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Delivery of a Solar-Powered Forward Osmosis Seawater Desalination Plant: Trevi's 500 m3/day Zero-Carbon FO Seawater Desalination Plant at NELHA

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Abstract:

This paper presents an account of Trevi's delivery of a 500 m3/day solar powered forward osmosis (FO) seawater desalination plant at the Ocean Science and Technology Park of the Natural Energy Laboratory of Hawaii Authority (NELHA). The project aimed to demonstrate the viability of solar thermal-powered desalination for agricultural applications through the integration of a 2MW micro-dish solar thermal array with a state-of-the-art FO system. Highlighted in the paper are the three distinct project phases; Planning and Design, System Construction, Installation & Testing followed finally by System Operation and Optimization. Results and decisions which led to the final plant design will be shared, highlighting how Trevi Systems succeeded in producing a zero-carbon FO seawater desalination plant with a projected Levelized Cost of Water (LCOW) estimate competitive with existing carbon-intensive RO technologies (based on some assumptions and the cost of heat which is required for FO). Trevi's design and implementation of a solar-powered FO seawater desalination plant at NELHA demonstrated groundbreaking advancements in sustainable desalination. The careful planning, strategic design selection, and innovative technological developments resulted in a zero-carbon, competitive LCOW desalination solution.

Keywords: Forward Osmosis, Solar-Powered Desalination, Seawater Reverse Osmosis, Renewable Energy, Environmental Sustainability

1. Introduction

The pressing global water crisis, exacerbated by population growth, climate change-induced disruptions, and the decline in freshwater reserves, underscores the urgent need for sustainable and innovative solutions in water resource management. This crisis has propelled the quest for advanced desalination technologies capable of mitigating freshwater scarcity and ensuring a reliable supply of potable water. Consequently, the imperative to develop efficient, energy-effective, and eco-friendly desalination technologies has never been more critical.[1]

Conventional desalination methods, primarily seawater reverse osmosis (SWRO), have been instrumental in augmenting freshwater supply. However, the widespread adoption of SWRO has been constrained by its carbon-intensive operation, reliant on non-renewable electrical energy resources. These approach, while technically effective, imposes a substantial environmental footprint and escalating cost as fossil fuels decline, rendering them less sustainable and economically viable in the long term.[2]

In response to these challenges, Trevi Systems Inc designed and produced a 500 m3/day solar-powered Forward Osmosis (FO) seawater desalination plant, made possible by a $4 million grant from the US Department of Energy and awarded to NELHA in 2019. The project's aim was to introduce a renewable-energy driven desalination system, leveraging the inherent advantages of FO technology to address the water crisis sustainably.

FO technology, predicated on utilizing the natural process of osmosis, osmotic concentration differentials, and low-pressure operation, offers a promising alternative to the energy-intensive nature of traditional reverse osmosis desalination method. By harnessing solar thermal energy and integrating FO instead of RO, Trevi sought to demonstrate an approach that alleviates the carbon burden associated with reverse osmosis.

Ultimately, the transformative potential of renewable FO technology heralds a promising era in zero-carbon water resource management, steering us towards a more resilient and sustainable water-dependent ecosystem.

2. Materials and Methods

The project was structured into three distinct phases, each delineating specific stages and decision-making criteria.

2.1. Project Phase 1: Planning and Design

This phase focused on establishing the groundwork for the renewable forward osmosis (FO) plant, encompassing environmental and logistical assessments and selection of critical components for the solar FO system. Key activities included:

2.1.1. Draw Solution Toxicity Assessment: Protocols were devised and implemented to evaluate the toxicity of the draw solution concerning a downstream algae farm user. In case of toxicity, mitigation strategies were identified and employed.

2.1.2. CSP Array Design Modifications & Recommissioning: A process was undertaken to re-power an idle Concentrated Solar Power (CSP) array, which had been inactive for nearly 8 years after it failed to meet electrical energy delivery targets.

2.1.3. Component Selection for the FO System: Evaluation and testing were conducted for crucial elements like membranes, draw solution cost, heat exchangers, and system instrumentation. Innovations in draw solution design, polymeric heat exchanger development, and FO membranes were explored to improve efficiency while reducing capital expenditure.

2.2. Project Phase 2: System Construction, Installation & Testing

During this second phase, the various key cost components of the solar FO systems were tested, followed by the construction and integration into the solar CSP plant at the NELHA site. This was undertaken despite challenges posed by the Covid outbreak and associated quarantine measures. Key activities involved:

2.2.1. Testing CSP Array: Testing was performed on the CSP array, accompanied by the replacement of outdated computer architectures, and configuring the array to operate with hot water storage of less than 130ºC.

2.2.2. FO plant metric performance identification: Three significant metrics were identified:

a. Verification of overall system operation during low water production (turndown range).
b. Ensuring the FO system did not release polymer into the environment through reverse diffusion through the FO membrane.
c. Utilizing the reconditioned CSP array to reliably provide and regulate heat to the FO plant.

2.3. Project Phase 3: System Operation and Optimization

This phase focused on multiple operational cycles, with water production, water quality testing and optimization procedures to enhance the plant performance. Key elements included:

2.3.1. Identifying and Measuring Performance Metrics:
  2.3.1.1. Ensuring the reconditioned CSP system met thermal production metrics.
  2.3.1.2. Validating the correct functioning of the thermal energy storage system.
  2.3.1.3. Determining water production rates from the FO system.

2.3.2. Cost Projection and Analysis: Calculations based on capital and operating costs of the pilot plant were utilized to project costs for a 20X scaled plant. These projections, informed by pilot plant data, aided in setting thermal energy cost targets for future CSP arrays to meet Levelized Cost of Water (LCOW) objectives. These estimates were compared to traditional seawater reverse osmosis (SWRO) estimates for a similar sized plant.

3. Results: Final FO Design Selection & Operation

This comprehensive three-phase structure led to results that informed the final selection and operational blueprint and guided the project toward a refined, sustainable, and renewably powered FO plant, marked by its technological advancements, sustainability, and alignment with cost-efficient water production.

3.1. Results from Project Phase 1: Planning and Design

3.1.1. Draw Solution Toxicity Assessment

This sub-phase of the project included conducting end-user testing of Trevi's forward osmosis (FO) draw solution polymer, evaluating its impact on the growth rate and productivity of commercially produced freshwater microalgae. The subcontractor Cyanotech carried out controlled laboratory tests on three key species of microalgae, assessing the effects of varying concentrations of the FO polymer on algae growth as shown by the two figures below.

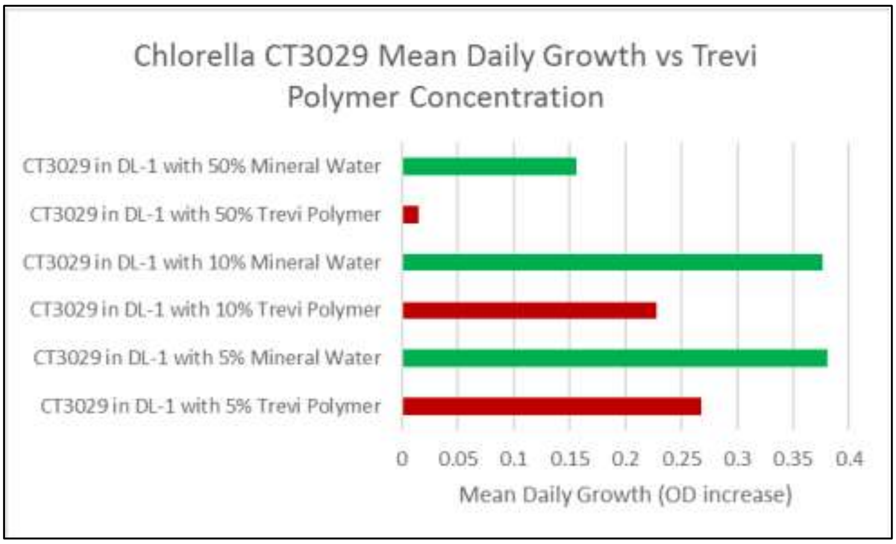


Fig 1: Chlorella growth vs. Polymer concentration

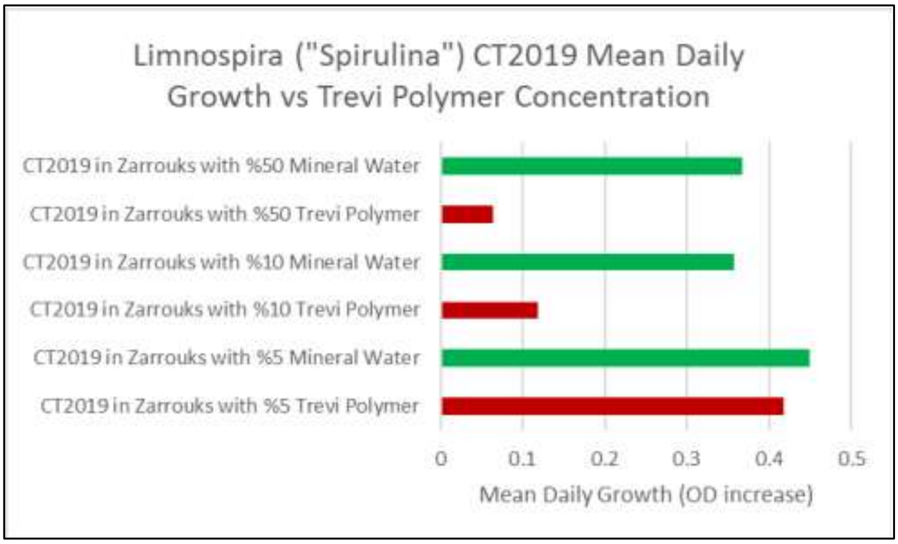


Fig 2: Limnospira Groth vs Polymer concentration.

The findings indicated that concentrations below 500 ppm had no discernible adverse effects on algal growth or appearance. However, concentrations exceeding 500 ppm led to growth suppression and eventual culture death. Daily additions up to 5 ppm did not impact growth. Additionally, FO polymer did not affect the microbiome of production cultures below 500 ppm. These results suggest that Trevi's FO system can deliver water that meets Cyanotech' s requirements for growing algae, provided the system implements fail-safe measures to prevent polymer concentrations from exceeding 10 ppm in the delivered water, alerting users in case of system failure. The study's findings offer valuable insights into ensuring the compatibility of FO systems with algal cultivation needs.

3.1.2. Design Modifications & Recommissioning of the CSP Array

There were 2 major undertakings in this sub-task. The existing CSP array had to be modeled to determine the operating range of its application as a thermal energy source and the necessary modifications were determined and designed for coupling with the FO system. The existing thermal energy storage system capacity was evaluated, and a supplemental storage system was also sized and specified for procurement and installation in a subsequent phase of the project.

3.1.2.1. Estimate of CSP System capacity

The CSP system, covering 8180 m^2 with 980 mirrors, yielded an annual production of around 17.4GWh/year with an average GHI of 5.6kWh/m2. Using NELHA's solar data, daily energy calculations and two thermal energy models for Trevi’s FO plant (38kWh/m^3 design and a stretch target of 32kWh/m^3), monthly water production was estimated, shown in Figure 3 below.

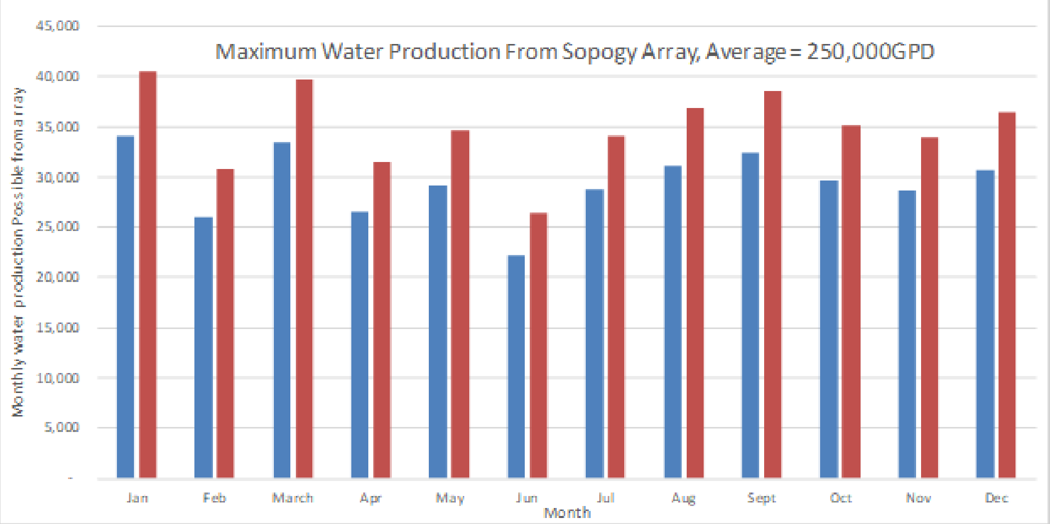


Figure 3 - Modelled Monthly Production Capacity of FO System Powered by the NELHA CSP Array

Figure 3 illustrates the monthly production capacity of the FO system powered by the NELHA CSP Array. Blue bars indicate existing (higher) thermal energy consumption (resulting in lower water production) from Trevi's current FO system, while red bars show increased water production if energy improvement targets are met. In June, the lowest solar output (worst-case blue bar) forecasted a production of 22,000m^3/month or 733m3/day (193,000gpd) assuming a 100% roundtrip thermal storage efficiency.

3.1.2.2. Supplemental Thermal Storage for CSP

This section evaluated adding additional thermal storage options for powering Trevi's 500m^3/day FO system. It projected storage sizing at 38 kWh (126 MJ) and for the stretch goal of 30kWh/m^3 production rate, factoring in 12% extra for heat loss, or approximating 40 kWh/m^3 in thermal energy. For daily operation, the system requires 20,000 kWh (72,000 MJ), needing 833 kW or 3,000 MJ per hour. Analysis suggests that during sunlight hours, the CSP array could sustain full capacity, but stored thermal energy is essential at night or when sunlight is unavailable. The existing NELHA CSP storage system comprises two tanks with 4500 gallons each of hot water storage. This provides approximately 2 hours of storage time under full production, so additional storage would be essential to meet capacity contracts. An investigation into numerous storage options was undertaken and Phase Change Energy Solutions' BioPCM showed increased storage capacity but at significantly higher costs compared to hot water, making hot water the most cost-effective choice. The following table presents a performance and cost comparison of their newest BioPCM storage system vs. hot water.

Operating Range	PhaseStor 180-170C	Water 180-170C	PhaseStor 180-80C	Water 180-80C
Volume and Mass	4.3m^3/4500lbs	4.8m^3/5300lbs	4.3m^3/4500lbs	4.8m^3/5300lbs
Latent kWh	175	0	175	0
Sensible kWh	12	27	125	272
Total Energy	187	27	300	272
Cost			$260,000	$17,740
Advantages	90% stored at high temp		90% stored at high temp	
Disadvantages				Stored over wide range (2 tank solution).

Table 1 - Thermal Storage Comparison of PhaseStor and Water

3.1.3. Component Selection for FO System

3.1.3.1. Draw Solution Optimization

Trevi opted for a liquid/liquid extraction methodology in the development of its fourth-generation FO system at NELHA. This approach hinges on utilizing a salt draw solution interfacing with the FO membrane, followed by a thermo-lytic polymer extraction stage. During the initial phase, three polymer and salt combinations were earmarked for testing. Suppliers were engaged to provide volume quotations for the required chemicals. However, environmental concerns arose regarding the selected ionic salts due to their potential promotion of organic growth in the environment, like the phosphates used in agricultural fertilizers. Subsequently, several amino acid salts, as well as organic salts such as Potassium Citrate, Potassium Tartrate, Choline Taurate, and Potassium Taurate, were scrutinized. Notably, some of these compounds also boast CO_2 carbon capturing capabilities, highlighting the potential of a draw solution that can both sequester CO_2 and leverage low-grade heat for regeneration, albeit beyond the scope of this grant.

Exploration of carbon capture abilities was undertaken using a CO_2 bubble column under pressure. Potassium Taurate, an alternative CO_2 sequestering salt, exhibited promising carbon uptake potential, suggesting its viability for both flue gas water purification using FO and carbon sequestration. For ease of sourcing, safety, low environmental impact, and for mitigating reverse diffusion concerns through the FO membrane, magnesium sulphate (Epsom salts) was chosen as the primary draw agent.

Regarding polymer optimization, Trevi's current TL1150-1 polymer exhibited commendable performance except for reduced osmotic pressure at higher temperatures. Despite Hawaii's cooler waters not posing a problem, further optimization of similar compounds was undertaken to enhance overall performance in future plants where the warmer Gulf seawaters would be a factor. Collaboration with Nippon Shokubai, a large Petro-chemical manufacturer yielded the EO-BO variety of polymers, with reduced thermal dependence as shown in Figure 4 below:

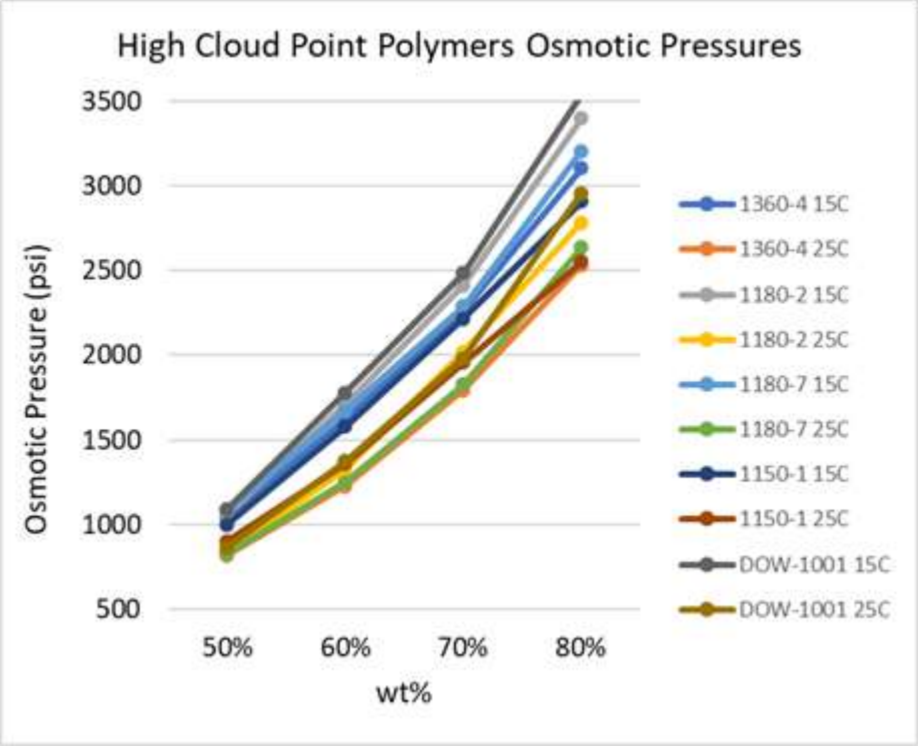


Figure 4 – Draw Solution Osmotic Pressure vs Concentration.

Adjustments were made to increase the osmotic pressure of the draw solution from a cloud point temperature of 65C to 75C, leveraging the solar thermal array's capacity to generate higher temperatures, as osmotic pressure is linearly correlated with cloud point for the thermolytic polymers under consideration.

Analysis of polymer osmotic pressure between 15C and 25C indicated osmotic pressures exceeding 3000psi, suggesting potential seawater recovery rates of over 80% (scaling neglected for the moment) in Hawaii. This higher recovery rate showcased the FO plant's potential to outperform RO systems, typically operating at around 45% recovery. This higher recovery in FO systems reduces the need for high pre-conditioning chemicals in the pre-treatment stages, subsequently curtailing both capital and operating costs proportionately.

Further qualification of additional vendors through testing was conducted based on a pre-defined specification from Trevi. Notably, polymers such as 55GI-1602, 70GI-2703, 55GI-2001, 55GI-2101, 55PI-1501, 55TG-36, GL-2015-BC, GL-2108, GL-2109, GL-2110, 70BI-2601, 70BI-1501, and 70GI-1803 showcased favorable properties. Conversely, approximately 5 polymers did not pass the rapid screening test, culminating in the selection of an EO-BO polymer from Nippon Shokubai for its advantageous phase separation characteristics, robust osmotic strength, and low toxicity.

3.1.3.2. FO Membrane Selection

Trevi had to evaluate available FO membrane suppliers through small-scale water production vs. cost analysis and identify the preferred membrane types and suppliers for integration into the FO system. The selection process considered both capital and operating costs designed for the nominal 500 m3/day configuration.

Assessments were carried out on three distinct membrane configurations:

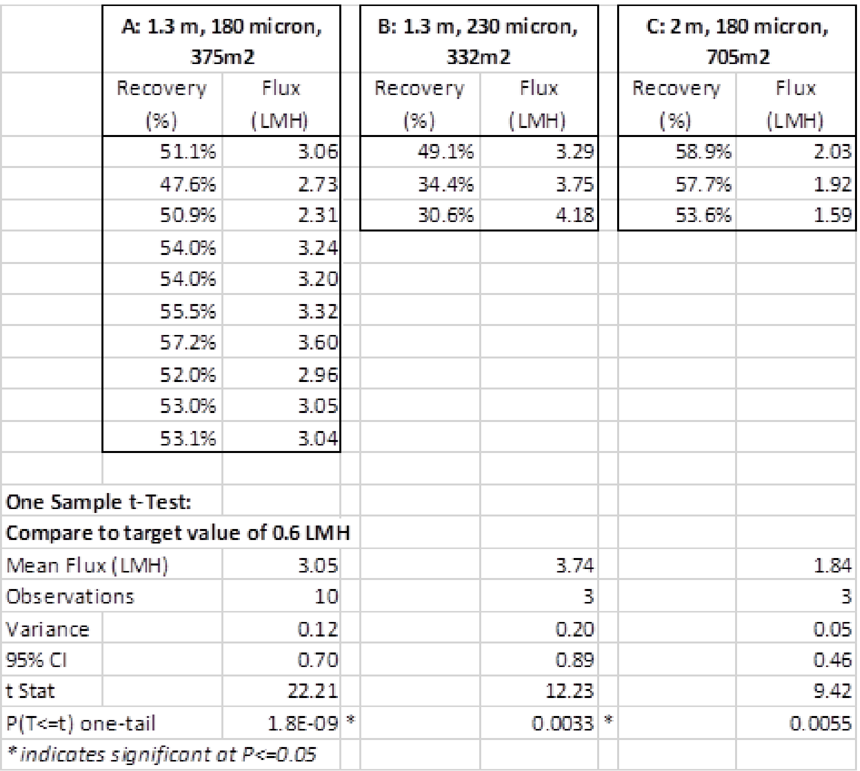
a) 180 micron/1.3m long hollow fiber membranes,
b) 230 micron/1.3m long hollow fiber membranes, and
c) 180 micron/2m long hollow fiber membranes.

Experiments entailed feeding concentrated polymer draw agent on the shell side of the membrane and synthetic seawater in the bore. Comparisons revealed that directing the strong draw from the outer circumference towards the center yielded nearly identical water production to the configuration with the draw was fed from the center towards the outer circumference as shown by Table 2 below.

Membrane Type	Strong Draw	Seawater Feed	Surface Area (m^2)	Strong Draw Flow (m^3/Day)	Feed Flow (m^3/Day)	Strong Draw Pressure (PSI)	Seawater Feed Pressure (PSI)	Water Produced (m^3/Day)	Flux (LMH)	Seawater Recovery Rate (%)
1.3m, 180 Micron	Shell In->Out	Bore	375	64.32	54.78	14.5	40	32.19	3.58	54.0%
1.3m, 180 Micron	Shell Out->In	Bore	375	68.68	53.42	16	40	31.34	3.48	53.1%
1.3m, 180 Micron - Modified	Shell In->Out	Bore	375	69.23	53.42	18.5	40	30.03	3.34	52.0%
1.3m, 230 Micron	Shell In->Out	Bore	332	63.23	87.21	14	40	32.16	4.04	34.4%
1.3m, 230 Micron	Bore	Shell In->Out	332	51.78	48.51	42	6	27.15	3.41	41.7%
2m, 180 Micron	Shell In->Out	Bore	705	61.05	55.06	10	42	33.41	1.97	60.7%
2m, 180 Micron	Shell Out->In	Bore	705	67.59	58.33	13	41	34.34	2.03	58.9%

Table 2 - FO Membrane Test Results

All three membranes surpassed the benchmark target of 0.6 LMH, displaying mean flux rates (± 95% CI) of 3.05±0.70, 3.74±0.89, and 1.84±0.46, respectively. Consequently, the tested membranes produced approximately 30 m^3/day of fresh water at a 50-55% recovery rate (refer to Table-3).



	A: 1.3 m, 180 micron, 375m2		B: 1.3 m, 230 micron, 332m2		C: 2 m, 180 micron, 705m2	
	Recovery (%)	Flux (LMH)	Recovery (%)	Flux (LMH)	Recovery (%)	Flux (LMH)
	51.1%	3.06	49.1%	3.29	58.9%	2.03
	47.6%	2.73	34.4%	3.75	57.7%	1.92
	50.9%	2.31	30.6%	4.18	53.6%	1.59
	54.0%	3.24				
	54.0%	3.20				
	55.5%	3.32				
	57.2%	3.60				
	52.0%	2.96				
	53.0%	3.05				
	53.1%	3.04				
One Sample t-Test:						
Compare to target value of 0.6 LMH						
Mean Flux (LMH)		3.05		3.74		1.84
Observations		10		3		3
Variance		0.12		0.20		0.05
95% CI		0.70		0.89		0.46
t Stat		22.21		12.23		9.42
P(T<=t) one-tail		1.8E-09 *		0.0033 *		0.0055
** indicates significant at P<=0.05*						

Table 3 - Comparison of FO Membrane Performance Results to Benchmark Metric

This enhanced performance compared to previous state-of-the-art solutions significantly reduces the expected membrane count and overall form-factor to one-third of the initially projected figures for the plant.

Pricing for the specified membranes were acquired from three commercial vendors. The lowest quotation for the 500m3/day demonstration system stands at $150,000, constituting a third of the original project budget for this aspect. Scaling up to a full commercial 10,000m3/day system sees the quoted unit pricing halve from this initial amount.

3.1.3.3. Heat Exchanger Development & Testing

This task focused on heat exchanger development and testing, aiming to compare new Trevi designs to commercially available options, optimize costs, sizes, and performance for integration into the FO system. The primary objective was to find cost-efficient alternatives to the conventional plate-and-frame heat exchangers, known for their poor performance when the substantial viscosity changes experienced in Trevi's FO polymer are taken into consideration.

To address this challenge, a two-pronged approach was employed: internally designing and fabricating a low-cost polymeric heat exchanger and outsourcing the development of a custom-built metal unit.

Polymeric Heat Exchangers - Pilot Scale:

A prototype of Trevi's inline "twisted tube in shell" polymeric heat exchanger was designed, built and bench tested. The heat exchanger consisted of PEEK tubes twisted around each other and bundled into an annular tubular space. Initial tests demonstrated promising heat transfer coefficients, but further optimizations were necessary for practical implementation.

Polymeric Heat Exchangers - Modelling Scale-up:

Numerical models were developed to assess tube diameter and length requirements for the novel heat exchanger design, factoring in fluid properties, tubing geometry, and performance metrics. These models allowed for comprehensive visualization of trade-offs and led to the selection of polypropylene as the low cost material of choice for cost-effective tubing.

Makai Thin Foil Heat Exchangers:

In a paid study Makai Engineering designed and tested Thin Foil Heat Exchangers (THFXTM), which show potential for weight and size reductions compared to traditional plate-and-frame units. Prototype testing of THFXTM revealed unforeseen behaviors due to low fluid velocities and the specific properties of the FO polymer, necessitating adjustments in the design.

Despite initial progress in developing proprietary polymeric heat exchangers and exploring Makai's THFXTM, unforeseen challenges arose, impacting their immediate integration into the FO system. To expedite the FO plant build and mitigate program risks, Trevi decided to procure standard commercial plate-and-frame heat exchangers. While innovative heat exchanger designs showed promise, unforeseen complexities prompted Trevi to opt for conventional units to meet immediate project timelines and minimize risks.

3.1.3.4. Nano-filtration Membrane Selection

This activity focused on developing and testing high-temperature nano-filters for potential integration into the FO system as a draw solution polishing step. The aim was to leverage these filters to modify the system design, reducing thermal energy consumption, heat exchanger sizes, and potentially cutting final nano-filtration costs.

A critical aspect of various applications, including forward osmosis desalination, is the acquisition of nano-filters that maintain useful permeate flux and effective rejection rates at high temperatures.

Initial testing of a commercially sourced ceramic Al_2O_3-based tubular ceramic membrane had promising results. This membrane achieved impressive rejection rates of the bulk draw solution at high fluxes and temperatures under moderate pressure (less than 80psi).

The project initially focused on internally fabricated elements utilizing nano-coated ceramic elements. These elements were manufactured by coating existing UF ceramic membranes with a thin layer of polymerized film. Although preliminary tests showed some success in terms of rejection rates and flux at high temperatures, the performance degraded over time, which is an ongoing area of research to resolve. Subsequently, the project shifted focus to electrochemically depositing metallic coatings on cost-effective substrates, but these results were also unsatisfactory due to poor rejection stability.

Eventually, the team identified, tested, and selected a commercially available ceramic nano-filtration membrane during the developmental phase, marking a shift toward procuring these ready-made units for the FO system.

3.1.3.5. FO System Design

We developed a completed FO system design and from this, a Process & Instrumentation Diagram was generated (see Figure 5 below). From the P&ID, a process flow diagram was generated (PFD) to determine the flow rates in the various parts of the system, aiding in pipe and pump sizing, as well as heat exchanger sizing. Thereafter, detailed 3D CAD spool drawings were done of all the various piping components to allow outside fabrication estimates of the assemblies.

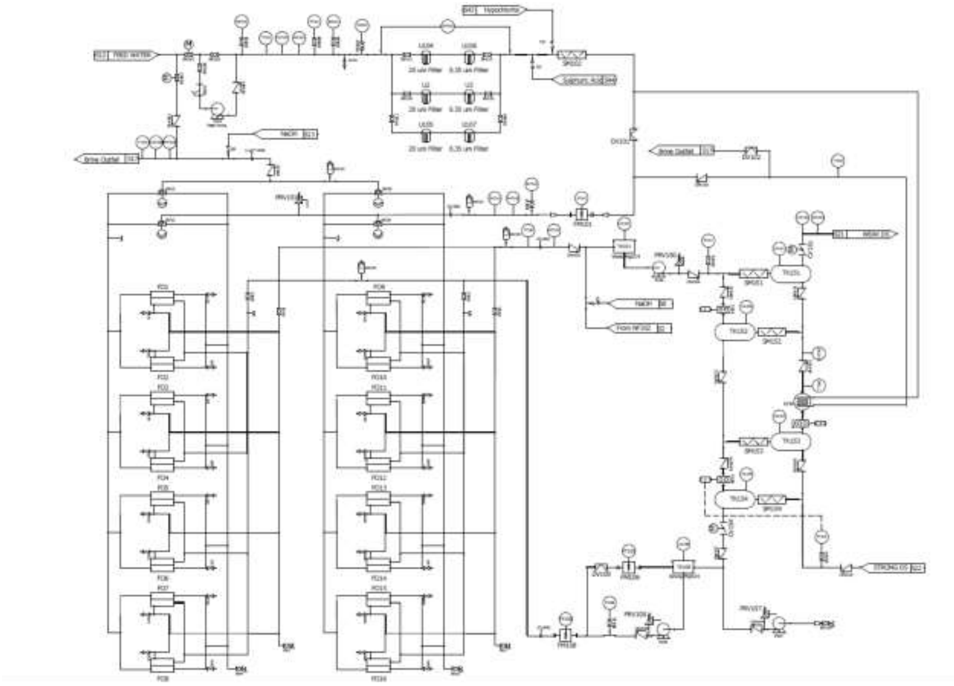


Figure 5 – P&ID 500m3/day FI System (1 of 4)

3.1.3.6. Project Costs

An extensive cost analysis of the project was done at this point to evaluate if it would be cost competitive to a commercially fabricated RO plant. A summary of the findings are as follows:

Heat Exchanger Cost Analysis:

The cost analysis outlined the expenses associated with the three types of heat exchangers for the 500m³/day FO system. Although the innovative Trevi Inline Twisted Tube in Shell Polymeric heat exchangers using 10” FRP housings offered potentially lower costs, this version was still in development and remained untested at full scale. The final FO system design incorporated commercial Plate and Frame heat exchangers.

Assembly Labor Cost Analysis:

An estimate of assembly manpower requirements was undertaken to compare against RO methods and materials of construction. RO plants require labor intensive stainless steel high pressure plumbing as well as costs associated with high voltage switchgear. Trevi sought to validate the budget allocation for a third-party EPC vendor, obtaining quotes from Hawaii-based contractors for fabricating the plastic piping and plumbing spools. Considering the complexity of the project and the challenges in finding skilled labor during the pandemic, Trevi opted to use in-house labor, with a budget allocation for specialized work by outside contractors.

Bill of Materials:

The material costs for the SunShot 500 m³/day FO system was detailed, indicating firm vendor-supported costs and those pending quotes. The total estimated costs were within the original budget estimate of $1.1 million.

Final Cost Analysis Review:

Several key items dominate the entire CAPEX bid package, these being the Forward Osmosis membranes and the Heat exchangers (making up 52% of the total system CAPEX). A price quote for 16 FO membrane units (sufficient for the 500m3/day) and for 320 FO membrane elements for the 10,000m3/day was received from the membrane vendor to project the 10,000m3/day system pricing more accurately. In addition, for the 500m3/day system, both the Trevi polymeric heat exchangers and the Makai metal heat exchangers were included in the costing of the 500m3/day system, with cost projections for both types received. In the 10,000m3/day system, only the polymeric heat exchanger option was selected.

The pie charts below (Figure 6) show the percentage cost contribution of the FO membranes and Heat exchangers for the 500m3/day system, and (using the volume pricing for these items received) and the projected CAPEX for the 10,000m3/day system:

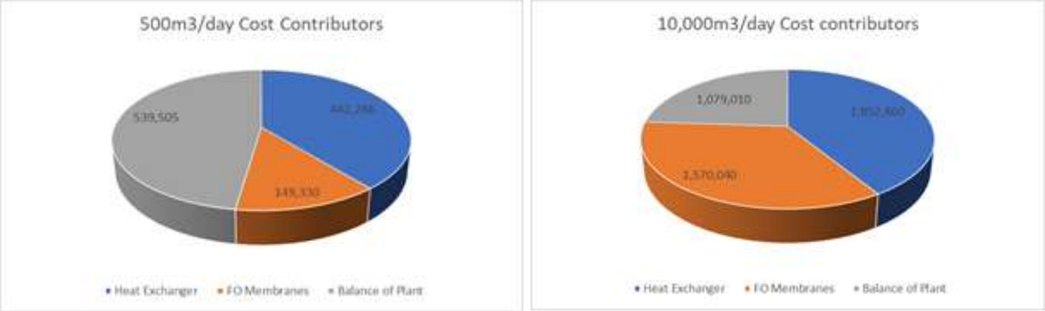


Figure 6 CAPEX Costs

The balance of plant scale-up is driven only by increased pipe, tank and pump sizes which scale in cost based on pipe diameter, therefore modestly. All instrumentation, controls and auxiliary equipment remains the same between a 500 and 10,000m3/day plant. Forward osmosis membranes point to an effort needed into cost reducing these, as the only remaining viable path to reducing CAPEX further for large plants. The projected 10,000m^3 day plant, based on these scaled up projections, indicates a CAPEX of around $4.5million is achievable (as originally projected), based on cost reductions for these two dominant pricing elements, heat exchangers and FO membranes.

3.2. Results from Project Phase 2: System Construction, Installation & Testing

In this stage, all the various components of the entire solar FO plant were received and verified. This was followed by the installation of the CSP and the construction of the FO system respectively. These were then integrated, commissioned, and verified. Initial data was used to verify energy consumption. The system was operated, occasionally shutting down to make modifications to install alternative components for testing.

3.2.1. Connecting the Utilities and Solar Array to the FO system

The FO system involved five crucial connections: an electrical feed, monitored by NELHA staff to determine the electrical power consumption (480v 3 phase) of both the solar array and the FO plant separately; a thermal measurement (flow and temperature difference) instrumented by Trevi on the primary water feed loop from NELHA and a secondary loop on the polymer flow within the system; connections for seawater feed, brine discharge, and permeate water. While the thermal measurements and flows for seawater, brine, and permeate are logged in Trevi's PLC system, the integration of electrical consumption data wasn't configured during the tests, necessitating manual recording.

3.2.2. Preparation for System Commissioning

The commissioning plan was structured into three significant components:

Hydrostatic Integrity Testing: As the system was too large for water-based leak detection, air pressurization at 30psi and 60psi levels was conducted, followed by a water fill. All pumps and associated components were exercised to ensure they met design flow rates. This phase confirmed no leaks and verified the functionality of the system's pumps and associated equipment.

Instrumentation Verification: A validation plan ensured that all sensors were visible on the system PLC, calibrated within required accuracy levels, and screened values aligned with expected ranges. This encompassed calibrating 40+ sensors (pressure, temperature, flow) and verifying their readings on the PLC system. It also involved testing alarm tables, data trending, PID tuning, and enabling remote operations via screens installed at NELHA and Trevi's headquarters in California.

Consumables Loading: This step involved installing and validating three types of membranes (FO, Hot NF, and Cold NF) and filling them with the required preservation solutions to ensure membrane integrity. Chemical pre-treatment loading and validation, included sulfuric acid (sea water pH adjustment), sodium meta-bisulfate (de-oxygenation), sodium hydroxide (pH re-adjustment), sodium hypochlorite (disinfection), and activated carbon (taste improvement), with pump dosing levels were verified to maintain correct chemical concentrations.

3.2.3. System Warm-up, Operation and Ongoing Refinement

During the commissioning phase, three checkpoints were set to evaluate system readiness, each offering significant insights amidst the construction challenges encountered. The Forward Osmosis (FO) system underwent bi-weekly operation, generating daily permeate water volumes ranging between 80 to 150m^3. However, outputs lower than 80m^3 were unattainable due to heat exchanger inefficiencies, resulting in a system turndown ratio of 16%. Performance logs were compared against anticipated benchmarks to refine the system. Automation was implemented for inline refractive index sensors which facilitated precise draw solution osmotic pressure measurement. Software enhancements enabled membrane flux calculation and heat exchanger balance. An innovative PLC algorithm enabled autonomous system operation with minimal manual intervention. Initial water production revealed multiple challenges.

Early operations unveiled various issues:

- Discrepancies in pump performance contradicted expected flow rates, requiring technical support and correctional measures.
- Vibration issues in motors prompted structural enhancements for stabilization.
- Inadequate seawater flow necessitated the replacement of an undersized seawater feed pump motor.
- Draw solution miscalculation demanded additional draw solution shipment to the site for adjustment.
- Extractor imbalance led to unexpected mixing, investigated via borescope, requiring design modifications.
- Extractor tank simulations determined that external mixing improved system performance over internal mixing.
- Elevated temperatures in nano-filtration (NF) impacted extraction efficiency, prompting the pursuit of suitable NF membranes and system modifications.
- TDS (Total Dissolved Solids) in permeate water exceeded target levels due to over mixing in the extractor.
- Polymer detection was below detection levels in the brine, but TDS was higher than desired in the permeate.
- Validation tests showed permeate exceeding the target Total Organic Carbon (ToC) limit of 5ppm due to mixer refinement needs and NF membrane mismatch.

The successful generation of water from seawater in early July marked a significant milestone. However, early water quality assessments revealed challenges related to Total Dissolved Solids (TDS) levels due to extractor imbalance, impacting the system's cost-effectiveness. Efforts persist to achieve the targeted TDS of 250ppm, which will be achieved once the extractor issue is resolved.

3.2.4. Operating Results

As mentioned above, at low speeds extractor imbalance is minimized and TDS can meet the 500ppm threshold, but with increasing production, TDS rises to 500-700ppm.

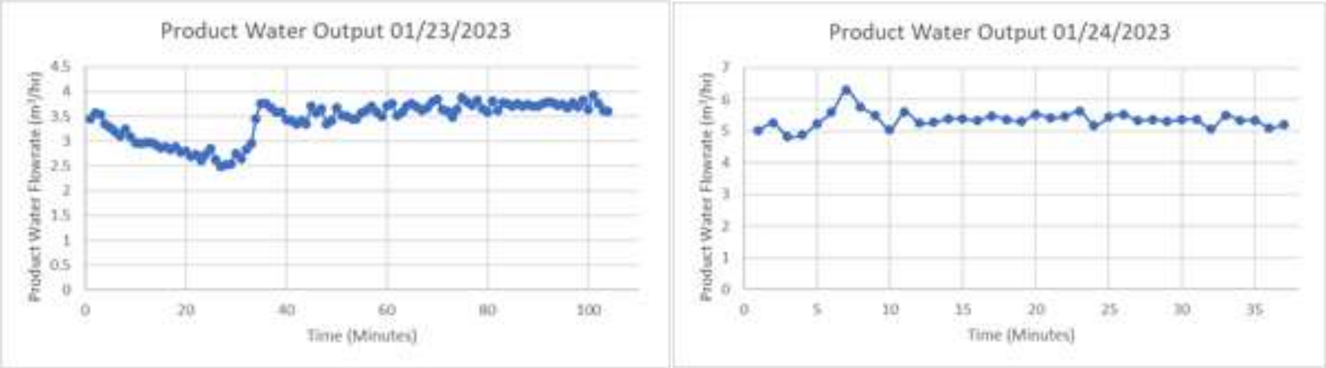


Figure 7 Permeate Production

A number of test-runs similar to the above two were performed with data summarized below in the T-test analysis showing the water production target was met, but not the TDS target:

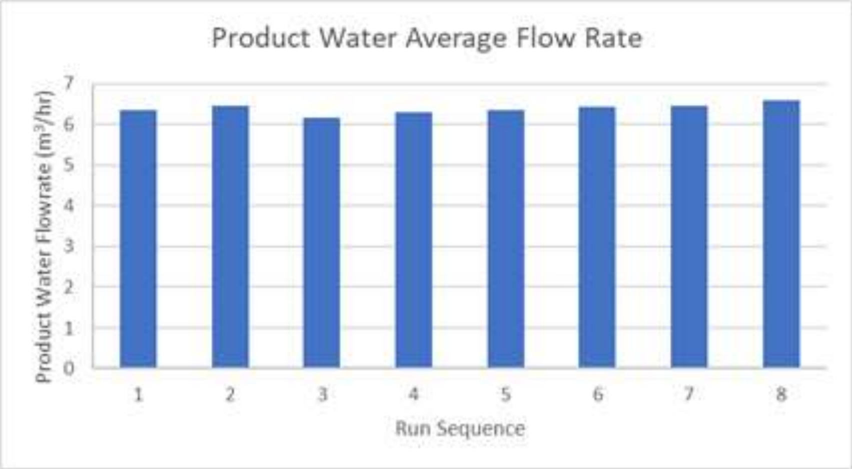


Figure 8: 5m3/day test runs

The recovery rate (permeate production to sea water feed) was also calculated for these runs and shown below:

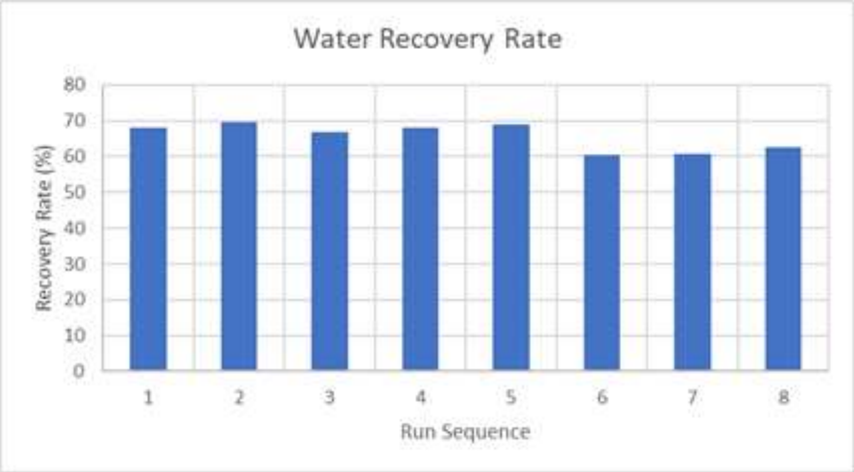


Figure 9: Recovery rate for 8 runs

The system has met the requirement for manual water production. Recovery rates at times approached 70%, higher than Ultra High-Pressure RO, which can only achieve a recovery of 65%. The FO result obtained is extremely encouraging for Zero Liquid discharge applications.

The investigation of the permeate water's Total Dissolved Solids (TDS) across 18 test-runs revealed levels typically doubling the 500ppm target ceiling as shown below:

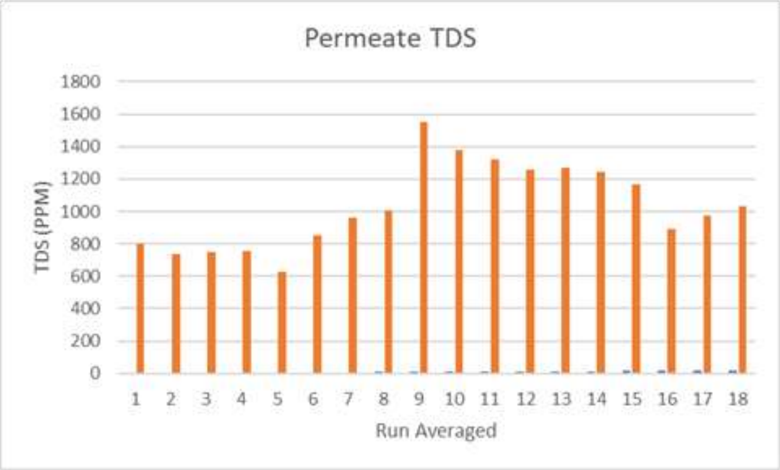


Figure 10 Permeate TDS over 18 runs

This increase in salt concentration mirrors the excessive polymer concentrations (ToC) in the permeate surpassing the 5ppm limit. Two primary causes for this overabundance of salts have been identified: excessive mixing in the extraction stage and the use of underperforming nano-filtration membranes.

While overmixing in the extractors contributes to the problem, the root issue stems from the substitution of nano-filter units rated at 99.5% rejection instead of the required 99.8% for divalent ions. Rectifying this discrepancy by replacing the current membranes with the appropriate rating is expected to reduce TDS levels by 62%, aligning with the design specifications and improving polymer rejection.

Additionally, the elevated operating temperature (45°-50°C) of the Nano filtration membranes has significantly reduced their rejection rates. To address this, proposed changes involve up-sizing the heat input control valve from the Concentrated Solar Power (CSP) array and installing a heat exchanger to cool the process stream before nano-filtration. These modifications aimed to lower system temperatures, enhancing rejection rates.

During the evaluation of permeate water quality, the analysis necessitated shipping samples to California on ice to prevent Total Organic Carbon (ToC) degradation in transit due to bacteria.

Unfortunately, obtaining local ToC measurements proved challenging, as only the University of Hawaii possessed equipment capable of measuring below 5ppm. Three samples were collected on different dates and sent to Trevi for analysis:

Date	Cold Nano Permeate TOC Measurement from Preliminary Runs Before Tuning Process
1/23/2023	41 ppm
1/24/2023	78.4 ppm
1/25/2023	55.6 ppm

Table 4 Water ToC

Tests on brine samples thus far have shown undetectable levels of polymer, using a highly sensitive analytical method with a lower detection limit of 1ppm. This indicates a low environmental impact of the draw solution to marine life.

Despite the extractor and NF challenges, the system achieved high water production performance and displayed promising recovery rates, exceeding those of Ultra High-Pressure Reverse Osmosis systems. However, ongoing optimization is crucial to meet water quality targets and reduce undesirable salt carry-over. Efforts to rectify NF membrane discrepancies and improve temperature control are underway, thereby enhancing system performance for consistent water quality output.

3.3. Results from Project Phase 3: Project CAPEX & Thermal Power consumption.

3.3.1. System Operation and Main Findings

This project phase focused on long duration system operation and data collection which was used to calculate energy consumption of the FO system. The three main findings were as follows:

Firstly, the capability of the Concentrated Solar Power (CSP) system to generate over 17,500kWh/day of thermal heat was successfully met. Secondly, the system's thermal storage capacity reached the required threshold of 1,100kWh/day. Finally, numerous test runs conducted over several months, surpassing more than 100-hours cumulative interval, yield an average permeate production close to 8m^3/day.

Although the system consistently operated for prolonged durations at 30gpm (163m^3/day), the operational time was constrained to 4 to 6 hours daily due to CSP array heat availability limitations. The bottleneck resulting in this lower than expected flow wasn't primarily due to CSP heat availability but rather stemmed from extractor imbalance issues causing water quality degradation at higher permeate production rates.

3.3.2. Project Estimates – CAPEX and Thermal Load

3.3.2.1. CAPEX

During one of the final stages of this project, Trevi revisited the plant's financial estimates, refining the CAPEX figures based on updates from June 2022 and March 2023. The pandemic posed challenges in procuring certain items, especially those requiring custom fabrication like coalescer tanks, extractors, and pump assemblies. These hurdles inflated earlier price estimates and were still not fully resolved in 2023.

Throughout the operational phase, modifications in the system's configuration were implemented, reducing the number and types of pumps needed. The original plan, calling for six expensive lobe pumps at around $26,000 each, was streamlined to only requiring three pumps, with the addition of more economical centrifugal types. Additionally, electrically operated valves were replaced with air-operated ones, accompanied by the incorporation of a central air compressor, significantly reducing costs compared to the initial design.

Further cost efficiencies were realized through the insulation of crucial components like coalescers and hot loop elements. Insulation significantly curtailed overnight temperature losses in the coalescer, minimizing startup time from roughly an hour to less than 5 minutes, thereby decreasing thermal operational expenses. Additional insulation efforts aimed at heat exchangers and pipes are anticipated to diminish overall thermal losses.

Key findings from the re-evaluation exercise encompassed several noteworthy points:

- A global surge in stainless steel costs by approximately 25-30%, affected components like heat exchangers, coalescers, and mixers.
- An inflation-adjusted increase of about 7% in costs related to small parts, piping, and valves within the CAPEX model.
- Introduction of plastic heat exchangers, a Trevi-manufactured solution, effectively mitigated the elevated costs linked with stainless steel components.
- Reducing the use of expensive lobe pumps.

- Transitioning non-critical elements of the PLC functionality to a cloud-based approach.
- Rationalizing the necessity and functionality of sensors, simplifying the design which was previously overly equipped for data collection purposes.
- Substantial reduction in FO membrane costs due to competitive pressure from a new Chinese vendor, dramatically affecting pricing.
- Direct procurement of components instead of relying on stocking distribution channels, a necessity during the pandemic.
- A significant drop in the cost of hot nanofiltration elements from $1300/element to $100/element, marking a considerable reduction in overall costs for the larger 10,000m3/day system.

Overall, the revised CAPEX estimate at $1,101/m3 (see breakdown of major components below) showcases competitive pricing compared to RO systems, and notably lower than UPRO systems at approximately $1,650/m^3, a trend likely to continue as prices evolve over time.

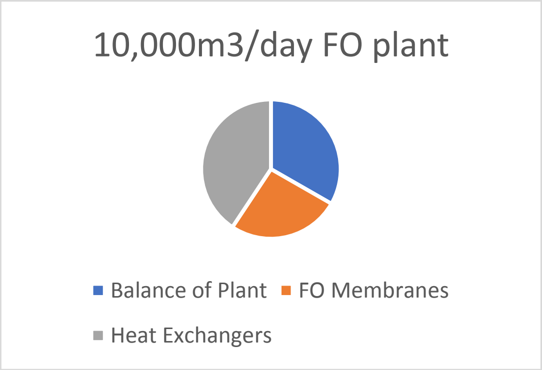


Figure 11 July 2023 Estimate $1,101/m3

3.3.2.2. Thermal Energy Demand

The FO system was benchmarked over 11 operating periods, where the thermal energy consumption was monitored both on the primary (water feed from NELHA) and secondary side (Polymer flow inside Trevi's FO system). Those results are shown below, with the hot water flow showing a slightly larger demand than the polymer flow. This discrepancy is probably due to the difficulty in estimating the heat capacity of the polymer flow. Trevi used the water flow heat load in its LCOH calculation of 24kWh/m3. This dramatic reduction from previous generations of Trevi's FO plants is primarily due to the 15% energy savings from the Hot nano retentate return, as well as the larger system size (previous generations of plants were 10x smaller, so radiative heat losses played a larger role in the overall consumption. The incoming temperature from the CSP array is also shown below, over a 91-85C range, showing only a modest correlation between increased temperature and increased thermal demand.

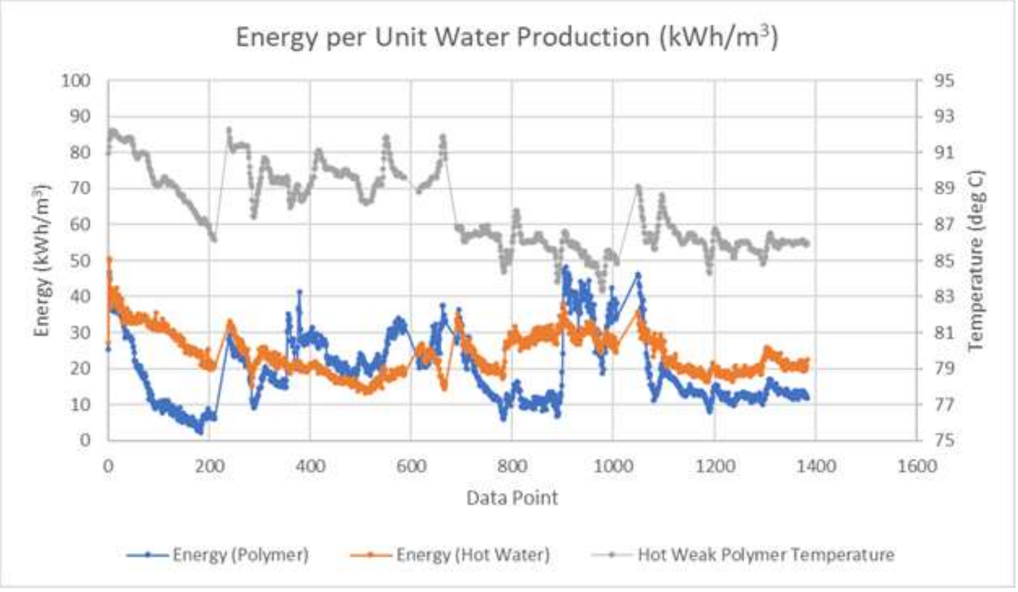


Figure 12 Thermal Energy Consumption

4. Discussion

4.1. Final FO Design Parameters with LCOH & LCOW Estimates

Trevi's planning during the initial phase led to the selection of crucial components for the FO system. Innovations in draw solution design and the development of polymeric heat exchangers aimed to advance the technology while simultaneously minimizing capital expenditure. Trevi's approach emphasized the importance of ensuring the safety of the ecosystem while advancing desalination technology.

1.1. LCOH and LCOW

The above estimates in section 3.2.2 were used in the projected levelized cost of heat (LCOH) and the levelized cost of water (LCOW) calculations at the 10,000m3/day size for a solar powered FO seawater desalination plant. The calculation of LCOW follows the formula:

$$\text{Levelized Cost of Water} = \frac{(\text{capital cost} \times \text{CRF}) + \text{annual O\&M costs} + \text{R\&R costs}}{\text{average annual yield in acre-feet}},$$

$$\text{where CRF} = \frac{r(1+r)^n}{[(1+r)^n]-1}; \quad n = \text{useful life (in years)};\ r = \text{discount rate}$$

The levelized cost of water (LCOW), assuming a 25-year lifespan and a 5% interest rate, is assessed for both a representative Reverse Osmosis (RO) system and the Forward Osmosis (FO) plant delineated in this report, factoring in Hawaii's prevailing electricity rate of 32 cents/kWh during the study period. Notably, recent studies advocating the use of exclusively renewable energy affect the approach for both systems. For an RO system, this necessitates considering the capacity factor of a photovoltaic (PV) system operating at 20% efficiency, along with a Battery Energy Storage System (BESS). Conversely, an FO system requires reducing the PV array size and integrating a thermal energy storage system. However, the exclusive renewable energy calculation is omitted here, suggesting an alternative approach of expanding the plant's capacity to store excess water rather than surplus energy.

In comparing the pricing of RO and FO systems, RO equipment costs exhibit pricing maturity and costs predominantly fluctuate based on localized conditions such as pipeline expenses, zoning regulations, and land costs. For this analysis, both the FO and RO systems are assumed to bear a capital cost of $4,500,000 for a 10,000m3/day system. Operating and Maintenance (O&M) cost estimations are drawn from the GWI database, utilizing a Specific Energy Consumption (SEC) of 3.5 kWh/m3 for the RO plant (UPRO is more than 2x this number).

Regarding Replacement and Renewal (R&R) costs, these expenses account for annual equipment replacements, constituting a percentage of the plant's capital cost. For RO systems, the R&R costs typically cover membrane replacements and high-pressure pump maintenance, while FO systems, devoid of high-pressure pumps, chiefly require low-pressure FO membrane replacements during their lifespan.

O&M expenses for RO plants encompass the cost of chemicals utilized for pre- and post-treatment, in addition to the SEC. In contrast, O&M costing for FO plants is rooted in the actual chemical consumption data from the NELHA plant. Notably, while RO systems typically employ an anti-scalant at 2-3 mg/l, the Trevi NELHA FO system necessitates draw solution replacement at approximately 10 mg/l. Cost assessments indicate anti-scalants at $35/kg and draw solutions at $15/kg. Moreover, both FO and RO systems employ sulfuric acid for pH adjustment and caustic soda for brine re-neutralization and permeate pH adjustment, with similar dosage levels, rendering chemical consumption estimates relatively independent of the membrane technology choice.

For both RO and FO plants, a production factor of 96% is assumed in annual water output.

The figure below shows the LCOW for a range of LCOH values for the thermal heat generated by the NELHA plant. These water costs are before operator profits, so they are to be considered the floor value for water production costs. In areas of high electricity cost such as in HI, the cost of thermal heat can approach 3c/kWh and still be competitive with an RO system located there. In areas where power is less expensive, an assumed price of electricity of 20c/kWh produces an equivalent LCOH of around 1.7c/kWh of thermal power.

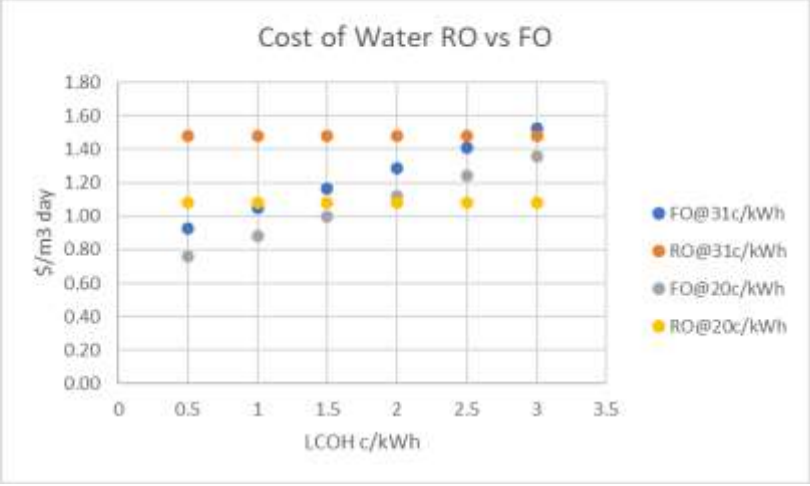


Figure 13 Cost of Water RO vs FO

5. Project Challenges and Accomplishments

Throughout this initiative, Trevi embarked on a dual path of innovation, targeting both individual components and the overall system architecture approach to reduce cost. At the component level, the efforts involved pioneering designs for forward osmosis (FO) membranes, the creation of novel draw solutions, and the manufacturing of polymeric heat exchangers and high-temperature nano-filtration membranes.

On the system front, Trevi introduced a new, 4th generation FO system. However, the complexity of a well-established chemical process—liquid/liquid extraction—proved more intricate at the operational scale within the stringent time constraints of the program. This challenge surfaced when the limitations of this mature process were encountered at Trevi's operational scale.

Amidst an aggressive technology development plan, the project contended with delays caused by the Covid pandemic's supply chain disruptions and multiple volcanic eruptions on the Big Island, presenting multiple challenges. However, despite these hurdles, the selection of the 4th generation FO system uncovered three remarkable breakthroughs in FO performance, paving the way for advancements in solar thermal technology for desalination:

- Demonstrated high recovery rates exceeding 70% on seawater, surpassing the recovery capabilities of the next generation of RO technology (UPRO) while consuming significantly less electrical power (1.7kWh/m^3 vs. 7kWh/m^3). This technology holds immediate promise for zero liquid discharge applications in high salinity brines across industrial and agricultural domains.
- Reduced thermal energy consumption to below 30kWh/m^3, a notable improvement compared to the current industry leader MED-TVC, achieving 65kWh/m^3 at similar operating temperature.
- Utilizing new ceramic nano-filtration membranes to enhance the FO process's efficiency.
- Development of an innovative twisted tube polymeric heat exchanger for megawatt-scale waste heat recovery.
- Creation of new draw solutions tailored for extremely high feed water Total Dissolved Solids (TDS) desalination.

While the 4th generation (dual salt/polymer) loop offers a technological edge for high TDS waters, such as in Oil and Gas produced waters, its complexity may limit its deployment in less sophisticated settings. Consequently, a simpler 5th generation FO system, stemming from this program, was developed to navigate liquid/liquid extraction intricacies, offering a more robust start-up and stop protocol.

The low thermal consumption of the FO process positions it as a competitive alternative to RO, especially in scenarios requiring renewable energy or encountering high TDS waters.

6. Conclusion

Trevi's Forward Osmosis (FO) technology has undergone significant evolution, advancing to its present version 4, and is now poised for a transformative leap to version 5. The new iteration introduces an improveddraw solution, eliminating complex extraction stages while maintaining high system flux. This new draw solution, marked by higher osmotic strength and lower viscosity, permits direct application of the polymer draw solution to the FO membrane, reducing system complexity and capital expenditure (CAPEX).

Furthermore, the development of polymeric heat exchangers, now ready for commercial implementation, presents an opportunity to integrate these advancements into the existing NELHA design or future models, driving down CAPEX costs. Moreover, substantial cost reductions in hot nano-filtration modules bolster savings within the system.

Ongoing work at the site to upgrade and complete the program awaits further funding from supportive agencies. Additional funding will facilitate the integration of the innovative draw solution and polymeric heat exchangers, enhancing efficiency and reducing operational costs. In tandem, as Trevi aims for larger-scale applications handling 10,000m3/day, research into improved thermal storage mechanisms like phase change materials, including salt hydrates, becomes imperative. These materials can significantly elevate storage efficiency and reduce costs at larger scales, pivotal for the success of expanded FO systems. Challenges in hot water storage beyond 3000m3/day necessitate cost-effective solutions, considering the escalating expense of water tanks.

The transition to version 5 signifies a critical milestone, positioning Trevi to meet the escalating demands for sustainable and efficient water treatment solutions. Despite the challenges faced during the program, Trevi's design and implementation of a solar-powered FO seawater desalination plant at NELHA demonstrated groundbreaking advancements in sustainable desalination. The careful planning, strategic design selection, and innovative technological developments resulted in a zero-carbon, competitive LCOW desalination solution. These achievements mark a significant leap forward towards a low-carbon future in desalination, emphasizing the importance of renewable energy integration, environmental sustainability, and technological innovation in zero carbon water treatment.

7. Acknowledgements:

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8. References:

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