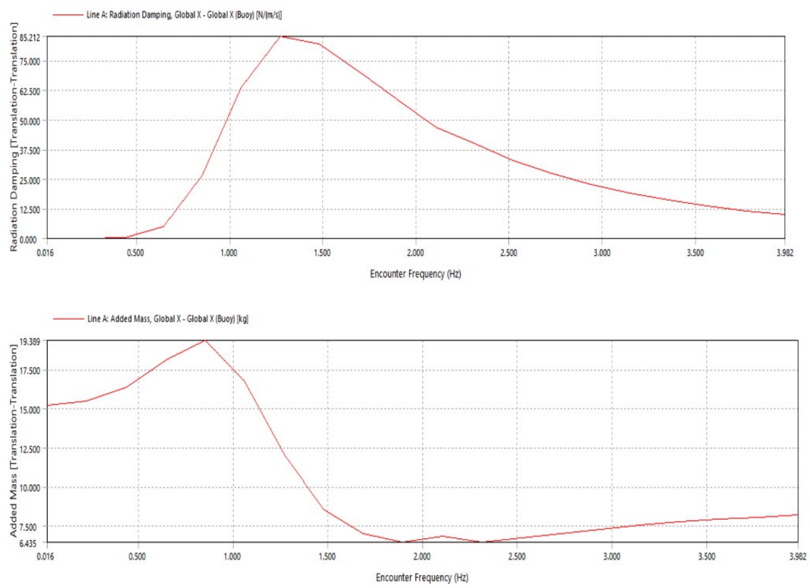

Figure 5. BEM Results for Radiation Damping and Added Mass as Functions of Encounter Frequency

The buoy has a high natural frequency, as shown by the peaks in radiation damping and added mass at just 1.3 and 0.8 Hz, respectively.

The hydrodynamic simulation is conducted across 190 possible wave conditions, with WVHT ranging from 0.5-2.3m with increments of 0.1m and DPD ranging from 4-13s with increments of 1s. The average of the data points from the NDBC buoy is, as mentioned, a WVHT of 0.9m and DPD of 9s, so these parameters are utilized to estimate average water production. Additionally, apart from the buoy's geometry, the mass is inputted based on the preliminary calculation results. Different buoy masses are also simulated to determine which is optimal for the geometry.

The simulation yields the average power output of the PTO using a linear PTO model. To estimate the PTO to water efficiency, I factor in a 60-67% (Davenport, et al., 2018) efficiency for desalination and a 40-50% energy loss due to other inefficiencies including friction in the pump, lever energy loss, and the fact, as mentioned earlier, that the PTO does not do work throughout the whole cycle because it only drives the lever down. This yields a total efficiency of 30%-40%, which is aimed for based on an expected recovery rate of around 20-30% (Miyakawa, et al., 2021) and pump measurements. Also, this low efficiency is reasonable for a small device. This power output is used to provide an estimation of the total water output of the device. Since pressure fluctuation and other effects on the membrane are not considered in the current analysis, a simplified estimated energy cost of RO water production of 4kWh/m^3 for renewable energy-driven RO systems is utilized (Kim, et al., 2019).

The simulation is run across 190 wave conditions, different damping coefficients, and different buoy masses. The damping coefficients simulated are 100 Ns/m, 250 Ns/m, 500 Ns/m, 750 Ns/m, and 1000 Ns/m. These values are selected due to the PTO's size and since the damping coefficient is typically on a similar order of magnitude as the PTO's power (López, et al., 2017), which is found to be in the tens and hundreds of watts through the simulation. However, since the device utilizes a hydraulic system, a higher order of magnitude, such as 1000 Ns/m, is also possible with tuning. Buoy masses of 35 kg and 45 kg are also simulated at a PTO damping coefficient of 1000.

On average, the 45 kg buoy produces 1.55 watts more than the 35 kg buoy, but this is essentially negligible, as when expressed as a percentage and rounded, the increase in power production is 0%. Thus, a 35 kg mass is used for the rest of the simulations. For the damping coefficients, expectedly, 1000 Ns/m produces the most power, on average 143.20 w, 98.5 w, 45.02 w, and 14.66 w more than 100 Ns/m, 250 Ns/m, 500 Ns/m, and 750 Ns/m, respectively. 750 Ns/m produces more power for all wave heights with a DPD of 4s and less power in all other conditions. However, since a DPD of 4s is quite rare, as shown in Table 1, 1000 Ns/m is optimal. Thus, the optimal parameters are a damping coefficient of 1000 Ns/m and a 35 kg buoy.

Table 3. Simulation results with a 35kg buoy mass and 1000 Ns/m damping coefficient

	DPD									
WVHT	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
0.5	37.7	32.5	27.1	22.6	18.9	16.0	13.6	11.7	10.1	8.8
0.6	54.1	46.7	39.0	32.5	27.2	23.0	19.6	16.8	14.6	12.7
0.7	73.4	63.4	53.0	44.1	36.9	31.3	26.6	22.9	19.8	17.3
0.8	95.5	82.6	69.0	57.5	48.2	40.8	34.7	29.9	25.9	22.6
0.9	120.4	104.2	87.2	72.7	60.9	51.6	43.9	37.8	32.7	28.6
1.0	148.1	128.2	107.4	89.6	75.1	63.6	54.2	46.6	40.4	35.3
1.1	178.5	154.7	129.7	108.3	90.8	76.9	65.5	56.4	48.8	42.7
1.2	211.7	183.6	154.0	128.6	107.9	91.4	77.9	67.0	58.1	50.7
1.3	247.5	214.9	180.4	150.7	126.5	107.2	91.3	78.6	68.2	59.5
1.4	286.0	248.5	208.7	174.5	146.5	124.2	105.8	91.2	79.0	69.0
1.5	327.1	284.5	239.1	200.0	168.0	142.4	121.4	104.6	90.7	79.2
1.6	370.8	322.8	271.4	227.2	190.9	161.9	138.0	118.9	103.1	90.1
1.7	417.1	363.4	305.8	256.1	215.2	182.6	155.7	134.2	116.3	101.7
1.8	466.0	406.2	342.1	286.7	241.0	204.5	174.4	150.3	130.4	113.9
1.9	517.3	451.3	380.3	318.9	268.2	227.6	194.2	167.4	145.2	126.9
2.0	571.2	498.7	420.5	352.8	296.8	252.0	215.0	185.4	160.8	140.5
2.1	627.5	548.3	462.7	388.3	326.8	277.5	236.9	204.2	177.2	154.9
2.2	686.2	600.1	506.7	425.5	358.2	304.3	259.8	224.0	194.4	169.9
2.3	747.4	654.1	552.6	464.3	391.1	332.3	283.7	244.7	212.3	185.6

Based on the table, the power output is proportional to WVHT and inversely proportional to DPD. This seems counterintuitive at first since longer wave periods contain more power. However, this is due to the high natural frequency of the buoy mentioned earlier. More tuning can be done on the buoy's geometry to lower the natural frequency to produce more power at the more common high-period wave conditions.

Additionally, all simulated power outputs from the PTO from Table 3 exceed the minimum power outputs calculated in Table 2 in their respective wave conditions. This means the buoy harvests enough energy to meet the RO pump's 62.5 psi optimal operating pressure and thus effectively powers desalination in any wave condition.

For the average wave condition, a graph for the power output of the PTO during the simulation with a buoy mass of 35kg, a damping coefficient of 1000, and wave conditions of 0.9m WVHT and 9s DPD over a time frame of 200 seconds, are depicted in Figure 6.

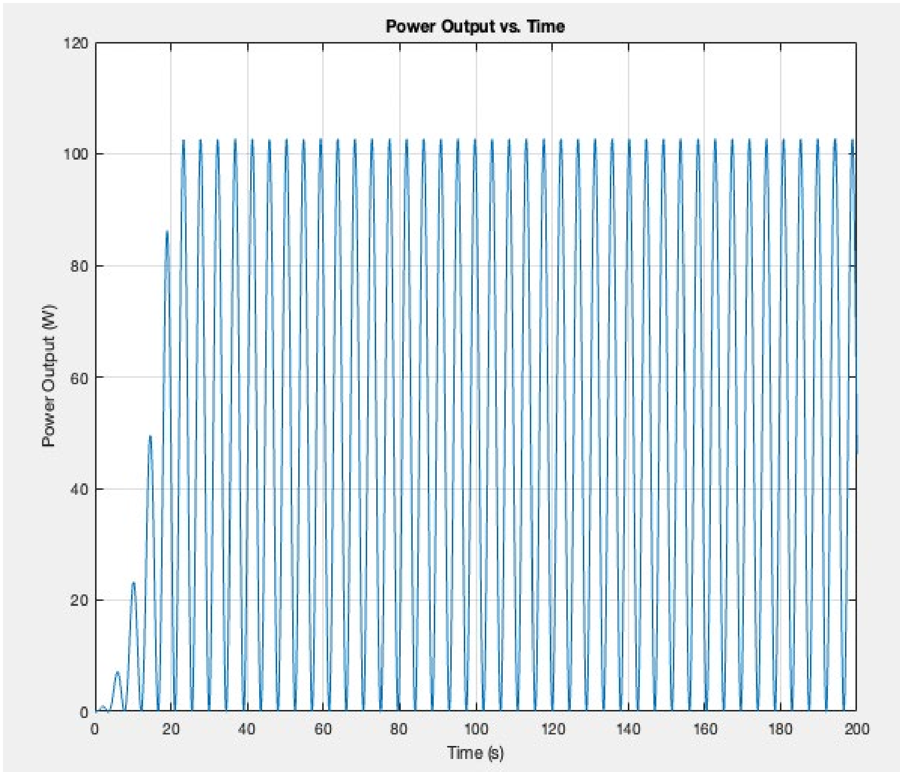

Figure 6. Power(watts) of Buoy as a Function of Time(s)

As shown in Table 3, the PTO power output in the average wave condition at Bethany Beach in 2023, which was 0.9 WVHT and 9s DPD, is 50.6 watts. Considering the PTO-to-water efficiency rate of 30-40%, the true power output is 15.18-20.14 watts. Utilizing the RO cost of energy figure of 4kWh/m^3 of water produced, the device can generate 6.8-9.0L/hr, yielding a daily production of 91-121.4L/day at Bethany Beach. Based on the estimated daily feed rate of the pump of 505L, this yields a recovery ratio, or the ratio of freshwater to inputted saltwater, of 18-24%. As mentioned, this is an expected figure, indicating that the preliminary calculations and simulation are relatively accurate.

According to the World Health Organization, the basic water requirement for drinking and hygiene per capita is 15L/day (World Health Organization, 2013), so the device could support 6-8 people, or around 2 families, in a remote coastal community. If only considering requirements for drinking (3.7L/day), as in an emergency, the device could support 25-33 people.

Techno-Economic Analysis

To determine the economic feasibility of the device, a techno-economic analysis is done to find its Levelized Cost of Water (LCOW), which represents the overall cost of water produced by the device ($/L) over its lifetime, as well as the cost of the device itself. Since LCOW measures the cost of water of the device over it's entire lifetime, it is a better indicator for the device's feasibility for long-term use in remote coastal communities. In emergencies, since the device is used in the short-term, the upfront cost of the device itself is a better indicator for feasibility in this case. The LCOW figure is compared to the LCOWs for desalination powered by a small generator. The generator-powered desalination LCOW allows for a comparison of economic feasibility for long-term use in remote coastal communities. Additionally, the LCOWs for different scales of production of the device are calculated and compared.

To determine LCOW, a modified equation for LCOE (Levelized Cost of Electricity) provided by the DOE (Labonte, et al, 2013) is utilized to suit water rather than electricity production. This approach is first utilized in by Yi-Hsiang Yu and Dale Jenne (Yu & Jenne, 2017):

$$LCOW = (FCR \cdot CapEx + OpEx)/AWP \quad (10)$$

CapEx, Capital Expense, represents capital expenditures needed to design, manufacture, and deploy the device. It is important to note that CapEx represents the cost of the device for an individual to purchase if there are no profit margins. OpEx, operating expenses, refers to the costs of operation and maintenance of the device. For the proposed design, only the cost of replacement filters, which have a lifespan of 1000L and cost $15 are considered for OpEx. Labor costs are not considered since they are relatively negligible. AWP refers to annual water production per device. FCR represents Fixed Cost Rate, which refers to the annual rate of return on the device to meet investor requirements. FCR can be calculated based on a fixed formula shown below and the lifespan of the device. In this case, the lifespan of the device is assumed to be 5 years, so N=5 in equation 11. This assumption was based on the average weather buoy lifespan of 3 years (Boatus, n.d.). The lack of sensors or electronics in this device increases the lifespan compared to this value. This makes the FCR equal to 27.9%.

$$FCR = \frac{r(1-D)}{((1-1/(1+r)^n)\cdot(1-\tau))} \quad (11)$$

$$D = \tau \cdot \sum_{t=1}^{6} \frac{MACRS_T}{(1+r)^t\cdot(1+i)^t} \quad (12)$$

R represents the real discount rate (0.07), i is the inflation rate (0.025), and τ represents the composite Federal-State Tax Rate (0.396). Financial variable values are based on the Reference Model 5 evaluated by the DOE (Yu, et al., 2015).

For large scale production, CapEx and OpEx decrease due to discount prices on bulk purchasing and economies of scale. To model this, a learning curve model provided by the National Energy Technology Laboratory (Kobos, et al., 2020). The model is representative of cost reductions due to experience in manufacturing and economies of scale at different production levels. The equation is:

$$C = I \cdot X^b \quad (13)$$

Where C is cost, I is the cost of the first device, X is the the number of devices produced, and b is the learning curve rate, defined as

$$b = \frac{log(1-R)}{log(2)} \quad (14)$$

R is the technology-specific learning rate. A high R-value is used for newer, less developed technology. Since this device is a novel design, a high value of 0.06 is used for CapEx. Since OpEx only consists of creaFor simplicity the value for the X^{th} product produced is considered as the cost per unit production of X-unit production.

LCOW Results

Table 4 depicts the cost assumptions and LCOW calculation based on a 50% capacity factor, or daily usage rate (12 hours deployed per day). Maximum daily water production is assumed to be the average of 91 and 121.4, or 106.2L/day.

Table 4. Summary of Cost Assumptions (for 1 unit production)

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Parameter	Value
FCR	27.9%
CapEx	$370
OpEx	$285
Capacity Factor	50%
Capacity	53L/day
AWP	19.4m^3
LCOW	**$0.02/L**

The CapEx assumption is based on estimated material and shipping costs depicted in Table 5. OpEx is calculated using the number required $15 filter replacements required based on AWP. These are plugged into Equation 10 to yield LCOW. The capacity factor of 50% is chosen because there is no significant decrease in LCOW at a higher capacity factor, while OpEx increases linearly. So, to minimize both OpEx and LCOW, the 50% figure is chosen. At the 50% capacity factor, the water production (53L/day) can still support a small family's basic water usage.

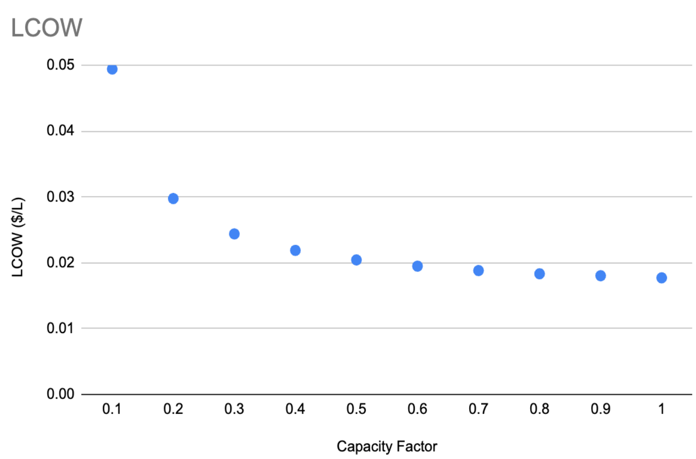

Figure 9. LCOW for one device based on Capacity Factor.

Table 5. Summary of CapEx Assumptions

CapEx Component	Cost
Pump & RO Membrane	$150
Chainwheel & Chain	$70
WEC Buoy & Counterweight	$115
Guide Rod	$10
Board	$10
Shipping	$15
Total	**$370**

To account for differing levels of mass production, 1 unit, 10 unit, 100 unit, and 1000 unit mass production are plugged into Equations 13 and 14. Again, the R-value used in CapEx is 0.06 since the device itself is novel, and the R-value used in OpEx is 0.03 since OpEx is based on RO membranes, which are already well developed. Table 6 shows the economic inputs for each case. Capacity Factor, Capacity, and AWP remain the same.

Table 6. OpEx, CapEx, and LCOW (per unit) Estimates for Different various Scales of Production

Number of Units	OpEx ($/1 unit)	CapEx ($/1 unit)	LCOW ($/L)
1	$285	$370	$0.02
10	$257	$301	$0.018
100	$232	$245	$0.016
1,000 10,000	$210 $190	$200 $163	$0.014 $0.012
Number of Units	**OpEx ($/1 unit)**	**CapEx ($/1 unit)**	**LCOW ($/L)**

Discussion

Based on Table 6, the LCOW along with expenses decrease by 40% from 1 unit to 10,000 unit production. Notably, at 10,000-unit production, the CapEx drops to $163, which means that the device is highly affordable for nearly all families. This means it is economically feasible in emergencies. Additionally, the LCOW for desalination powered by a small 4kW generator is calculated to be around $0.011/L for the same water capacity as the device based on market prices for a generator and fuel. This is very close to the LCOW value of the device, meaning that the device is also economically competitive for long-term use in remote coastal communities as well.

Conclusion

This paper proposes a novel portable wave-driven desalination device that utilizes a point absorber type WEC and a bidirectional rotational PTO with a counterweight and chain for RO desalination. The device could be widely utilized in emergencies and in remote coastal communities and is verified through a comprehensive feasibility analysis. Preliminary results from the hydrodynamic simulation conducted across 190 wave conditions, various damping coefficients, and different buoy masses, suggest the PTO can meet minimum power outputs found through preliminary calculations. Additionally, in the average wave condition at Bethany Beach, DE, the device can produce between 91-121.4 liters per day. To verify the economic feasibility of the device, a techno-economic analysis is conducted as well. With the Capital Expense for one device being just $163 at 10,000-unit production, the device is highly affordable, meaning it is feasible for widespread use in an emergency situation. Additionally, with a LCOW of just $0.011/L, which is competitive with the LCOW for small-generator powered desalination, the device is also suitable for long-term use in remote coastal communities.

The proposed design has several innovations which provide advantages in the intended applications over current portable wave-powered desalination designs. The system does not require mooring since it can be secured to near-shore infrastructure, making it more practical and reliable in an emergency situation. Consequently, it is easy and convenient to collect the produced freshwater due to the device's proximity to shore. Lastly, the device is portable and easier to deploy, which is especially important considering the financial and resource circumstances in remote coastal communities and emergencies. Overall, the novel design makes a significant improvement over the current designs, and, once adopted, could generate significant positive impact on both remote coastal communities and emergencies.

As water resources become ever scarcer, and environmental protection as well as the elimination of fossil fuels becomes a global priority, the proposed device has tremendous potential impact; it supports the resilience of coastal communities, which constitute 40% of the global population, in emergencies and supplies remote coastal communities with freshwater all using wave energy, meaning there is little carbon footprint or environmental impact.

Limitations

The first avenue for future research is the testing of a physical prototype in order to better understand the power translation, forces required, and feasibility of the device. Additional research is needed to enhance the simulation by utilizing the Simulink software to better model the PTO and desalination processes for more accurate results. Lastly, the development of an inflatable artificial pole could allow the device to be deployed in offshore locations, eliminating the current design's reliance on near-shore infrastructure.

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