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MARINE ENERGY COLLEGIATE COMPETITION 2022

Written Report

Purdue University

Integrating Wave-Powered Batch Reverse Osmosis with Pressure Retarded Osmosis for Higher Efficiency Desalination Method

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List of Terms

BOM	Bill of Materials
BRO	Batch Reverse Osmosis
CAD	Computer Aided Design
CapEx	Capital Expenditure
CDR	Critical Design Review
CFRO	Counterflow Reverse Osmosis
CP	Circulation Pump
CRO	Continuous Reverse Osmosis
FDR	Final Design Review
GHG	Greenhouse Gas Emissions
HP	High Pressure
HPP	High Pressure Pump
HS	High Salinity
LCOE	Levelized Cost of Electricity
LCOW	Levelized Cost of Water
MECC	Marine Energy Collegiate Competition
NREL	National Renewable Energy Laboratory
MS	Mid-Salinity
NPT	National Piping Thread
OARO	Osmotically Assisted Reverse Osmosis
OpEx	Operation Expenditure
PDR	Preliminary Design Review
PRO	Pressure-Retarded Osmosis
PTO	Power Take-Off
PV	Photovoltaic
RO	Reverse Osmosis
CRO	Continuous Reverse Osmosis
SEC	Specific Energy Consumption
WEC	Wave Energy Converter

EXECUTIVE SUMMARY

Overpopulation, intensive industrial water usage and climate change are some of the occurrences that are exacerbating global water scarcity. By 2050, the United Nations predicts that over 6 billion people will be affected by water scarcity. Over 70% of the earth's surface is covered by oceans yet its water remains unusable due to the high salinity of seawater. Reverse Osmosis (RO) is the most common method of desalinating water but is dependent on non-renewable generated electricity to meet its high energy requirements. The majority of the power supplied to desalination plants is generated using emission-heavy fuels. Given the UN's goal of reaching net-zero greenhouse gas emissions by 2050, renewable energy production is expected to increase over the next 30 years [13]. In response to this issue, our team has developed *PRO-BRO*, the first desalination system that uses both wave power and pressure retarded osmosis (PRO) to power clean water production and generate electricity using common equipment already present in reverse-osmosis desalination plants. The system has the additional capability of behaving as an energy storage method to assist in unmanageable energy surplus or deficiencies in the local grid. The design also includes an improved WEC-side connection to decrease energy loss from wave power. *PRO-BRO*'s functionality will be shown in a Matlab and Simulink full-scale plant model and a lab-scale prototype displaying the performance of the bimodal membrane and improved WEC-side connection.

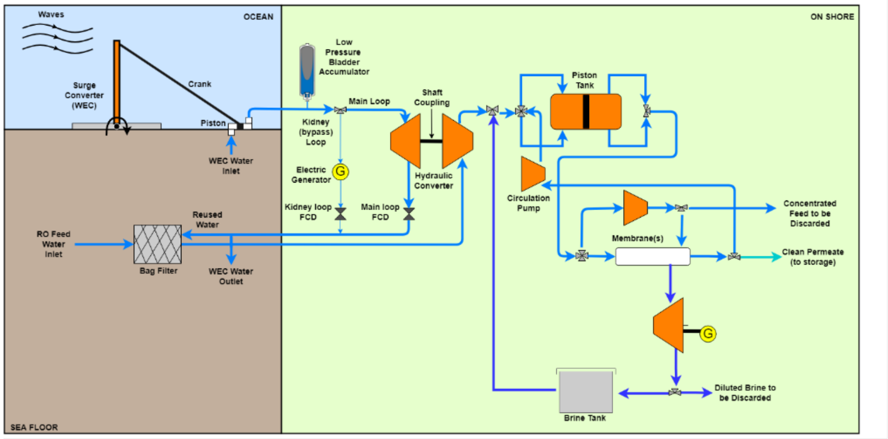


Figure 1: *Prototype PRO-BRO schematic combined with the improved WEC design.*

To supplement the theoretical design and to assess the viability of the *PRO-BRO*, a physical prototype was built. The two-part prototype consists of the bimodal desalination membrane and WEC-side improvement. The energy generation and desalination functions of the design were divided between two sub-teams. Manufacturing of *PRO-BRO* prototype included multiple phases starting with the creation of a component level diagram, CAD modeling, electronic assembly, wiring, and the creation of a VI user interface.

In this report, the details of the *PRO-BRO* will be discussed in the Business Report and Technical Design Report. The Business Report will first describe the problems and needs that are addressed by *PRO-BRO* in the Concept Overview. Then, the marketability of the system's full-scale deployment is discussed in Market Deployment Feasibility and Relevant Stakeholder sub-sections. Based on the interviews with stakeholders, end users and experts in the desalination field, the team gained valuable insights on the gravity of problems that need to be addressed and received numerous suggestions on ways to improve the system. In the Development and Operation sub-section, the plans associated with the development of *PRO-BRO* are discussed in detail. The profitability of the full-scale system is evaluated in the Financial and Benefits Analysis sub-section. The Technical Design Report will detail the objectives of the design and its innovations against existing technologies. The power production capabilities of the PRO and WEC as well as the power consumption of the BRO-based desalination plant are outlined in the Innovation and Power Performance sub-section. The electrical and mechanical loads of the preliminary prototype design are explained in the Load Analysis subsection. Figures and schematics that further detail the design will be shown in the System Design portion of the report. Future developments of the *PRO-BRO* design could be retrofitted to coastal desalination plants, allowing for a fleet of clean and cost-effective water and energy-producing plants.

1. BUSINESS ANALYSIS

1.1 Concept Overview

Utilizing the same wave-powered batch reverse osmosis (BRO) system from last year's submission – *Osmocean* –, *PRO-BRO* introduces additional functionality in the form of pressure retarded osmosis (PRO). The PRO function is equipped in the system as a response to the brine discharge issue that is in concomitant with the BRO design from *Osmocean*. The system's brine reject has a salinity of approximately 67 ppt which is double the salinity of the ocean water. Releasing the brine byproduct at a point source with no prior mixing has the potential of negatively affecting the ocean ecology within the plume of brine released. The extremely high salt concentration and contaminants can alter the chemical composition of the seawater which consequently endangers marine life that can not tolerate these changes.. This is one of the reasons why desalination projects are often rejected by local communities. In Orange County, California, despite the communities' dire need of clean water, the proposal to build Huntington Beach Desalination Plant faced immense backlash from locals and environmentalists due to the brine's potential threat to aquatic life [1].

With the addition of the PRO cycle in the system, brine discharge salinity is decreased from 67 ppt to 56 ppt due to additional mixing with sea water intake prior to discharge. This helps mitigate the salinity effects on osmotic pressure-sensitive organisms that are in direct contact with the plume.

Desalination plants additionally have a high indirect impact due to high energy intensity. The BRO system is measured to intake 4.66 MW of energy per 1500 m^3 of permeate produced. Using coal as the primary source of energy for this system would result in 6375 lbs of CO^2 being released into the environment. The system helps mitigate the energy intensity of the BRO system by producing energy via a wave-energy-converter (WEC) and utilization of PRO. Energy derived from the WEC produces 1.72 MW of instantaneous energy to supply the energy requirement of the plant in BRO desalination mode.

With PRO's integration into the wave-powered BRO, the team saw a potential to leverage PRO's potential as an energy recovery device (ERD). PRO process involves using a small pressure difference to initiate the natural osmotic flow of the mid-salinity stream and the brine output from BRO. PRO as an ERD is favorable for the use of small- to medium-sized communities who are not able to afford conventional ERD like Pressure Exchanger (PX). The system is then coupled to a generator so that the recovered energy can be used to produce electricity. The team plans to integrate the electricity with existing power grids to distribute electricity to the communities.

Additionally, *PRO-BRO* allows for a flexible energy storage system at a low cost. In *PRO-BRO,* the high salinity brine from BRO is the source of energy recovery stream in PRO. The brine can be stored in the tanks at atmospheric pressure for later use during PRO process. This method of energy storage allows for on-demand mode of energy production, simultaneously avoiding the energy waste issue of having to discard excess energy. It also fills the gap caused by intermittent energy for when the wave energy is irregular and can potentially cause negative curtailment.

1.2 Market Deployment Feasibility

1.2.1 Market Opportunity

The desalination market has grown in capacity by 20% between 2016 and 2020, and it will continue to grow as population increases and freshwater sources are depleted [2]. Over 70% of the earth's surface is covered by oceans [3]. And with 40% of the world population living within 100km of the coast, wave-powered desalination can be the ideal solution for water scarcity.

The global desalination equipment market was valued at $7B in 2021 and is projected to steadily increase to $25B in 2032 at compound annual growth rate (CAGR) of 9% [4]. In regions such as North America, South America and Asia Pacific, the demand for water desalination systems is the highest due to growing population and abundant sources of brackish water. Not only that, but the demand for desalination system is also expected to skyrocket in developing nations like India, Malaysia and Thailand, owing to the rapid industrial development and increasing water demand from agricultural and industrial sectors [5].

The performance of *PRO-BRO* can be evaluated by comparing its LCOW to that of other wave-powered desalination systems. Figure 2 shows the comparison of LCOW of wave-powered desalination systems from various desalination companies in comparison to the projected LCOW of *PRO-BRO*. The commercialization of *PRO-BRO* shows a promising potential to compete with other established desalination technologies in the market, especially with Wave$_2$O^{TM} by Resolute Marine Energy, which has the lowest LCOW at present [2]. Wave$_2$O^{TM}, however, produces a low permeate recovery ratio of only 35% while *PRO-BRO* is able to consistently maintain a permeate recovery ratio of 50%. The team is confident that the high permeate recovery ratio, coupled with a relatively low LCOW, provides a competitive edge for *PRO-BRO* to find a niche as a reliable desalination technology in the market.

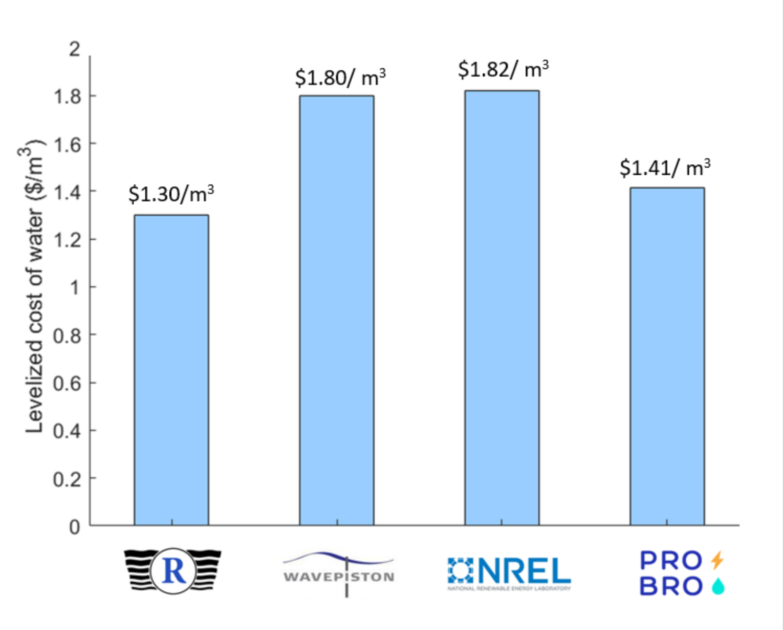


Figure 2: *The comparison of LCOW of various wave-powered desalination systems by different desalination companies.*

1.2.2 Competition

Since *PRO-BRO* is equipped with several functions, benchmark analysis will be carried out based on the primary functions of the system such as brine management method and cost-competitiveness to other renewable energies.

The brine management methods that are extensively used in the market are qualitatively compared with that of *PRO-BRO's* method as shown in Table 1. Deep well injection refers to the process of injecting brine into the underground such as the shallow soil layer. This form of brine discarding practice is prevalent in Kuwait. Brine evaporation is carried out by evaporating brine that is collected in ponds which ultimately produces crystallized salt.

Table 1: The table below summarizes the advantages and disadvantages of different brine management methods that are widely used today in comparison to *PRO-BRO*'s brine management method.

Competitors – Brine Management Method		
	Advantages	Disadvantages
Deep well injection [6]	• Remove large volume of brine quickly • Low maintenance cost	• Emits CO_2 from transporting brine to well locations by trucks • Numerous reported cases of leaked wells and brine emerging from soil and contaminating nearby ponds/lakes • Limited to geological formation
Brine evaporation [7]	• Easy implementation and operation	• Limited to small desalination plant • Climate dependent; not effective in places with cold and damp climate • Toxic substances from brine may percolate to water aquifer beneath the pond and contaminate water and soil
PRO-BRO (Mixing solutions during PRO)	• Easy implementation • Simultaneously recovers energy from salinity gradient potential • Environmentally friendly	• High maintenance cost at large scale

From an environmental standpoint, *PRO-BRO* is the best at treating the brine while minimizing environmental effects. Aside from the system controls, *PRO-BRO* operation requires less human supervision making it an ideal intermediate technology to be introduced to communities that do not have resources to sustain it. The system's operation also does not rely on fossil fuel, which is a resource that is very inconvenient to import to remote places according to an interview with a coastal landowner in Greece, Maher Cherfan.

On the other hand, a large-scale *PRO-BRO* may be quite costly to maintain. However, the system is expected to avoid negative curtailment effect and gain some payback from the energy recovered from brine which provides room for additional revenue that can cover a portion of the maintenance cost. Additionally, *PRO-BRO* offers a long-term solution for brine management while not taking up lands or restricted by the availability of space.

Several renewable energy resources like solar, wind, hydropower and wave energy are prospects for powering a desalination system while minimizing environmental impacts. Thus, *PRO-BRO*'s cost competitiveness as a wave-powered technology is compared with these alternatives of renewable energy sources.

Table 2: The table below summarizes the economic performance of various renewable energies as established sources clean water and electricity in comparison with *PRO-BRO*.

Competitors – Renewable Energies				
	LCOW ($/m^3)	LCOE ($/kWh)	Availability	Capacity Factor (%)
Solar PV	0.35	0.057	Intermittent	16
Wind	1.80	0.039 - 0.084	Intermittent	36 - 40
Hydropower	N/A	0.039	On Demand	46
PRO-BRO (Wave)	1.41	0.22	On Demand	49

Competing renewable power generation technologies have advantages and disadvantages. Specifically, hydropower is severely geographically limited and approaching saturation with current technology. The other three renewables listed in Table 2 are all intermittent, meaning they rely on weather patterns or other factors to produce energy. Wave energy is also intermittent but by utilizing PRO to bolster electricity production, energy that is produced during high tide can be stored in tanks at atmospheric pressure for later use. This enables *PRO-BRO* to deploy on-demand electricity generation in locations that are more geographically diverse than hydropower.

Storing energy in the form of brine in a tank is relatively cheap as the cost of energy storage only goes to the one-time capital expense of purchasing tanks and PRO systems, and the maintenance of the PRO system is supplemented by energy sales. Other forms of energy storage technologies like hydraulic accumulators and batteries are relatively more expensive due to the cost per unit of energy that is associated with storing energy in the long term and maintaining a certain level of pressure or electricity in the systems. The cost of storing energy is $270.8/kW in batteries, $75/kW in hydraulic accumulators and $217/kW in ultracapacitors [25].

Of all the renewable energy sources, wave power is the least developed and its components may not be as optimized as others. The previous design, *Osmocean*, has an LCOW of $1.94/ m^3 [2]. To reduce the LCOW, *PRO-BRO* offers a solution of producing water when the price of water is high and switching to producing electricity when the cost of energy is high. This way, the system will be able to overcome negative curtailment and avoid significant losses, especially during earlier stages of deployment where reaching a break-even point is one of the utmost priorities to remain relevant in the market.

1.2.3 Relevant Stakeholders

PRO-BRO's business model continues to address *Osmocean*’s market, targeting the desalination sector of the blue economy in the three market stages as shown in Figure 3 [2]. The markets, which will be addressed progressively in tandem with the growth of *PRO-BRO*, includes the target market, then expanding to the expansion market and finally aiming for the total addressable market.

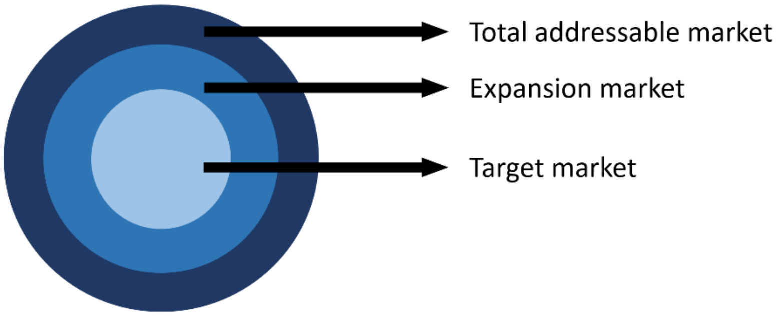


Figure 3: *Diagram illustrating the target, expansion, and total addressable markets. The total addressable market circle will expand as time progresses and as the team discovers more users that may benefit from PRO-BRO.*

<u>Target market</u>

The target market for PRO-BRO will be the existing RO companies that are using wave energy to operate standard CRO processes like Resolute Marine as well as WEC developers that can couple WEC systems with PRO-BRO [2]. The entry strategy is to retrofit a BRO and PRO process to existing commercial RO processes so that the capital cost can be reduced by demonstrating the system’s technical feasibility using already-profitable infrastructure. This target market will allow PRO-BRO to generate revenue while the system is perfected.

In addition, based on our interviews with industry representatives, we find that the best way to demonstrate PRO’s proof-of-concept at this stage is by using the electricity generated by PRO to power the BRO operation and nearby facilities. This is because the process to integrate a new energy producing system with a local energy grid requires that the system can produce a stable and massive amount of energy, which is impossible given that the PRO system is still in its early deployment stage. Moreover, the team will need to go through a lengthy process of applying for permission from federal agencies and local municipal organizations to connect the system with local grids. Therefore, the electricity produced by PRO at this stage can be reused to power the pretreatment process and pumps in BRO so that the desalination system can produce more water at a low cost.

<u>Expansion market</u>

The expansion market involves more stakeholders such as remote island residents, governments, hotels, and non-profits. Once *PRO-BRO* can generate stable profit from the target market phase, the system will then be implemented at a full-scale, focusing on small remote island communities such as *Hawaii*, *Caribbean*, and *Greece*. The system will also be installed in other small locations that are in dire need of clean water such as liveaboard marinas in *Marina Del Ray, California*. Such a strategy is pursued as small and isolated communities tend to rely on expensive imported diesel fuel to power water treatment and are thus in the most need of an environmentally sustainable alternative.

Moreover, *PRO-BRO* will be able to substitute for the conventional ERD in RO desalination plants to accomplish energy recovery function without interrupting clean water supply. ERD is often a necessity for small communities as it reduces RO plant's energy consumption by 60% which in turn, reduces LCOW. Even though the traditional ERD like pressure exchanger (PX) only takes up only 1 – 2% of the desalination's capital cost, any failure of the ERD will completely shut down the desalination plant, consequently cutting clean water supply for days and costing the communities a fortune for maintenance [8]. Based on the survey carried out, communities often experience an average of 25.5 days of downtime due to piston-type ERD failure. While medium to large-sized communities can afford cascading several ERDs in a parallel layout to combat the downtime issue, small communities often do not have similar privileges due to financial constraints. In *PRO-BRO*, PRO as an ERD is separated from BRO layout which guarantees continuous water supply despite failure in PRO. Not only that, but the minimized mechanical operation in PRO also reduces the number of components that are prone to failure due to extensive operation. In this market stage, the electricity produced by PRO can be channeled for small communities' use, especially those who are currently receiving unstable electricity supply from old underwater cables that are connected to the mainland like islanders living in *Isle au Haut, Maine*. When the cables fail, the islanders receive power from a backup diesel generator which costs them triple the standard cost of electricity due to legal regulations [9]. The diesel generator is also difficult and expensive to maintain as well as not climate friendly. *PRO-BRO*, which is a localized system at this stage, will be able to replace the diesel generator and ensure consistent electricity supply at a low cost.

Total Addressable Market

Once the expansion market is saturated, *PRO-BRO* aims to utilize the system to serve all coastal communities. To reach this market waypoint, *PRO-BRO* heavily relies on the maturation of wave energy conversion and PRO technology so that they are competitive with other renewable energy sources and plant-scale ERD. This will help bolster general acceptance towards *PRO-BRO* and convince investors and the public that the system is worth investing in. The team's long-term business goal is to integrate the *PRO-BRO* system into the existing desalination plants as well as introducing the system to coastal regions across the globe.

Furthermore, based on an interview conducted with Josh Bradley who lives on a boat in Washington, USA, the team discovered a potential room to serve the liveaboard community. Mr. Bradley reveals that his family of 5 spends most of their time on water and sails to the dock occasionally to collect clean water. However, his boat can only carry up to 182 gallons of water which only lasts for a week with careful water consumption. He finds having to frequently sail to docks or marinas inconvenient as it is far from liveaboards sailing spots and consequently, consumes his boat's already-limited fuel. As the desalination process is carried out offshore, the team is interested in exploring future opportunities to build an offshore water marina to serve liveaboards like Josh Bradley.

The discovery of the liveaboard community encourages the team to research other communities that may benefit from offshore water marina. In Southeast Asia, a local tribe named Bajau is known to live their whole life on houseboats. In Bangladesh, the Manta community is living a similar lifestyle. These communities have trouble accessing clean water due to water pollution, extreme poverty, and unfavorable geographic conditions for connection to electricity and water grid [10] [11]. Addressing the needs of these communities aligns with the concept of Corporate Social Responsibility (CSR) which will help *PRO-BRO* gain a remarkable public image that will in turn draw investors in and increase customer loyalty.

1.3 Development and Operation

1.3.1 Research and Development (R&D)

The concept of *PRO-BRO* includes the enhancement of features from the previous design of Osmocean. To continue developing the system, the current Purdue MECC team has been recruiting students to carry the project forward, perform further design iterations to improve *PRO-BRO's* performance and compete in future MECC competitions. The current *PRO-BRO* system has a robust design, and its feasibility is well-supported by empirical data from computational modelling. Nevertheless, future work is necessary to further perfect the system such as reducing downtime between BRO and PRO mode to maximize plant capacity and increasing the autonomy of the system to minimize human intervention. The integration of innovative coupling design and control strategy between wave power and *PRO-BRO* will require the team to form partnerships with researchers, expertise in wave energy and local municipal organizations.

To ensure *PRO-BRO*'s long-term success, the team planned a 3-Stage Deployment Phase which corresponds to the three phases of market in Figure 3. Due to the complexity of the system and PRO's status as an immature salinity gradient technology, the team will spend almost a decade developing the system, earning public's confidence and establishing dominance in the desalination industry.

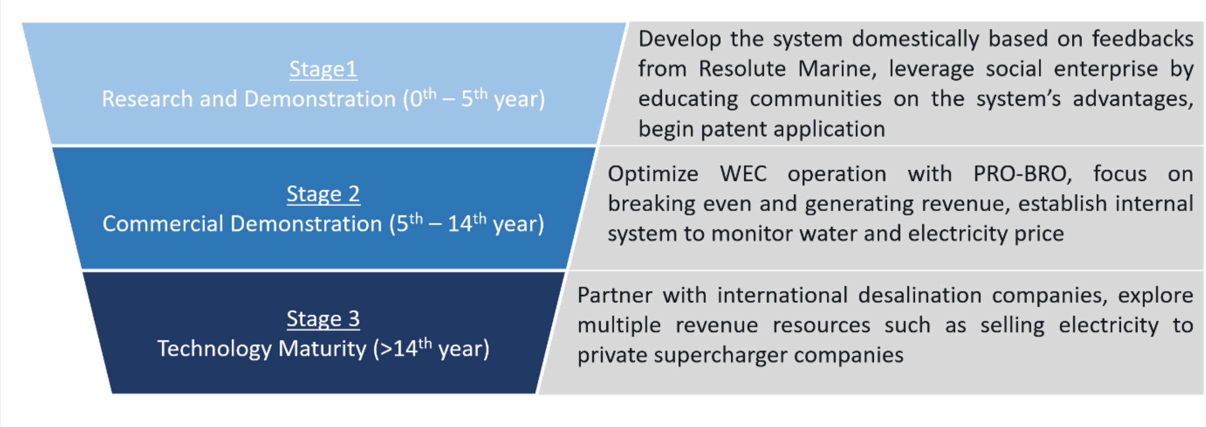


Figure 4: *The 3-Stage Development Phase of PRO-BRO is established to perfect the system while gradually reinforcing the public's acceptance towards the system.*

1.3.2 Manufacturing and Deployment Process

The development of *PRO-BRO* system remains the same as that of *Osmocean*, taking into account the supply chain process as shown in Figure 5. This supply chain process may be different during the stages of initial full-scale deployment as only PTO and PRO-BRO raw materials can be retrofitted to the existing RO desalination systems [2].

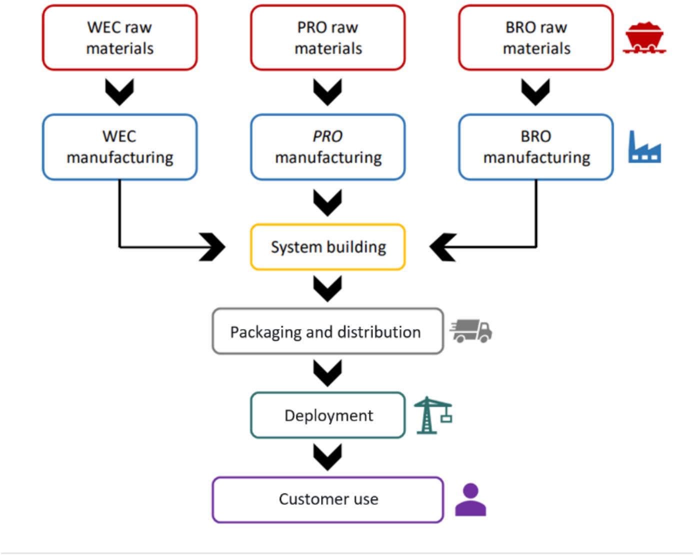


Figure 5: *Supply chain diagram illustrating the development of the PRO-BRO from the perspective of all the components from raw materials (red) through manufacturing (blue) through system assembly (yellow) through transportation (gray) through deployment (teal) through customer use (purple).*

1.3.3 Partnerships

Sultan Alnajdi, a PhD candidate researcher who has directly worked with numerous water desalination companies, provided valuable insight on the feasibility of the system's full-scale deployment. In addition, the team also collaborates with researchers from Purdue University's School of Health Sciences to research ways to mitigate membrane fouling to increase the lifespan of PRO-BRO's membrane

The team also aims to develop partnerships with several key players in the desalination industry, notably governmental and academic institutions as detailed below:

Table 4: *PRO-BRO* partnership goals with various institutions.

Partnership	Action Items
Public programs promoting sustainable water like WaterTalks	Network with water communities and end users to gather more information on market needs that need to be addressed and conduct educational talk to promote *PRO-BRO*
Resolute Marine	Develop plans to integrate *PRO-BRO* with existing wave-powered RO desalination system
The U.S Environmental Protection Agency (USEPA)	Learn about the legal framework of water production and apply for necessary permits and grants
Governmental agencies in charge of energy like the Federal Energy Regulatory Commission	Discuss plans to distribute electrical energy and a centralized method to record electricity cost offset

The team established a partnership with BBC Pump and Keyence, all of which provided useful advice regarding the appropriate specification of equipment like high-pressure pumps, motors and flow sensors for the *PRO-BRO* prototype that will be presented in the Build & Test report. Besides, the connection that was established with Swagelok Company from *Osmocean* project allowed the team to obtain check valves and pressure relief valves at discounted price. The team will continue to leverage partnership with these companies and looks forward to establishing more connections in the future.

1.3.4 Potential Risks and Mitigation Strategy

This section outlines the risks associated with the development of PRO-BRO in various areas including environment, human-centered factors, technical implications and full-scale deployment.

Environmental Risks

The team was able to conduct a short interview with an environmental advocate based in Chile, Eduardo Nunez, who voiced out concerns that the desalination plant will attract flocks of fishes and cause the fishes to get stuck in the WEC or killed by collision with any exposed rotor blades. To avoid this circumstance, the full-scale WEC will be equipped with two layers of mesh netting to make sure no marine creatures end up in the WEC nor the *PRO-BRO* system.

Social Risks

Balancing stakeholders' needs and making trade-offs are the main social risks that the team discovered. The primary objective of *PRO-BRO* is to supply clean water to local communities who are in need of clean water at a low cost. Environmental sustainability, on the other hand, is the foremost goal for coastal island resorts and non-profit organizations. In contrast, local municipal organizations' primary concern is the economic feasibility which echoes *PRO-BRO*'s concern of generating revenue to continue developing the system in the future .An interview with Amadou Maguette Dieng, who is a resident of Mamelles Beach in Senegal, unveils the locals' concern of desalination plant project changing the landscape of the land where the community resides. He is worried that the accessible beach area will be reduced, and the community gardens will be destroyed to make way for the desalination plant. To address this issue, the team will construct accompanying plans to relocate gardens. Not only that, but the team will also conduct more research to learn *PRO-BRO*'s location feasibility and ideal scale size to minimize displacement of commercial beaches.

Technical Risks

The technical risks that afflict current membrane-based desalination plants will apply to *PRO-BRO* design as well. Corrosivity can cause damage to system components and lead to contamination of water [14]. In response stainless steel (SS) 316 was chosen for the full-scale design and the prototype to withstand high desalination pressure and flow rates of saltwater. Hydraulic equipment such as pumps and hydroturbines have lifespans of up to 20 years with little maintenance if operated as intended. To supplement this, a filter was added at the inlet of the system to remove large contaminants that could cause damage to downstream components. The system includes many components that operate at high pressures. *PRO-BRO* sub-section operates at a nominal 1015 psi which requires piping that can provide an adequate factor of safety while balancing system cost. The team determined that the minimum factor of safety (FOS) that the system must meet is 2.0. The team chose hydraulic hose rated for a pressure of 2250 psi, giving a FOS of 2.21 [26].

Market Risks

One significant risk of developing a full-scale *PRO-BRO* is the willingness of customers to invest. Since wave-powered BRO is a relatively new system, capital investors will be wary of sponsoring such technology in full-scale without empirical data on the system's performance and proof that the project is profitable. Getting loans from banks is possible but even then, they will likely charge a high interest rate which will delay the time for *PRO-BRO* to reach break-even point. Unless smaller *PRO-BRO* systems are proven feasible, the large-scale market is almost impenetrable. [2] This risk can be mitigated by refining the appropriate data to be validated during Stage 1 of the 3-Stage Development Phase.

Not only that, based on our interview with Sultan Alnajdi, distributing electricity to communities will be immensely challenging because it requires each household to switch to smart meters that are capable of recording *PRO-BRO*'s electricity usage in real-time. In Carlsbad, for example, people refuse to install smart meters in their homes due to privacy issues. They believe that the information of real-time water and energy consumption gives away whether they are at home or away, their daily routine based on water-intense activities and many more. Moreover, they are comfortable with using the analog meter and refuse to spend extra money to install smart meters that they are not familiar with. For this reason, *PRO-BRO* explored the option to offer a one-time rebate for installing smart meters in homes.

Lastly, smaller deployment of PRO-BRO to small, remote communities necessitates that the system is able to operate and sustain with locally available resources. If custom parts like the hollow-fiber membrane require replacement or maintenance, the communities may not have adequate resources to fix the parts and will be left without water and electricity. With that reason, *PRO-BRO* is designed with equipment that lasts long and require little maintenance. Based on an interview with Sina Nejati, an expert in membrane technology, the team has been advised to implement ultrafiltration (UF) and chlorination methods to prolong the membrane's lifespan so that it only requires replacement every 5 years instead of months.

1.3.5 Social Impact and Opportunity

PRO-BRO maintains a similar goal as *Osmocean* of reducing LCOW and increasing accessibility to clean water. On top of that, *PRO-BRO* hopes to accomplish that goal while preserving the environment. The system also has potential in these areas to create job opportunities that correspond to the skillsets of the community members. Job opportunities include sectors such as plant operations and transportation [2].

1.3.6 Failure Maintenance

A variety of the sub-assemblies associated with *PRO-BRO* design use Run-to-Failure (RTF) Maintenance. RTF involves a deliberate plan of remedial actions to be taken post-breakdown. This method applies to large equipment such as turbines, pumps, membranes, etc. These components have long product life cycles when operated within the intended conditions, allowing them to run to failure and be replaced according to a suitable plan for disposal, recycling, or reuse. This mode of failure maintenance is especially beneficial since it lowers costs incurred on preventive maintenance, streamlines operations, and eliminates excessive maintenance [15].

1.4 Financial and Benefits Analysis

1.4.1 Capital Expenditure (CapEx)

The financial analysis of a full-scale *PRO-BRO* includes the cost of WEC CapEx, as well as BRO & PRO CapEx. *PRO-BRO*'s WEC CapEx is assumed to be the same as NREL's calculated CapEx for the PTO-Sim model which is $3,800,000 [2]. Since the WEC in *PRO-BRO* has a similar dimension to the WEC used in NREL's Osmo-Sim model – 18-meter wide – the assumption is valid.

To find the total PRO & BRO CapEx, the budget is assumed to be reasonably scaled according to the system's permeate capacity. For example, the PRO & BRO CapEx shown in Table 5 is calculated for a permeate production capacity of 100 m^3/day while the CapEx of similar system with 2600 m^3/day capacity will be 26 times the cost of the 100 m^3/day system which is $5,125,614. Since there is no other full-scale system to date that combines RO and PRO processes, the team finds comparing the *PRO-BRO*'s RO & PRO CapEx to the RO CapEx of other desalination systems acceptable for the sake of evaluating cost competitiveness. An NREL study calculated a full-scale RO CapEx to be $3,685,000. For a 1700 m^3/day RO system in Greece, the RO CapEx is estimated to be $3,363,000 according to DesalData [2][12]. The BRO & PRO CapEx for our system is higher in comparison, which is valid since the costs not only include components for BRO but also for PRO.

Table 5: System component cost

System Component	Cost ($)
Pumps	$37,790
Sensors	$9,675
Generator	$13,744
Hollow Fiber Membrane	$45,487
Filter	$3,077
LP Bladder Accumulator	$5,000
Bag Filter	$3,000
Pipes and Fittings	$16,332
Valves	$22,763
Tanks	$28,272
Estimated Shipping Cost	$12,000
Total	**$197,139**

1.4.2 Operational Expenditure (OpEx)

The OpEx for WEC is also assumed to be the same as NREL's, $68,100. As for the BRO & PRO OpEx, the cost is estimated using NREL's BRO OpEx methodology. The summary of the components that are included in the OpEx calculation is shown in Table 6. The value of OpEx highly depends on the permeate production capacity (m^3/day). In addition, BRO & PRO OpEx is calculated under the assumption that a full-scale system comprises 100 similar systems arranged in parallel, which aligns with the CapEx assumption of 100 m^3/day permeate production capacity. Annual water production (AWP) is calculated by multiplying the amount of water produced by 100 systems per day by the number of days in a year and a capacity factor of 49% which accounts for the system's downtime and energy interruption.

Table 6: Additional operating and process costs

Parameter	**Cost ($)**
Direct Labor Costs	$29,700/laborer
Management Labor Costs	$66,000/manager
Spare Parts	$\$0.04/\text{m}^3 \times \text{AWP}$
Pretreatment	$\$0.03/\text{m}^3 \times \text{AWP}$
Posttreatment	$\$0.01/\text{m}^3 \times \text{AWP}$
Membranes	$\$0.07/\text{m}^3 \times \text{AWP}$
Insurance	0.5% of PRO-BRO CapEx

1.4.3 Levelized Cost of Water (LCOW)

The economic feasibility of *PRO-BRO* was measured with LCOW which estimates the overall cost for the system to deliver a cubic meter of water. The process for determining *PRO-BRO*'s LCOW was adapted from NREL's methodology of calculating LCOW for a WEC-RO system [12]. Equation 1 shows the method to calculate LCOW using the CapEx and OpEx values analyzed in prior subsections.

$$LCOW = \frac{(FCR \times CapEx) + OpEx}{AWP} \qquad \text{Eq. 1}$$

where FCR is a fixed charge rate of 10.8%. CapEx includes the sum of $\text{CapEx}_{\text{WEC}}$ and $\text{CapEx}_{\text{PRO-BRO}}$ while OpEx is the sum of OpEx_{WEC} and $\text{OpEx}_{\text{PRO-BRO}}$. Table 7 sums up the total cost of each CapEx and OpEx as well as the computed LCOW for a full-scale *PRO-BRO*.

Table 7: Total system CapEx and OpEx costs

$\text{CapEx}_{\text{WEC}}$	$387,789,600
$\text{CapEx}_{\text{PRO-BRO}}$	$200,263,000
OpEx_{WEC}	$6,810,700
$\text{OpEx}_{\text{PRO-BRO}}$	$30,279,100
AWP	2.673×10^7
LCOW	$\$1.41/\text{m}^3$

The LCOW of the *PRO-BRO* is competitive as proven in section 1.2.1.

1.4.4 Levelized Cost of Electricity (LCOE)

Since *PRO-BRO* is also producing electricity, the team carried out LCOE analysis to evaluate the cost of energy generated by *PRO-BRO* and estimate the minimum price at which electricity must be sold in order for the system to break even in the market. Equation 2 demonstrates the method to calculate *PRO-BRO*'s LCOE.

$$LCOE = \frac{\Sigma \frac{I_t + M_t + F_t}{(1+r)^t}}{\Sigma \frac{E_t}{(1+r)^t}} \qquad \text{Eq. 2}$$

where I_t is the CapEx of *PRO-BRO* plant in year t, M_t is the OpEx of the plant in year t, F_t is the fuel expenditures in year t which is 0 because our system is driven entirely by wave-energy and does not utilize fossil fuels, and E_t is the energy generated in year t which is 59.68 kWh/hour. The analysis was made over the period of study, t, of 14 years which is the timeframe before *PRO-BRO* system reaches maturity. Ultimately, *PRO-BRO*'s LCOE is computed to be \$0.22/kWh which is proven to be competitive when compared to energy prices at countries like Bahamas (\$0.262/kWh) and Rwanda (\$0.252/kWh). Depending on the countries where *PRO-BRO* is implemented and regulated, the cost of energy may slightly increase or decrease from the anchored value of LCOE calculated using the aforementioned method. However, the team is confident that given ample time for *PRO-BRO* to mature, the system will be able to find niche as a stable source of energy and earn acceptance from users globally.

2. Technical Design Report

2.1 Design Objective

2.1.1 Selected Design Targets and Restrictions

Investigation of other methods of desalination and renewable energy technologies allowed for a frame of reference to set the LCOW is \$1.5/$m^{3.}$ These values are not significant improvements to the competition in both markets, but the strength of the design lies in the flexibility to participate in both permeate and energy production as well as provide energy storage potential for variable grid systems. The dual functionality of the system allows it to effectively run as both water and power generation using a single membrane. In BRO mode, the system is expected to function in the same manner as a normal BRO cycle in that it can produce low salinity permeate from a higher salinity feed. The high salinity feed will represent typical ocean salinity levels at 35 parts per thousand (ppt). Permeate will adhere to safe drinking water standards and contain no more than 0.2 ppt as per World Health Organization (WHO) recommendations [16]. The reject brine from the BRO process is expected to have a salinity of 67.2 ppt. The PRO cycle of this system utilizes the high salinity brine generated during the BRO cycle to generate electricity by running it through the hollow fiber membrane alongside a lower salinity feed. Decreasing the output salinity allows the brine to be returned to the marine ecosystem while posing a significantly lower risk to local marine life. The ultimate output of the system will be the two mid-salinity stream outputs from the PRO mode of operation that are expected to be 56 ppt. salinity.

2.1.2 BRO Background

The most common non-thermal seawater desalination systems use continuous reverse osmosis. This method passes seawater at a constant pressure through specialized RO membranes to separate brine from the permeate. Batch reverse osmosis cycles the brine discharge back through the RO system, while varying the pressure and salinity of the feedwater through the use of a piston cylinder. Figure 6 illustrates the differences in applied pressure for continuous RO and BRO at a feed salinity of 35 g/kg and a permeate flux of 15 L/(m^2-hr) (LMH). As the recovery ratio increases, BRO follows the osmotic pressure curve, or minimum instantaneous pressure required to perform RO. This reduces energy consumption in relation to continuous RO [20, 21]. This BRO process was selected for our desalination plant due to the increased efficiency and reduced operating cost benefits it provides over traditional continuous RO.

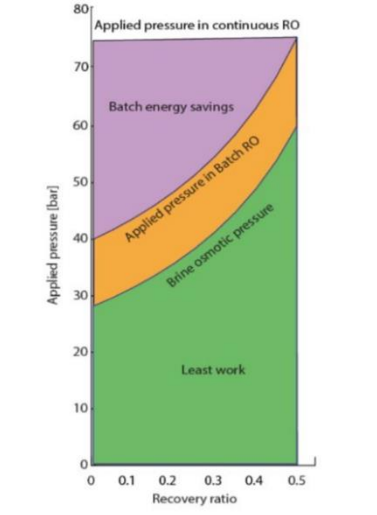


Figure 6: *BRO and CRO energy expenditure according to applied pressure and recovery ratio [24]*

2.1.3 PRO Background

PRO could be considered the inverse process of RO. In PRO, water permeates through a semipermeable membrane from a low concentration feed stream into a high concentration stream. Although the draw solution is partially pressurized, its hydraulic pressure is less than its osmotic pressure. Therefore, there is still a net osmotic driving force for the transport of water from the feed to the higher salinity solution. The permeate stream becomes pressurized with the increased flow and dilutes the draw solution. The energy in the pressurized permeate solution can then be converted into mechanical/electrical energy via a pressure exchanger or hydroturbine [22]. The direction of the flow patterns of the feeds and products are shown in Figure 14.

2.1.4 Design Overview

The design of *PRO-BRO* system improves and combines existing wave energy and desalination technologies. The plant utilizes a hollow-fiber membrane which allows desalination to occur in both the parallel and counterflow directions depending on the pressure applied to each stream. The desalination portion of the plant consists of the hydraulic equipment needed to feed seawater into the hollow-fiber membrane and remove the high-salinity brine and produced permeate. The same equipment can be used to redirect the brine collected from permeate production and the seawater feed into the membrane where the pressure retarded osmosis process creates a pressure gradient. The pressurized stream is fed through a turbine that will convert the mechanical energy into electrical energy to supply the local grid. While this “energy-generating” PRO mode can provide energy, it is not intended to satisfy the majority of the desalination plants' energy consumption. One concern with the increasing dependency on renewable energy as producers of both base and peak load energy is how the intermittent nature of renewables could threaten grid stability. In cases of deficient energy production, the desalination plant could serve as grid energy storage capacity in reserving its brine and seawater volumes in preparation for energy production. Due to the need for seawater for desalination, the plants are often located near shores with wave presence. This provides an opportunity for renewable tidal energy production. The movement of waves is captured by a submerged oscillating surge wave energy converter. The WEC is pushed back and forth, and this rotational motion drives a gearbox that uses a rack and pinion to move a double-acting hydraulic piston back and forth. This piston forces water through check valves into the BRO piston tank where it remains pressurized due to the one-way flow allowed by the check valves. Thus, WEC motion in both directions will lead to strictly increasing pressures provided to the BRO piston tank. A variable-pressure gas-charged accumulator allows for more control of this pressure independent of the frequency and amplitude of the waves. If the desalination plant is producing permeate for the full day, at the selected operating parameters of a 50% recovery ratio, and an overall plant permeate flowrate of 30 LMH for the permeate producing mode, the estimated levelized cost of water was found to be \$1.41/m^3 and the SEC was found to be 3.1163 kW/m^3.

2.2 Innovation and Power Performance

2.2.1 Improvements

A novel improvement was the inclusion of a PRO mode of operation in the existing infrastructure needed for BRO desalination. Additional flow streams, valves, and collection tanks were needed to accommodate this new mode of operation, but other large-scale equipment, such as an energy recovery hydro turbine, high-pressure pump, and circulation pump remained. This combined PRO and BRO desalination system utilizing hollow-fiber membranes is powered by its local grid collection and an improved WEC connection for direct pressurization of the input feeds.

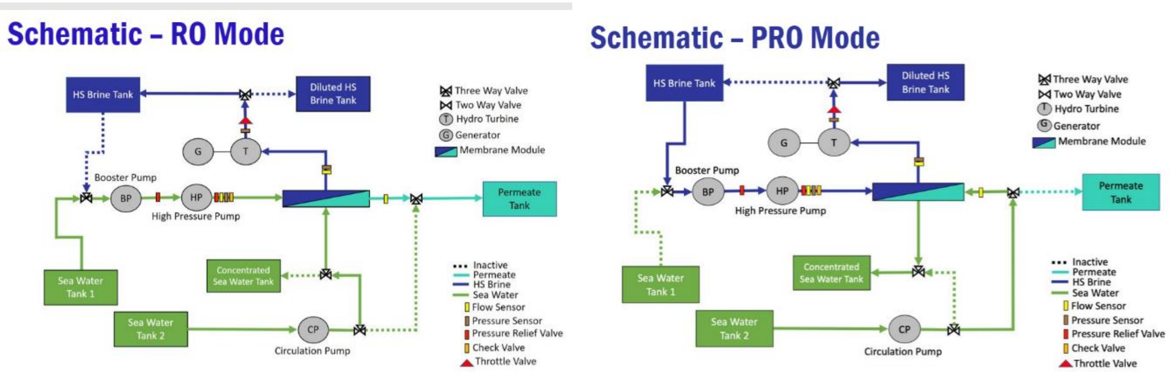


Figure 7: *Prototype PRO-BRO flow diagrams. The team decided to physically test the feasibility of the hybrid system with a CRO process instead of BRO process due to financial and time constraints. This also allowed the team to configure the layout of the system in a way that permits both modes to operate using one membrane.*

The improved WEC-BRO coupling shown in Figure 8 allows for the replacement of the high-pressure pump used in BRO with a high-pressure piston tank that is pressurized directly by the input of wave energy. This design minimizes the amount of energy lost between the WEC and the pressurized feedwater associated with the conversion of WEC motion into electricity then from electricity back into hydraulic pressure using a pump. The WEC-BRO system pressurizes the feedwater directly which avoids conversion loss. The gas-charged accumulator dampens the oscillations in pressure which allows the pressure profile required by BRO to be closely followed. The pressure requirements of BRO are different from a continuous RO process which further adds to the novelty of the design.

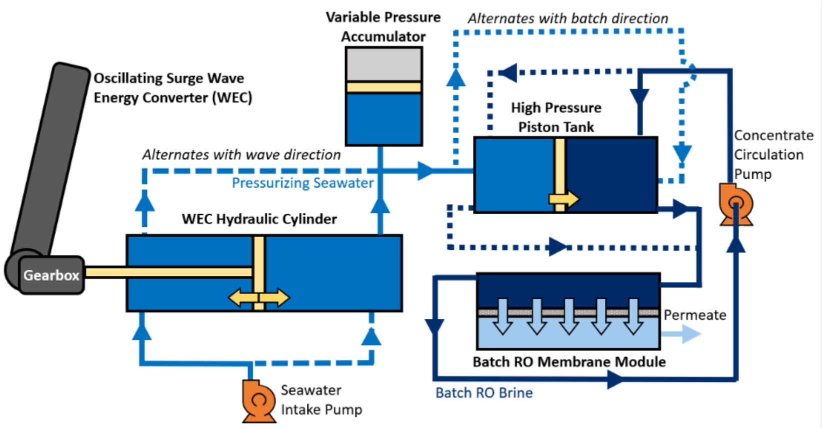


Figure 8: *The improved WEC-BRO design's simplified schematic*

2.2.2 Power Production

In comparison to other established renewable energy generation methods, PRO does not outperform cost-wise. PRO, however, can be viewed as a long-term energy storage solution. Whereas other forms of renewable energy such as wind and solar deal with intermittency due to nature and weather patterns, the BRO-PRO system can utilize seawater and recycled high salinity brine to recover energy on demand. By storing brine in large tanks, customers will be able to switch from water production to energy production in a matter of minutes. Furthermore, storing energy in the form of water with varying salinities avoids traditional energy losses over time associated with batteries or thermal energy storage methods. Assuming incoming seawater of 35 ppt salinity and a BRO recovery ratio of 50%, the *PRO-BRO* system will be able to produce 0.8289 kWh of energy per cubic meter of brine. This feature could be useful to customers in a variety of different situations, including disaster relief, variable electric grid pricing, or as a supplement to other renewable energy sources. The high hydrodynamic efficiency of the WEC coupled directly to BRO allows for wave energy to be harnessed when available and stored as salinity while the PRO process can recover this energy as needed. The success of the WEC in its ability to supply the power needed to operate a desalination plant of this scale is detailed in the previous *Osmocean*'s publication [12].

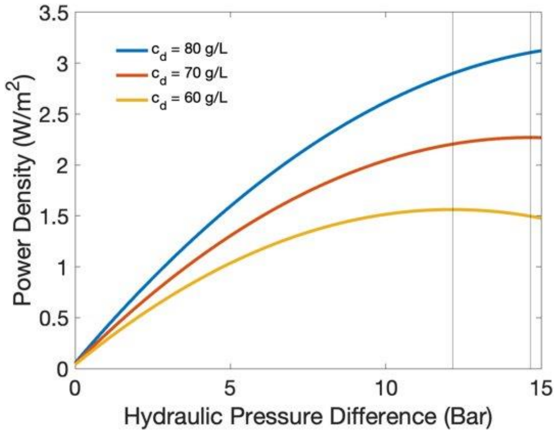


Figure 9: *PRO Power density with hydraulic pressure difference*

2.2.3 Power Consumption and Related Needs

The specific energy consumed by the desalination plant during the BRO mode of operation increases with the system flux and with an increased recovery ratio. The overall specific energy consumption at the desired parameters of 30 LMH and 50% recovery ratio was found to be 3.1163 kWh/m^3. This value becomes 4657.31 kW for one day of permeate production. The largest contributors to the power consumption of the system were the high-pressure pump and circulation pump. The change in the BRO mode specific energy consumption with respect to the desired recovery ratio is shown in Figure 10.

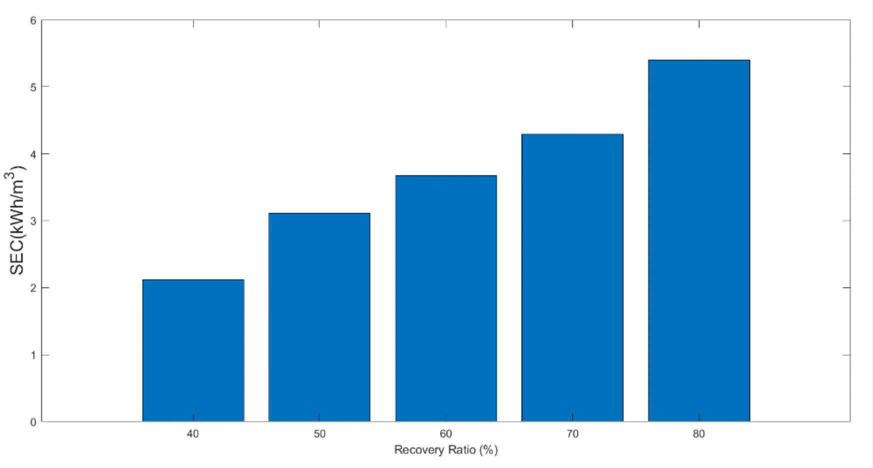


Figure 10: *Specific energy consumption of BRO operation in respect to recovery ratio*

2.3 Mechanical and Electrical Load Analysis

2.3.1 Pressure Loads

The various hydraulic components and valves were chosen to operate within the desired pressure range of 870-1015 psi (about 60-70 bar) [26,27]. The hollow fiber desalination membrane and the selected hydraulic hoses used in the construction of the preliminary prototype were rated to withstand pressures double the target working pressures. Standard NPT fittings with Teflon tape wrapped around the male side was chosen for all connectors, pipes, and hoses to improve the seal between components. All components were made of 316 stainless steel to prevent corrosion and loss of strength.

2.3.2 Electrical Loads

The system was designed with as much load uniformity as possible, with most of the system running on 24V DC power. The 24V supply powered each of the five three-way valves used to switch better BRO and PRO flow paths, the throttle valve used to build pressure during PRO operation, as well as both flow and pressure sensors. Wires for the sensors and valves were placed within a sealed box to protect spliced wires from the wet spaces and minimize hazards within the workspace. Additionally, a 12V DC supply was needed to power the circulation pump and followed the same wiring precautions as above. The largest load comes from the HPP using a 230V three-phase power supply. Since the HPP is the largest driver of fluid within the system, it is expected to require the most power to operate. An emergency stop, circuit breaker, and wire containment as described above were used to prevent the pump from reaching unsafe operational levels and provide a general failsafe. The pump in reverse used as the generator was expected to reach no higher than 0.5 hp. While this component would typically be connected to a grid or other device, it was connected to a 5000Ω 500W rheostat to allow the generated power to be safely dissipated from the prototype.

2.4 System Optimization

2.4.1 Membrane Model Validation

Not enough information was provided by the manufacturer of the membrane to investigate this assumption and quantify the result. To ensure that the hollow fiber membrane was modeled correctly, a combination of the manufacturer-provided performance examples and relevant literature was used. Modeling of the standalone performance of a single hollow fiber membrane began by gathering the given membrane and water parameters from the manufacturer and using literature to provide the remaining needed. The selected literature was an investigation into the brine concentration capabilities of a similarly sized Toyobo hollow fiber membrane. Since the membrane types were of the same manufacturer, type, and of similar size, the provided membrane parameters were used as starting guidelines. The equations for the concentration, water flux, salt flux, and volumetric flowrates from this literature were used. These equations were run in a standalone MATLAB program with the provided performance example inputs and membrane parameters. The equations and parameters were able to output results within ± 0.05 of the values of the desired outputs of each example case provided in Figure 11. This meant that the mathematical model for the hollow fiber membrane accurately reflected the physical membrane's performance. These equations and parameters were placed in the full-scale desalination plant model. Additional changes were made to the model to accurately reflect the design of the *PRO-BRO* system. The wave pattern type that is input into the WEC-SIM was changed to regular waves, meaning that the randomly generated variation in waves was removed to provide results that did not vary with each run of the model.

$$Q_{\mathrm{shell}(n,m+1)} = Q_{\mathrm{shell}(n,m)} - J_{\mathrm{W}(n,m)}A_{\mathrm{m}(n,m)} \quad \text{[Eq. 3]}$$

Shell-side flowrate equation for the single hollow fiber membrane validation model.

$$Q_{\mathrm{bore}(n+1,m)} = Q_{\mathrm{bore}(n,m)} + J_{\mathrm{W}(n,m)}A_{\mathrm{m}(n,m)} \quad \text{[Eq. 4]}$$

Bore-side flowrate equation for the single hollow fiber membrane validation model.

$$C_{\mathrm{shell}(n,m+1)} = \frac{C_{\mathrm{shell}(n,m)}Q_{\mathrm{shell}(n,m)} - J_{\mathrm{S}(n,m)}A_{\mathrm{m}(n,m)}}{Q_{\mathrm{shell}(n,m+1)}} \quad \text{[Eq. 5]}$$

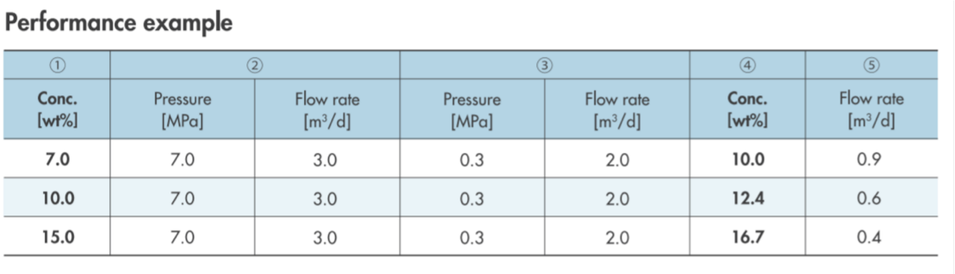
Shell-side concentration equation for the single hollow fiber membrane validation model.

$$C_{\mathrm{shell}(n,m+1)} = \frac{C_{\mathrm{shell}(n,m)}Q_{\mathrm{shell}(n,m)} - J_{\mathrm{S}(n,m)}A_{\mathrm{m}(n,m)}}{Q_{\mathrm{shell}(n,m+1)}} \quad \text{[Eq. 6]}$$

Bore-side concentration equation for the single hollow fiber membrane validation model.

$$J_{\mathrm{S}} = \frac{B}{\beta RT}\left(\Delta P - \frac{J_{\mathrm{W}}}{A}\right) \quad \text{[Eq. 7]}$$

Salt flux equation for the single hollow fiber membrane validation model [22].



Performance example

①	②		③		④	⑤
Conc. [wt%]	Pressure [MPa]	Flow rate [m³/d]	Pressure [MPa]	Flow rate [m³/d]	**Conc. [wt%]**	Flow rate [m³/d]
7.0	7.0	3.0	0.3	2.0	**10.0**	0.9
10.0	7.0	3.0	0.3	2.0	**12.4**	0.6
15.0	7.0	3.0	0.3	2.0	**16.7**	0.4

Figure 11: *Performance example result for the Toyobo FS5255S membrane [23]*

2.4.2 Desalination Parameter Optimization

The LCOW and the SEC of the full-scale desalination plant with the hollow fiber membrane in BRO mode were plotted in response to the recovery ratio in Figure 12. To lower plant construction and operation costs, and to reduce plant energy consumption, a low SEC and LCOW are desired. The desired recovery ratio was chosen as 50%. Recovery ratio is the percentage of the volume of feed water that can be recovered as fresh water. A larger recovery ratio significantly increased the SEC with minimal decreases in LCOW. This value is also a common industry standard. More emphasis was placed on reaching the LCOW target due to the additional energy production capabilities provided by the PRO mode operation.

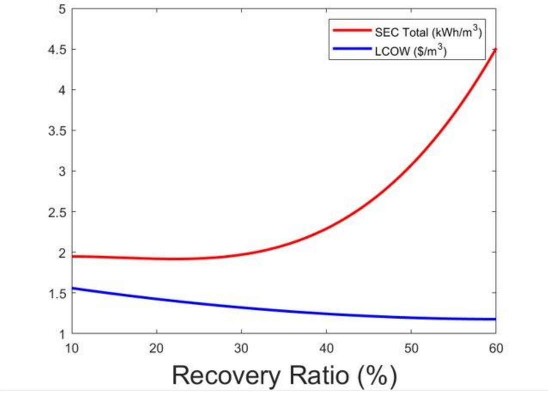


Figure 12: *SEC and LCOW with Recovery Ratio*

Figure 13 reveals the performance contours relating the dependence of the power density of the PRO mode of operation on the hydraulic pressure difference and concentration difference. The hydraulic pressure difference is the difference in pressure between the two input streams of PRO: the brine output of BRO and seawater stream. The concentration difference is the difference in salinity between the two streams. A larger power density is desired for PRO, indicated in the yellow areas on the top right of the figure.

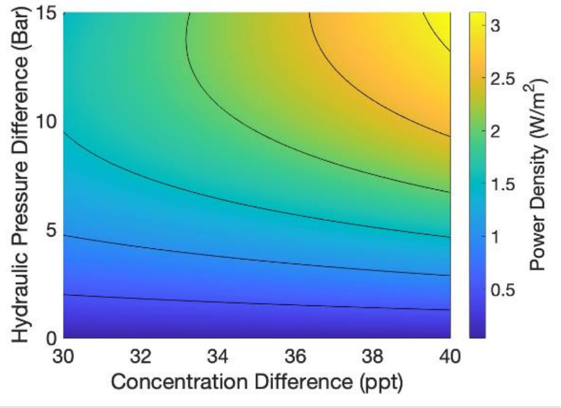


Figure 13: *Hydraulic Pressure Difference and Concentration Difference*

2.5 System Design and Results

Figure 14 details the timing and orientation of the various flow streams of PRO and RO modes through a singular membrane using the same hydraulic equipment. A detail to note is that the figure showing RO is applicable to BRO, with the addition of the piston-cylinder tank in place of the high-pressure pump. In Figure 7, a high-pressure pump was also shown. This was due to budget limitations that prevented the purchase of the equipment to simulate a true batch system. In both the WEC and *PRO-BRO* prototypes, the piston was replaced by a valve and pump, respectively. In the full-scale plant design, pressurization is achieved using the WEC and piston design shown in Figure 16. A circulation pump (CP) pushes seawater across the membrane module. The CP maintains circulation to mitigate boundary layer effects and overcome pipe friction. It consumes less than a tenth of the energy compared to HPP.

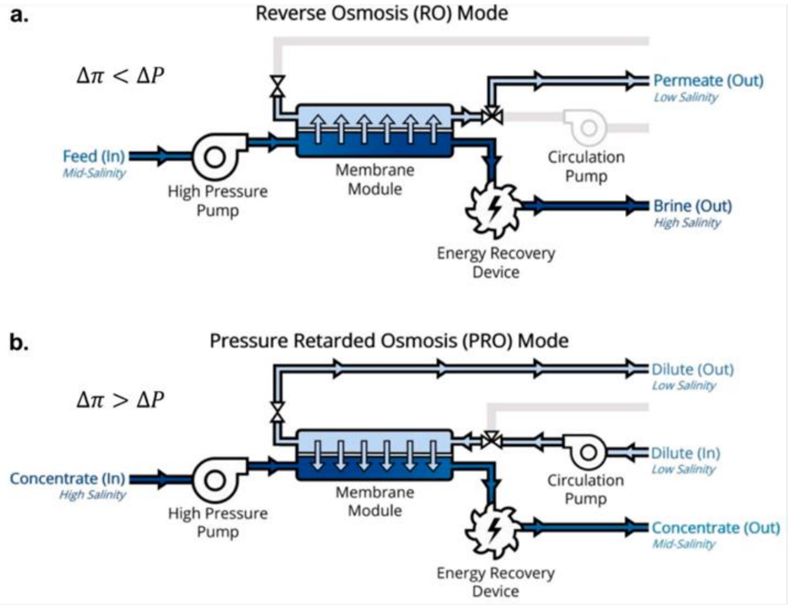
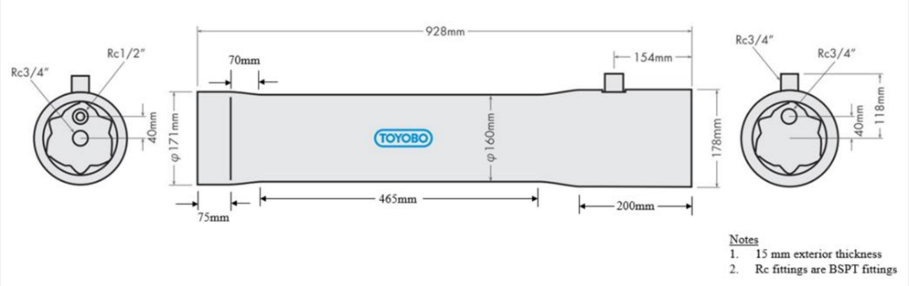


Figure 14: *Feed flow paths of RO and PRO through a single membrane,*

a. Reverse Osmosis, b. Pressure Retarded Osmosis [24]

A turbine is used as the energy recovery device in the system, which produces electricity that is stored in a variable electric grid. As is shown in Figure 14, the two modes cannot occur simultaneously, so a stakeholder can determine which mode to use based on energy demand. Due to global supply chain delays, the team used a pump-in-reverse as a replacement for a hydroturbine. Traditional RO membranes cannot support a PRO mode of operation. Therefore, the team utilized the Toyobo FS5255S membrane, a hollow fiber membrane that can concentrate in either direction across the membrane depending on the applied pressure difference. Since the membrane is not optimized for RO, it results in less efficient desalination performance. The same desalination system with a similarly-sized, traditional RO membrane yielded a LCOW of around 1.2 $/m^3. Details of the membrane performance are discussed in Section 2.4.1.



Notes
1. 15 mm exterior thickness
2. Rc fittings are BSPT fittings

Figure 15: *TOYOBO membrane manufacturing drawing [23]*

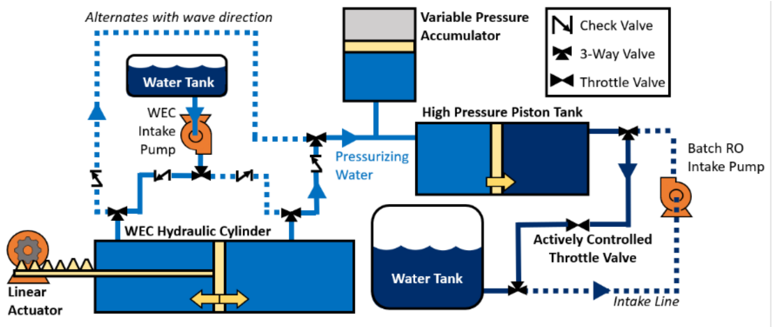


Figure 16: *Experimental Schematic for WEC-BRO Testing*

Figure 16 above shows the experimental design for the improved WEC design. This design uses an off-the-shelf cylinder with 2 ports and a system of check valves to imitate an inlet from a seawater tank and an outlet to the accumulator and BRO piston tank. The hydraulic cylinder takes in seawater on one side. Then on the reverse stroke, it pushes this seawater into the high-pressure accumulator and BRO piston tank. The pressure is transferred to the feed water on the right side of the BRO piston tank where the scaled-down pressure requirements for a batch desalination process are approximated using the actively controlled valve which will change its opening aperture to provide the specified pressure drop, simulating a membrane load. The feed intake is not continuous since the process is full batch, so the feed intake loop will run at the beginning of a batch and then be shut off and valves closed while the water is pressurized and "desalinated." Due to the physical constraints of the valves, only one batch will be simulated at a time for this experiment.

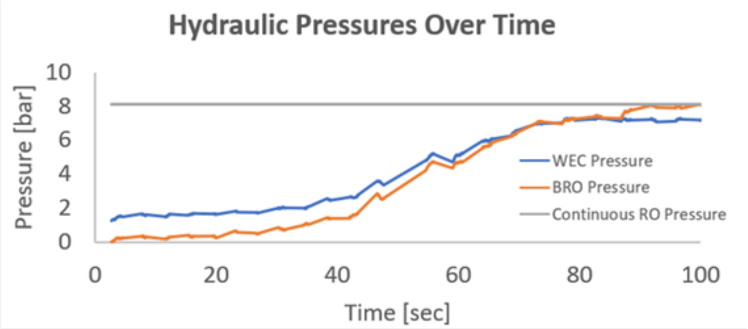


Figure 17: *Experimental Results from WEC-BRO Testing*

Figure 17 above shows the measured hydraulic pressures on either side of the Batch RO piston cylinder. The red line shows the pressure maintained by closing the throttle valve on the desalination side of the BRO piston cylinder. This pressure was controlled to follow an increasing pressure profile within the pressure ratings of the experimental components. Approximating a batch process, this pressure follows the osmotic curve and thus, presents energy savings over the horizontal grey line which is symbolic of a continuous RO process. The area between the grey RO line and red BRO line is representative of this energy savings. The blue line shows the measured pressure on the WEC/wave side of the batch RO piston. The goal of the WEC-BRO design was to have the coupling and valving configuration allow this WEC pressure to follow the BRO pressure. As Figure 17 shows, this goal was successful, and the WEC-BRO coupling has the ability to follow a desired pressure profile. While these results are at low pressure, the same behavior should be observed at the large scale which is demonstrated with MATLAB Simulink modeling of the WEC-BRO system.

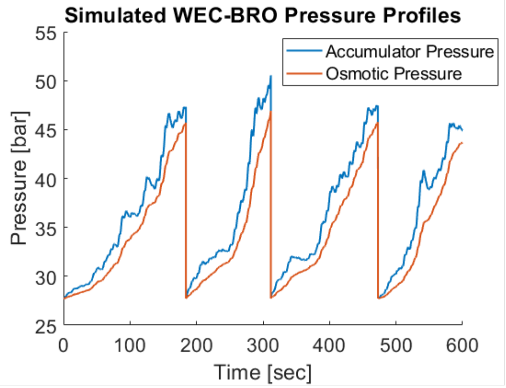


Figure 18: *MATLAB Results from WEC-BRO Simulations*

Figure 18 above shows the results of a MATLAB Simulink model of the WEC-BRO coupled system. The red line shows the osmotic pressure that must be exceeded to drive desalination. The blue line shows the achieved pressure in the variable-pressure accumulator resulting from the input of wave energy to the WEC. The figure shows multiple batches of desalination at high pressure as compared to the experimental setup which only tested one batch at low pressure. Note that the modeling results validate the experimental testing in showing that the configuration of the WEC-BRO coupling with an accumulator allows the WEC-provided pressure to follow the required BRO profile.

2.6 Environmental and Sustainability

The primary components in the system assembly use stainless steel 316-based material. This material is particularly effective in desalination applications due to its resistance to high temperatures and corrosive environments due to exposure to high salinity fluid. Stainless steel 316 also has a high recyclability potential due to its high intrinsic value [2]. Moreover, stainless steel 316 is a very long-lasting material, effectively reducing the energy demands during the production of new material, making it a very sustainable material [2]. Figure 19 shows the percentage of Global Warming Potential (GWP) for *PRO-BRO* system. Considering *PRO-BRO*'s lifespan of 20 years, these are considered by the Environmental Protection Agency to be sufficiently low values of GWP.

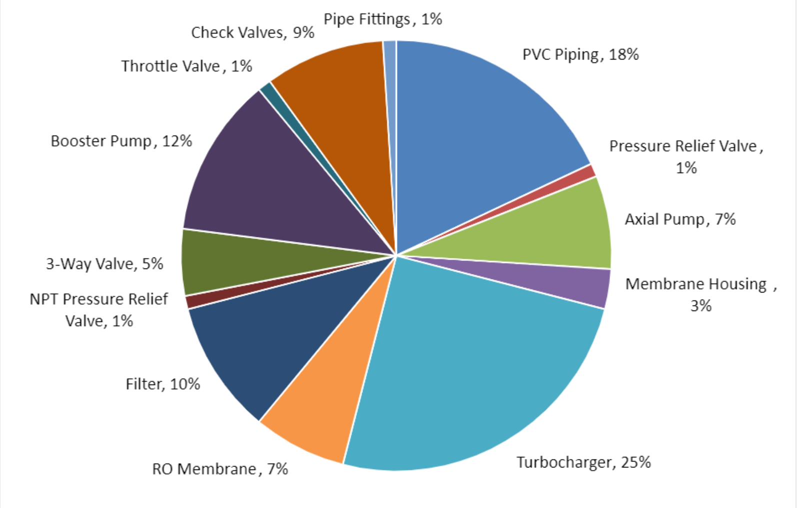


Figure 19: *Global Warming Potential (GWP) contributions of PRO-BRO components. The total for the large-scale assembly is 3630 kg equivalent of* CO_2*.*

High salinity brine byproduct as a result of RO processes which is released to the environment has the potential to harm the ecology of the area directly surrounding discharge. High salinity brine has a significantly higher specific weight than ocean water and due to this, sinks quickly if no prior mixing occurs. The system's BRO brine reject has a salinity of 67 ppt, about 32 ppt higher than the ocean water intake salinity. Releasing the brine byproduct at a point source with no prior mixing has the potential of negatively affecting the ocean ecology within the plume of brine released. Marine organisms exist in an osmotic balance with their surroundings which consistent discharge of high salinity plumes would disrupt. Invertebrates, marine biota, and young offspring are a few of the most vulnerable marine organisms due to their increased sensitivity to dehydration [18].

With the addition of the PRO cycle in the system, brine discharge salinity is decreased from 67 ppt to 56 ppt due to additional mixing with sea water intake prior to discharge. The addition of mixing prior to discharge helps to mitigate plume salinity effects on osmotic pressure sensitive organism in direct contact with the plume. Lowering the salinity of the concentration additionally lowers the specific weight of the discharge, making the concentration more buoyant and susceptible to mixing upon release to the ocean. The addition of this mixing is important to the sustainability of the ecosystem for the point of impact of the discharge and should be evaluated based on the characteristics of the environment being discharged into. These characteristics include wave intensity, current speed, and depth [17]. Desalination plants additionally have a high indirect impact due to the large amount of energy supplied primarily by pollutant-producing generation methods. The BRO system is measured to intake 4.66 MW of energy per 1500 m^3 of permeate produced. Using coal as the primary source of energy for this system would result in 6375 lbs. CO^2 being released to the environment [19]. The system helps mitigate the energy intensity of the BRO system by producing energy via a wave-energy-converter (WEC) and utilization of PRO.

Lastly, to preserve the life of the membrane, any seawater intake for *PRO-BRO* feed will be chlorinated to disinfect the water and kills microorganism that can cause membrane fouling. However, since chlorine can potentially degrade the quality of the membrane, the chlorine must be added after the feed passes the hydraulic coupling in BRO and downstream of the circulation pump in PRO and removed right before the feed enters the membrane. To dechlorinate, solutions like HCl will be added to the chlorinated feed. Additionally, ultrafiltration (UF) – a filter system with super small pores – is implemented in the system to filter large sediments and prevent them from contaminating the membrane. The bag filter in Figure 1 can be replaced with UF.

2.7 User-Based Design

PRO-BRO aims to serve all coastal communities in areas where geographical conditions are unfavorable for supporting traditional electrical grid-systems. Additionally, all communities not bound by this limitation, but who utilize desalination systems and are subject to curtailment bids (negative energy prices) from the market instability. As was found in the various stakeholder interviews, these communities could range from small rural groups to large, developed communities such as Hadera, Israel who depends on desalination for potable water and experiences energy market fluctuations. More detail regarding user influence on the design goals and parameters is given in Section 1.2.3.

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