“Using Ocean Thermal Gradients to Desalinate Water for Remote Island Communities”

by the Marine EnergY & Oakland University
(ME & YOU) Team

Marine EnergY & Oakland University
ME & yOU
“Because clean energy and clean water is for everyone”

Student Team:
Matthew Brauer, Team Lead/Technical Design Lead, mbrauer@oakland.edu
Gerard Griest, Community Connections Lead, gtgriest@oakland.edu
Saber Khanmohammadi, Graduate Advisor, skhanmohammadi@oakland.edu
Lance Markowitz, Business Plan Lead, Lmarkowitz@oakland.edu
Mike Zheng, Build and Test Lead, mzheng@oakland.edu
Sanjana Yagnambhatt, Business Graduate Advisor, chintalacheruvu@oakland.edu

Faculty Advisor:
Prof. Jonathan Maisonneuve, maisonneuve@oakland.edu

Word Count:
Technical Design Challenge: 5,322
Business Plan Challenge: 7,081
Build and Test Challenge: 4,517

05 / 06 / 2024

Executive Summary

The utilization of ocean thermal gradients for energy and freshwater production has been a subject of interest since the 1800s, with ongoing research aimed at realizing its potential benefits. We present the collaborative efforts of an interdisciplinary team of undergraduate students from Oakland University in Auburn Hills, Michigan, focusing on addressing the energy and water challenges faced by remote island communities. Our study revolves around the implementation of Direct Contact Membrane Distillation (DCMD) technology to enhance freshwater production efficiency by utilizing the temperature difference between surface and deep ocean waters. Specifically, our investigation targets American Samoa, chosen for its tropical climate, proximity to deep water access, and high energy costs.

Our findings indicate the effectiveness of DCMD in generating freshwater from seawater, capitalizing on the natural thermal gradient present in ocean environments. Beyond providing a sustainable solution for freshwater scarcity, this technology holds promise for advancing ocean thermal energy conversion (OTEC), which simultaneously produces electricity and freshwater. Moreover, DCMD presents an avenue for delivering essential resources to remote communities, thereby reinforcing their resilience and sustainability. Our research underscores the potential of Direct Contact Membrane Distillation as a practical and scalable approach to addressing the pressing water and energy needs of remote island communities, offering not only immediate relief but also paving the way for broader advancements in renewable energy.

Table of Contents

I.Technical Design Challenge

II.Business Plan Challenge

III.Build and Test Challenge

Technical Design Challenge

1. Introduction

1.1. Motivation and Objectives

Remote islands face significant challenges in accessing clean water and reliable energy sources. The scarcity of potable water and dependence on imported fuels often exacerbate economic struggles and hinder sustainable development efforts. According to the World Bank, approximately 2.2 billion people worldwide lack access to clean water, with many residing in isolated island communities. These regions often struggle with the dual burden of water scarcity and energy insecurity, highlighting the urgent need for innovative solutions that leverage available resources effectively [1].

For example, as of 2022 the American Samoan population that doesn't have clean water supply is 89.85% [2]. When it comes to the primary sources of water supply, groundwater accounts for approximately 99% of the total. The Water and power authority tasked with ensuring access to this vital resource typically engages in drilling procedures to uncover new water sources [2]. However, a significant challenge arises from the substantial loss of treated water, amounting to a staggering 70% as classified under non-revenue water [3]. This inefficiency poses a considerable threat to sustainable water management, potentially necessitating a reduction in production levels over the long term. Additionally, efforts are underway to address the escalating electricity costs associated with water supply operations. Despite these challenges, ongoing projects seek to extend water accessibility to all segments of the population.

Ocean thermal gradients present abundant energy potential, particularly in subtropical and tropical regions where temperature differentials between surface and deep ocean waters are substantial. The concept of ocean thermal energy systems, which exploit these gradients to generate power and or water, has garnered significant attention in recent decades. Research by the National Renewable Energy Laboratory (NREL) underscores the vast energy potential of ocean thermal energy, estimating that ocean thermal gradients could theoretically produce nearly 10,000 terawatt-hours of electricity annually, equivalent to over half of the current global electricity consumption [4].

Despite promising energy potential, traditional ocean thermal energy plants primarily focus on power generation, with limited attention given to addressing water scarcity challenges. The history of marine energy harvesting is replete with attempts to harness this abundant resource, predominantly through ocean thermal energy conversion (OTEC) systems. However, challenges such as cost-effectiveness and scalability have hindered widespread adoption, underscoring the need for innovative approaches that integrate energy and water production.

Our concept prioritizes water production over electricity generation. Leveraging the principle of direct contact membrane distillation (DCMD), our system utilizes ocean thermal gradients to drive desalination, offering a sustainable solution to water scarcity. The integration of DCMD facilities represents a paradigm shift, highlighting the potential to harness ocean thermal gradients for concurrent water. Figure 1 illustrates the core concept of our approach, wherein cooler deep water is pumped up to facilitate the desalination process. This water cools the fresh water permeate side of the membrane, while warmer seawater is drawn in at the surface to drive the distillation process. By maintaining a temperature differential of approximately 25℃ across the membrane, our system achieves efficient desalination.

The objectives of our project align with the pressing needs of remote island communities like American Samoa. By seamlessly integrating water production infrastructure, we aim to develop a sustainable solution that addresses water scarcity and insecurity. Through rigorous design optimization and feasibility analysis, we seek to demonstrate the viability and scalability of our approach, laying the groundwork for broader implementation in similar island contexts.

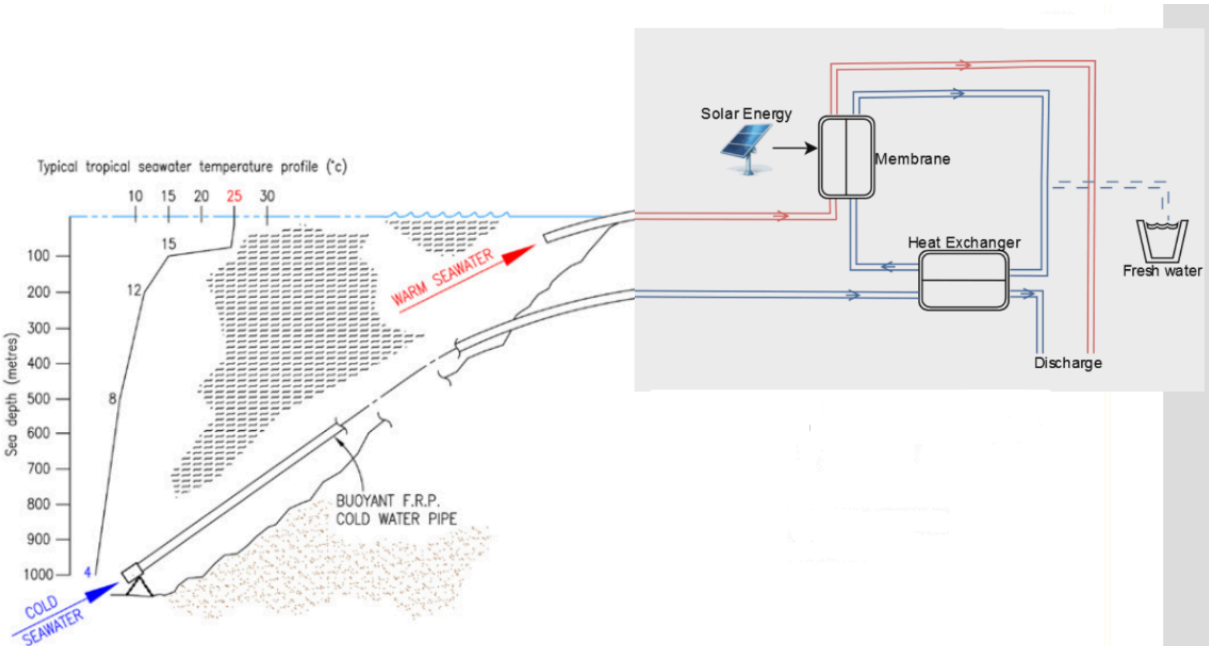


Figure 1. The process of utilizing ocean thermal gradients to drive desalination via membrane distillation. The figure demonstrates the flow of cooler deep water and warmer surface water, as well as the operation of the system to produce freshwater.

1.2. Previous Work

Oakland University was a part of MECC last year as well. The goal of our 2023 team was to improve the energy efficiency of reverse osmosis (RO) desalination by harnessing the energy of salt gradients that is available from the high concentration brine that these plants discharge into the sea. To achieve this goal a pressure retarded osmosis (PRO) process was developed for converting salt gradient energy into useful mechanical work that can be recycled back to the RO desalination plant. Reflecting on our previous project, we determined that PRO faces several challenges for commercialization. Consequently, our efforts to enhance energy efficiency in desalination through PRO encountered scalability challenges.

As a result, we pivoted our focus this year to thermal desalination using direct contact membrane distillation. In this approach, the primary energy demand lies in thermal energy. By harnessing heat from the ocean, we can substantially reduce energy expenses, bringing us closer to achieving our objectives. In addition to this, we forged relationships with numerous desalination industry experts during last year's competition through our industry connections segment. These connections proved invaluable in soliciting expert opinions on our proposed concept and fostering new collaborations this year.

The system our team is designing uses direct contact membrane distillation (DCMD) which works based on the thermal gradient of the ocean. Membrane distillation (MD) is a separation process that uses a vapor pressure difference to drive vapor permeate across a hydrophobic porous membrane. This technology is promising for desalination, as it allows for high salt and solute rejection, and is well-suited for integration with ocean thermal gradients, as it can make use of low-grade heat and operate at low temperatures. By leveraging the insulating properties of water, the system pumps hot ocean water on the surface of the ocean and cold water from ocean depths to establish the temperature gradient necessary for the distillation process. This project is an introduction to what is possible for MDas well as, awareness of

OTEC for power generation and fresh water in places such as the American Samoa. The team has been in close contact with power authorities in efforts to gain a better understanding of the current state of water and power availability so that we could raise efforts for communities with similar needs and ideal locational benefits.

2. Theory

2.1. Ocean Thermal Energy Conversion

The possibility of using ocean thermal gradients as a renewable energy source has been considered for many years. For the most part, this energy source has been considered for producing electricity in what is called an ocean thermal energy conversion (OTEC) cycle. Our system is different because it uses ocean thermal gradients to produce water by desalination instead of producing electricity, but it is still useful to learn about OTEC since it has been more commonly studied.

The concept of OTEC traces its origins to Jules Verne's novel "20,000 Leagues under the Sea," first published in France in 1869. However, it was formally proposed by French physicist Jacques Arsene D'Arsonval in 1881. The idea gained traction when French engineer and businessman Dr. Georges Claude built an OTEC open cycle plant in Matanzas Bay, Cuba, in 1930, utilizing a 22-kW generator system to illuminate a series of lamps. Despite its brief operation, the plant succumbed to destruction by a severe storm [5,6].

During the 1950s and 1960s, numerous research and development initiatives unfolded, including proposals from Energie de Mers and the Sea Water Conversion Laboratory at the University of California, Berkeley. In subsequent decades, the U.S. federal government spearheaded various R&D programs, encompassing performance evaluations, preliminary designs, and demonstration plants. Notable endeavors included the Applied Physics Laboratory's preliminary design for a 40-MWe closed cycle floating plant, heat exchanger performance tests by the Argonne National Laboratory, and the establishment of demonstration plants such as (Mini-OTEC and OTEC-1 in Hawaii)[7].

Further advancements occurred with the construction of a 100-kW closed cycle land-based plant in the Republic of Nauru by Toshiba/Tokyo Electric Power and studies conducted at the Natural Energy Laboratory of Hawaii (NELHA), culminating in the operation of a 210-kW open-cycle pilot plant for simultaneous electricity generation and potable water production [8]. Presently, the technology required for OTEC plant construction is well-established, with commercially available components and equipment commonly utilized in other applications. However, the primary obstacle to the realization of commercial OTEC plants has been economic viability.

Throughout the 1970s and 1980s, the federal government's focus on nuclear energy diverted funding away from OTEC development. Subsequently, the decline in oil prices to as low as $10 a barrel in the 1990s, coupled with limited awareness of global warming, diminished interest in OTEC and other renewable energy sources[9].

2.2. Membrane Distillation

Our proposed system uses ocean thermal gradients to desalinate water by driving a membrane distillation process. Membrane distillation (MD) is a thermal separation process that relies on a hydrophobic porous membrane to facilitate the separation of a hot feed solution (surface water) from a cold permeate solution (deep ocean water). The driving force for this separation is the vapor pressure difference created by a temperature gradient across the membrane that has a specific permeability coefficient. As shown in figure 2, Direct Contact Membrane Distillation (DCMD) is a distinct variation of

MD where the feed and permeate solutions come into direct contact with each other on opposite sides of the membrane. This direct contact enhances mass transfer, maintaining a high concentration gradient across the membrane and leading to increased vapor flux (1). The membrane's hydrophobic characteristic ensures that only vapor molecules can pass through, while liquid water and solutes are retained on the feed side and require cleaning to prevent fouling, the porous structure of the membrane selectively allows vapor molecules to permeate through. As vapor molecules pass through the membrane, they condense on the cold side to form a permeated stream containing pure solvent. This leaves behind non-volatile components in the feed solution. DCMD offers several advantages, such as high selectivity, low fouling tendency, and suitability for treating solutions with high salinity or concentration. This technology holds promise for applications such as desalination which is the main objective in this experiment.

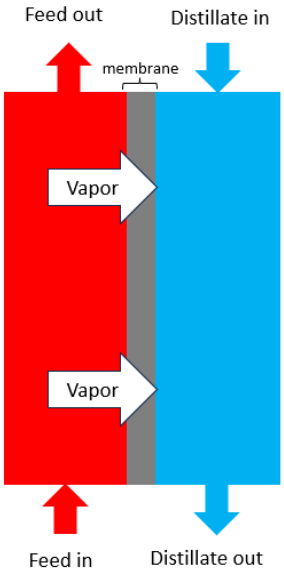


Fig 2. A schematic of DCMD system

The driving force for the membrane distillation process is the vapor pressure difference created by a temperature gradient across the membrane that has a specific permeability coefficient (figure 2). Considering different vapor pressure in both feed and permeate sides, the water flux through the membrane can be defined as follow:

$$J = K\left(p_{H2O,F} - p_{H2O,D}\right) \tag{1}$$

K denotes the permeability coefficient of membrane, $p_{H2O,F}$ and $p_{H2O,D}$ are vapor pressure at membrane feed and distillate sides. Several methodologies have been explored in the literature to achieve permeability coefficients, including a combination of Knudsen diffusion, molecular diffusion, and Poiseuille flow transition model, as well as purely Knudsen diffusion and the Monte Carlo simulation approach [1]. While the coefficient K typically varies with operating conditions such as temperature and pressure, it can be treated as a constant under certain specific conditions and specific membrane characteristics. The vapor pressure of distillate side $p_{H2O,D}$ is equal to absolute water vapor pressure p_o, which is calculated from Antoine equation as follow [2]:

$$p_{H2O,D} = p_o = e^{\left(A_o - \frac{B_o}{C_o + T}\right)} \tag{2}$$

A_o, B_o, and C_o are constants which are provided in Table 1. However, when dealing with solutions that have non-volatile solutes, like the feed flow in DCMD, the vapor pressure is not simply that of pure water. The presence of solutes lowers the vapor pressure which can be represented as follow [2]:

$$p_{H2O,F} = p_o \, exp\left(\frac{V_m}{R\,T}(p - \pi)\right) \tag{3}$$

Here V_m, R, and π denotes the molar volume of water, universal gas constant, and osmotic pressure respectively.

In addition to the applied pressure on the feed side, osmotic pressure arises due to the salinity of the feed stream. This osmotic pressure can be calculated as follow:

$$\pi = i\,R\,T\,c \tag{4}$$

Where i is Vant Hoff coefficient, R is universal gas constant, and c shows the concentration.

The energy required for running membrane distillation systems can be supplied by various sources. The choice of heat source can significantly affect the system's overall efficiency, cost, and environmental impact. Common sources of thermal energy for running DCMD systems include the waste heat coming from industrial processes, power plants etc., solar energy, geothermal energy, and ocean thermal energy.

Ocean thermal energy, as a consistent and abundant form of marine renewable energy, is a promising source for driving sustainable desalination systems specifically on remote islands. However, the limited temperature difference is a challenge to its standalone application. Considering this, we propose a hybrid distillation desalination system energized by both solar and ocean thermal sources. This system is designed to mitigate the limitations of solar desalination systems, which are prone to operational disruptions during nighttime, while enhancing overall productivity.

To determine the power required to pump cold seawater to the surface, we can use equations (5), where $\dot{V}$ represents the volumetric flow rate of the water and Δp is the pressure difference calculated from equation (6). This equation calculates the mechanical power necessary to overcome the pressure difference and transport the volume of water needed for the cooling process.

The pressure at a certain depth in the ocean can be calculated using the equation (6), where Δp is the pressure difference, ρ is the density of seawater, g is the gravity acceleration, and Δh is the depth difference. This equation provides the increase in hydrostatic pressure experienced with depth, which is critical for understanding the forces operating in deep sea conditions.

$$P = \frac{\dot{V}\,\Delta p}{\eta_p} \tag{5}$$

$$\Delta p = \rho g \Delta h \tag{6}$$

Table 1 presents the constants and inputs essential for the modeling of the membrane distillation system. It specifies the Van't Hoff factor i utilized for osmotic pressure calculations, the universal gas constant R, and the Antoine constants (A_o, B_o, C_o) for determining the vapor pressure of water. These parameters are critical for analyzing and predicting the performance of membrane distillation processes under various operational conditions.

Table 1: Baseline conditions and constants

Number of ions i	2
Gas constant R	8.314 J/mol/K
Pressure p	100 kPa
Membrane permeability K	3.52×10^{-6} g/s/m²/Pa
Feed temperature T_F	25 °C
Distillate temperature T_D	5 °C
Feed concentration c_F	35 g/l
Distillate concentration c_D	0
Pump efficiency η_p	85 %
Antoine constant A_o	16.3872
Antoine constant B_o	3885.7
Antoine constant C_o	230.17

3. Results

In the present section, we elucidate the outcomes of a theoretical model that simulates the performance of a membrane distillation system which is integrated with an ocean thermal energy gradient source. A theoretical sensitivity analysis has been conducted to discern the factors that most significantly influence the vapor pressure difference and permeate flux as the most important parameters. Figure 3 illustrates the increasing vapor pressure difference with feed temperature. The vapor pressure difference is typically driven by the temperature difference between the hot feed and the cold permeate. As the feed temperature increases, the vapor pressure on the feed side of the membrane increases according to the Clausius-Clapeyron relation, enhancing the driving force for mass transfer through the membrane.

In American Samoa, the temperatures are typically warm throughout the year due to its tropical marine climate. The average temperature usually ranges from about 23°C (73°F) at night to about 30°C (86°F) during the day. This relatively stable temperature range is maintained by the surrounding Pacific Ocean, which helps to moderate extreme temperature fluctuations. Regarding high dependency of DCMD system to temperature gradient of feed and permeate the more temperature difference, lead to more vapor pressure difference and subsequently more flux. Using solar radiation to increase feed temperatures in DCMD systems could enhance efficiency and reduce energy costs. Solar collectors absorb sunlight, heating a transfer fluid to elevate the system's initial temperature. This process decreases the need for additional energy, aligning with sustainability goals by lowering reliance on non-renewable resources and reducing greenhouse gas emissions. Such integration is especially beneficial in remote locations with high solar potential, promoting ecological and economic sustainability.

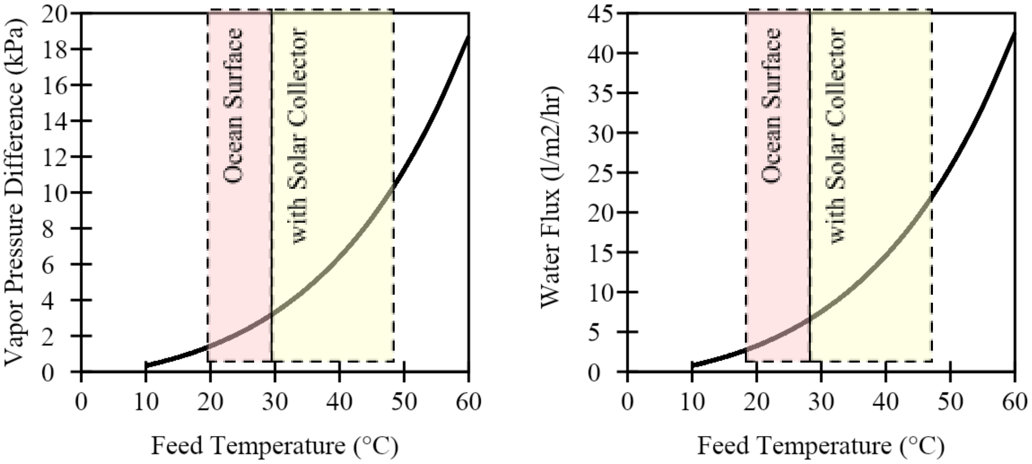


Figure 3. Variation of a) vapor pressure difference and b) water flux with feed temperature. Results are based on default baseline conditions from Table 1.

The effect of decreasing temperature of distillate side on vapor pressure difference is shown in Figure 4a. It can be seen that decreasing permeate temperature led to increasing vapor pressure difference which is around 25% higher from 10 to 5 °C. Figure 4b illustrates the decrease in temperature with ocean temperature with depth. Up to a depth of 1000 m, there is a significant drop in temperature, decreasing from about 22 °C at the surface to 4.9 °C at 1160 m. Beyond this depth, the rate of temperature decrease slows considerably. Over the next 1000 m, the temperature decreases by only 0.8 °C. Figure 4c depicts the variation in vapor pressure difference with depth. This figure highlights the significant changes in vapor pressure difference up to a depth of 1100 m, where it jumps from 1.8 to 2.2. However, at greater depths, the changes in vapor pressure difference are less pronounced. Indeed, to achieve a slightly higher vapor pressure difference, one would need to reach a depth of approximately 4000 m which is not considered worthwhile.

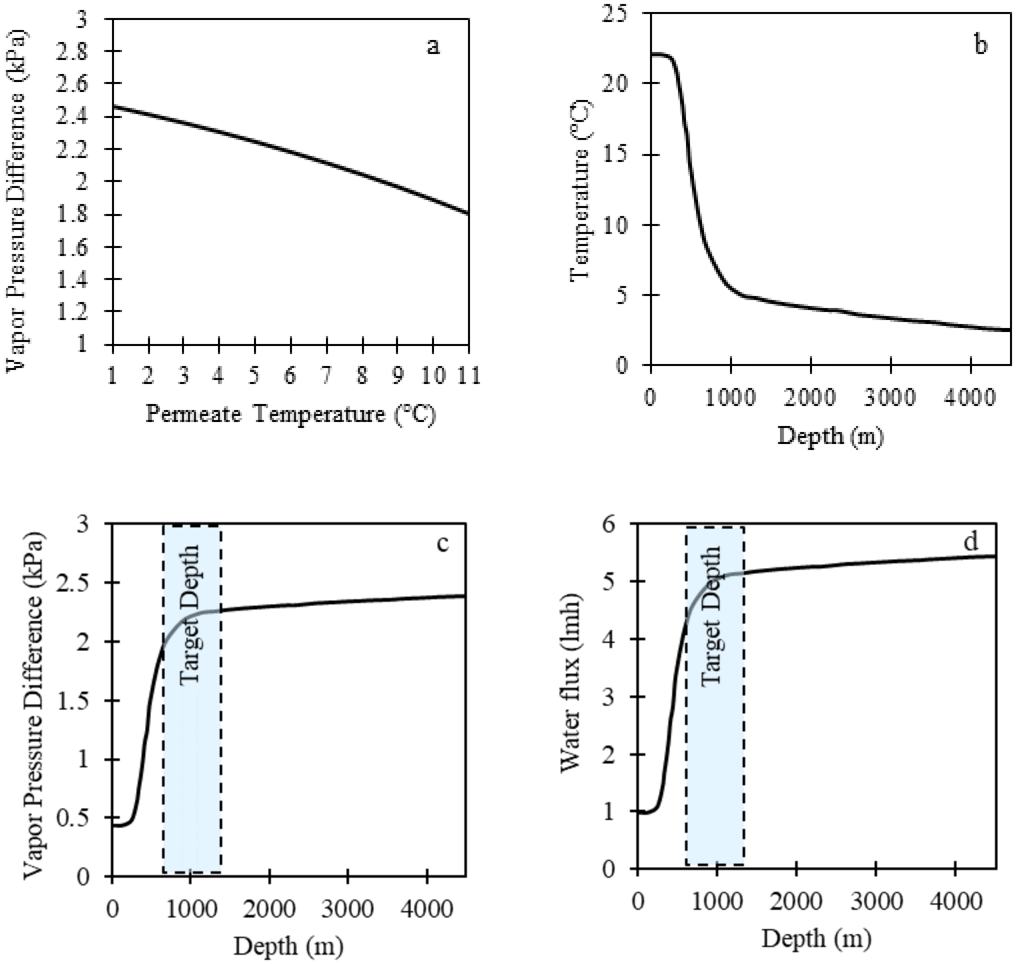


Figure 4. a) the effect of permeate temperature on vapor pressure difference b) variation of ocean temperature with depth c) variation of created vapor pressure difference versus ocean depth. Results are based on default baseline conditions from Table 1.

Increasing the depth is associated with higher power costs and increased energy consumption. As shown in Figure 5a, the suction head of the pump increases with depth, which subsequently increases the power consumed, as depicted in Figure 5b.

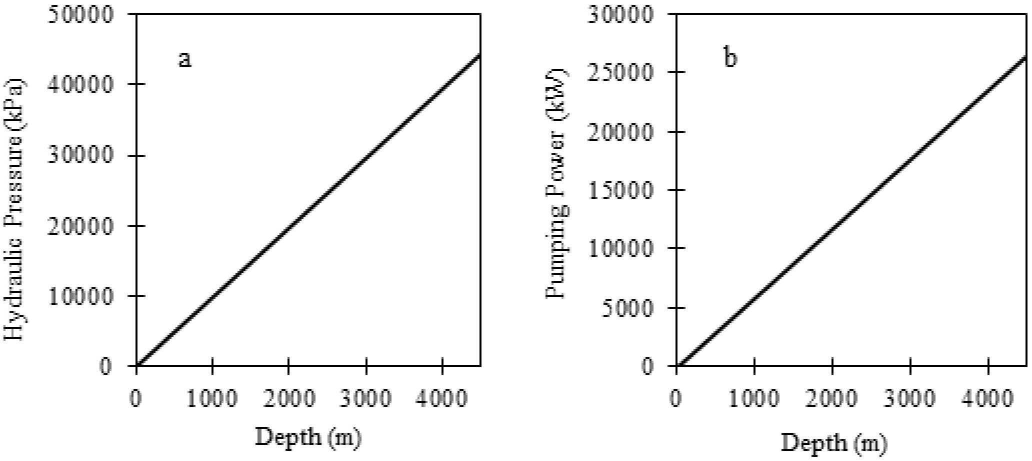


Figure 5. The variation of a) hydraulic pressure b) pumping power. Results are based on default input parameters from Table 1.

The impact of concentration on the feed side was investigated, as shown in Figure 6a. Increasing the feed concentration leads to decreasing vapor pressure difference mainly due to the effects of boiling point elevation and concentration polarization. A higher concentration of solutes in the feed reduces its vapor pressure, which decreases the driving force across the membrane that's essential for distillation. This phenomenon, known as boiling point elevation, directly diminishes the vapor pressure differential, which is the core driving mechanism in DCMD. Concurrently, concentration polarization causes a layer of concentrated solution to form at the membrane surface, further decreasing the effective vapor pressure and creating additional mass transfer resistance. These effects are compounded by increased viscosity and the potential for fouling as solute concentrations rise, both of which impede the flow of vapor through the membrane, thus reducing the overall permeate flux in the system.

Figure 6b depicts how the vapor pressure difference decreases as the recovery ratio increases. Initially, the vapor pressure difference is almost stable, indicating consistent driving force for distillation. As the recovery ratio reaches its maximum, the curve drops, showing a sharp decline in driving force. This drop can be related to several limiting factors such as temperature and concentration polarization, which suppress the vapor pressure difference and, therefore, the efficiency of water vapor transport through the membrane. This trend highlights the existence of an optimal recovery ratio, beyond which the efficiency of the system is compromised. In our survey, we are working with a recovery ratio of 0.5, which corresponds to a vapor pressure difference of 2.18 kPa.

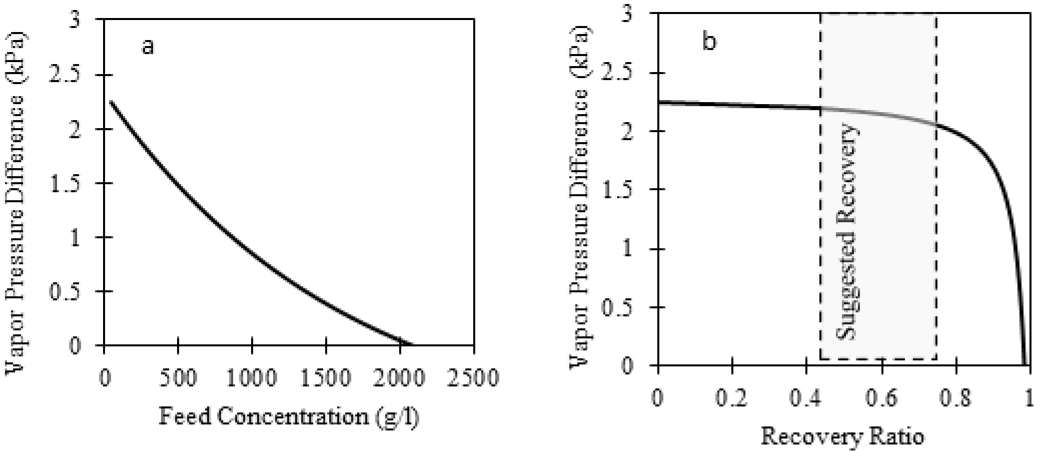


Figure 6. The effect of a) feed concentration and b) recovery ratio, on vapor pressure difference.

4. Discussion

4.1. Application to Remote Island Communities

American Samoa was selected as an ideal location for implementing Ocean Thermal Energy for desalination efforts due to its tropical climate and proximity to a deep-water shelf within 3 km, allowing for the establishment of an onshore desalination plant. This choice eliminates the need for offshore mooring systems and long power cables, reducing installation and maintenance costs [10]. Figure 7 presents data taken from 2019 that shows data taken near American Samoa. This data represents the different thermal gradients within the ocean compared to the depth.

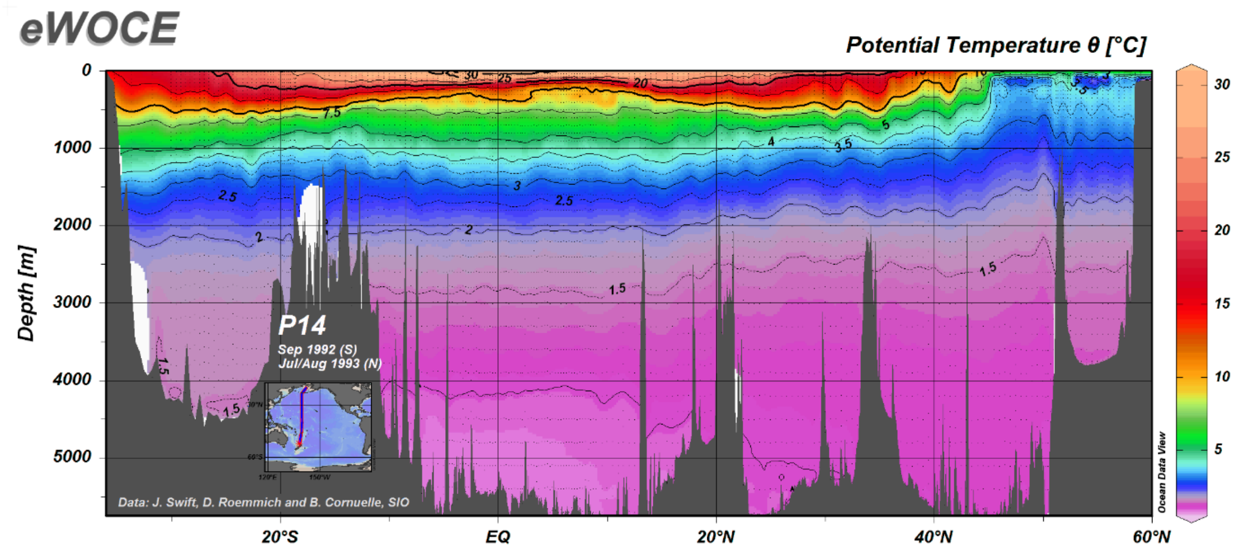


Figure 7. Temperature contour map with depth and location[20]

There was an extensive number of interviews that the team went through to get in contact with people that we thought fit the criteria for this technology. Mainly, we were able to get in direct contact with Katrina Mariner: Water and Wells System Engineer American Samoa Power Authority. She stated that groundwater is 99% of their water source through drilling into the ground. It is feasible so far but 70% of this water is lost in the process due to leaks. This process is also costly due because waterline connection projects and new water utility infrastructure implementation is approaching. There are ongoing projects to get everybody on the main island as well as a push for cheaper electricity costs which currently range from 0.05 to 0.45 USD/kWh [13] . Water that is already treated is very expensive to get as well as electricity. This needs to be shipped or flown over, which takes time and money and is considered to be unreliable and variable just like trying to harvest rain water to drink. When it rains the water gets murky and it makes it hard to harvest and drill.

The team conducted extensive interviews to identify suitable candidates for implementing a new technology, ultimately connecting with Katrina Mariner, a Water and Wells System Engineer at ASPA. Mariner revealed that groundwater accounts for 99% of their water source, extracted through drilling into the ground. However, a significant portion of this water, about 70%, is lost due to leaks in the system, making the process costly. The region is facing challenges with ongoing waterline connection projects and the implementation of new water utility infrastructure, especially on the main island. Additionally, there's a push to reduce electricity costs, which currently contribute to the high expense of treated water. Importing treated water and electricity from elsewhere is expensive, unreliable, and subject to variability, mirroring the challenges faced in attempting to harvest rainwater due to its murky quality after rainfall.

Mariner, with a background in environmental marine engineering and a decade-long tenure at ASPA, is on course for new projects to install a desalination plant on a small island with a population of only 500 residents. The island currently relies on two wells for water, but during high tides, the water turns brackish, and during dry spells, the well water becomes salty. Although rainwater harvesting was considered, its unreliability led to the decision to pursue desalination for its consistency and reliability. While exploring renewable energy options to fund the desalination project, logistical challenges remain for implementing renewable energy on other islands due to staffing constraints. However, plans are underway to train personnel within the next 2-3 years. Currently, the desalination project is in the pilot phase, aiming to provide a sustainable water source for the island's residents amidst challenges posed by existing water infrastructure and resource availability.

The selected market analysis delves into a specific geographical region characterized by consistent temperature differentials throughout the year, 1000 meters below the surface. Notably, the American Samoa region stands out, with its proximity to such conditions, as it spans a distance of 3 kilometers. This choice was deliberate, considering American Samoa's status as a U.S. territory and its substantial energy potential, estimated at 1300 TWh [14]. Additionally, the American Samoa Renewable Energy Committee (ASREC) has set ambitious targets, aiming for 50% renewable energy by 2025 and complete reliance on renewable sources by 2040 to fulfill all energy requirements. The significant poverty rate in American Samoa, currently at 60%, further underscores the urgency for sustainable energy solutions tailored to the region's unique advantages. Given these factors, the viability of a technology capable of harnessing energy from the specific environmental conditions present in American Samoa emerges as a logical market choice.

4.2. Load Requirements and Storage Capacity

The proposed design incorporates a storage component depicted in Figure 1, where the desalinated water is stored for future use. This storage unit serves as a pivotal aspect of the system, facilitating accessibility and usability of the desalinated water for various applications. By integrating a watering system, the stored water becomes readily available to civilians in need, enhancing its practicality and usefulness in addressing water scarcity challenges. Furthermore, the inclusion of this storage system offers several compelling advantages. Firstly, it enables the long-term preservation and utilization of desalinated water, ensuring a sustainable and reliable water supply even during prolonged periods of drought or water scarcity. Moreover, the storage system provides a vital resource reserve that can be mobilized swiftly in response to emergencies, such as natural disasters or infrastructure failures. Additionally, the storage component offers versatility in water management, allowing for strategic distribution and allocation of desalinated water resources based on fluctuating demand patterns or specific needs. This adaptability enhances the system's resilience and responsiveness to dynamic water supply challenges, ensuring optimal utilization of available resources.

The cold water pipes (CWP) represent a critical component in OTEC and MD systems, posing significant challenges due to internal flow stability and the risk of pipe failure. Historically, numerous OTEC installations have encountered issues with CWPs, leading to project failures and abandonment, as evidenced by cases like Rio de Janeiro in 1935 and India in 2003 [15,16]. These failures underscore the complexity and importance of ensuring the reliability of CWPs in OTEC projects. Additionally, cost estimates reveal that CWPs alone can account for a substantial portion, approximately 15-20%, of total capital costs for OTEC installations, as highlighted by[17]. It is worth noting that these estimates are based on installations within the United States; however, implementation in locations like American Samoa may incur even higher cost percentages, further emphasizing the financial challenges associated with CWP procurement and installation for ocean thermal energy techniques.

For a land-based OTEC plant with a power output of around 2.5 MW, a cooling water pipe (CWP) with a diameter of approximately 2.5 meters, typically made of High-Density Polyethylene (HDPE), is required [10]. This size is readily available from suppliers and has been utilized in projects such as the seawater intake pipe for the Ras Djinet Gas Turbine Combined Cycle power plant in Algeria Figure 8 . Practical considerations, such as installation costs and the availability of local resources like tugboats and crane vessels, often dictate the maximum diameter of the CWP. While larger pipes could be installed, they would require more sophisticated techniques and potentially costly vessels from outside the local area. Despite the challenges, a 2.5 MW OTEC plant can serve as a valuable baseload power source for many Small Island Developing States (SIDS). However, justifying the relatively high initial investment, particularly for seawater systems, can be difficult for such small-scale projects. Fortunately, apart from the seawater intake systems, the rest of the equipment required for a 2.5 MW OTEC system is conventional and should be reliable, as demonstrated in previous installations in Hawaii and Kumejima. Engagement with industry stakeholders underscores the importance of providing feed-in tariffs for electricity and fresh water generated through OTEC to enhance the attractiveness of these projects to commercial investors.

Figure 8. Concrete collars on a 2.5m water intake pipeline,

Ras Djinet Gas Turbine Power Plant, Algeria[10]

4.3. Safety and Environmental Considerations

MD offers several key advantages for sustainable water production. Firstly, it operates without consuming fuel, making it highly sustainable over the long term. Additionally, MD does not produce conventional air pollutants, particulates, or solid wastes, thereby contributing to a cleaner environment. The discharge of seawater post-MD operation closely resembles ambient water, minimizing ecological disturbances. Furthermore, MD emits negligible amounts of carbon dioxide, aligning with global efforts to combat climate change [10].

Despite these benefits, it is important to address potential environmental impacts associated with an on shore desalination plant. [19] focuses on understanding the effects of releasing deep seawater on local phytoplankton communities. This research underscores the need to determine an optimal discharge depth that avoids harming surface-dwelling phytoplankton, which are crucial components of marine ecosystems. Traditionally, the goal is to release water at a temperature and elevation that prevents nutrient-rich deep water from reaching the surface, thereby minimizing the risk of algal blooms and other disruptions [19].

However, there remains a lack of established guidelines for mitigating these environmental impacts, particularly in the context of emerging technologies like OTEC and MD. Further research is essential to develop comprehensive strategies for managing the discharge of deep seawater from these types of plants. Specifically, future studies should focus on how these could be used to benefit local marine life.

4.4. Membrane Limitations

The driving force for mass transfer is the partial vapor-pressure difference across the membrane. Pore size, material, temperature and thickness are all major proponents that take part in the mass transfer for membrane distillation. In membrane distillation (MD), the driving force for mass transfer lies in the partial vapor-pressure difference across the membrane [11]. Several factors play crucial roles in facilitating mass transfer, including pore size, material composition, temperature, and membrane thickness. Direct Contact Membrane Distillation (DCMD) operates continuously as a baseload technology. However, there are concerns regarding the long-term performance of the membrane. Continuous efforts are underway to enhance flux capability and address long-term effects on the membrane. These efforts aim to reduce costs and maintenance requirements for scale-up versions and commercial deployment.

MD is influenced by feed temperature, with the flux being greatly affected by temperature. While MD systems can operate at lower temperatures compared to other thermal desalination processes, higher temperatures generally result in greater flux. optimizing the feed temperature within the operational limits of the membrane and heat source can significantly enhance the performance and efficiency of the MD system, ultimately improving desalination output and reducing energy consumption.

4.5. Temperature Considerations

When operating with flat sheet membranes like those from Sterlitech [18] with temperature and pressure limitations of 200℃ and 45 psi respectively, we found the pressure threshold was not a concern at our standard atmospheric pressure. However, although the temperature ranges we worked within didn't come close to the limit, it is essential to recognize potential issues if those limits were exceeded. Surpassing the temperature threshold could trigger a cascade of problems. Thermal degradation becomes a primary worry as the membrane material may degrade, compromising its structure and lifespan. Additionally, there's a risk of pore enlargement, altering filtration characteristics and reducing effectiveness. Elevated temperatures can worsen membrane fouling, requiring more frequent maintenance. Selectivity might decrease, allowing undesired substances to pass, and structural damage such as warping or cracking may manifest. Chemical reactions could also occur, further impairing membrane function and possibly releasing harmful byproducts.

5. Conclusions

The theoretical model presented in this study provides insights into integrating membrane distillation with ocean thermal energy gradients. Leveraging solar radiation to elevate feed temperatures in DCMD systems shows promise for enhancing efficiency and reducing energy costs, particularly in regions like American Samoa with stable tropical climates. However, accessing deeper, colder ocean waters must be carefully considered due to increased power costs. The study underscores the influence of feed concentration and recovery ratio on vapor pressure difference and permeate flux, emphasizing the need for optimization. Overall, integrating membrane distillation with ocean thermal energy gradients offers a pathway to address water scarcity, but further refinement and research are essential for sustainable desalination solutions and advancing global water security agendas. The integration of Ocean Thermal Energy Conversion (OTEC) and membrane distillation (MD) presents a promising solution for addressing water scarcity challenges in regions like American Samoa. Leveraging the stable tropical climate and proximity to deep-water shelves, onshore desalination plants can be established, reducing installation costs and logistical complexities. Interviews with local experts, such as Katrina Mariner, highlight the urgent need for sustainable water solutions amidst existing infrastructure challenges. While OTEC offers potential as a baseload power source, challenges with cooling water pipes (CWPs) and financial viability persist. Storage components play a crucial role in ensuring water availability and resilience, while considerations for safety, environmental impacts, and membrane limitations underscore the need for comprehensive research and optimization. By addressing these factors, OTEC-MD integration can contribute to sustainable development and resilience in island communities facing water scarcity.

6. References

[1] The World Bank, “World Bank Group - International Development, Poverty, & Sustainability,” World Bank, 2024. https://www.worldbank.org/en/home 18

[2]“American Samoa Poverty Rate 1960-2024,” www.macrotrends.net. https://www.macrotrends.net/global-metrics/countries/ASM/american-samoa/poverty-rate (accessed May 02, 2024).

[3] M. K. Mariner, “American Samoa Power Authority,” Apr. 2024.

[4] C. Turchi, S. Akar, T. Cath, J. Vanneste, and M. Geza, “Use of Low-Temperature Geothermal Energy for Desalination in the Western United States,” 2015. Available: https://www.nrel.gov/docs/fy16osti/65277.pdf

[5] Brown, M.G. Gauthier, M. Meurville, J-M. 2002. George Claude’s Cuban OTEC Experiment: a Lesson of Tenacity for Entrepreneurs. IOA Newsletter. Winter.

[6] Claude, G. 1930. Power from the Tropical Seas. Mechanical Engineering. Volume 52. No.12. December.

[7] T. Plocek, M. Laboy, and J. Marti, “Ocean Thermal Energy Conversion (OTEC): Technical Viability, Cost Projections and Development Strategies,” Proceedings of Offshore Technology Conference, May 2009, doi: https://doi.org/10.4043/otc-19979-ms.

[8] Daniel, T. 1999. A Brief History of OTEC Research at NELHA. Natural Energy Laboratory of Hawaii.

[9] Avery, W.H. Wu, C. 1994. Renewable Energy from the Ocean, A Guide to OTEC. Oxford University Press. New York, NY.

[10] LEA, “WHITE PAPER OCEAN THERMAL ENERGY CONVERSION OTEC 2O21,” 2021. Accessed: Jun. 22, 2023. [Online]. Available: https://tethys-engineering.pnnl.gov/sites/default/files/publications/oes-white-paper-on-otec.pdf

[11] C. Turchi, S. Akar, T. Cath, J. Vanneste, and M. Geza, “Use of Low-Temperature Geothermal Energy for Desalination in the Western United States,” 2015. Available: https://www.nrel.gov/docs/fy16osti/65277.pdf

[12] Z. Kuang, R. Long, Z. Liu, and W. Liu, “Analysis of temperature and concentration polarizations for performance improvement in direct contact membrane distillation,” International Journal of Heat and Mass Transfer, vol. 145, no. 145, p. 118724, Dec. 2019, doi: https://doi.org/10.1016/j.ijheatmasstransfer.2019.118724.

[13] Lazaros Aresti, P. Christodoulides, Constantine Michailides, and Toula Onoufriou, “Reviewing the energy, environment, and economy prospects of Ocean Thermal Energy Conversion (OTEC) systems,” Sustainable Energy Technologies and Assessments, vol. 60, no. 60, pp. 103459–103459, Dec. 2023, doi: https://doi.org/10.1016/j.seta.2023.103459.

[14] L. Kilcher, M. Fogarty, and M. Lawson, "Marine Energy in the United States: An Overview of Opportunities," National Renewable Energy Laboratory, Technical Report, NREL/TP-5700-78773, February 2021. [Online]. Available: https://www.nrel.gov/docs/fy21osti/78773.pdf

[15] L. A. Vega, "Ocean thermal energy conversion," in Encyclopedia of Sustainability Science and Technology, R. A. Meyers (Ed.), vol. 6, Springer, New York, 2012, pp. 7296–7328. 19

[16] A. Miller and M. Ascari, "OTEC advanced composite cold water pipe: final technical report," 2011. [Online]. Available: https://www.osti.gov/biblio/1024183. (Accessed: 10 March 2019).

[17] L. Martel, P. Smith, S. Rizea, et al., "Ocean thermal energy conversion life cycle cost assessment: final technical report," 2012. [Online]. Available: https://www.osti.gov/servlets/purl/1045340. (Accessed: 10 March 2019).

[18] Sterlitech.com, 2024. https://www.sterlitech.com/membrane-distillation-md.html (accessed May 03, 2024).

[19] Giraud, Mélanie, et al. “Potential Effects of Deep Seawater Discharge by an Ocean Thermal Energy Conversion Plant on the Marine Microorganisms in Oligotrophic Waters.” Science of the Total Environment, vol. 693, Nov. 2019, p. 133491, https://doi.org/10.1016/j.scitotenv.2019.07.297. Accessed 27 May 2022.

[20] “eWOCE Gallery - Pacific,” www.ewoce.org. https://www.ewoce.org/gallery/Map_Pacific.html (accessed May 06, 2024).

Business Plan Challenge

1. Introduction

1.1. Background

Remote islands like the Commonwealth of the Northern Mariana Islands often struggle from water insecurity due to inconsistent water infrastructures [1]. In fact, the Northern Mariana Islands only recently started providing 24-hour access to fresh water to residents on the territory's three main islands [1]. Many islands are dependent on groundwater for freshwater, and islands like Hawaii struggle to adapt during droughts [2]. Climate change has further exacerbated water insecurity, as rising ocean levels mix with freshwater rivers and lakes, causing the water to become brackish [3].

Furthermore, remote islands have incredibly high energy costs, often as much as triple or quadruple the average energy costs of the fifty U.S. states [4,5]. Water insecurity and energy volatility led us to develop a system that could be completely self-sufficient using renewable energy, while also producing fresh water without being negatively impacted by droughts and climate change.

1.2. Ocean Thermal Energy

According to The National Renewable Energy Laboratory, "Marine energy [includes] power generated from ocean waves, currents, tides, and temperature changes [and] is the world's largest untapped renewable energy resource" [6]. Our system uses thermal energy from the ocean to desalinate water, which is an unexplored area of marine energy. The main development in ocean thermal energy comes from research in Ocean Thermal Energy Conversion (OTEC) which refers to the energy created by harnessing the temperature difference between warm surface water and cold water of the deep ocean [7]. Even though our system is different from OTEC, both technologies use the ocean's thermal gradient and OTEC research has created the foundation for the work that we have done.

The ocean depth benchmark for a large enough thermal gradient to be feasible is typically seen as one thousand meters in depth [7]. Ocean thermal energy is appealing because there is always a temperature gradient in the ocean regardless of the time of day and it is always available (in hot climates) unlike wave and wind energy [8].

Ocean thermal energy has conceptually existed since the 1880's, but increased investment did not begin until the 1970's [9]. To this day, the largest plant – which is in Hawaii – has an output of one hundred kW, which is only capable of powering one hundred and twenty homes [10]. Despite few plants being built, thermal energy is shown to have some of the highest energy potential, particularly in Island Territories like American Samoa, which was found to have the potential to meet thirty-two percent of the total energy needs of all fifty U.S. states [11].

1.3. Membrane Distillation

Since ocean thermal energy has yet to be profited from, there are lots of gaps in current research. One important gap is the coupling of ocean thermal energy with other technologies, including desalination. Desalination expands remote island's water sources to the entire ocean, effectively eradicating a dependency on rainwater. There are many methods to desalinate water, but one of the most common is Direct Contact Membrane Distillation (DCMD). In the context of our project, DCMD consists of heating up water, so it can travel across a membrane as water vapor thus separating the fresh water from the salt [12]. Fresh water is already a byproduct of some ocean thermal energy systems, but by pairing ocean thermal energy with DCMD we can focus solely on desalination as opposed to energy generation [13].

The fresh water produced by our system must be competitively priced, but high current energy and water costs in remote islands make it easier for our technology to compete [3].

1.4. Project Objectives

Our overall objective is to assess the feasibility of ocean thermal energy powered desalination. As an extension of this objective, we aim to promote marine energy research and connect with industry professionals including end users, to ensure that we develop a robust foundation for the continuation of our research.

1.5. Concept Overview

Figure 1 represents the theoretical foundation for our system. The sun is what drives the thermal gradient in the ocean, and will additionally be harnessed to increase the delta temperature. This concept was only explored in our theoretical design, as after continued funding, we will begin running testing that accounts for a solar input, and will run economic analysis to maximize the efficiency of our project.

The pump is responsible for pumping the hot surface water (the feed side) into the membrane. Signified below the feed side is the permeate which has a blue arrow. The permeate is a closed loop, which means that it will be pumping the same working fluid (which will be water) through the membrane and down into a heat exchanger where it is continually cooled by the deep ocean water and then brought back up into the membrane. The deep ocean water will be continually pumped from 1000 meters in depth. The pumps will be battery powered and the process will yield a product of salt and other minerals separated during the desalination process (signified by the concentrate). To summarize, this process yields fresh water and separated minerals, both of which can be monetized.

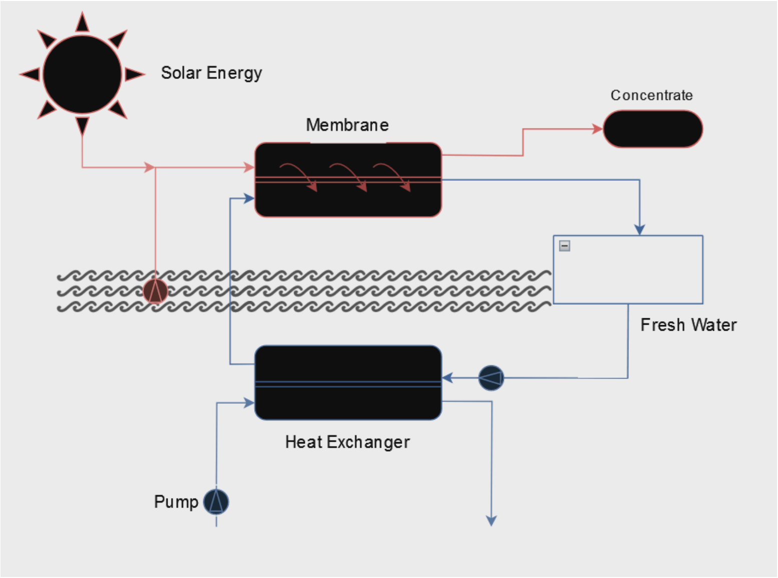


Figure 1: Schematic of DCMD powered by Solar and Ocean Thermal Energy.

1.6. Lessons from the 2023 MECC

Oakland University also competed in MECC in 2023. The goal of our 2023 team was to improve the energy efficiency of Reverse Osmosis (RO) desalination by harnessing the energy of salt gradients that is available from the high concentration brine that these plants discharge into the sea. To achieve this goal, a pressure retarded osmosis (PRO) process was developed for converting salt gradient energy into useful mechanical work that can be recycled back to the RO desalination plant. Reflecting on our previous project, we determined that PRO faces significant challenges for commercialization. Consequently, our efforts to enhance energy efficiency in desalination through PRO encountered scalability challenges. As a result, we pivoted our focus to thermal desalination using direct contact membrane distillation. In this approach, the primary energy demand lies in thermal energy. By harnessing heat from the ocean, we can substantially reduce energy expenses, bringing us closer to achieving our objectives.

In addition to this, we forged relationships with numerous desalination industry experts during last year's competition through our industry connections segment. These connections proved invaluable in soliciting expert opinions on our proposed concept and fostering new collaborations this year. The 2023 team conducted thorough literature reviews on the levelized cost of water across various desalination technologies. This groundwork laid the foundation for this year's business model, allowing us to further expand their analysis of our proposed OTED system.

1.7. Vision & Business Model

The foundation for our path towards profitability relies on the strategic maximization of all end products. Our system will yield freshwater which has both residential and industrial applications. Products such as bottled water clash with our core value of sustainability, so we will not be monetizing single-use plastics. Additionally, the sale of salt and mineral concentrates and potential usage of the salt gradient in the brine produced will help increase efficiency and cost effectiveness, to make the path towards profitability easier. Additionally, while our system focuses solely on the pairing of ocean thermal energy with DCMD to produce fresh water, the usage of ocean thermal energy has potential in power generation and air conditioning. This highlights the potential for islands, like American Samoa, to become energy exporters, creating a brand new industry to drive revenue in the region.

Our project provides financial, social, and environmental value to American Samoa. The financial value comes from our financing approach, which takes on no debt, and instead focuses solely on government subsidies and private equity. Our interview with Katrina Mariner from ASPA (referenced later) highlighted the impact of the brain drain on the American Samoa economy. This phenomenon refers to the migration of individuals pursuing higher degrees outside of American Samoa, which perpetuates scarce specialized job opportunities and the development of industry. Our system helps to drive revenue to American Samoa to help break this cycle. Environmentally, our technology facilitates the success of American Samoa in meeting its internal sustainability goals and replacing a groundwater system that Katrina Mariner believed was not sustainable.

2. Market Opportunity

2.1. Identifying a Need

First, we started our analysis by assessing all potential U.S. locations. Of course, this immediately removes landlocked states, leaving potential locations as either coastal states or U.S territories. California immediately stood out as a potential coastal state, with San Francisco and San Diego having the highest and second highest tap water costs respectively out of any U.S. city (within the fifty states) [14]. Both these cities are also on the coast, making the ocean readily accessible. Florida was also identified as having potential due to a Makai report that had laid the theoretical foundation for an OTEC plant in Florida [7].

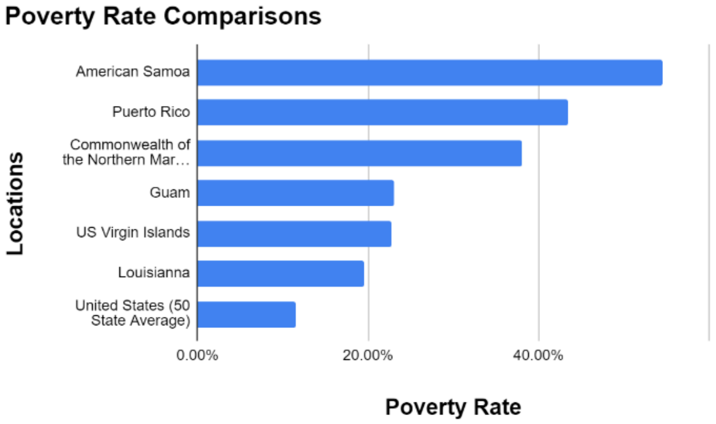


Figure 2: Comparison of Poverty Rates in U.S. Territories [15-20]

With this initial digging, we decided to start investigating high success indicators that help to differentiate ideal locations. Locations were first evaluated on a need-based criteria. Poverty rates were then selected as our first indicator for need. As our team's name suggests (Me & yOU), Diversity, Equity, and Inclusion must be integrated at every step of our project, and our technology has a greater potential to help more people in impoverished areas. Florida and California both have a slightly higher than average poverty rate (for U.S. States), with Florida having the eighteenth highest poverty rate at 13.2% and California having the twenty third highest poverty rate at 12.3%, but further investigation revealed that every U.S. territory had a poverty rate exceeding Louisiana's nation-leading poverty rate of 19.5% [15–19]. As can be seen on Figure 2, American Samoa had the highest poverty rate by far at 54.6%, with the next highest being Puerto Rico at 43% [17, 20].

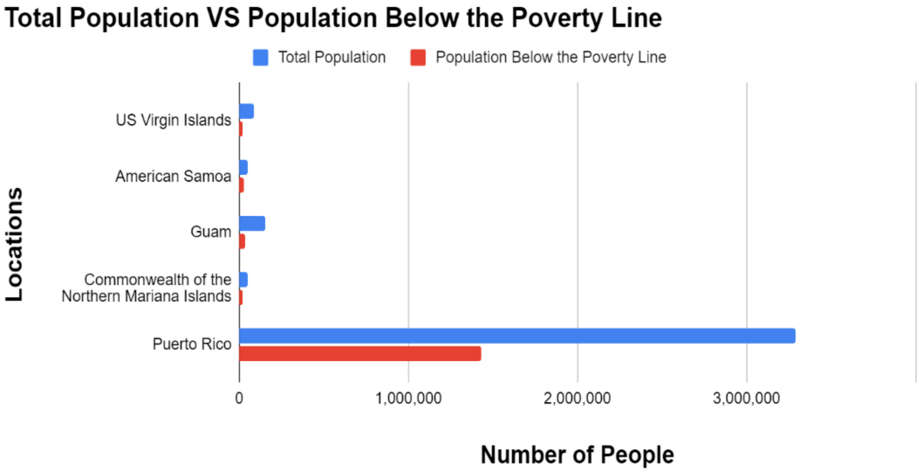


Figure 3: A Comparison of the Amount of People Below the Poverty Line in U.S. Territories [20-22]

Figure 3 highlights Puerto Rico as having the largest overall impoverished population, which is boosted by their total population which is twenty-one times larger than every other U.S. territory [21, 22]. Additionally, the vast majority of the populations of Puerto Rico, along with Guam, and the Northern Mariana Islands live on one island [20,21]. This is in direct contrast to the Virgin Islands where their population is significantly more spread out [21]. While we want our technology to support some of the territories' most impoverished nations, it is important that we still select a location large enough to benefit from economies of scale.

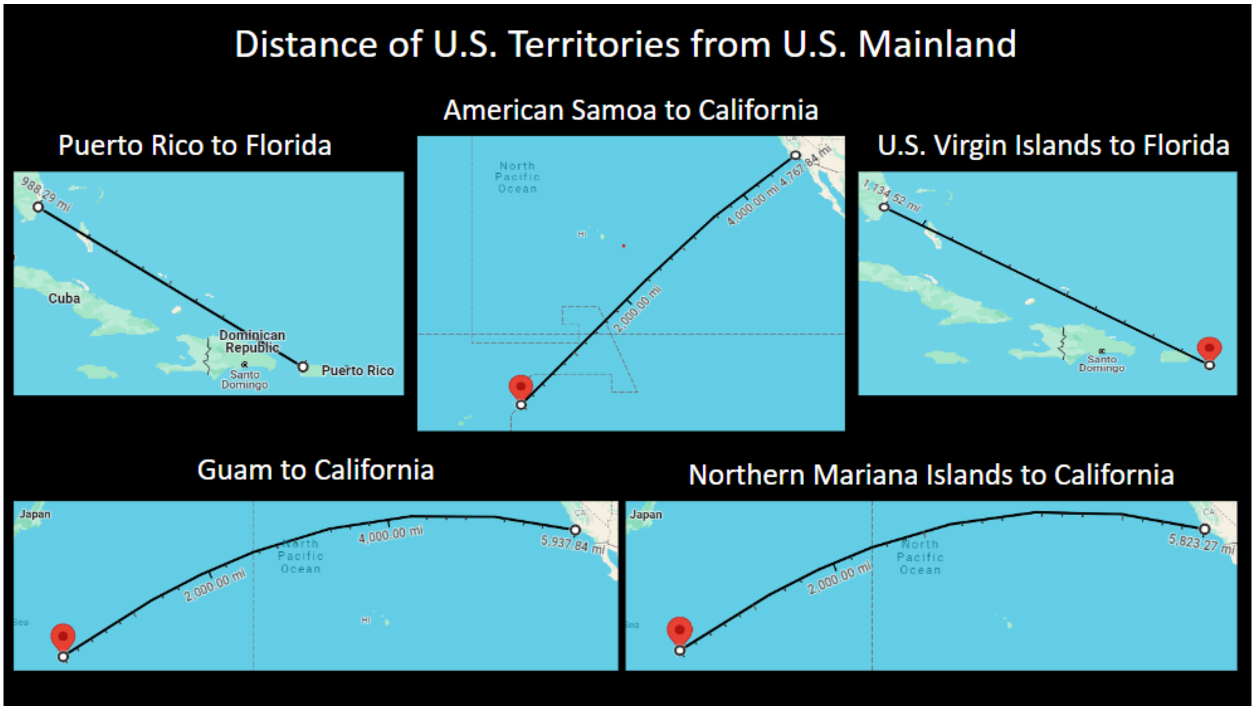


Figure 4: The Geographical Representation of the Distance between U.S. Territories and the U.S. mainland [23-27]

While considering poverty rate, we also assessed proximity to the U.S. mainland, as closer territories lead to decreased transportation costs, in addition to the logistical advantages of sharing closely related time zones. Figure 4 helps to contextualize the distances. Puerto Rico and the U.S Virgin Islands are closest to the U.S. mainland at 1,000 and 1,100 miles respectively, American Samoa is 4800 miles away, and the Northern Mariana Islands are 5800 miles away, and Guam is 5900 miles away [23–27].

2.2. Finding a Fit

Distinguishing population density allowed us to disqualify the U.S. Virgin Islands from our selection process, as the population is split primarily between St. Croix Island and St. Thomas Island [21]. St. John Island also has nearly four thousand people, and transporting freshwater and energy to multiple islands provides additional challenges and costs that would make our technology less feasible [21]. Furthermore, we came across a portable solar-powered Reverse Osmosis system, which is more adapted to service multiple islands. The system is significantly smaller and cheaper to produce than our system and more adaptable in times of crisis, such as during disaster relief [26]. Part of identifying opportunistic markets is identifying existing technology that could outcompete our system in certain markets, and this Portable RO system is further along in its development as its already being piloted in the Federated States of Micronesia [28].

A high temperature gradient is another critical characteristic of an ideal location for our system, as a greater thermal gradient increases the efficiency of our technology [29]. Location-specific deep ocean temperatures are hard to come by, so for our calculations we used thirty nine degrees Fahrenheit (3.89°C) for deep ocean temperatures [30]. Below 200 meters in depth the deep ocean has relatively stable temperatures, but for our analysis we used 1000 meters in depth, as Makai's OTEC specific report cited that 1000 meters was the industry standard for ocean thermal energy [7].

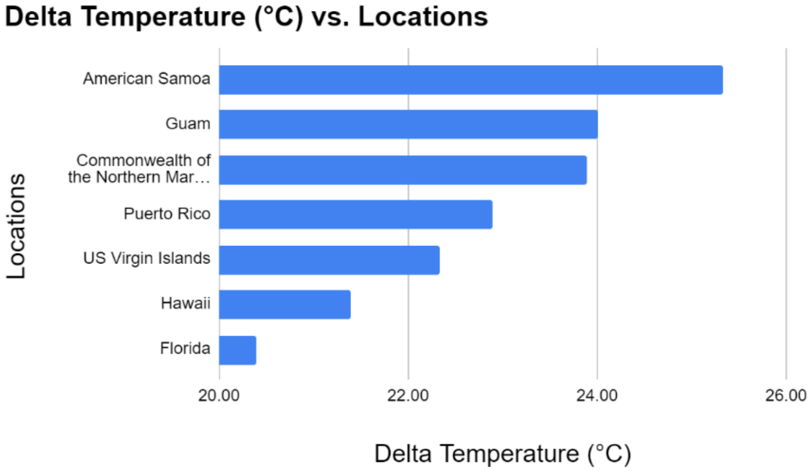
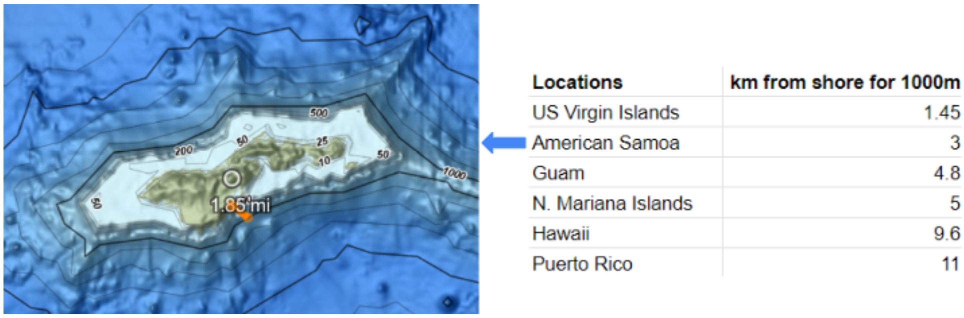


Figure 5: A Comparison of the Amount of the Delta T in U.S. Territories [7, 31-34]

According to Figure 5, American Samoa had the highest Delta Temperature at 25.33°C [7,31]. We included Hawaii in this analysis, because even though it is not a territory, it faces a lot of the same challenges that incorporated territories face. Additionally, Hawaii is home to a small 100 kW OTEC plant making it ideal for comparison [35]. Florida was also used for comparison as it is one of the few continental states that has a warm enough climate to be considered [7]. While reading the chart, it is important to identify the break in the graph, which was used for clarity in highlighting the difference between values.

The next factor assessed was the distance of continental shelves from the shore. Continental shelves signify a drop-off in depth, which is where we are likely to achieve a depth of 1000 meters. An ideal location reaches 1000m in depth as close to shore as possible, which helps reduce production and maintenance costs. The U.S. Virgin Islands had the quickest drop-off at only 1.45 kilometers from the shore as shown in Figure 6, followed closely by American Samoa at 3 km from the shore (1.85 miles), and then Guam and the Commonwealth of the Northern Mariana Islands. (American Samoa Distance from Shore) Puerto Rico Distance from Shore [7, 36-39].



Locations	km from shore for 1000m
US Virgin Islands	1.45
American Samoa	3
Guam	4.8
N. Mariana Islands	5
Hawaii	9.6
Puerto Rico	11

Figure 6: Distance from the shore to 1000 meters in depth using the National Oceanic and Atmospheric Administration (NOAA) mapping tools [7, 36-39]

2.3. Making a Selection

In our final selection process poverty rate, proximity of continental shelves to the shore, and delta temperature were weighted most heavily. For clarification, no factors related to the Direct Contact Membrane Distillation were assessed as this technology is versatile. As a result, American Samoa stood out immediately as it placed highest in nearly all categories assessed. While our technology would benefit from lower transportation costs in locations closer to the U.S. mainland, American Samoa matches more closely with our DEI goals. American Samoa's poverty rate highlights the immense disparity in resources available to the U.S states, versus U.S. territories. With such a strikingly high poverty rate, American Samoa is in dire need of resources that can help fuel economic development. Additionally, the high delta temperature and quick drop-off to 1000 m in depth significantly increase the efficiency and cost effectiveness of our system.

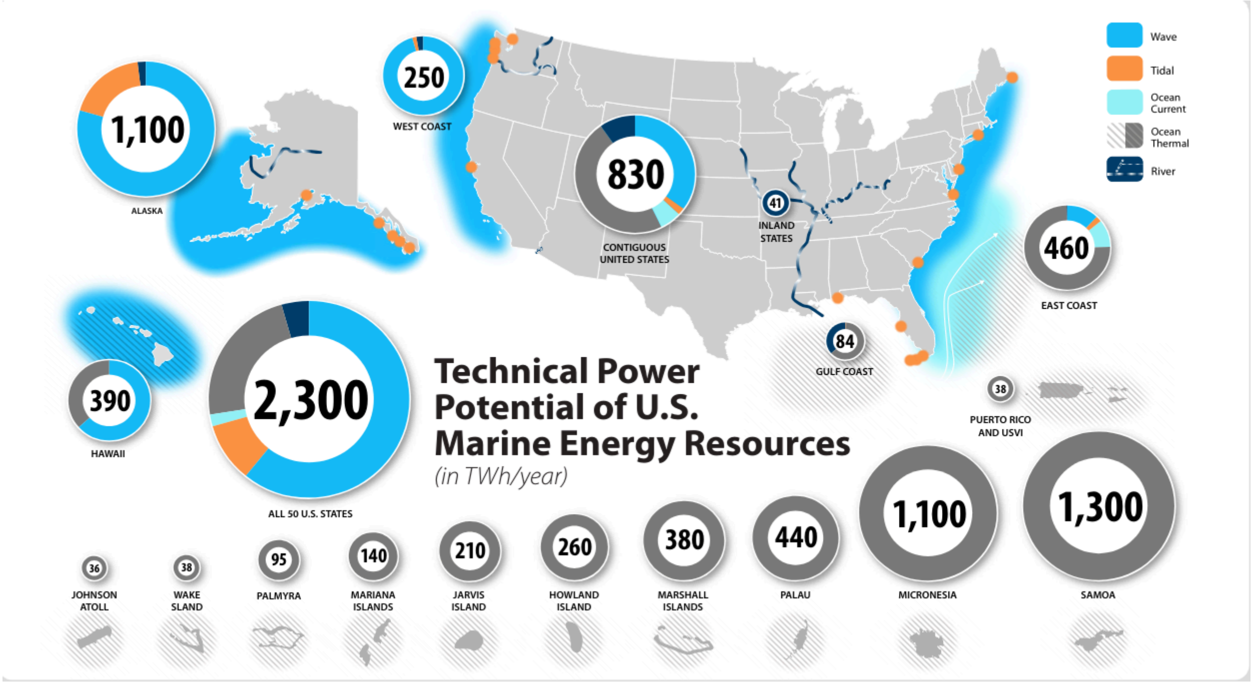


Figure 7: Comparison of the Marine Energy Potential of U.S. States and Territories [11]

Additionally, a report by NREL concurred with our findings, identifying American Samoa with significant marine energy potential [11]. The report gave a breakdown of marine energy potential (based on multiple sources of marine energy (OTEC, wave, tidal, etc.) of all coastal locations in the U.S. based on Terawatt Hours generated per year. American Samoa ranked highest with 1300 TWh of marine energy potential, all of which coming from ocean thermal energy, as it was the only marine energy source assessed for the region [11].

Hawaii, despite already having a small, but functional OTEC plant, was evaluated as having a greater wave energy potential output than ocean thermal energy. This finding helped us conclude that Hawaii was a disadvantaged location in comparison to American Samoa, as Hawaii was more suited to the wave energy converters being developed by our competitors [11]. This report was the final evidence needed to conclusively choose American Samoa for our system. Through ocean thermal energy, American Samoa could meet 32% of the total energy needs of the 50 U.S. states [11], which in addition to powering our desalination system, provides the potential for American Samoa to become an energy exporter.

Additionally, while renewable energy often meets pushback in the continental US, American Samoa has already set internal goals of becoming 50% renewable by 2025 and 100% by 2040 [40]. They have taken aggressive action in meeting these goals, and ocean thermal energy will help diversify their renewable energy sources.

2.4. Competition

According to Fonoti Perelini Perelini, one of our industry connections who serves on the Board of Directors to the American Samoa Power Authority (ASPA), the three renewable energy projects that are currently being constructed are solar, wind, and waste to energy plants. Mr. Perelini highlighted that this would take American Samoa to 80% renewable energy by 2027. The Waste to Energy plant is only 1200 KW, so the majority of the energy will be coming from solar and wind. These energy projects do not devalue a need for our project, as ocean thermal energy still provides the American Samoa with the possibility of being an energy exporter, even if the technology is only used for the remaining 20% of their energy. Since our primary focus is producing fresh water, our self-sufficient system is relatively unaffected by their current investments in renewable energies. While Mr. Perelini did say that although they are improving the piping efficiency of their water systems, they still depend on groundwater, which is not as sustainable as desalination.

Additionally, Katrina Mariner, a water and wells engineer at ASPA (referenced in our relevant stakeholders section) pointed out that a small-scale desalination plant is in the pilot phase of development that relies on diesel power to run a Reverse Osmosis system. This proof of concept project could work to our advantage, as she pointed out that this is American Samoa's first desalination system, which will help open the door for future desalination projects. The expedient pursuance of desalination by settling for a diesel powered system allows for a strong argument for our project that runs on clean energy.

Our biggest challenge, as pointed out by Mr. Perelini, is that American Samoa has already begun investing in their well systems to increase efficiency. The more money that American Samoa invests in their wells, the harder it becomes to justify a brand new system.

2.5. Price

The price is determined based on the Levelized Cost of Water (calculated in the Financial and Benefits analysis). For our system, the LCOW \$2 to \$25/ m^3 depends on factors such as plant capacity, heat source, and feed water flow rate. To provide the greatest value, we will pursue the lowest possible cost of water which would require a large plant capacity, high flow rate, and the maximization of waste heat. According to Wallon Young Fong, Executive Director of ASPA, American Samoa currently has a cost of water of \$1.17 m^3 . Additionally, the possibility of using waste heat instead of geothermal heat can further help to reduce the cost of water to 1.3 \$/m^3 . This analysis does not calculate the effect of a solar input which will help to further bring the cost down.

3. Relevant Stakeholders

3.1. Overview

Our industry connections have been instrumental in informing each aspect of our project. Our goal was to develop a large variety of connections that not only helped provide overarching support, but provide specialized feedback, and seek out strategic partnerships. Even though we are in the proof of concept stage with this technology, our connections with our colleagues working for ASPA have provided a head start towards implementation, as Fonoti Perelini Perelini pointed out that their two largest renewable energy projects involve purchase agreements with IPP's, which will likely be the path for our system as well.

We wanted to make sure that we dedicated a significant amount of this report to our industry connections, to demonstrate the level of impact their feedback has had on our project. We reached out to over forty industry professionals to ensure robust and diverse stakeholder feedback.

3.2. Dr. Jörg Vogel

- Sector: Industry / Research and Development
- Job Title and Organization: VP Open Innovation, Aquaporin (Denmark)
- Business Takeaways: Aquaporin is a water filtration company working towards profitability. First off, since they develop membranes, they could become a supplier for our system upon implementation. Secondly, Dr. Vogel was able to emphasize the importance of third party funding. Governmental funding cannot be the only source of funding, which is why we are pursuing private equity investors to generate the rest of the necessary capital. Additionally, he pointed out the possibility of extracting minerals such as Lithium in the desalination process that can be sold.

3.3. Dr. Carlos Michelén Ströfer

- Sector: Government
- Job Title and Organization: Marine Renewable Energy Researcher, Sandia National Laboratories (New Mexico, USA)
- Business Takeaways: In contrast to the meeting with Dr. Vogel, Dr. Ströfer, of Sandia National Laboratories, was able to provide feedback through the non-profit lens. Even though Dr. Ströfer works in the nonprofit sector, he pointed out that while marine energy is not currently economically viable, we must focus our efforts on identifying niche economies where it is most likely able to compete. This feedback influenced our desire for such a robust market analysis to ensure that our selection process was precise, and evidence based. Additionally, he highlighted the importance of seeking out government funding and recommended investigating the Water Power Technologies Office (WPTO), for their plethora of funding opportunities. Lastly, Dr. Ströfer helped shape the value proposition of marine energy, by pointing out that marine energy is not negatively influenced by seasons in the same way that wind and solar are. This is an important distinction to make, because MECC is not just about designing the best marine energy system, but to differentiate marine energy from other renewable energy sources.

3.4. Peter Stricker

- Sector: Industry
- Job Title and Organization: Chief Executive Officer, SeaWell LLC (California, USA)

- Business Takeaways: SeaWell, like Aquaporin, is a for-profit organization. Similarly, they have yet to become profitable, but have a five year plan that aims to push them closer to profitability. This interview was incredibly helpful in understanding the competitive landscape as SeaWell is one of our competitors. Mr. Stricker was able to point out SeaWell's competitive advantage as its flexibility, and discussed how Seawell's buoys are easily implementable with any renewable energy source making their technology "plug and play." Additionally, their buoys can be quickly installed, and the capacity can be easily adjusted. Buoys are then connected to a central water station that can be operational within weeks of commissioning. Learning about SeaWell's competitive advantages helped spark a dialogue about our value proposition to ensure market differentiation.

  Mr. Stricker was also able to highlight the importance of understanding the existing water infrastructure of the community we choose. It is easy to make assumptions about the existing water infrastructure, but he cited one unique example of an area in Mexico that relies on water trucks for the transportation of fresh water. This insight helped inspire us to connect with experts living in American Samoa. Additionally, he referenced the importance of aligning products with the organizational values of the company. At SeaWell, this meant focusing on water to meet agricultural needs, as opposed to a product like bottled water that would contrast their company value of sustainability.

  Our last business takeaway from this interview revolved around forward thinking. Despite being in the proof of concept stage, Mr. Stricker relayed the importance of descriptive plans to receive proper permits, as this can be a major barrier for desalination projects. He mentioned that a desalination plant in Carlsbad, California took around twenty years to get all the necessary permits. Having a clear and realistic permitting plan helps increase investor confidence in the project, which is crucial for our system, since we will be pursuing private equity investors.

3.5. Hossam El Rafie

- Sector: Industry

- Job Title and Organization: Area Sales Manager, Pure Aqua, Inc. (California, USA)

- Business Takeaways: Hossam El Rafie works for Pure Aqua which is a for-profit company specializing in designing custom water filtration systems. This interview was incredibly impactful as he persuaded us from being price obsessed. He noted that Pure Aqua produces products that are considered mid to high end, which means that they are not the cheapest. Their specialty is custom systems, but this means increased lead time as they maintain no stock. However, they are adaptable to the customer base as he pointed out that they have a diverse range of clients, including nonprofit organizations, as they just completed a project for a nonprofit organization in El Salvador.

  Throughout our project, one of our primary focuses has been cost and while cost is important, Mr. El Rafie cautioned that, just like them, we will never win a price war. Instead, they focus on differentiation through quality and customization. This changed our approach for our project, as we shifted to focus on creating the best product for American Samoa, instead of the most efficient, cost-effective product for everywhere in the world, because this just is not realistic. Quality is the adherence to specifications, and this definition guided us to ensure that we identify American Samoa's needs, and we fulfill them. To be competitive with nonprofits for example, he cited how their system is designed to meet minimum water quality standards. In contrast, their industrial systems may need to meet significantly more stringent filtration metrics, but that comes with a cost. He emphasized that understanding the requirements of your clients has been their key to success, as their reputation now carries their business.

3.6. Nancy Kupa

American Samoa Power Authority

- Sector: Government
- Job Title and Organization: Quality Improvement & Compliance Officer/Human Resource Manager, ASPA (American Samoa)
- Business Takeaways; Nancy Kupa works for the ASPA which is a government-run organization that is responsible for meeting the energy needs of Samoans. Our dialogue with Ms. Kupa was split between a brief phone conversation and an email chain. She was able to validate the prioritization of renewable energy in American Samoa, by pointing out that on April 12th (2024), ASPA was holding a groundbreaking for a 20 MW solar farm and she also cited a 42 MW wind energy plant that is in the planning stage that will help meet 70% of American Samoa's energy needs upon completion. This information is crucial to understanding the feasibility of our project. Our main takeaway from our conversations is how dedicated American Samoa is to becoming fully renewable. While these projects seem to negate a need for other sources of renewable energy, it is important to keep in mind how volatile large projects can be, and despite set deadlines, there is never a guarantee that these projects will be successfully completed. For example: Ms. Kupa mentioned a Geothermal drilling project, that despite receiving initial positive feedback and ASPA funding, was eventually canceled due to unexpected challenges.

  Our last takeaway revolved around funding as Ms. Kupa said that the Independent Power Producer was funding the wind energy project. The more funding pathways that we become aware of, the more opportunities we have to ensure the continuity of our research.

3.7. Katrina Mariner

- Sector: Government
- Job Title and Organization: ASPA Water and Wells System Engineer (American Samoa)
- Business Takeaways: Ms. Mariner works on water engineering and construction projects for ASPA and was able to provide a clarified view on American Samoa's water infrastructure. She said that about 99% of their water comes from groundwater and her main job is drilling to find new water sources. She pointed out that while their system of wells is working now, she is skeptical about the sustainability of these wells for long term water production. She believes that production will have to eventually be lowered and at present, 60% of their water is non-revenue water, which highlights significant deficiencies. With that being said, they do have some wells that are located inland that have high yields due to good mountain front recharge.

  She mentioned that they are working with an off island vendor to develop the island's first diesel run desalination plant on a small island called Aunu'u Island. The island is small enough that its current wells are close to shore and during high tide all the well water becomes brackish, and droughts result in a very salty product. The main island, despite having most of its wells inland, has some wells closer to shore that share these same problems and will inevitably have to be replaced by new wells further inland. She discussed that the appeal of the desalination plant is consistency in water quality. The main issue that they have encountered with similar ideas for desalination plants is a lack of staffing. Oftentimes, the only qualified individuals are on the main island, so people from the mainland must travel to the smaller island, to train the local staff in the operational requirements of the plant. She believes that the lack of staffing will be quickly remedied and expects staffing to no longer be an issue within 2-3 years. Since our plant will be stationed on the main island, staffing should not be a problem.

Additionally, Ms. Mariner has extensive experience in permitting and has relayed the necessary information for each permit that we will have to apply for. Even though she advised us not to apply for permits until we had secured significant funding and a plan to travel to American Samoa, she acknowledged that understanding the intricacies of which permits are required will help to expedite future operations, as permitting is often the most time intensive portion of projects.

3.8. Tim Bodell

- Sector: Industry / Government
- Job Title and Organization: Current Utility Director of AJO Improvement Company (Water, Power, and Sewer Company in Arizona), Former Technical Advisory Engineer for the American Samoa Environmental Protection Agency (American Samoa)
- Business Takeaways: Tim Bodell was able to provide a wide variety of feedback for our project based on his current work experience and experience working in American Samoa on renewable energy projects. He managed a project related to Geothermal Drilling and was involved with the implementation of a solar project on Ta'u which is an island in the American Samoa. Even though our system only generates water he also pointed out the potential of ocean thermal energy production, recommending hydrogen as a storage vehicle for excess energy. This is something to consider if we are able to pursue ocean thermal energy for applications beyond desalinating water.

To fund our project, Mr. Bodell recommended the Hawaii National Energy Institute (HNEI) and the Blue Planet Organization, which he has connections with from his time working in American Samoa. Lastly, he highlighted the importance of identifying the non-economic factors of a project and talked extensively about the importance of taking the time to learn the culture and develop relationships with the local community to ensure the success of the project.

3.9. Fonoti Perelini Perelini

- Sector: Government
- Job Title and Organization: Serves on the ASPA Board of Directors, Commission Member of the American Samoa Public Service Commission, and former project manager at American Samoa Electric Power Corporation.
- Business Takeaways: Mr. Perelini was our first contact in American Samoa that was familiar with ocean thermal energy, which was very exciting since the technology is still underdeveloped. He mentioned that OTEC specifically had been studied not just in American Samoa, but also in the Marshall Islands for power, air conditioning, and

the production of fresh water. The study in American Samoa took place in 1986, and at the time high costs made the technology infeasible. There have been significant advances in ocean thermal energy since the mid 80's, which led Mr. Perelini to recognize that the same studies may conclude different results now.

Mr. Perelini also explained the current three renewable energy projects that are being pursued, including a 20 MW solar plant, a 42 MW wind farm, and a 1200 KW waste to energy power plant. He mentioned that these combined projects will allow American Samoa to reach 80% renewable energy by 2027. He also touched on the current water infrastructure saying that their current production is 14 million gallons per day, with a significant amount of water lost as non-revenue water. They are currently repairing old pipelines to improve efficiency by decreasing non-revenue water to 20%.

3.10. Wallon Young Fong

- Sector: Government
- Job Title and Organization: Executive Director of ASPA
- Business-Related Takeaways: Mr. Wallon Young Fong was able to provide our team with the current cost of electricity per KWh in American Samoa which is USD 39 cents and the cost of water in American Samoa which is USD $4.41 per 1,000 gallons (USD $1.17 per cubic meter). These figures are crucial to evaluating the competitiveness of our system. Additionally, Mr. Fong was able to clarify that the previous Ocean Thermal Energy Study did not lead to a project due to a lack of funding.

4. Development & Operations

4.1. Permitting

As we are in the proof of concept stage, we wanted to ensure that we provide a roadmap for implementation, including gathering information on permitting. Our industry interview with Katrina Mariner from ASPA was incredibly helpful in understanding the permitting process and timeline. As a Water and Wells System Engineer, Ms. Mariner is constantly working with permits, so she informed us that our project would need "ASHPO Concurrence (Section 106 Archaeological Request to Survey), PNRS (Land Use Permit), ASEPA Permit to Construct, Right of Way Easement, ARMY Corps Permit, [and] DMWR Concurrence letter." There are no costs associated with the permits themselves and Ms. Mariner advised not to apply for these permits until we have secured significant funding. However, she said that the ARMY Corps Permit takes the longest to get approved, as it also requires a definitive plan. She recommended that at the time of application, we should write a letter asking if we can use ASPA's assistance for right of way, which will help to expedite the process. Permitting Readiness is crucial to preventing extended wait times for permitting information to be processed.

4.2. Environmental Considerations & Deployment

As a renewable energy source, no pollutants are given off, and only a miniscule amount of Carbon is released into the atmosphere [41]. Additionally, the cold water (permeate) that is being continually pumped from the deep ocean, should be released deep enough that the nutrients do not float to the surface, as this could disrupt the local ecosystems and contribute to an algal bloom [41].

Our plant will be on shore which is preferable for American Samoa as there is a relatively short distance from shore to get to 1000 meters in depth [4]. On shore plants are advantageous as they do not require mooring systems or lengthy pipes to bring the desalinated water to shore [4]. Some areas of consideration when preparing for implementation, is that our design must be robust to ensure durability against wave and current activity [4]. The proximity to shore also allows for ease of access to make adjustments.

When the project is ready to be implemented, most of the necessary equipment is available off the shelf or will be compatible with minor modifications [41]. It is important to note that the life of the heat exchangers and biofouling mitigation are two potential challenges that should be addressed [41]. Our greatest advantage in addressing these challenges are the connections we have made. Specifically, our connection with Dr. Jörg Vogel of Aquaporin serves as a valuable partnership as Aquaporin can provide upkeep recommendations if we purchase their membranes. Additionally, Pure Aqua can also be a strategic partnership because of their specialization in deploying desalination systems.

Lastly, to ensure ease of deployment we would assemble an experienced team by partnering with a civil engineering firm to lead site development and construction in addition to assembling an engineering management team. A significant opportunity of this project is to bring specialized job opportunities to American Samoa, so it is crucial that these opportunities are also reflected in the implementation of the system.

5. Financial & Benefits Analysis

5.1. *Levelized Cost of Water*

The product of an ocean thermal energy powered desalination plant is fresh water. To measure the efficiency of the desalination process, we will measure the levelized cost of water (LCOW). LCOW describes the cost of producing a unit of water and is a commonly used metric for evaluating the cost-effectiveness of different desalination technologies.

The LCOW calculation method used for our OTED analysis is adapted from the literature [42,43]. As expressed in equation (1), LCOW is largely a function of the capital costs, energy costs, and other operational costs throughout the life of the plant.

$$LCOW = \frac{C_{CAPEX} \times CRF + C_{OPEX}}{\Delta V} + C_{elec} \times E_{elec,\,MD} \tag{1}$$

Where C_{CAPEX} and C_{OPEX} are the capital costs and the annual operation costs of an ocean thermal energy driven membrane distillation plant, $E_{elec,MD}$ is the electrical energy consumption associated with the desalination plant, C_{elec} is the cost of electricity, and ΔV is the volume of freshwater permeate produced by the RO-PRO plant.

CRF is the capital recovery factor, which is obtained from equation (2):

$$CRF = \frac{i\,(1+i)^{N}}{(1+i)^{N}-1} \tag{2}$$

Where i is the interest rate on capital, and N is the total plant life.

Capital costs, CAPEX, are given by the equation (3).

$$C_{CAPEX} = C_{membrane} + C_{pumps,MD} + C_{HX,MD} + C_{HX,OTE} + C_{pumps,OTE} \tag{3}$$

Where C_m, is the membrane cost per m^3 of permeate produced, $C_{pumps,MD}$ is the cost of purchased pump used in membrane distillation unit, $C_{HX,MD}$ cost of heat exchanger used in membrane distillation unit, , $C_{HX,OTE}$ cost of heat exchanger used in ocean thermal energy extraction, and , $C_{pumps,OTE}$ is the cost of pumping ocean water to the heat exchanger for heat extraction.

Operating costs, OPEX, are given by the equation (4).

$$C_{OPEX} = C_{SM} + C_{insurance} + C_{labor} + C_{RMD} \tag{4}$$

Where C_{SM}, is the service and maintenance costs associated with the desalination system, is the insurance costs associated, is the cost of labor and is the cost of replacing membranes in the MD system.

The principal differences between this expression and one that would describe a typical MD plant are the additional heat exchanger costs associated with extracting heat from warm surface level ocean water and transferring it to the feed of MD plant, warm water pump costs. Additionally, if cold water from the ocean is used to cool the distillate side of the process to increase the temperature gradient and hence the vapor pressure difference between feed and distillate to improve the performance of MD plant, then pumping and heat exchanger costs associated with cool water pump should also be considered.

Table 1 provides a summary of the values used for LCOW analysis, which were selected from the literature. Unless specified, all parameters are taken from [42].

Table 1. LCOW input parameters

Feed flow rate $\dot{V}$	180 L/hr
Distillate flow rate $\dot{V}$	180 L/hr
Pump power demand, pumping ocean water, W_{OTE}	100 KW [44]
Freshwater permeate produced ΔV	10000 m^3/year
Cost of electricity C_{elec}	0.056 \$/kW
Electric energy consumption of MD plant $E_{elec,MD}$	2 kWh/m^3 [45]
Interest rate i	8 %
Plant life N	25 years
Annual operating time Δt	7920 hrs/year
Specific membrane cost C_m	0.2 \$/m^3
Cost of pump, $C_{pumps,MD}$	$6900 + 206\,\dot{V}^{0.9}$

Cost of heat exchanger, C_{HX}	$24000 + 46(0.59)^{0.9}$
Cost of pumping ocean water $C_{pumps,OTE}$	700 W_{OTE} [46]
Service and maintenance costs , C_{SM}	2.5% $C_{investment}$
Insurance costs, $C_{insurance}$	0.5% $C_{investment}$
Specific labor cost C_{labor}	0.03 \$/m^3
Replacement cost of MD modules, C_{RMD}	15% C_m / year

Figure 8 shows the LCOW for ocean thermal powered desalination plant as the electric energy consumption, cost of electricity, ocean water pump power demand and desalination plant capacity are varied (starting from top and going from left to right). Major changes in LCOW are observed when the ocean water pump power demand and the plant capacity change. As the plant capacity increases from 1000 to 10,000 m^3 the LCOW drops by 89%. Similarly, considering ocean water pump power, as this value increases from 100 kW to 1000 kW, the LCOW increases by over 400%.

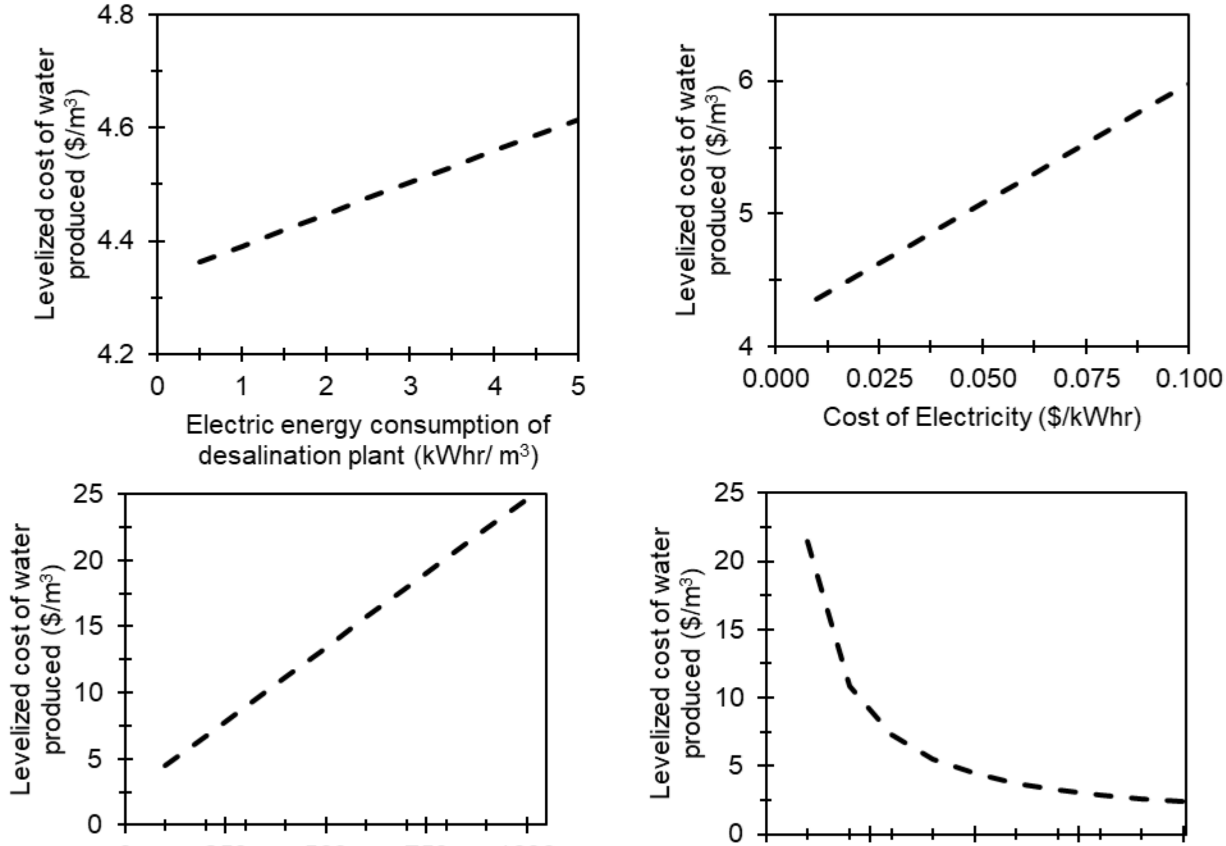


Figure 8: LCOW for ocean thermal powered desalination plant.

The LCOW of an DCMD desalination plant can fluctuate greatly based on factors like plant capacity, heat source, and feed water flow rate. For instance, when scaling up the plant from 1000 m^3/year to 15,000 m^3/year, the LCOW reduced by 70% to 2.2 \$/m^3 [42]. Using waste heat instead of geothermal heat, the

LCOW was further reduced to 1.3 \$/m^3 also yielding environmental benefits through decreased greenhouse gas emissions and enhanced energy efficiency.

Another study indicates that feed water flow rate significantly impacts costs. For instance, at a flow rate of 3-5 L/hr, the LCOW can spike to 80 \$/m^3, while at 2630 L/hr, it is around 10 \$/m^3 [43]. This suggests a decrease in LCOW as flow rate increases, but the specific energy consumption at higher flow rates must also be factored in for efficient energy use alongside cost reduction.

In the realm of solar-powered DCMD, the LCOW spans widely from 0.3 to 56.5 \$/m^3 [47,48]. Results reported for our OTED system also vary notably, ranging from \$2 to \$25/ m^3 as different parameters are adjusted. OTED demonstrates comparable costs to DCMD and solar-powered DCMD, indicating potential for commercialization in this technology.

6. Conclusions

Through robust research and industry outreach, OTED has proven to have potential in American Samoa, with connections in place that ensure a swift transition to implementation. This report did not calculate the incorporation of a solar input which would allow for a further maximization of the temperature gradient in the ocean and still our calculated LCOW comes within \$.10 of the current cost of water. With this solar input and further research into increasing the efficiency of our system, by maximizing by-products like waste heat and extracted concentrates, OTED will not only be able to compete with current water costs, but provide a more sustainable and resistant source of freshwater for the main island. Furthermore, the introduction of ocean thermal energy will help stimulate the American Samoan economy by bringing specialized jobs to the island, to help retain American Samoans that are currently immigrating to other countries to find specialized work.

7. References

[1] U.S. Pacific territory modernizing pre-WWII water infrastructure, (n.d.). https://www.awwa.org/AWWA-Articles/us-pacific-territory-modernizing-pre-wwii-water-infrastructure (accessed May 5, 2024).

[2] L. Cohen, Hawaii is “on the verge of a greater catastrophe,” locals say, as water crisis continues - CBS News, (2024). https://www.cbsnews.com/news/hawaii-water-crisis-climate-change/ (accessed May 5, 2024).

[3] Small island states fight back against nature loss, climate change, UNEP (2023). http://www.unep.org/news-and-stories/story/small-island-states-fight-back-against-nature-loss-climate-change (accessed May 5, 2024).

[4] Electric Power Monthly - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/electricity/monthly/epm_table_grapher.php (accessed July 27, 2022).

[5] American Samoa Profile, (n.d.). https://www.eia.gov/state/print.php?sid=AQ (accessed May 5, 2024).

[6] Marine Energy Basics, (n.d.). https://www.nrel.gov/research/marine-energy.html (accessed May 5, 2024).

[7] L. Martel, P. Smith, S. Rizea, J. Van Ryzin, C. Morgan, G. Noland, R. Pavlosky, M. Thomas, J. Halkyard, Ocean Thermal Energy Conversion Life Cycle Cost Assessment, Final Technical Report, 30 May 2012, Lockheed Martin, Manassas, VA (United States), 2012. https://doi.org/10.2172/1045340.

[8] L. Aresti, P. Christodoulides, C. Michailides, T. Onoufriou, Reviewing the energy, environment, and economy prospects of Ocean Thermal Energy Conversion (OTEC) systems, Sustainable Energy Technologies and Assessments 60 (2023) 103459. https://doi.org/10.1016/j.seta.2023.103459.

[9] C. C. K. Liu, "Ocean thermal energy conversion and open ocean mariculture: The prospect of Mainland-Taiwan collaborative research and development," *Sustainable Environment Research*, vol. 28, no. 6, pp. 267–273, Nov. 2018, doi: https://doi.org/10.1016/j.serj.2018.06.002.

[10] J.H. VanZwieten, L.T. Rauchenstein, L. Lee, An assessment of Florida's ocean thermal energy conversion (OTEC) resource, Renewable and Sustainable Energy Reviews 75 (2017) 683–691. https://doi.org/10.1016/j.rser.2016.11.043.

[11] L. Kilcher, M. Fogarty, and M. Lawson, "Marine Energy in the United States: An Overview of Opportunities," 2021. Available: https://www.energy.gov/sites/default/files/2021/02/f82/78773_3.pdf (accessed May 5, 2024).

[12] M. Tomaszewska, Direct Contact Membrane Distillation (DCMD) Applications, in: E. Drioli, L. Giorno (Eds.), Encyclopedia of Membranes, Springer, Berlin, Heidelberg, 2015: pp. 1–4. https://doi.org/10.1007/978-3-642-40872-4_186-1.

[13] Ocean Thermal Energy Conversion: Technology Brief, (2014). https://www.irena.org/publications/2014/Jun/Ocean-Thermal-Energy-Conversion (accessed May 5, 2024).

[14] U.S. tap water prices in select cities 2021, Statista (n.d.). https://www.statista.com/statistics/1232861/tap-water-prices-in-selected-us-cities/ (accessed May 5, 2024).

[15] U.C. Bureau, Census Bureau Releases 2020 Census Demographic and Housing Characteristics Summary File for the U.S. Virgin Islands, Census.Gov (n.d.). https://www.census.gov/newsroom/press-releases/2023/2020-dhc-summary-file-usvi.html (accessed May 5, 2024).

[16] U.C. Bureau, National Poverty in America Awareness Month: January 2024, Census.Gov (n.d.). https://www.census.gov/newsroom/stories/poverty-awareness-month.html (accessed May 5, 2024).

[17] Puerto Rico Profile, (n.d.). https://www.census.gov/geographies/island-areas/puerto-rico.html (accessed May 5, 2024).

[18] OP-ED: Dear SCOTUS, 3.5 Million Americans in territories deserve same federal benefits, (2021). https://oag.dc.gov/release/op-ed-dear-scotus-35-million-americans-territories (accessed May 5, 2024).

[19] Poverty, (n.d.). https://data.ers.usda.gov/reports.aspx?ID=17826#P8814a89d43714ca6a17cec442f68deef_3_229iT3 (accessed May 5, 2024).

[20] Puerto Rico PYs 2020-2023 - WIOA State Plan Common Elements - Economic Analysis - ac4bf4bd-a966-4aa0-94db-0a8a41026d07 | WIOA State Plan Portal, (n.d.). https://wioaplans.ed.gov/node/13521 (accessed May 5, 2024).

[21] U.C. Bureau, 2020 Population of U.S. Island Areas Just Under 339,000, Census.Gov (n.d.). https://www.census.gov/library/stories/2021/10/first-2020-census-united-states-island-areas-data-released-today.html (accessed May 5, 2024).

[22] U.S. Census Bureau, "National Poverty in America Awareness Month: January 2023," *Census.gov*, Jan. 2023. https://www.census.gov/newsroom/stories/poverty-awareness-month.html#:~:text=Official%20Poverty%20Measure

[23] Pago Pago · Eastern District, American Samoa, Pago Pago · Eastern District, American Samoa (n.d.). https://www.google.com/maps/place/Pago+Pago,+Eastern+District,+American+Samoa/@-9.9855121,121.6011687,3z/data=!4m6!3m5!1s0x71a684b79248fdc9:0x358e33ecce15412b!8m2!3d-14.2732727!4d-170.7030577!16s%2Fm%2F0dj42f5?entry=ttu (accessed May 5, 2024).

[24] Puerto Rico - Google Maps, (n.d.). https://www.google.com/maps/place/Puerto+Rico/@19.8303872,-67.9707758,4z/data=!4m6!3m5!1s0x8c0296261b92a7f9:0xf336ec2818049b1a!8m2!3d18.220833!4d-66.590149!16zL20vMDVyN3Q?entry=ttu (accessed May 5, 2024).

[25] Capitol Hill · Saipan 96950, CNMI, Capitol Hill · Saipan 96950, CNMI (n.d.). https://www.google.com/maps/place/Capitol+Hill,+Saipan+96950,+CNMI/@36.6307449,149.0221532,3z/data=!4m6!3m5!1s0x66d8b0ca8db5aac7:0x916f06076a050b76!8m2!3d15.2143729!4d145.7512198!16s%2Fm%2F05b65hf?entry=ttu (accessed May 5, 2024).

[26] St Croix - Google Maps, (n.d.). https://www.google.com/maps/place/St+Croix/@14.8354363,-68.423527,5z/data=!4m6!3m5!1s0x8c1aca18b9e986fb:0x222f1b9699885a5c!8m2!3d17.7245968!4d-64.8347992!16zL20vMDFoZDYz?entry=ttu (accessed May 5, 2024).

[27] Dededo · Guam, Dededo · Guam (n.d.). https://www.google.com/maps/place/Dededo,+Guam/@24.5175522,151.5563502,3z/data=!4m6!3m5!1s0x671f83cc77667b6f:0x6e7bfae3bb882ea!8m2!3d13.515531!4d144.8346748!16zL20vMDdyNTZj?entry=ttu (accessed May 5, 2024).

[28] For a World without Water Shortage | October 2017 | Highlighting Japan, (n.d.). https://www.gov-online.go.jp/eng/publicity/book/hlj/html/201710/201710_11_en.html (accessed May 5, 2024).

[29] NOAA Office for Coastal Management | About the Office, (n.d.). https://coast.noaa.gov/czm/thermalenergy/ (accessed May 5, 2024).

[30] N.O. and A.A. US Department of Commerce, How does the temperature of ocean water vary?: Ocean Exploration Facts: NOAA Office of Ocean Exploration and Research, (n.d.). https://oceanexplorer.noaa.gov/facts/temp-vary.html (accessed May 5, 2024).

[31] C. G. S. Temperatures-A.-C. Ltd, “american samoa | Search | | Sea Temperatures,” *www.seatemperature.org*. https://www.seatemperature.org/locations/search?search_keywords=american+samoa (accessed May 07, 2024).

[32] C. G. S. Temperatures-A.-C. Ltd, “Charlotte Amalie Water Temperature | Virgin Islands | Sea Temperatures,” *World Sea Temperatures*. https://www.seatemperature.org/central-america/virgin-islands/charlotte-amalie.htm (accessed May 07, 2024).

[33] C. G. S. Temperatures-A.-C. Ltd, “Lamboglia Water Temperature | Puerto Rico | Sea Temperatures,” *World Sea Temperatures*. https://www.seatemperature.org/central-america/puerto-rico/lamboglia.htm (accessed May 07, 2024).

[34] Sea Temperatures, “JP Tinian Town pre-WW2 Water Temperature | Northern Mariana Islands,” *World Sea Temperatures*, Jan. 18, 2012. https://www.seatemperature.org/australia-pacific/northern-mariana-islands/jp-tinian-town-pre-ww2.htm (accessed May 07, 2024).

[35] “Frequently Asked Questions | Makai Ocean Engineering,” *Makai.com*, 2020. https://www.makai.com/faq/#:~:text=For%20a%20large%2C%20100%2Dmegawatt

[36] *Arcgis.com*, 2014. https://noaa.maps.arcgis.com/home/webmap/viewer.html?layers=5f98dbc4708e4a7e99c0a7fe043d70a1&basemapUrl=https://tiles.arcgis.com/tiles/C8EMgrsFcRFL6LrL/arcgis/rest/services/GEBCO_basemap_NCEI/MapServer&center=-65 (accessed May 07, 2024).

[37] “Map Viewer,” *noaa.maps.arcgis.com*. https://noaa.maps.arcgis.com/apps/mapviewer/index.html?layers=5f98dbc4708e4a7e99c0a7fe043d70a1&basemapUrl=https://tiles.arcgis.com/tiles/C8EMgrsFcRFL6LrL/arcgis/rest/services/GEBCO_basemap_NCEI/MapServer&center=-65 (accessed May 07, 2024).

[38] *Arcgis.com*, 2014. https://noaa.maps.arcgis.com/home/webmap/viewer.html?layers=5f98dbc4708e4a7e99c0a7fe043d70a1&basemapUrl=https://tiles.arcgis.com/tiles/C8EMgrsFcRFL6LrL/arcgis/rest/services/GEBCO_basemap_NCEI/MapServer&center=-65 (accessed May 07, 2024).

[39] ”Map Viewer,” *noaa.maps.arcgis.com*. https://noaa.maps.arcgis.com/apps/mapviewer/index.html?layers=5f98dbc4708e4a7e99c0a7fe043d70a1&basemapUrl=https://tiles.arcgis.com/tiles/C8EMgrsFcRFL6LrL/arcgis/rest/services/GEBCO_basemap_NCEI/MapServer&center=-65 (accessed May 07, 2024).

[40] United States - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/beta/states/states/AQ/analysis (accessed May 5, 2024).

[42] V. Okati, A.J. Moghadam, M. Farzaneh-Gord, M. Moein-Jahromi, Thermo-economical and environmental analyses of a Direct Contact Membrane Distillation (DCMD) performance, Journal of Cleaner Production 340 (2022) 130613. https://doi.org/10.1016/j.jclepro.2022.130613.

[43] K. Ali, M.I. Hassan Ali, Energy and cost analysis of a multiple channel direct contact membrane distillation module: Case study, Case Studies in Chemical and Environmental Engineering 8 (2023) 100449. https://doi.org/10.1016/j.cscee.2023.100449.

[44] S. Lim, J. Yoon, H. Lee, H. Kim, Performance Evaluation of Control Compatibility for an OTEC Pump Shutdown Condition, Journal of Marine Science and Engineering 11 (2023) 155. https://doi.org/10.3390/jmse11010155.

[45] R. Ullah, M. Khraisheh, R.J. Esteves, J.T. McLeskey, M. AlGhouti, M. Gad-el-Hak, H. Vahedi Tafreshi, Energy efficiency of direct contact membrane distillation, Desalination 433 (2018) 56–67. https://doi.org/10.1016/j.desal.2018.01.025.

[46] C.R. Upshaw, Thermodynamic and economic feasibility analysis of a 20 MW ocean thermal energy conversion (OTEC) power plant, (2012). http://hdl.handle.net/2152/ETD-UT-2012-05-5637 (accessed May 3, 2024).

[47] J. Choi, J. Cho, J. Shin, H. Cha, J. Jung, K.G. Song, Performance and economic analysis of a solar membrane distillation pilot plant under various operating conditions, Energy Conversion and Management 268 (2022) 115991. https://doi.org/10.1016/j.enconman.2022.115991.

[48] M.I. Soomro, W.-S. Kim, Performance and economic investigations of solar power tower plant integrated with direct contact membrane distillation system, Energy Conversion and Management 174 (2018) 626–638. https://doi.org/10.1016/j.enconman.2018.08.056.

Build and Test Challenge

1. Introduction

Access to clean water is a global challenge, particularly in remote regions without easy access to transported water. Currently, about ¼ of the global population lacks access to safe drinking water. Since freshwater resources are limited, accounting for just 3 % of all the water on earth, engineering solutions are needed to produce freshwater from seawater and brackish water. For this reason, desalination plants are being developed at a rapid pace, with global water production capacity now exceeding 100 million m3 per day. However, conventional desalination methods such as reverse osmosis (RO) often require significant energy requirements to generate the pressure gradients needed for (RO). Meanwhile, at many of these same remote locations, there is a tremendous renewable energy resource in the form of ocean thermal gradients. These gradients result from warm surface water that is heated by solar radiation while the deep seawater remains cool. In tropical regions, temperature differences from 20-30 °C are common [6]. The system our team is designing aims to solve this issue by using a direct contact membrane distillation (DCMD) system, which will work based on the ocean's thermal gradient, to desalinate seawater. Membrane distillation (MD) is a separation process that uses a vapor pressure difference generated by a thermal difference to drive vapor permeate across a hydrophobic porous membrane. This technology is promising for desalination, as it allows for high salt and solute rejection, and is well-suited for integration with ocean thermal gradients, as it can make use of low-grade heat and operate at low temperatures. By leveraging the insulating properties of water, the system pumps hot ocean water from the surface and cold water from ocean depths to establish the temperature gradient necessary for the distillation process. This bypasses the typical need to convert electricity required in conventional (RO) desalination processes. Thus, by exploiting the natural thermal gradients found in the oceans, the system can directly convert ocean energy to potable water. This approach offers the potential for more efficient desalination compared to reverse osmosis. An example DCMD system is shown in Figure 1, where warm seawater from the ocean surface is fed to the membrane module. Freshwater, cooled by the deep ocean, is circulated on the opposite side of the membrane to induce a vapor pressure difference. This causes water to evaporate from the feed, distill across the porous membrane, and condense on the permeate interface, expanding the volume of clean freshwater.

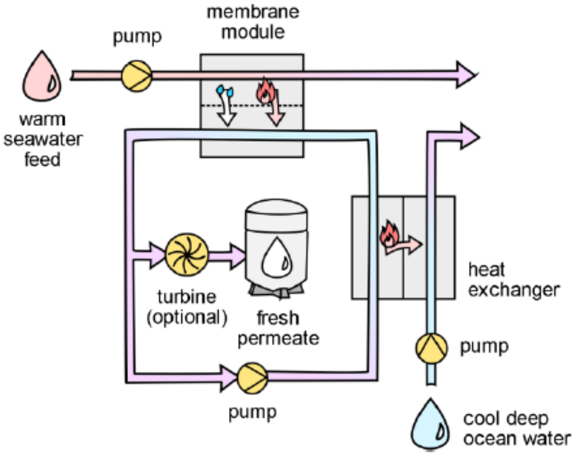


Figure 1: Desalination via membrane distillation driven by thermal gradients between warm surface seawater and cool deep ocean water. Simultaneous power generation is optional by depressurizing the expanding permeate volume across a turbine.

2. Theory

2.1. Prototype Design

The overarching objective of the research is to investigate the feasibility of utilizing ocean thermal gradients for direct contact membrane distillation of seawater. The development of the test plan commenced with a series of discussions among the research team, focusing on delineating achievable objectives within the constraints of scale model experimentation and available budget. Initial objectives were established, centered on assessing the effectiveness of ocean thermal gradients as a driving force for membrane distillation. Key data parameters such as ensuring consistent thermal gradients during testing and calculating permeation rates, were identified to guide the design process. A mock-up of the full-scale model was conceptualized based on identified parameters and objectives. Modifications were then made to the full-scale system to allow for bench size testing while ensuring as much accuracy to the full-scale model as possible. Benchmarks and examples of scaled models related to the project were researched and utilized as references to validate the design [1]-[2]. To facilitate the construction of the bench-scaled model within budgetary constraints, certain components were simplified. For instance, the solar panel in the full-scale model was replaced with a predetermined voltage supply to power pumps or a set increased temperature on the feed side. Simulated temperature gradients using temperature-controlled water tanks were employed, and ocean temperature data were used to determine permeate line temperatures. Seawater properties were approximated by mixing sodium chloride with distilled water in appropriate ratios. This resulted in the finalized prototype design shown in Figure 2.

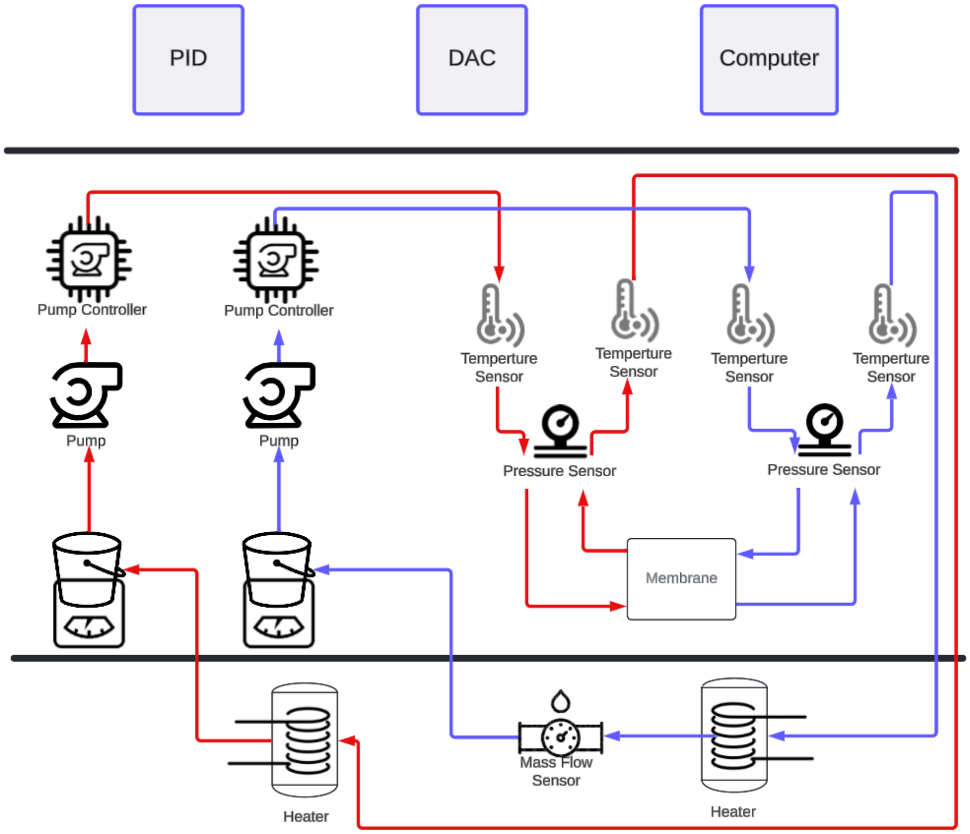


Figure 2: Prototype direct contact distillation membrane parts and instrumentation diagram.

Figure 2 shows the placement of equipment to ensure safety and reduce friction in the pipes. The membrane is set with counterflow to allow for greater temperature difference increasing efficiency. The permeate is weighted to verify the permeate rate data from the flow rate sensors. The prototype is built on three levels to ensure minimal contact between the electrical components and water. All potentially hazardous electronics are placed on the upper layer while the liquids are placed on the lowest layer, with required sensors and equipment for testing in the middle layer. The blue and red lines show the hot and cold loop of the system respectively.

2.2. Scaling Factors

The scaling factors considered when creating the prototype are as the size of a membrane increases, several factors can affect its permeation rate. These factors can broadly be categorized into intrinsic properties of the membrane material, external operating conditions, and geometric considerations. Larger membranes may have a wider distribution of pore sizes, which can affect the overall permeability. Pores that are too large may allow unwanted solutes to pass through, reducing the selectivity of the membrane. Membrane thickness has an inverse relationship with the permeate fluxes of PVDF and PTFE membranes [2]. However, thicker membranes may be needed to increase mechanical stability. This is addressed by selecting membranes with smaller pore sizes to account for the variance in pore size in larger membranes. Feed spacers can be used to mimic the hydrodynamic conditions of large-scale membrane modules by changing the flow regime and creating turbulence inside the flow channel mimicking conditions on spiral wound elements [5]. This ensures that the scale model operates under conditions representative of the full-scale system, minimizing potential discrepancies in permeation behavior. Ensuring that the thickness of the membrane in the scale model is correctly scaled down from the full-scale system is important because, by maintaining the same ratio of membrane thickness to surface area, the diffusion path is preserved. Balancing the need for thicker membranes for mechanical stability without decreasing the permeate rate can be done by using reinforcing materials or structural supports in the scale model to maintain stability without significantly increasing membrane thickness. In addition, as membranes increase in size, they are more susceptible to fouling, where particles or solutes accumulate on the membrane surface or within its pores. Fouling can decrease the effective surface area available for permeation and thus hinder mass transfer, reducing the permeation rate. External technologies such as bubbling, ultrasonic, electric field, and magnetic field can be employed to actively clean and mitigate membrane fouling without interrupting MD processes [4].

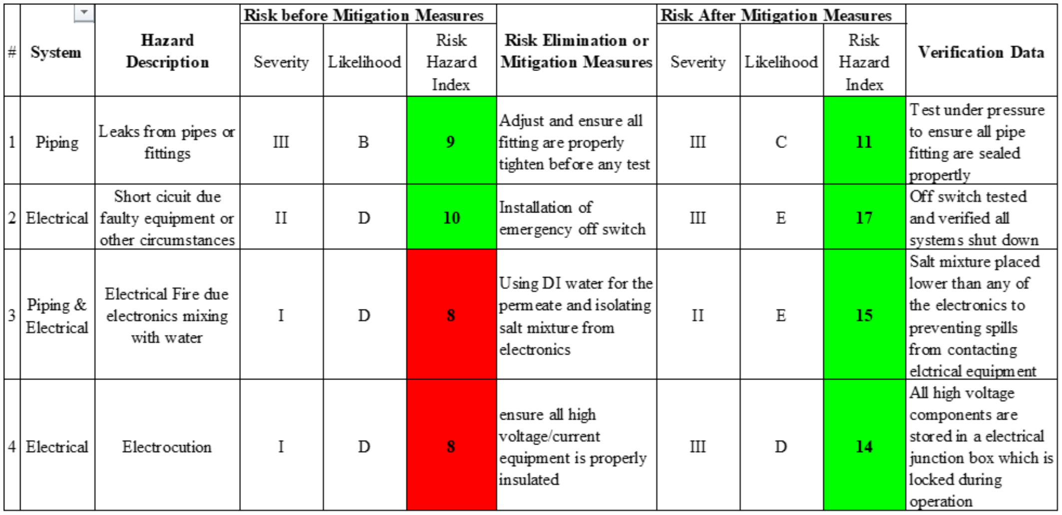
In addition to scaling down operating conditions such as pressure, temperature, and concentration gradients in proportion to the size reduction of the membrane system. Increases in the length of the pipe increase friction losses along the pipe walls, this is due to the greater surface area in contact with the fluid. Frictional losses result in a decrease in fluid velocity and pressure along the pipe length, leading to a reduction in flow rate. Larger pipe diameters generally result in lower friction losses and pressure drop compared to smaller diameters for a given flow rate. However, larger diameters also require higher fluid volumes to achieve the same flow velocity, which may result in increased energy consumption. The overall layout and design of the pipeline system, including the number and arrangement of fittings, bends, and valves, can impact fluid travel. Poorly designed systems with excessive bends or sudden changes in direction can lead to additional pressure losses and flow disturbances. Temperature loss along long lengths of the pipeline will lower the theoretical thermal gradient possible from the ocean. Most of these scaling factors can be accounted for by adjusting values such as pump flow rate to match larger pipe systems and temperature gradients used in the prototype testing.

Some assumptions are necessary due to the limitations of the current prototype setup. In a real ocean thermal system, the thermal gradient would be around 4-20 °C. However, the current prototype is set up with two heated baths used to achieve the temperature difference, which makes a 4-25 °C temperature delta not possible. These assumptions are inaccurate due to the entropy differences between the prototype and the real system, affecting the heat transfer quality. Pumping and heat losses are assumed to be neglectable due to designing efficient pipe layouts and calculating piping sizing and insulations to reduce losses. Assuming other factors remain constant, the rate of permeation increases linearly with the surface area. This relationship stems from Fick's first law of diffusion, which states that the rate of diffusion is directly proportional to the surface area over which diffusion occurs. In a real-world system, the conditions needed for Fick’s law are not guaranteed and testing is required to ensure this assumption holds true. These assumptions are discussed in a later section on future improvements and changes to the prototype made to prevent inaccuracies.

2.3. Risk Mitigation

For the prototype safety the Hazard Identification (HAZID) analysis was used for risk mitigation. Hazard Identification (HAZID) analysis is an industry-standard process used across various sectors to systematically identify potential hazards and risks associated with a particular activity, process, or facility. Considering factors such as equipment, materials, procedures, and environmental conditions. By identifying potential hazards early in the planning or design phase, appropriate control measures to mitigate or eliminate risks before they lead to accidents or injuries. Table 1 shows some of the critical technical risks the team considered in the design process and the actions done to address to reduce these risks. The left side of the table describes the type of hazard along with a description and results in a risk score, red coloring indices an unacceptable risk that needs to be addressed. The right side lists the measures taken in increase the risk index number, where a higher number of indices less risk.

Table 1: Improvement to prototype safety using the HAZID risk assessment



#	System	Hazard Description	Risk before Mitigation Measures			Risk Elimination or Mitigation Measures	Risk After Mitigation Measures			Verification Data
			Severity	Likelihood	Risk Hazard Index		Severity	Likelihood	Risk Hazard Index	
1	Piping	Leaks from pipes or fittings	III	B	**9**	Adjust and ensure all fitting are properly tighten before any test	III	C	**11**	Test under pressure to ensure all pipe fitting are sealed propertly
2	Electrical	Short cicuit due faulty equipment or other circumstances	II	D	**10**	Installation of emergency off switch	III	E	**17**	Off switch tested and verified all systems shut down
3	Piping & Electrical	Electrical Fire due electronics mixing with water	I	D	**8**	Using DI water for the permeate and isolating salt mixture from electronics	II	E	**15**	Salt mixture placed lower than any of the electronics to preventing spills from contacting elctrical equipment
4	Electrical	Electrocution	I	D	**8**	ensure all high voltage/current equipment is properly insulated	III	D	**14**	All high voltage components are stored in a electrical junction box which is locked during operation

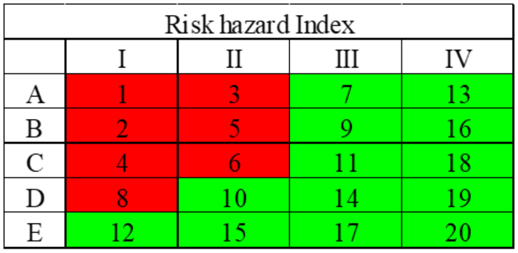
Table 2 describes the risk hazard index ranking, where the Roman numerals represent the severity and letters represent the likelihood of occurrence.

Table 2: Risk category and level descriptions

Description	Category	Hazard Severity	Description	Level	Individual Item
Catastrophic	I	Death or serious injury to people or major damage equipment and surrounding area	Frequent	A	likelihood of occurrence greater than 10^{-2}
Critical	II	Major injnury or major equipment damage	Probable	B	likelihood of occurrence less than 10^{-2}
Marginal	III	Minor injury to the people or minor damage equipment.	Occasional	C	likelihood of occurrence less than 10^{-3} but greater than 10^{-5}
Negligible	IV	Not serious enough to cause injury to people or equipment damage.	Improbable	D	Unlikely but possible to occur in the life of an item, with a likelihood of occurrence less than 10^{-5} but greater than 10^{-6}
			Extremely Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a likelihood of occurrence less than 10^{-6}

Table 3 describes the acceptable risks based on the category and level description in Table 2. The red highlighted portions are deemed high risk and immediate action is required to reduce the risk. The green highlighted portions indicate acceptable risk but are recommended to reduce risk if the index number is close to falling into the red zone.

Table 3: Risk acceptability matrix



Risk hazard Index				
	I	II	III	IV
A	1	3	7	13
B	2	5	9	16
C	4	6	11	18
D	8	10	14	19
E	12	15	17	20

3. Materials and Methods

3.1. Laboratory Prototype

To demonstrate the operation and performance of the proposed MD system concept, a membrane distillation laboratory-scale test prototype was designed and built. The prototype consists of a 4-port flat-sheet membrane cell (CF042A, Sterlitech, Kent WA) that is supplied with feed and distillate solutions from two variable speed pumps (GAF-T23-DE MSE, Micropump, Vancouver WA) that are controlled by mass flow controllers (KF-F200A-SCF-S0A-KA-2X and KF-D100A-SCF-S0A-KA-2X, Alicat Scientific, Tucson AZ). A mass flow meter mounted at the distillate outlet (KD100A-SCF-S0A-KA-2X, Alicat Scientific, Tucson AZ) is used to establish a mass balance between flow in and out and thereby determine water permeate rates. Pressure applied to the feed solution is controlled by a pressure controller (PCS-100PSIG-D-PCA17/5P, Alicat Scientific, Tucson AZ) positioned at the feed outlet. Pressure losses along channels on both sides of the membrane are measured by differential pressure sensors (PS-30PSID-D/5P, Alicat Scientific, Tucson AZ). A commercial software package (FlowVision v2, Alicat Scientific, Tucson, AZ) that was supplied by the flow controller and pressure controller manufacturer was used to send input signals to the mass flow controllers and pressure controller and to acquire data from the flow and pressure sensors. Figure 3 shows the plumbing of the built prototype following the schematic with accompanying labels.

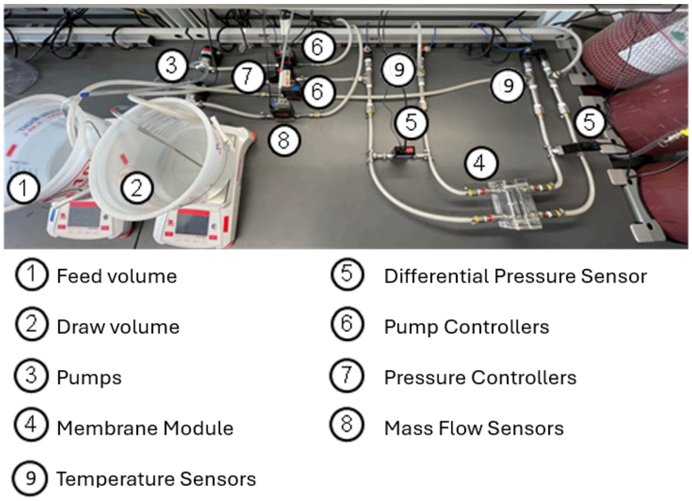


Figure 3. Laboratory scale membrane distillation test prototype at Oakland University.

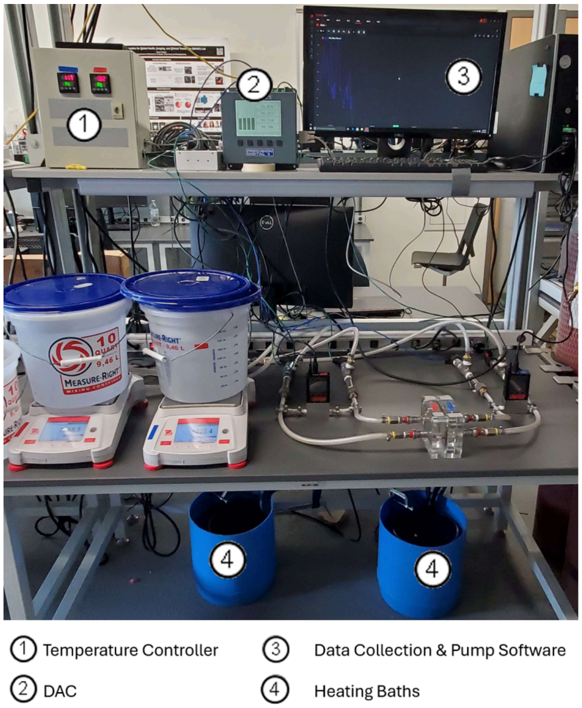


Figure 4. Optimized bench configuration for safety with labels for data acquisition and simulation equipment

Figure 4 shows the prototype layout, the sensitive electrical equipment is elevated to reduce the likelihood of water damage. The bottom contains the liquids so that if any leak occurs, it will not encounter any electrical equipment. The middle layer is the interlink between the two where equipment needs to be near the pipes, with only low-voltage sensors and equipment placed in this layer for safety. A careful design approach is necessary to ensure both functionality and safety. Placing only the necessary low-voltage sensors and equipment near the pipes reduces the risk of electrical hazards. The sensors are linked to the DAC and the computer for data processing and collection. On the bottom are the temperature baths controlled by PID. The temperature controller is installed in a separate container which is locked during testing for safety due to the 120v input for the heaters and to protect the sensitive equipment from potential water damage.

3.2. Temperature Control and Instrumentation

As shown in Figures 5 and 6 the temperature of the bath is controlled using an SSR-60DA switch and an Auber SYL-2352 PID controller for each bath. The use of a PID controller allows for precise and consistent thermal conditions needed for the tests. The proportional component responds to the present error, the integral component integrates past errors over time, and the derivative component predicts future error trends. By balancing these components, PID controllers effectively regulate the heating element in the temperature bath, minimizing oscillations and achieving rapid response to disturbances. This makes PID ideal compared to PI or PD controllers, as permeation rates are directly proportional to the temperature gradient and any temperature variation will negatively affect the data collected. Figure 5 demonstrates the detailed wiring diagram for the temperature prototype layouttrols a 120v resistive heater via a switch to allow for rapid heating of the temperature bath needed to maintain high temperatures for test applications.

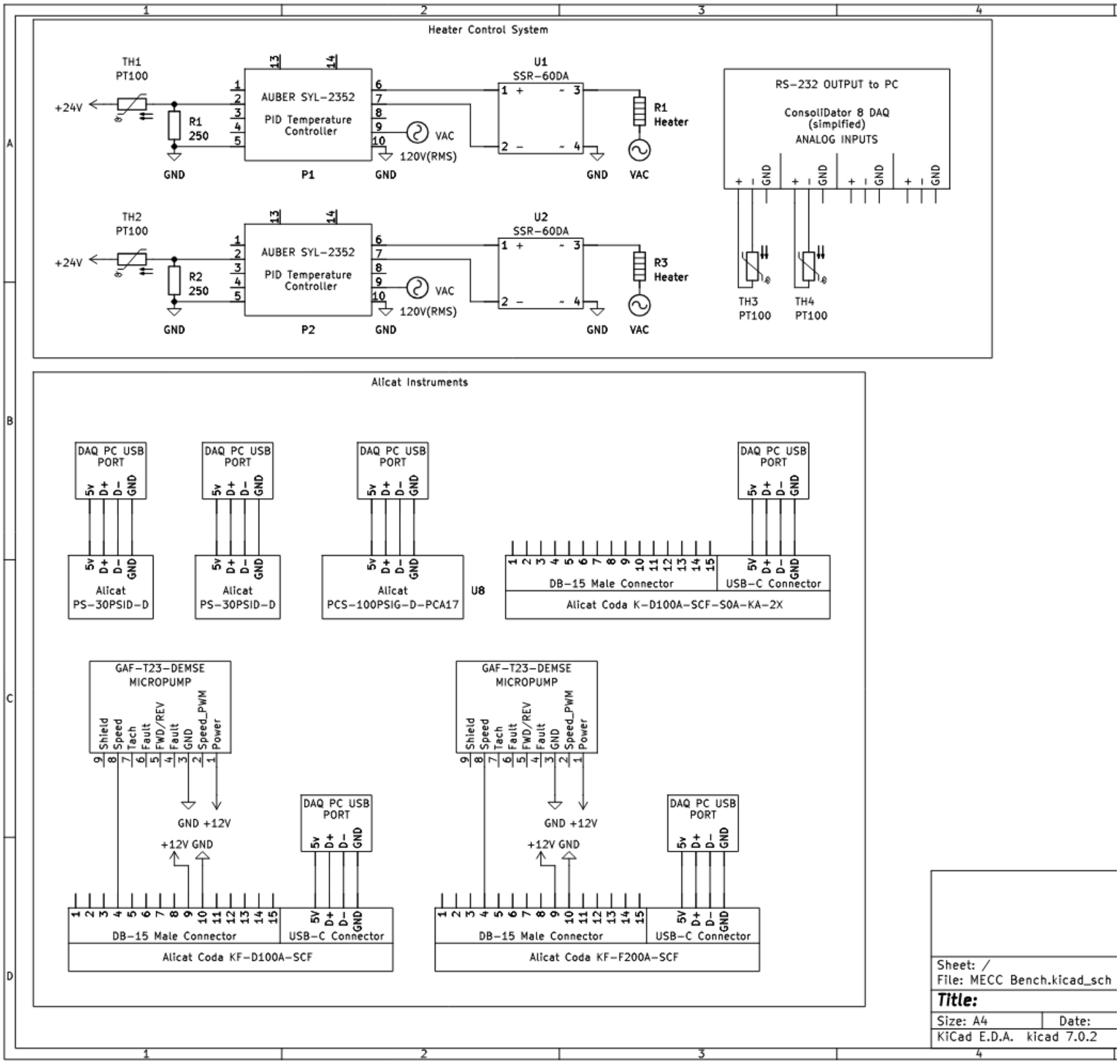


Figure 5: Wiring schematics for the prototype

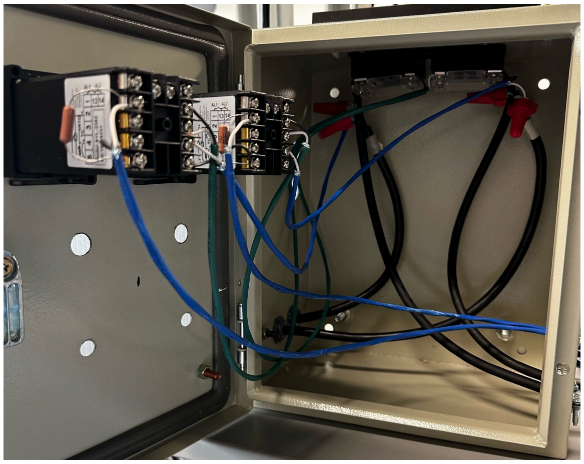


Figure 6: Temperature controller in the electrical junction box.

The temperature of the feed stream is regulated by circulating fluid through the custom PID-controlled thermal bath (WRNK-171S K-type thermocouple and SYL-2352 PID temperature controller, Auber Instruments, Alpharetta, GA). Temperature transmitters (± 0.465 °C, 800-200-1-1-8-8-040-6 RTD, Noshok, Berea, OH) are mounted at inlet and outlet membrane ports. Temperature data is recorded by an auto-logging system (EW-30005-35 Precision Digital, Hopkinton, MA) connected to a PC. The concentration of the distillate at the outlet is measured using a conductivity probe (±20µS, CDCE-90-1, Omega, Norwalk, CT). Table 4 provides a list of all instrumentation with key specifications.

Table 4. Instrumentation list and specifications.

Instrument	Supplier	Model #	Full Scale ± Uncertainty
Feed mass flow controller	Alicat Scientific (Tucson, AZ)	KF-F200A-SCF-S0A-KA-2X	10 kg/h ± greater of 0.2 % full scale or 0.6 % reading
Distillate mass flow controller	Alicat Scientific (Tucson, AZ)	KF-D100A-SCF-S0A-KA-2X	1 kg/h ± greater of 0.2 % full scale or 0.6 % reading
Mass flow meter	Alicat Scientific (Tucson, AZ)	KD100A-SCF-S0A-KA-2X	1 kg/h ± 0.2 % full scale or 0.6 % reading

Temperature sensor	Noshok (Berea, OH)	800-200-1-1-8-8-040-6 RTD	93.33 ± 0.465 °C
Applied pressure controller	Alicat Scientific (Tucson, AZ)	PCS-100PSIG-D-PCA 17/5P	21 bar ± 0.25 % full scale
Differential pressure sensor	Alicat Scientific (Tucson, AZ)	PS-30PSID-D/5P	1 bar ± 0.25 % full scale
Conductivity probe	Omega (Norwalk, CT)	CDCE-90-1	10000 ± 20µS

3.3. Membrane Selection

As shown in Figure 7, a commercial PTFE Flat Sheet Membrane, Unlaminated, 0.45 Micron was selected for this study. This membrane has the potential for increased performance with preparation using Poly (1,4-phenylene ether ether-sulfone) and zinc oxide nanoparticles, combining the prepared membrane and DCMD results in a reduction of various components of seawater. The elimination of ions like sodium, magnesium, and potassium, in the range of 90-99% [3]. Flat-sheet membrane coupons were mounted in the clear acrylic module accommodating samples with an effective surface area of 42 cm2 (107 mm length × 39 mm width). Characteristic membrane properties including water permeability, salt permeability, and effective thickness for this membrane were experimentally evaluated and the results are reported in Table 5. To facilitate operation at the desired flow velocities and provide support to the membrane, shims were inserted into both the feed and distillate channels reducing the effective depth to 0.801 mm. The feed channel was also equipped with a 31-mil diamond-shaped spacer to provide support and mimic conditions of spiral wound membranes mentioned in a previous section.

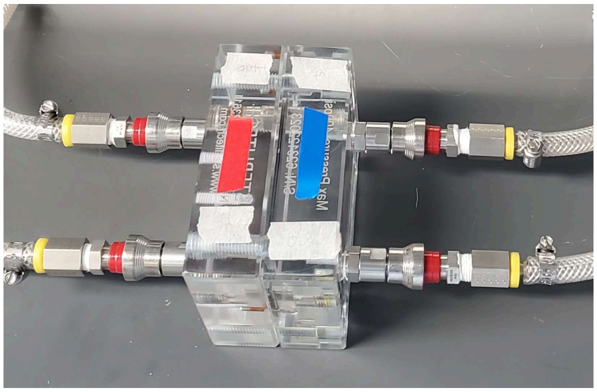


Figure 7: Sterlitech counter flow direct contact membrane module with 42 cm^2 active contact area

Table 5: Membrane and module parameters.

Membrane properties	
Supplier	Sterlitech (Auburn, WA)
Material	Polytetrafluoroethylene (PTFE)
Water permeability	0.42 ± 0.01 lmh/bar
Salt permeability	0.40 ± 0.05 lmh
Structure parameter	0.607 ± 0.01 mm
Module properties	
Configuration	flat sheet
Dimensions	107 mm × 39 mm
Area	42 cm^2
Channel depth	0.801 mm
Feed channel spacer	31-mil diamond-shaped

o

3.4. Test Plan

Extensive testing was conducted to evaluate the performance of the DCMD system. Feed and distillate concentrations of 35 and 0 g/l were used to approximate the use of seawater and DI water. The feed solution was prepared using sodium chloride NaCl (> 99% purity, Fisher Scientific, Hampton, NH) dissolved in deionized water. Solutions are supplied to the membrane cell at circulation rates of 0.15 m/s. Performance was evaluated across a range of feed and temperatures from 21–46 °C and applied pressures from 0. The distillate is maintained at room temperature of 20 °C. A summary of test conditions is provided in Table 6.

Table 6: Experimental test conditions.

Flow configuration	Counter flow
Flow velocity	0.15 m/s
Salt	NaCl
Feed concentration	35 g/l
Feed temperature	20-45 °C
Distillate concentration	0 (deionized)
Distillate temperature	20 °C
Applied pressure	0

3.5. *Data Analysis and Uncertainty*

Water permeate flux and concentration of distillate at the outlet were experimentally evaluated in real-time as operating conditions were varied by the maximum power point tracking algorithm and controller. Testing was conducted on a laboratory scale PRO bench at Oakland University. Table 7 provides a detailed description of how measured data is analyzed to calculate water permeate flux along with propagation of experimental uncertainty. As shown, the permeate flux is calculated with the mass flow rate gathered from the inlet and outlet of the distillate side. The water quality is measured using a conductivity probe to ensure potability of the distillate. The temperature readings are also gathered to correlate the effects of temperature on permeate flux. Paired with inlet temperatures of the hot and cold flows, a graph of the effect of temperature on permeate rate can be obtained. These results will signify whether ocean thermal energy is a viable energy source to drive distillation of seawater.

Table 7: Data analysis and propagation of experimental uncertainty.

Parameter	Value	Measurement or Analysis
Preparation of feed solution		
Feed water mass m_{Fw}	5276.0 ± 0.2 g	Mass balance, AX8201, Ohaus (Parsippany, NJ), 8000 ± 0.2 g
Feed salt mass $m_{F,s}$	182 ± 0.2 g	Mass balance, AX8201, Ohaus (Parsippany, NJ), 8000 ± 0.2 g
Feed concentration c_F	35.05 ± 0.04 g/l	$c_D = \frac{m_{D,s}}{m_{D,w}}\rho$, $\frac{\delta c_D}{c_D} = \sqrt{\left(\frac{\delta m_{D,w}}{m_{D,w}}\right)^2 + \left(\frac{\delta m_{D,s}}{m_{D,s}}\right)^2}$ $\rho = 1000$ kg/m^3
Measurements at steady state		
Inlet feed flow rate $m_{F,in}$	4.4530 ± 0.0267 kg/h	Mass flow controller, KF-F200A-SCF-S0A-KA-2X, Alicat Scientific (Tucson, AZ), 10 ± 0.06 kg/h or 0.6 % reading
Inlet distillate flow rate $m_{D,in}$	0.5998 ± 0.0036 kg/h	Mass flow controller, KF-D100A-SCF-S0A-KA-2X, Alicat Scientific (Tucson, AZ), 1 ± 0.006 kg/h or 0.6 % reading (greater of the two)
Outlet distillate flow rate $m_{D,out}$	0.5702 ± 0.0034 kg/h	Mass flow meter, K-D100A-SCF-S0A-KA-2X, Alicat Scientific (Tucson, AZ), 1 ± 0.006 kg/h or 0.6 % reading
Feed temperature T_F	36.155 ± 0.465 °C	Temperature transmitter, 800-200-1-1-8-8-040-6 RTD, Noshok (Berea, OH), 200 ± 0.837 °F
Distillate temperature T_D	23.494 ± 0.465 °C	Temperature transmitter, 800-200-1-1-8-8-040-6 RTD, Noshok (Berea, OH), 200 ± 0.837 °F
Distillation rate at steady state		
Water permeate flux J_w	7.127 ± 1.182 l /m^2/h	$J_w = \frac{\dot{m}_{D,out} - \dot{m}_{D,in}}{a\,\rho}$, $\delta J_w = \sqrt{\delta \dot{m}_{D,out}^{\,2} + \delta \dot{m}_{D,in}^{\,2}}$ a = 0.0042 m^2 , $\rho = 1000$ kg/m^3
Distillation quality		

Permeate conductivity σ_P	497.5 ± 20 µS/cm	Conductivity probe, CDCE-90-1 Omega, (Norwalk, CT), 10000 ± 20µS
Permeate concentration c_p	0.23 ± 0.02 g/l	$c_p = f\,\sigma_p\ ,\ \frac{\delta c_p}{c_p} = \sqrt{\left(\frac{\delta\sigma_p}{\sigma_p}\right)^2 + \left(\frac{\delta f}{f}\right)^2}$ f = 0.000452 ± 0.0000278 by linear interpolation of Table 4

4. Results

Water permeate flux and concentration of distillate at the outlet were experimentally evaluated in real-time as operating conditions were varied by the maximum power point tracking algorithm and controller. Testing was conducted on a laboratory-scale PRO bench at Oakland University. As shown, the moving average of sensor data is used to filter noise when evaluating water permeate rate and power, especially related to the draw side pressure loss which shows very high variability. All experiments were done under an inlet flow rate of 1000 g/h for the cold side, 2000 g/h for the hot side, and under 1 psi of pressure to ensure consistent tests and ensure temperature is the main driving force for desalination. The water permeate rate uncertainty averages around 2 liters per meter squared hour for each test. The water conductivity of the permeate was taken to determine salt content, however, the results given the conductivity probe were inconsistent. Conductivity equipment falls within the uncertainty range for salinity testing. In future tests, a refractometer should be used for more consistent and precise results.

4.1. Effect of Temperature on Water Permeate Rates

The results are gathered from the average flux after reaching a steady state at a varying delta T (temperature difference) ranging from 0 to 30 °C. Increasing the delta T beyond 20 °C shows the effect of adding solar energy in the system to further heat the feed side. Figure 8 shows the performance of temperature gradients as a driving force for membrane desalination. As shown, the permeate flux is linearly correlated with delta T, however, the flux rate experiences a dip at a delta of 25 °C which might be due to the uncertainty of 2 liters per square meter hour. The graph indicates whether using ocean thermal energy is a viable option to convert marine energy to clean water. Resulted in acceptable water permeate rates compared to 3-6 LMH of other membrane distillation processes [1].

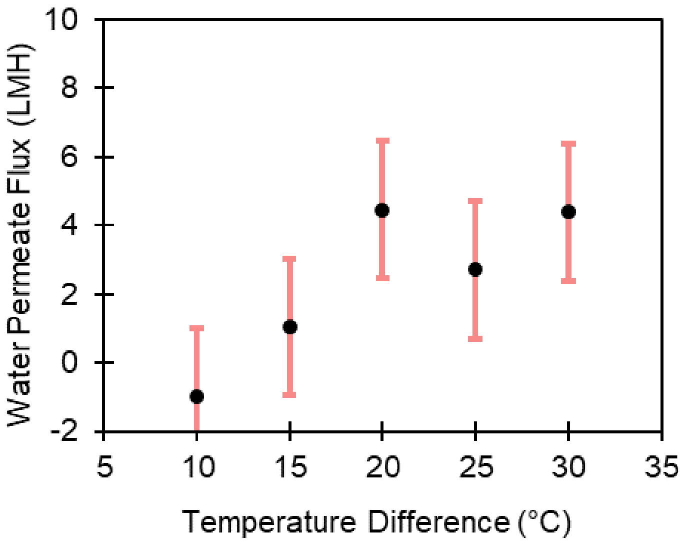


Figure 8: Effect of temperature difference on water permeate rates.

4.2. Effect of Feed Concentration on Water Permeate Rates

Testing with different feed concentrations up to 140 g/l to show the effect of different feed sources on permeation rate. Increasing the feed concentration above 35 g/l shows the effect of recovering a lot of water from the feed, in which case its concentration would increase. As shown in Figure 9, salt concentration negatively affects the water permeate rate. However, at a certain point, the higher concentrations of salt no longer affect the permeate flux rate. This result shows that salt concentration found in seawater does not severely affect the permeation rate of the system, Indicating the proposed system using ocean thermal gradients would be well suited for desalination purposes.

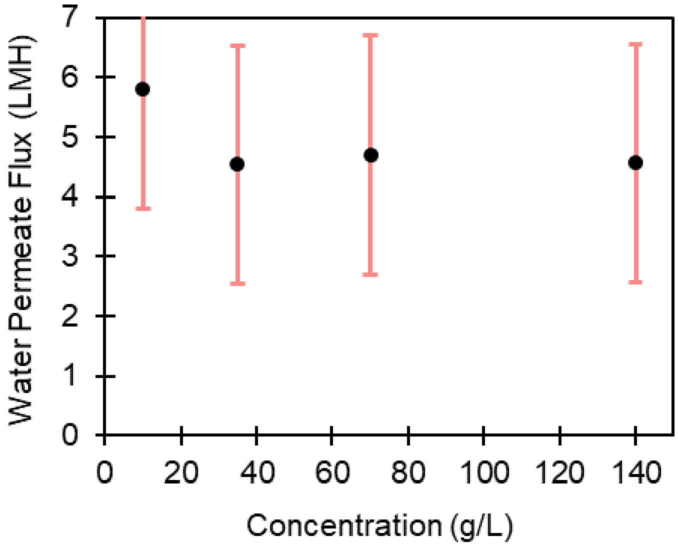


Figure 9: Effect of concentration on water permeate rates.

4.3. Combined Effect of Temperature and Concentration on Water Permeate Rates

To verify the relationship between concentration temperature and permeate rates is correct, a test with a concentration of 10 g/l at varying temperature deltas was performed. The result as shown in Figure 10, shows that the slope is similar to Figure 8, with the permeates rate shifted higher due to the reduced salt concentration in the feed. This falls within expectations, however, the same dip in flux rate is seen in a delta of 25 °C, which could signify that it is not due to uncertainty. Further testing is required with higher precision equipment to determine the cause of this dip.

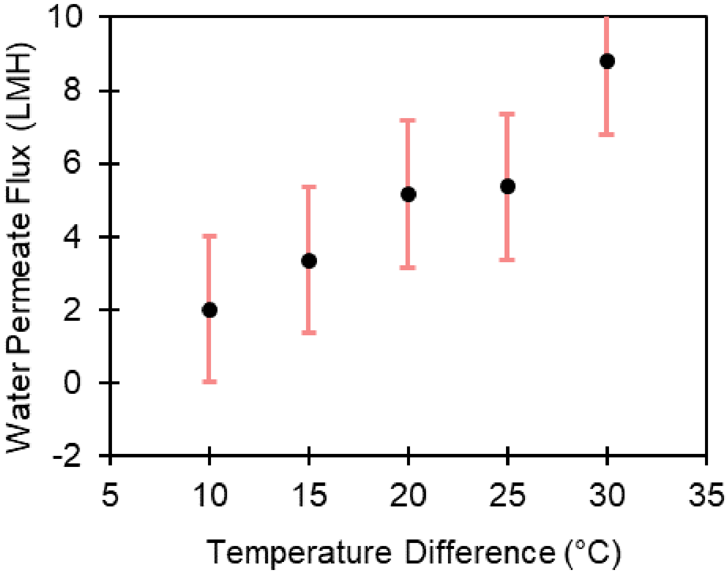


Figure 10: Effect of concentration and temperature on water permeate rates.

4.4. Durability of the System

The durability of the DCMD systems is usually limited by the product lifetime of the membrane. Figure 11 depicts membrane fouling after several tests which is an unexpected result, especially when the feed only consists of distilled water and salt. The likely cause could be contaminants present in the piping system or rust buildup, which inadvertently introduced impurities into the feedwater stream, leading to fouling. This fouling could contribute to some of the inconsistencies in the test results. Implementing an in-line filter before the membrane unit is recommended to address this issue in future tests. This filter would serve as an additional barrier to remove any contaminants or particulate matter present in the feedwater, thereby preventing their accumulation on the membrane surface. Further testing should consist of testing the effectiveness of inlet filters along with other methods to increase the durability of the system.

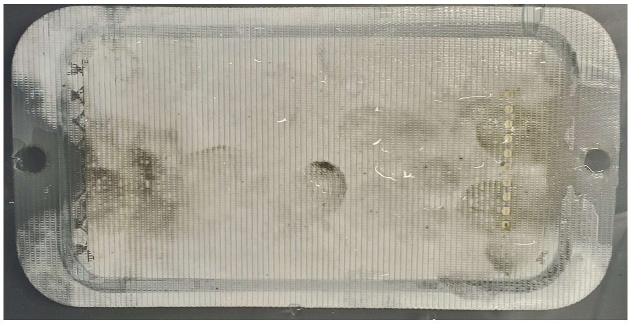


Figure 11: Membrane fouling over continuous testing.

5. Conclusions

The current setup faces limitations in achieving the desired real delta T (temperature difference) of 5-20 °C. Piping and heat loss losses were not accurately considered, impacting the accuracy of the data. To address this, improvements for future iterations are as follows. Instead of using two heated baths to represent the delta T, which introduces inaccuracies due to entropy, a high-capacity cooler along with a heat exchanger could be implemented to simulate the real system’s temperature gradient more accurately. Additionally, introducing contamination to induce fouling would allow testing of membrane life and better cost analysis of the system, along with testing inlet filters and other methods mentioned in the report to prevent the build-up of unwanted particulates on the membrane. Material testing for insulation and pipe size calculations would allow for a more accurate assessment of heat losses and pump losses. These improvements aim to enhance the accuracy of the tests, ensuring higher consistency with a real DCMD system running about ocean thermal gradients. However, further limitations arise from assumptions made about the system's behavior, such as assuming steady-state conditions and linear scalability of the permeate rate to the area due to Fick's first law of diffusion. In a real system, these assumptions may not hold true, as turbulent flows can prevent steady-state conditions, and real-world scenarios may deviate from idealized boundary conditions. Future testing will need to verify this relation with empirical data. Future work could focus on developing models that account for non-homogeneous mediums, spatial variations in diffusion coefficients, and dynamic boundary conditions to refine the underlying assumptions and improve the system's predictive accuracy. Improvements to the current system such as a higher rated flow controller and refractometer will prevent some of the difficulties in gathering data on the current prototype.

6. References

[1] S. Adham, J. Minier-Matar, and A. Hussain, “Pilot plant evaluation of membrane distillation for desalination of high-salinity brines,” *Applied Water Science*, vol. 13, no. 12, Nov. 2023. doi:10.1007/s13201-023-02017-x

[2] Y. Zhou *et al.*, “Experimental investigation of the desalination process for direct contact membrane distillation using plate and frame membrane module,” *Applied Sciences*, vol. 13, no. 16, p. 9439, Aug. 2023. doi:10.3390/app13169439

[3] C. Hegde and R. Ribeiro, “Preparation and characterization of hydrophobic membranes and their seawater desalination performance study by direct contact membrane distillation,” *Nature Environment and Pollution Technology*, vol. 21, no. 4, pp. 1599–1608, Dec. 2022. doi:10.46488/nept.2022.v21i04.012

[4] S. Du, P. Zhao, L. Wang, G. He, and X. Jiang, “Progresses of advanced anti-fouling membrane and membrane processes for high salinity wastewater treatment,” *Results in Engineering*, vol. 17, p. 100995, Mar. 2023. doi:10.1016/j.rineng.2023.100995

[5] S. Jankhah, “Hydrodynamic conditions in bench-scale membrane flow-cells used to mimic conditions present in full-scale spiral-wound elements,” *Membrane Technology*, vol. 2017, no. 5, pp. 7–13, May 2017. doi:10.1016/s0958-2118(17)30096-4

[6] K. Rajagopalan and G. C. Nihous, “Estimates of Global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model,” *Renewable Energy*, vol. 50, pp. 532–540, Feb. 2013. doi:10.1016/j.renene.2012.07.014