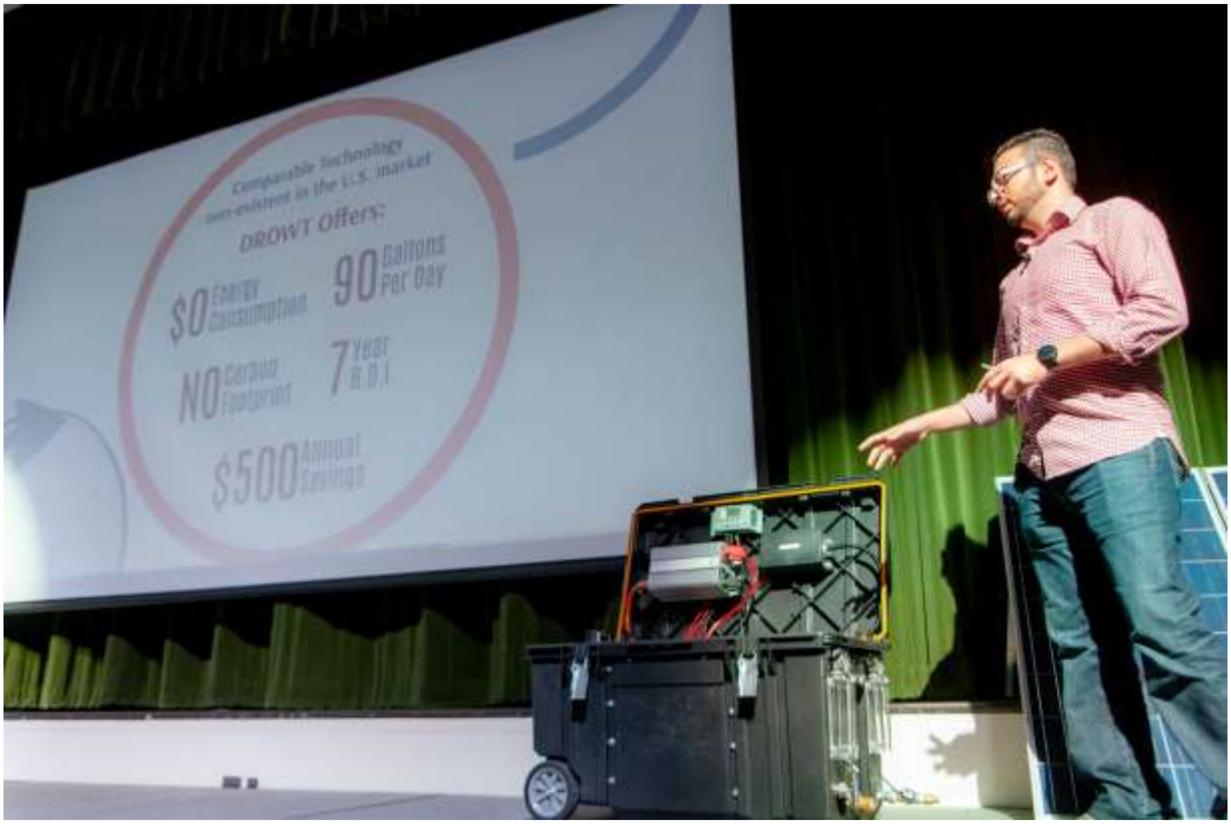
CAL POLY POMONA
Deliverable 4 (Final Report)
March 2019



Innovative Conservation Sub-award Program

Agreement No.	167250
CPP Foundation Project #	006410
Lead Recipient:	California State Polytechnic University, Pomona
Project Title:	Graywater Reuse: Development of a Solar-powered Decentralized Graywater Treatment Unit
Principal Investigators:	Prof. Reza Baghaei Lakeh,
Date of Report:	March 21, 2018
Reporting Period:	April 10, 2017– March 20, 2019

1- Introduction

The project developed a low-cost, robust, and solar-driven treatment unit for greywater. The product of the system is a permeate water that can be used for non-potable use. The system includes a multi-layer filtration system, including Microfiltration (as pre-treatment), solar-driven Reverse Osmosis, followed by an Ultra Violet disinfection process.

2- Status of Project Tasks

The progress of all tasks of the project is shown in Table 1. The project progressed according to the timeline. Task 1 (conceptual and system-level design) and Task 2 (Component-level Design and Fabrication) and corresponding sub-tasks (1-1: Facility Build-up and Literature Review and 1-2: System Level Design and 2-1: Reverse Osmosis Hydraulic Design and Fabrication, 2-2: Pre-treatment and Filtration Design and Fabrication, 2-3: Ultra Violet (UV) post-treatment Design and Fabrication, 2-4: Solar Photovoltaic System, 2-5: Control System Design and Integration), Task 3 (Demonstration and Dissemination), and Task 4 (Tech-to-Market Assessment) are completed according to the milestones of the ICP grant.

Table 1 – Project tasks and percentage of progress (ICP Grant Milestones)

Task	Subtask	Progress %
1: Conceptual and System-level Design	1-1: Literature Review & Facility Build-up	100%
	1-2: System-level Design	100%
2: Component-level Design and Fabrication	2-1: Reverse Osmosis Hydraulic Design and Fabrication	100%
	2-2: Pre-treatment and Filtration Design and Fabrication	100%
	2-3: Ultra Violet (UV) post-treatment Design and Fabrication	100%
	2-4: Solar Photovoltaic System	100%
	2-5: Control System Design and Integration	100%
3: Demonstration and Dissemination	3-1: Testing and Troubleshooting	100%
	3-2: Outreach	100%
4: Tech-to-Market Assessment		100%

The team performed a detailed review of previous and existing decentralized and membrane-based projects. More than 50 existing projects in different parts of the world were identified that utilize decentralized membrane-based technology for water treatment. Despite large number of projects, the peer-reviewed published articles are limited and most of the available information is through published reports or white papers. Please see **Appendix A** for more details about the literature review.

The investigating team built up a facility for the project in Energy Laboratory of the College of Engineering at Cal Poly Pomona. Due to the nature of the project, a mobile lab was developed. The Mechanical Engineering Department provided funding for the project to acquire a 40 ft shipping container which is modified and converted to a mobile lab. A photo of the mobile lab is provided in **Appendix B** of this report. Every academic year, the faculty investigators announce the availability of research positions in the College of Engineering and conduct a series of interviews to form a cohort of qualified graduate and undergraduate students to assist with performing the tasks of the project. **Appendix C** shows a picture of the student cohorts who have worked on the project in 2016-2017, 2017-2018, and 2018-2019 academic years. All students (in the first two cohorts) received scholarships from the grant based on their level of involvement in the project and their contributions. The new cohort of students in 2018-

2019 academic year consist of 12 Civil Engineering students who are assisting the faculty advisors in finalizing the project. The team is currently working beyond the ICP grant on integrating the developed system with a residential home in Coachella valley (a disadvantage community).

2-1- Demonstration

The team designed, fabricated, and tested the 1st version of the proposed off-grid multi-layer water treatment system to gain experience in membrane selection, designing hydraulic and electrical circuits, and computer-based data acquisition. The design and fabrication of the 2nd version of the proposed system has been successfully done and extensive tests are underway. The status of 1st and 2nd version of the developed product is explained below.

Figure 1 shows the developed prototype (ver. 1) and the P&ID of the system. The objective of designing a preliminary system was to test the feasibility of running a multi-layer filtration system solely on solar panels and independent of the power grid. In the preliminary tests, a series of experiments were conducted using saline water as the feed to make sure the system is capable of desalinating and treating saline water. In the next step, synthetic graywater was utilized as feed water to test the system more rigorously. The results confirmed that the quality of the generated permeate water is acceptable for non-potable reuse.

The results of the preliminary tests on ver. 1.0 is published and presented in the proceeding of 2017 American Society of Mechanical Engineering's International Mechanical Engineering Congress and Exposition (ASME-IMECE). The team secured internal funding for the student team to present the paper in November 2017 in Tampa, FL. A copy of the published conference paper is provided in **Appendix D** of this report. The team is finalizing a journal paper based on the final test results that are collected from ver 1.0 using synthetic graywater. The draft of the journal paper is provided in **Appendix E** of this report.

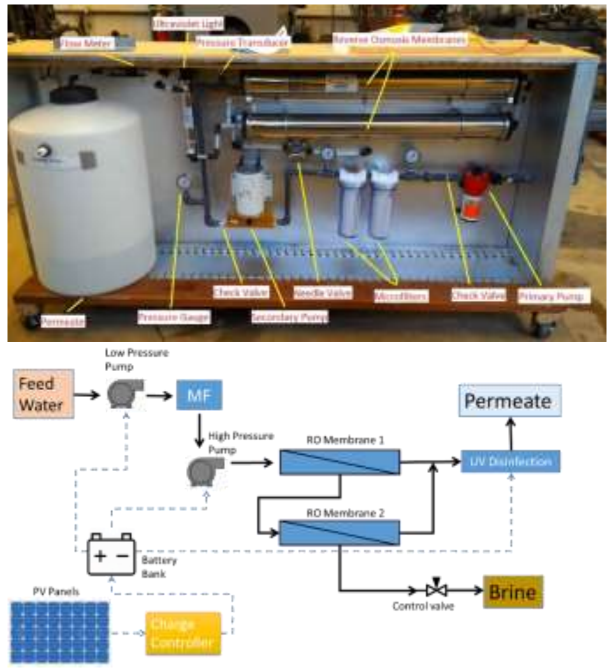


Figure 1 – Version 1.0: Decentralized multi-layer filtration system, aka ver. 1.0 (Top); P&ID of the system (Bottom)

The team has concluded design and fabrication of the 2nd version (final design) of the decentralized water treatment unit using lessons learned from testing the 1st version. Figure 2 shows a schematic of the developed decentralized water treatment unit. As illustrated, the 2nd version has a smaller footprint and has major differences with version 1.0. It was decided to increase the number of RO membranes to 3 (from 2 in version 1) and to include a feedback loop to protect the membranes from excessive fouling as suggested by the manufacturer. The electric motor that is utilized to run the RO pump runs with AC power and a voltage inverter is implemented to convert the DC voltage of the battery bank to 110V AC. The team has performed water quality tests and performance tests on version 2 and compiled a conference paper which is published in 2018 American Society of Mechanical Engineering's International Mechanical Engineering Congress and Exposition (ASME-IMECE). Using funding provided by Cal Poly Pomona Office of Undergraduate Research, Justine Nguyen attend the conference in November 2018 in Pittsburgh, PA and presented the results and brainstormed with other experts in the field. A copy of the published conference paper is provided in **Appendix F** of this report.

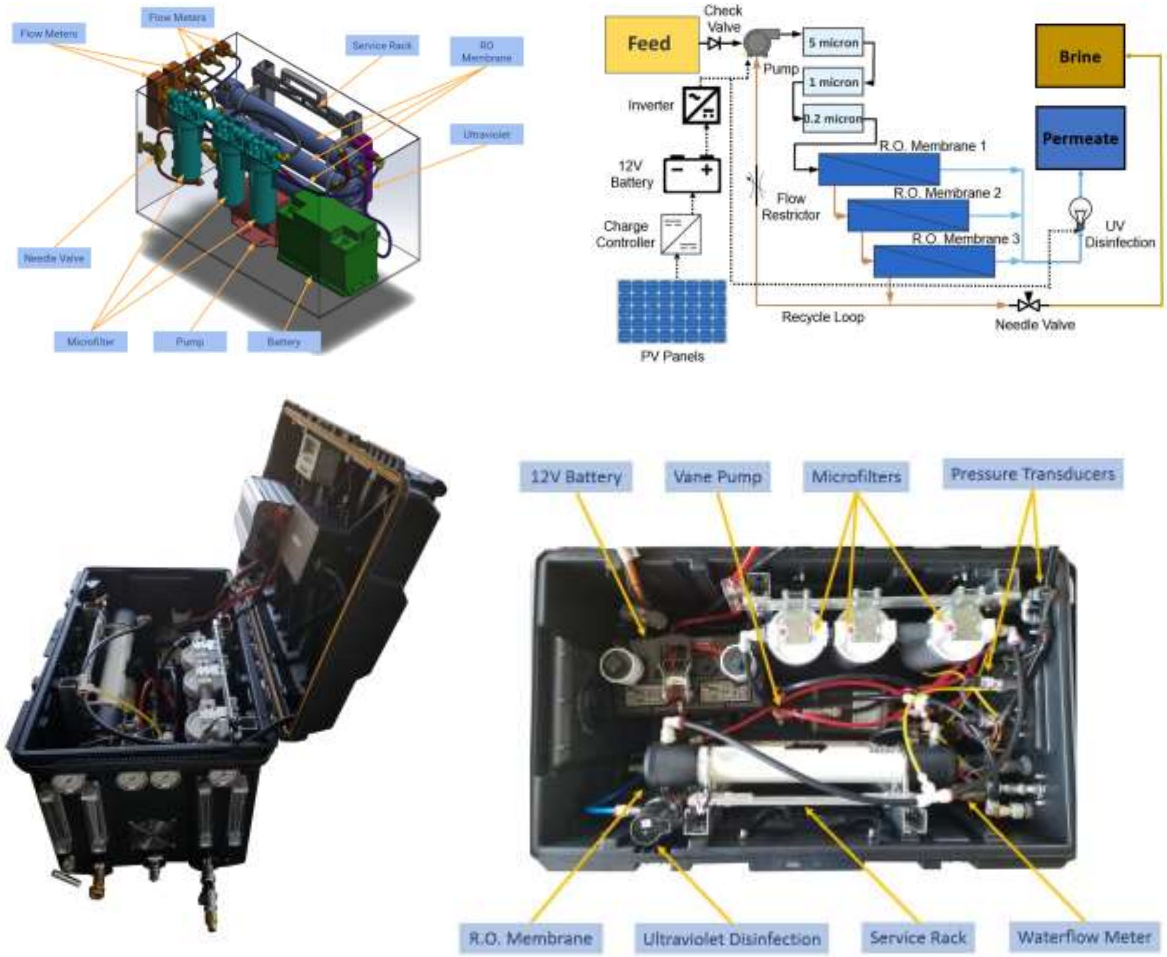


Figure 2 – Version 2.0: Decentralized multi-layer filtration system, packaging of the components using SolidWorks modeling (Top-left); P&ID of the system (Top-right), Photos of version 2.0 in service mode (bottom)

Endurance Test and Permeate Water Quality

Figure 3 – Team members performing on-sun endurance and water quality tests on DROWT 2.0

The team conducted an endurance test to assess the performance of the developed product in different operating conditions. Figure 3 shows the experimental setup during the on-sun endurance test. The endurance, extended time tests were performed using solar energy only and the performance of the system was analyzed. The results of the endurance test and permeate water tests are included in **Appendix G**. It was shown that the DROWT product is capable of achieving a recovery rate of 68% and salt rejection rate of 99%. The energy consumption of the system was consistently near 0.9 kWh/kgal. The water quality test results show that significant improvement in the quality of the water is achieved. The electrical conductivity (TDS) of the water is down from 400 (feed) to less than 10 (permeate) micro-S/cm while the Chemical Oxygen Demand (COD) is down from 1000 (feed) to 50 (permeate) mg/L which is consistent with the quality required for reclaimed water.

The team also performed an analysis to estimate the Levelized Cost of Water (LCOW) produced by DROWT system. The LCOW calculation yielded a low value of $1466.25/acre.ft ($0.45/gallon) based on 4 hours of daily operation, and a high value of $2929.17/acre.ft ($0.902/gallon) based on 2 hours of operation daily. The details of LCOW calculations are provided in **Appendix H.**

2-2- Tech-to-Market Activities

In order to spread the knowledge and inform the community about the progress of the project, a website is developed in collaboration with the Computer Science Department at Cal Poly Pomona. The website is accessible under http://www.drowt.org and is updated routinely. The team also attended MWD Spring Green Expo in 2017 and 2018 to showcase the developed technology and raise awareness of the community about the importance of graywater reuse as a new water resource.

Figure 4 – Student members, John Kest, Kyle Miller, and Mohammad Modabernia receiving the 2nd place award in Bronco Start-up Challenge for DROWT, a spin-off start up based on the MWD-supported project

In a more recent development, a start-up company is being coordinated by students to facilitate market penetration of the DROWT product. The team initiated a tech-to-market activity to develop a business plan for the product of the project. The DROWT product was presented to a team of entrepreneur judges in Cal Poly Pomona's Bronco Start-up Challenge in 2018 and received the 2nd place award including $3000 of cash award and office space in Cal Poly Pomona Student Innovation Idea Lab, aka, iLab. Figure 4 shows the award ceremony of Bronco Start-up Challenge. John Kest, Mohammad Modabernia, and Kyle Miller represented the team to receive the 2nd place award. In continuation of the tech-2-market activities, 2 student members (Justine Nguyen and John Kest) attended the Cal Poly Pomona Intellectual Property Boot Camp and Entrepreneurship Summer Camp to gain experience in completing the business model for DROWT product. The project was also assessed by Bluetech Valley, an initiative to support CSU-based start-ups. The message from Bluetech Valley experts was that finding the correct market and securing the intellectual property is two major challenges of the project for commercialization. The team also applied for the California Sustainable Energy Entrepreneur Development Initiative (CalSEED) funding opportunity; however, the project was not selected for funding. Figure 5 provides a snapshot of the pitch that was given to Blutech Valley and Bronco Start-up Challenge.

In an effort to secure funding to continue the project beyond the current ICP support, the team presented the product to King Lee Technology, a San Diego-based company in the field of water treatment. A collaboration was formed to design an app for the DROWT product to integrate the product with an on-line user interface. Once the design and implementation of the app and user interface is finalized, the user will be able to turn on, turn off, and monitor the performance of the DROWT product online and using iPhone or android platforms. Kings Lee Technologies donated $145,000 to the project to facilitate integration of "Internet-of-Things" with the DROWT product. This task is currently ongoing beyond the ICP grant objectives to develop a market-ready product.

Figure 5 – Snapshot of Business Plan and Sales Approach for DROWT product

The DROWT team participated in a week-long program sponsored by the National Science Foundation (NSF) in collaboration with Cal Poly Pomona (CPP) called CPP NSF I-Corps in February, 2019. This program teaches teams about the foundations of a start-up and facilitates the customer discovery process.

The training begins with each team creating a small slide deck with a brief explanation of the team and the product or service and to include a Business Model Canvas. During each teams' presentations, the I-Corps instructors provided live feedback and frank commentary. The presentations are followed by a lecture on identifying customer segments and the process of customer discovery, then each team is assigned five interviews with people of varying customer roles. As five interviews are too few to properly cover the entire scope of customer roles within one's customer segment, teams were told to focus on users, influencers, and decision makers.

The DROWT team identified and interviewed five individuals of varying backgrounds and was able to identify other potential customer segments and needs. The five people that were interviewed are the following: Maria Kennedy, a homeowner with a sustainable farm; Dr. Majid Sedighi, California homeowner in Redondo Beach; Lita Patel, a condo tenant living with family; Diana Hoag, in charge of paying for utilities in her household, and Dr. Andrew Ghazarian, California multiple home owner and lives with family.

The DROWT team successfully completed the week-long program which is the first phase to getting the NSF I-Corps grant and support to further develop the project's business aspect. DROWT will be participating in the second phase of the NSF I-Corps program which will take place virtually between 03/20 - 03/27 /2019. In the event of qualifying through phase 2 the team will compete on the national level among other teams for the I-Corps grant. This will be highly beneficial for DROWT since this program aims at preparing engineers to extend their focus beyond the university laboratory and accelerating the economic and societal benefits of projects that are ready to move toward commercialization. It will also provide the team members with key skills in entrepreneurship through training in customer discovery and guidance from established entrepreneurs. Figure 6 illustrates the business model canvas that was drafted in preparation for the NSF I-Corps proposal.

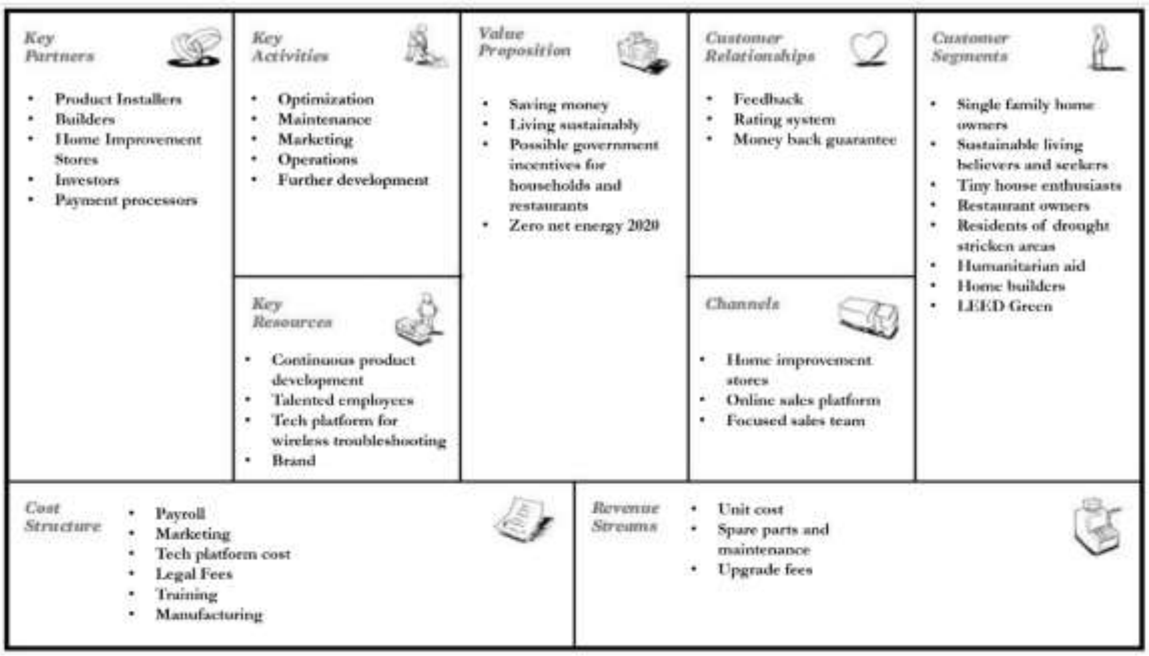


Figure 6 – Draft of business canvas for DROWT

The DROWT team hosted an outreach event for local high schools to increase awareness of the community about the need for water re-use in the coming years. About 60 high school students attended the program and the student team showcased the DROWT technology and explained the basics of multi-stage water filtration for students and teachers. Figure 5 shows a few snapshots of the DROWT outreach event.

Figure 5 – DROWT team hosted an outreach event for local high schools in Fall 2018

3- Project Outcomes

Invention Disclosures

- An Ultra-low-cost Thermal Energy Storage System using Reverse Osmosis Concentrate, filed with CPP Office of Research, Innovation, & Economic Development. Provisional patent is underway.

Awards and Honors

- 2nd Place in Eco Innovators Award of Excellence, World Water Forum, Metropolitan Water District of Southern California, 2017
- 2nd Place in Bronco Start-up Challenge, Cal Poly Pomona, 2018
- Best Project Award, Cal Poly Pomona Research Scholarly and Creative Activities symposium, 2018
- Represented Cal Poly Pomona in California State University research symposium, 2018

Publications

- Reza B. Lakeh, et al. “A Case Study Of Decentralized Off-Grid Water Treatment Using Reverse Osmosis,” published in Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition, IMECE2017, Tampa, FL
- Reza B. Lakeh, et al. “Design And Testing of A Solar-Driven Wastewater Treatment Unit for Off-Grid Applications,” ASME 2018 International Mechanical Engineering Congress and Exposition, IMECE2017, Pittsburgh, PA
- Reza B. Lakeh, et al. “A Case Study of Decentralized Solar-powered Graywater Reuse Unit,” In preparation for Water Science and Technology

Presentations

- Annual Conference of California State University Water Resources and Policy Initiative (WRPI), San Jose, CA, April 2017 (Invited)
- Cal Poly Pomona Student Research, Scholarship & Creative Activities Conference, 2017

- Cal Poly Pomona Senior Design Symposium, 2017
- Metropolitan Water District (MWD) Spring Green Expo, MWD headquarter, Los Angeles, CA, 2017
- ASME International Mechanical Engineering Congress and Exposition (IMECE 2017)
- Southern California Conferences for Undergraduate Research (SCCUR 2017)
- Cal Poly Pomona Senior Design Symposium, 2018
- Annual Conference of California State University Water Resources and Policy Initiative (WRPI), Palm Springs, CA, April 2018
- Metropolitan Water District (MWD) Spring Green Expo, MWD headquarter, Los Angeles, CA, 2018
- California State University System-wide Student Research Competition, Sacramento, CA, 2018
- Bronco Startup Challenge, 2018
- American Association for the Advancement of Science (AAAS)
- Southern California Conferences for Undergraduate Research (SCCUR 2018)
- Metropolitan Water District (MWD) Spring Green Expo, MWD headquarter, Los Angeles, CA, 2018
- ASME International Mechanical Engineering Congress and Exposition (IMECE 2018)

Media Coverage

- PolyCentric:http://polycentric.cpp.edu/2017/05/engineering-students-finish-second-at-mwd-green-expo-competition/
- https://www.cpp.edu/~engineering/CoeMagazine/2018/coemag18-19.pdf

Additional Support

- Southern California Gas Company, Environmental Champions Grant, $10,000 to expand the outreach activities related to the project.
- King Lee Technologies, A donation of $145,000 was received to support water-related senior design projects.
- CPP Office of Undergraduate Research Travel Award for 5 student researchers.
- 3 Student researchers accepted in CPP Engineering Scholars Program (Kyle Miller), McNair Scholars Program (Thuan Nguyen), and Achieve Scholars Program (Justine Nguyen)
- Bronco Start-up Challenge 2nd place award of $3000.

APPENDIX

Appendix A (Literature Review)

Project/Study Name	Project Type (RO, MF, NF, UF, ...)	Feed Flow Rate (GPM)	Power Consumption (Watts per gallon of treated water)	Foot print (dimensions)	Renewable E Source? (Y/N)	Link for more info
Aqua2use GWTS 500	Matala progressive biofiltration.3-D biofiltration	150 gal/day	7.57Wh/gal	H:49.5" , L:56.9", W:21.3"	N	http://waterwisegroup.com/wp-content/uploads/2016/08/Aqua2use-GWTS-Brochure.pdf http://www.aqua2use.com/
ewuaqua - iClear 200 indoor S	Membrane bio-reactors (MBR)	200 l/day	N/A	max 5m^2	N	http://www.ewu-aqua.de/fileadmin/user_upload/downloads/kataloge_informationen/grauwasserbroschuere_D_GB_NL/grey_water_brochure.pdf
Elsevier MBR prototype	Membrane bio-reactors (MBR)	up to 1500L/day	2.9 kWh/m3	7m ^2	N	http://www.sciencedirect.com/science/article/pii/S0921344913000050
ReFlow G2R2	filtration/pumping system	70L	N/A	6-7 inch width, 7ft tall	N	http://p3nlhclust404.shr.prod.phx3.secureserver.net/SharedContent/redirect_0.html
Small Unit Water Purification Sysytem	Stacked-disc pre-filtration >> Ultra-filtration>>RO	240 gal/day	N/A	15 inch * 15 inch * 15inch	Y	https://ext.sharepoint.ctc.com/ctcComContent/StageMedia/WCCD4U/Water_Small%20Unit%20Water%20Purification%20System.pdf
Thermal Control + Panel Cooling + Concentrating Mirror to increase RO system productivity	Solar powered, RO, saline water	N/A	4kWh/m3	N/A	Y	http://www.sciencedirect.com.proxy.library.cpp.edu/science/article/pii/S0011916412006443
A.M.I Solar UF and RO Systems	Solar powered, RO	50GPM	N/A	20ft. x 8ft. x 8.5ft. (ISO 20ft container)	Y (Hybrid)	http://www.appliedmembranes.com/solar-powered-uf-and-ro-water-treatment-systems.html#details
Skyjuice Skyhydrant	Ultra Filtration, Gravity Fed	700 L/hr	None	143x18x25cm	Y	http://www.skyjuice.com.au/skyhydrant.htm

Trunz Brackish System 300	Mobile, Solar Powered, RO, desalination	650 L/hr	N/A	1770mm x 1560mm x 1510mm	Y	http://www.trunzwatersystems.com/water-treatment/products/tbs-300/
Island Water Tech - REGEN	Solar powered, Integrated Fixed-film Activated Sludge (IFAS)	12500, 25000, 37500, 75000L/day	N/A	20ft. x 8ft. x 8ft. 40ft. x 8ft. x 8ft. (ISO 20ft., 40ft. container)	Y	http://www.islandwatertech.com/regen/
UltraGTS GWTS	Membrane Bio-Reactor, UV disinfection	1130L/day	N/A		N	http://www.wastewateraustralia.com.au/greywater/domestic-wastewater
Seawater desalination System SS100 / SB002	Solar powered using 3 RO for sea water, anorganic contamination	160-290 liter/hour	N/A	1600x900x1150 mm	Y	http://www.dwc-water.com/technologies/solar-reverse-osmosis/up-to-3500-litersd/index.html
GP XM 2500 Water system	Solar powered portable Ultra filtration	9500 l/day	N/A	82.5 x 52 x 28.7cm	Y	http://www.genproenergy.com/genpro-products-solutions/product-catalog/water/water-filtration-and-purification/fresh-water-purification/gpxm-2500-portable-solar-powered.html
Bond strong SOLAR RO-5000 MODEL	Solar powered RO system	5000l/day	N/A	5750 x 2200 x 1780mm	Y	http://www.bondstrong.com/wp-content/uploads/2015/07/Bondstrong-Solar-RO-Brochure.pdf
Low Strength graywater Characterization and Treatment by Direct Filtration	Ultrafiltration (30200 and 400 kDa MWCO) and nanofiltration (200 Da MWCO)	150 l/h and pressure 6-10 bar	n/a		N	http://www.sciencedirect.com.proxy.library.cpp.edu/science/article/pii/S0011916404800286
Low Pressure nanofiltration	NF membrane (Dow/Filmtec NF-4040)	70 l/min	n/a		N	http://www.sciencedirect.com.proxy.library.cpp.edu/science/article/pii/S0043135407003326
Water Reuse system	N/A	55-150gal/day	N/A	N/A	N	https://www.google.com/patents/US4162218
Grey-Water Reuse and Reclamation	Carbon and Media Filter	3-8gal/min	N/A	N/A	N	https://www.google.com/patents/US5106493

Anaerobic Baffled Reactor (ABR)	Anaerobic Baffled Filtering	0.37 - 36.7 GPM	N/A	0.8m x 0.35m x 0.35m	Y	http://www.sswm.info/category/implementation-tools/wastewater-treatment/hardware/semi-centralised-wastewater-treatments-8
MBR Microfiltration System (RHMBR-10)	Membrane bio-reactors (MBR)	1.83 GPM	N/A	1.8m x 1.5m x 1.8m	N	https://www.alibaba.com/product-detail/Promotiona-sewage-treatment-system-plant-river_60492113704.html
PENTEK RO-3000/3500 Advanced Reverse Osmosis Water Filtration System	Reverse-Osmosis (RO)	0.005 GPM	N/A	0.349m x 0.121m x 0.318m	N	http://waterpurification.pentair.com/Files/KnowledgeBase/ItemDownload/en/1-146250-rev-f-fe14.pdf
IDE's modular Sea/Brackish Water Reverse Osmosis (SWRO/BWRO)	Solar Powered RO system	starting 500 m3/day - 30,000 m3/day	N/A	N/A	Y	http://www.ide-tech.com/solutions/desalination-2/membrane-ro/
Shuwaikh RO Project, Kuwait	ERI supplied 187 PX-260 energy recovery & RO	136,000m3 /day	N/A	N/A	Y	http://www.water-technology.net/projects/shuwaikh-ro-project/
Perfector-E potable water treatment system	RO UV membrane filtration, UV disinfection	2000 l/h	N/A	1100x1100x2200 mm^3	N	https://books.google.com/books?id=fWGZLmhpxvgC&pg=PA68&lpg=PA68&dq=pwn+perfector+E+specs&source=bl&ots=PpAPtXBkgm&sig=SXKMC7Ci3G1EsvVde6simxW7u48&hl=en&sa=X&ved=0ahUKEwjhyqeix9bQAhWCiFQKHczoCPQQ6AEIIDAB#v=onepage&q=pwn%20perfector%20E%20specs&f=false
Nubian Greywater Recycling System	Solids separation, biofiltration, UV, UF, chlorination	500-100,000 L/day	N/A	N/A	N	https://www.environmental-expert.com/downloads/nubian-greywater-recycling-system-brochure-319638
MBR at Quechan	Membrane Bio-reactor (MBR)	0.15 MGP				http://www.wateronline.com/doc/small-footprint-big-results-california-casino-wins-with-mbr-0001

Casino Resort Winterhaven,CA						
Coca-cola FEMSA	Membrane Bio-reactor (MBR)	456m^3/h	N/A	N/A (smaller than conventional)	N	http://www.wateronline.com/doc/rwl-water-provides-coca-cola-femsa-with-wastewater-treatment-for-reuse-0001
ProMinent Dulcosmose® ecoPRO	RO	100-1500 L /h	N/A	1400 x 500 x 320 mm ... 1650 x 700 x 720 mm	N	https://www.prominent.com/resources/Catalogue/English/9268/Water-Treatment-Water-Disinfection-ProMinent-Product-Catalogue-2016-Volume-4.pdf
MegaEngineering Smart Solar Desalination (SSD)	Hybrid solar-powered, RO	1100 m3 / day	0.43 kWh / m3	N/A	Hybrid	http://www.mega-group.it/wp-content/uploads/megacivic-ssd-2015-09-04.pdf
Ultra Mega Power project	RO coal fired plant	4622 GPM	N/A	N/A	N	http://www.aquatech.com/wp-content/uploads/47.-CGPL-SWRO.pdf
Reverse Osmosis Recovery Maximization	RO	16 gpm	N/A	N/A	N	https://www.usbr.gov/research/AWT/reportpdfs/report119.pdf
Transportable Reverse Osmosis Water Purification Unit	RO	20 gpm	N/A	5.5m x 2.1m x 1.7m	N	https://docs.google.com/viewer?url=patentimages.storage.googleapis.com/pdfs/US5244579.pdf
Acqualogic Advanced Greywater Treatment System	multi-media filter -> GAC filter -> UV	N/A	N/A	N/A	N	http://acqualogic.com/acqualogic-advanced-greywater-treatment-system/
Aquacell G series	Biological treatment ->Ultrafiltration ->UV	N/A	2kWh per 275 gal	N/A	N	http://www.dewater.com/media/121289_greywater4.pdf
Innovation of a Grey Water filter	multi-layer filter and UV	N/A	N/A	N/A	Yes, solar cell	https://wrrc.arizona.edu/sites/wrrc.arizona.edu/files/pdfs/Greywater_Filtration_sustainable_water_11_2011.pdf

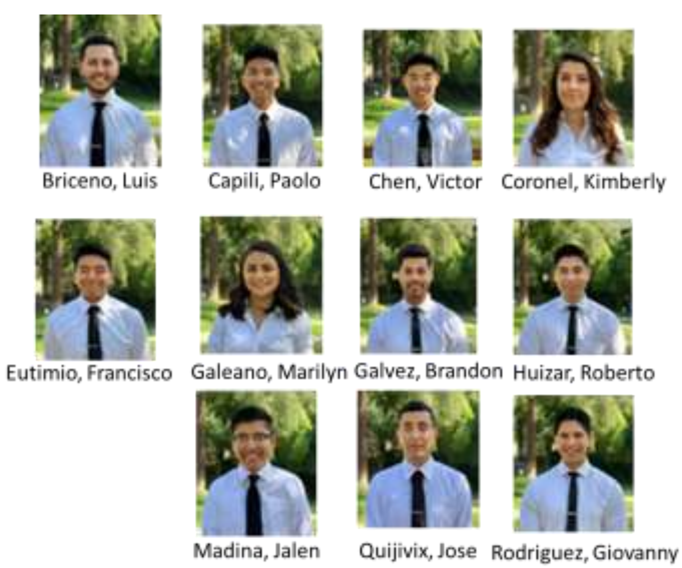
Appendix B (Laboratory and Facility)

Appendix C (Student Members)

2016-2017 Student Cohort

2017-2018 Student Cohort

2018-2019 Student Cohort



<u>**Appendix D (2017 ASME Conference Paper)**</u>

Proceedings of the ASME 2017 International Mechanical Engineering Congress and Exposition
IMECE2017
November 3-9, 2017, Tampa, Florida, USA

IMECE2017-70828

A CASE STUDY OF DECENTRALIZED OFF-GRID WATER TREATMENT USING REVERSE OSMOSIS

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BSTRACT

Decentralized water treatment consists of a variety of water treatment techniques for dwellings, industrial facilities, homes, and businesses independent of the power grid. According to the United States Geological Survey, brackish groundwater is abundant in the southwestern states including California; hence it can potentially be considered a new source for California's water portfolio. Most of membrane-based desalination technologies (e.g. reverse osmosis) have high energy demand and cost. Using renewable energy (mostly solar photovoltaics) in concert with membrane-based water desalination can be utilized to develop decentralized and off-grid brackish water desalination systems especially for remote and rural regions. In this paper, the results of a case study on decentralized off-grid brackish water system have been presented and discussed. The system utilizes a high pressure pump that can provide a feed flow rate of 2.2 gpm of at 140 psi. The system is run by solar photovoltaic panels through a battery bank. The results of the study show that the system is capable of treating brackish water at a salt rejection rate of more than 97.5% and a recovery rate up to 80%.

INTRODUCTION

Water crisis is going to be the greatest challenge that human race has been exposed to in the recorded history soon. World Economic Forum identified the water crisis as the first and third global risk based on impact to society in 2015 and 2016, respectively [1]. Statistics show that 1 in 10 people worldwide and 8 of 10 people who live in rural areas do not have access to safe drinking water [2]. Data show that the number of people worldwide who have a cellular phone is more than the ones who have access to sanitary toilet [3]. Although the number of people who live in remote rural areas of the world has a decreasing trend, the number of people who live in those areas is more than 46% of world's population [4].

Decentralized water treatment systems can potentially provide the people who live in remote areas with a reliable source for drinking water. The design requirements of decentralized water treatment systems have parallels with centralized systems; however, there are important considerations that should be noted. In general, decentralized water treatment systems are expected to be robust, affordable in terms of capital cost, low-maintenance, and energy-efficient. Access to the power grid is usually limited in rural areas and operation of decentralized water treatment systems should ideally be grid-independent. The residents of remote communities often rely on brackish groundwater, rainwater from cisterns, or water found in open ponds, streams or rivers.

Water reuse is an appealing option to increase water availability for remote rural areas. Water reuse is a fairly new trend, as new water treatment technologies have been developed over the years. It should be noted that water reuse applications require different water quality specifications and thus demand different treatments varying from simple processes to more advanced ones.

Membrane technologies provide a cost-effective solution for water and wastewater treatment and desalination. These technologies appear to be a reliable alternative for conventional water treatment methods. The membrane technologies can be categorized into two main categories: pressure driven membranes such as reverse osmosis and electrical driven membranes such as electro dialysis. Pressure driven membranes are in four different types based on the membrane pore sizes: Microfiltration (MF, screens particles from 0.1 to 0.5 microns), Ultrafiltration (UF, screens particles from 0.005 to 0.05 microns), Nanofiltration (NF, screens particles from 0.0005 to 0.001 microns), and Reverse Osmosis (RO, ranging molecular size down to 10 MWCO) [5].

Literature on decentralized RO-based water treatment is limited. Many of the decentralized membrane water treatment systems that currently exist are larger scale and a majority of the systems treat brackish water and seawater. The systems are most commonly used in small communities of several households and villages, but not to the extent that it is considered a plant. Elsaad et al. [6] from MIT developed a decentralized RO-based water treatment system to produce potable water for a village in Yucatan Peninsula of Mexico. Their system was able to treat groundwater as well as rainwater collected in cisterns at a feed flow rate of 1.9 gpm. The high pressure pumps of the system was powered by two 400W solar PV panels. In a similar approach, Qiblawey et al. [7] developed a photovoltaic-driven Reverse Osmosis (PV-RO) system in Jordan that is capable of producing 132 gallons of permeate daily with a feed water flow rate of 0.67 gpm. In their technology a softener unit is considered before the RO system as a pre-treatment step to eliminate mineral ions that cause scale problems. In addition to the softener, a train of 5-micron sediment filter, a granular activated carbon filter, and a 1-micron sidemen filter was used.

In a different and more recent effort, Gökçeks [8] developed a wind-driven RO system for remote locations in Turkey to desalinate seawater. They tested the RO system in conjunction with a variety of wind turbines, ranging from 6 to 30 kW. The excess power generated by wind turbines were exported to the local power grid. They demonstrated that their wind-driven system produces water at a rate of 4.4 gpm and at a slightly higher cost compared to a grid-tied desalination unit.

In the current study, the preliminary results of Decentralized Renewable Off-grid Water Treatment (DROWT) project are presented. The developed technology incorporates a solar driven RO filtration system that is designed to operate independent of the power grid. Although the ultimate goal of the project is developing a water reuse technology for dwellings in remote areas, the system is also applicable for brackish water desalination.

REVERSE OSMOSIS THEORY

RO is a membrane-based technology that is widely used for water treatment. In this method, raw water that includes particles and contaminants, is pushed through a semi-permeable membrane. The membrane is only permeable to water due to its small molecular size and impermeable to dissolved and suspended particles. The flowrate of the RO process product (permeate) is found by Eq. (1)

$$Q_w = (\Delta P_{Hyd} - \Delta P_{Osm}) \times K_w \times S \quad (1)$$

where Q_w is the permeate flow rate, ΔP_{Hyd} is the hydrostatic pressure across the membrane, ΔP_{Osm} is the osmotic pressure of the feed water, K_w is the water permeability coefficient, and S is the wetted surface area of the membrane [9] . In order for RO process to generate product flow, the hydrostatic pressure across the membrane must overcome the osmotic pressure of the feed water. The osmotic pressure of the feed water is found by Eq. (2)

$$\Delta P_{Osm} \approx RT\,(C_{feed} - C_{per}) \quad (2)$$

where R is the ideal gas constant (8.3144598 kg m^2 s^{-2} K^{-1} mol^{-1}), T is the temperature of feed water (K), and C_{feed}, C_{per} are molar concentration of dissolved species (mol m^{-3}) in feed and permeate flows, respectively. Since the concentration of the dissolved solids in the permeate flow is smaller than that of feed water (i.e., $C_{feed} \gg C_{per}$), the osmotic pressure of the feed water is almost linearly related to the concentration of dissolved solids in the feed water. The molar concentration of dissolved solids is commonly represented by Total Dissolved Solids (TDS) and the electrical conductivity of the feed water.

CONFIGURATION OF THE SYSTEM

In this effort, a solar-driven and off-grid water treatment system is fabricated, and tested. Figure 1 illustrates the configuration of the test setup. The hydraulic circuit of the system include the following components. A low pressure 12V DC pump (Seaflow 12V, 4.5 GPM Model No. SFDP1-045-040-41) is used to receive the raw water from the feed tank and pressurize it to about 75 psi, and send the water to an array of two micro-filtration(MF) units (Polystyrene Plastic, 4gpm, 5 microns), a ½ inch spring check valve is installed downstream of the low-pressure pump to prevent backflow. Pressure gauges are installed upstream and downstream of the MF configuration. A secondary high-pressure pump (PumpTec Model No. 350U) is installed downstream of the micro filters to increase the pressure beyond the osmotic pressure of the feed (maximum of 150 psi). Similarly, a check valve is installed downstream of the secondary pump to prevent backflow and damp potential vibration of the flow. An analog pressure gauge and a digital pressure transducer are installed downstream of the high pressure pump.

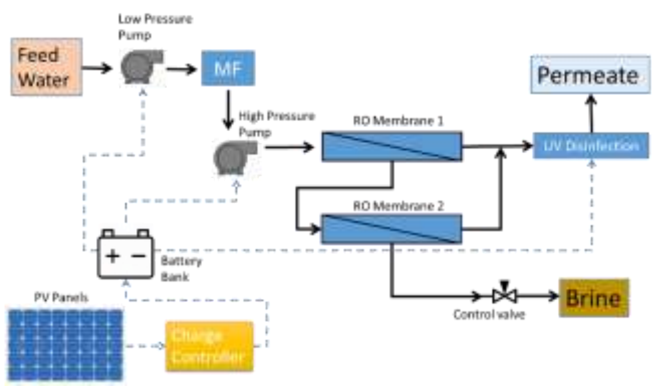

Figure 1 – Hydraulic and Electrical Circuits

The high pressure water is sent to a train of two Toray 4” RO membranes (Model No. SU-710L) that are installed in 2 stages with 1x1 configuration. The reject of the first membrane is fed to the second membrane for increasing the recovery rate. The brine of the second membrane passes through a digital, Arduino-compatible flowmeter before being collected in the disposal tank.

The permeate flows from both membranes are combined and diverted through an Ultra Violet (UV) disinfection unit. The UV disinfection unit (Viqua Model No. S2Q-P/12VDC) ensures that the micro-organisms that may have escaped through the RO process are deactivated by the UV light. The treated water was then sent through a digital flow meter and sent to permeate storage tank as seen on

Figure 1. The recovery rate and feed pressure of the system is manually regulated by an accurate needle-valve that is installed on the reject line of the second stage.

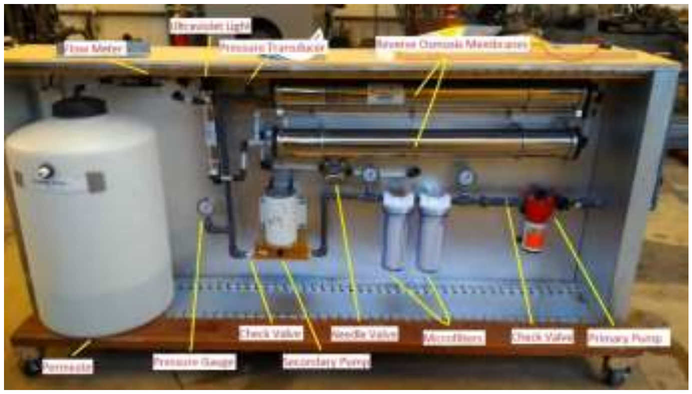

Figure 2 – Configuration of the system

The low- and high-pressure pumps as well as the UV disinfection unit are powered by a two wet-cell lead acid batteries that operate at 12V and are rated at 115 amp-hrs. The batteries are charged by two 115 Whr NewPowa solar panels through a charge controller (Sun YOBA Solar Charge Controller Solar Controller 80A 12V 24V Solar80). The pressure transducers and flow meters are connected to an Arduino MEGA 2560 for data acquisition. The energy consumption of the system is evaluated by measuring the amount of DC current that is withdrawn from the battery bank during the tests.

EXPERIMENTAL PROCEDURE

The feed water was prepared by solving lab grade sodium chloride (NaCl, 99% purity) in deionized water. The salt was added to the deionized water until the solution reaches a conductivity of 2000 µS/cm which is within the range of brackish groundwater. Per the quality assurance protocol, the experiment was performed after calibration of flow mater sensors, pressure transducers, electrical conductivity sensors, and current sensors. At first, the needle valve (control valve) was remained fully open and the low-pressure pump was turned on to receive the feed water from the tank and push the water through MF units. Once the flow is stabilized, the high-pressure pump was turned on and the system ran for a twelve minutes before data acquisition starts. The data acquisition system read and recorded the values of all sensors with a resolution of 5-second. The data was stored on a SD memory card.

The recovery rate and feed pressure are controlled by the needle valve, installed on the concentrate line. Recovery rate is defined as the ratio of permeate flow to the feed flow rate. Closing the needle valve on the concentrate line, increases the hydraulic resistance imposed on the concentrate line and the total resistance of the hydraulic circuit. As a result, the feed pressure and the recovery rate increase, leading to generation of more product. The needle valve was adjusted to reach higher feed pressures and a new set of data was recorded every ΔP_{feed} = 20 psi. The test was carried out until a maximum feed pressure of 140 psi was achieved. Increasing the feed pressure beyond 140 psi leads to extremely high recovery rates and was avoided to prevent damaging the RO membranes due to fouling.

RESULTS AND DISCUSSION

Figure 3 illustrates the change in feed and permeate flow rates and recovery rate as a function of feed water pressure. The permeate flow rate and the recovery rate show an increasing trend with the feed water pressure. The linear change in permeate flow rate and recovery rate are in agreement with the theoretical predictions of Eq. (1). Since the osmotic pressure across the membrane (ΔP_{Osm}) does not significantly change by increasing the hydraulic pressure, it is expected that the permeate flow increases almost linearly with feed water pressure. The feed flow rate does not significantly change during the test; however a minor reduction is observed due to increased hydraulic resistance in concentrate line.

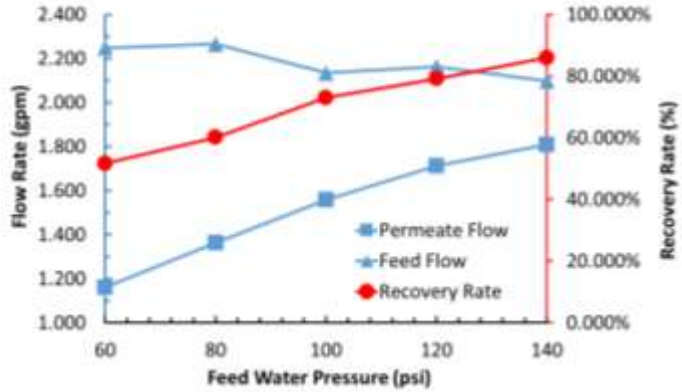

Figure 3 – Feed and permeate flow rates and recovery rate as a function of feed water pressure

The effectiveness of RO process in desalinating the feed water is shown in Figure 4. The conductivity of the permeate flow is plotted as a function of feed water pressure. The results show that the conductivity of the permeate flow (20~50 μS/cm) is significantly reduced in comparison to the feed water (2000 μS/cm), leading to a salt rejection rate of more than 97.5%. Increasing the pressure of the feed flow leads to higher conductivity of permeate flow due to the fact that more salt molecules will penetrate through the membrane and show up in the permeate at higher feed pressures.

Energy consumption per unit volume of the permeate flow (aka Specific Energy Consumption or SEC) as a function of feed water pressure is plotted in Figure 4. The variations of SEC during the test exhibits an interesting trend. Higher feed water pressure leads to generation of more permeate water volume and increased consumption of energy concurrently; however, the effect of permeate volume on the SEC appears to be more dominant in smaller recovery rates (or feed water pressures). The results show that the effect of energy consumption will be more significant in the higher recovery rates. As a result, the values of SEC start to increase at higher feed water pressures, leading to appearance of a minima. This phenomena has been previously reported by Li [10] in an effort to optimize the operation of brackish water RO desalination plants. The optimal operation point of the current system appears to be at about 120 psi of feed water pressure. The existence of an optimal point for specific energy consumption is an important consideration when designing an off-grid system that relies on solar energy.

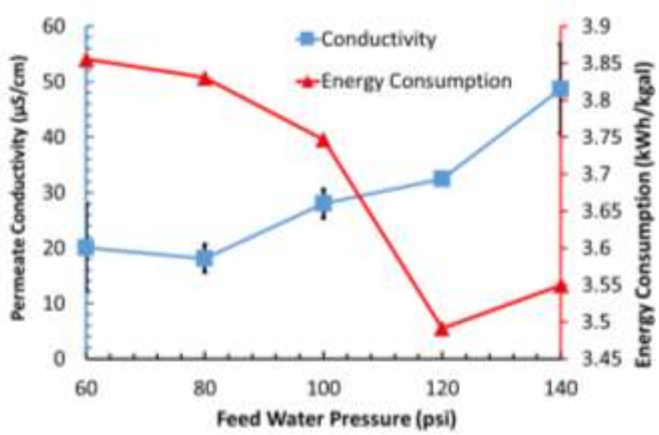

Figure 4- Energy consumption per unit volume of product and conductivity of permeate flow as a function of feed water pressure. The conductivity of the feed is ~2000 μS/cm

CONCLUDING REMARKS

In this effort, a decentralized grid-independent, zero carbon-footprint water treatment system is developed. The system utilizes a micro-filtration pretreatment, a two-stage reverse osmosis, and an ultra violet disinfection posttreatment. The system is solely powered by solar-photovoltaic panels through a battery bank.

The developed system is capable of desalinating and disinfecting a permeate flow rate of 1.2-1.8 gpm with a recovery rate of 60-80%. A minimum salt rejection rate of 97.5% is achieved at 140 psi of feed water pressure.

A preliminary energy consumption analysis show that the specific energy consumption of the system varies between 3.5-3.85 kWh/kgal. The results of this study show that the specific energy consultation of the system reaches a minima at intermediate recovery rates.

FUTURE WORK

The ultimate goal of the Decentralized Renewable Off-grid Water Treatment (DROWT) project is developing a commercially available, standalone, portable, and grid-independent water treatment for graywater reuse and ground water desalination. In the next steps, the team will work on reducing the footprint of the system and increasing the robustness and reliability of the system along with a more rigorous data analysis. In addition, contaminants of emerging concerns (CECs) [11] will be studied in graywater treatment using this process.

ACKNOWLEDGEMETS

This work is supported by Metropolitan Water District of Southern California through Innovative Conservation Program (agreement number 167250) and World Water Forum College Grant Program (agreement number 163706) and the Cal Poly Pomona Strategic Interdisciplinary Research Grant (SIRG).

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Appendix E (Draft of Journal Manuscript)

In preparation for Water Science and Technology

A Case Study of Decentralized Solar-powered Graywater Reuse Unit

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Crystal Mena**, Kevin R. Anderson* , and Mohammadali Sharbatmaleki**

Introduction

Water scarcity has been a major problem to which no permanent solution has been found yet. It is easy to dismiss the severity of a drought, given that about 70% of planet Earth is covered with water. However, only 3% of Earth's water makes up the freshwater used for agriculture and drinking; it is estimated by the EMDAT that over 50 million people are affected by drought conditions. (Stanke, Kerac, Prudhomme, Medlock, & Murray, 2013). Another concern that arises with population growth is the increasing stress and damage on current alternative and natural water sources; including pollution of rivers, lakes, and oceans. Drought conditions not only impacts the wellbeing of humans, but their economic and political systems. Many studies have proven that the drought experienced by Syria was a substantial factor to the unrest suffered by this region (Selby, Dahi, Fröhlich, & Hulme, 2017). This, in turn, led to a large-scale internal migration and spurred Syria's civil war. Other cities like Cape Town in South Africa are now enforcing laws that make it illegal to fill pools, water gardens, and wash cars due to the lack of water. Cape Town citizens have been warned to cut their water consumption to less than 50 liters per day, which is less than one sixteenth of what the average American uses, to preserve as much water as possible (Welch, 2018). One of the biggest cities in the Western hemisphere, Sao Paulo is facing its most critical water crisis over the last 80 years. The problem in this city goes beyond water scarcity to the highly polluted and intoxicated water resources; their reservoirs are muddy and full of unclear milky water.

Due to the exponentially increasing scarcity of water, researchers have been studying new methods to supply freshwater for irrigation, industrial, and domestic uses. One proposed method is water reclamation, which is the process of recycling wastewater by purifying it to bring it up to the required standards of freshwater. The water treatment process consists of three major steps: preliminary, primary, and secondary treatment. The preliminary phase consists of screening out large solid materials and grit removal to protect the equipment against unnecessary wear. The primary phase targets matter that floats on the water's surface. Finally, the secondary treatment phase is utilized to remove suspended solids and dissolved organic matter. Following these steps, agents such as Chlorine and UV radiations are utilized to disinfect the water from pathogens, including viruses, bacteria, and protozoa. Engineering technology advancements have provided various methods of fulfilling these stages of the water treatment process. Such techniques include, but are not limited to, microfiltration, nanofiltration, reverse osmosis, activated carbon, biological filtration, and chemical oxidation. Thus allowing water reclamation to be a viable means of alleviating the stress on the current water systems, provide alternatives to supply freshwater, and will aid in decreasing the severity of water crisis in the cities around the world.

Like any discovery, water reclamation has advantages and disadvantages. The main advantage of water reclamation is cost. Although this could be counterintuitive, recycling wastewater has been proven more efficient than generating new freshwater. Recycling water reduces stress on the infrastructure because it can be generated locally within the city, which reduces transportation costs and reliance on public utilities. Another advantage of this technology is conservation. The process of reusing water grants the city independency by putting the water directly into use; such water could be harvested for irrigation in agriculture. Due to the nature of water treatment for non-potable use certain chemicals like nitrogen can help plants fertilize. On the other side of the spectrum, water reclamation has certain disadvantages. Health concerns quickly arise when recycled water is used for drinking. The public is still very concerned about accidental precipitations of bacteria such as E. coli that could lead to health problems. Another concern that ascends with this new technology is the psychological and social public perception of recycled water. Despite the possible benefits that this discovery can provide, the public is very cautious about the idea drinking reused water.

There are different treatment technologies and techniques used to treat greywater, the leading process used by the industry is Reverse Osmosis (RO) membranes. By 2008 RO membranes were used by 53% of the water industry (Ali A). Water treatment plants that use RO membranes can have recovery rates of 25-40% for seawater and a high of 90% for brackish water. The main source of energy consumption in the RO system is focused on the pressurization of the feed water that must overcome the osmotic pressure. The energy required for a RO system ranges from 3-10 kwh/m3of fresh water produced (Catherine 2009). The cost of the filtration system is highly dependant on the quality of feed water and the model of membrane used. To further minimize costs, microfilters are often used as pretreatment to improve the quality of feed water.

Renewable energy alternatives have begun to be implemented to power these systems as freshwater and conventional energy sources become more scarce. Renewable energy is a non depletable clean energy source that does not contribute to air pollution, global warming or greenhouse gas emissions. (Ali A). Theoretical simulations have been performed by Bilton AM on the technical and economical feasibility of PV as a renewable energy source for salt water reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) in several locations such as Jordan, Australia, Los Angeles, Cyprus and many more. The projected cost is 2.11-2.41 $/m3 and 4.96-7.01 $/m3for BWRO and SWRO systems respectively. BWRO costs were 50% less compared to Diesel Power Generation and SWRO was about the same cost(Ange 2014). Diesel Power Generation is power generated by diesel fuel which is one of the most reliable source of energy. (diesel Forum)

The most common use of decentralized water reuse units are for landscape irrigation. Decentralized units allow for onsite use and eliminate the cost of long distance transportation to a centralized system. Decentralized units allow for the opportunity to replace the use of potable water for uses such as irrigation which do not require high water quality. The most common onsite wastewater treatment systems are comprised of two components, a septic tank (ST) and a soil absorption system (SAS). These components require no energy. A ST removes large particle through sedimentation and degradation over time. The SAS filters the water from the ST through natural percolation.

There have been extensive studies conducted on the water quality parameters of permeate produced by RO membranes. The findings verify the membranes ability to produce high quality water. A study conducted by Bunani and Sert found that the average conductivity rejection percentage for AK- Brackish water reverse osmosis(BWRO), AD- Sea water Reverse osmosis (SWRO) membranes were approximately between 95-98% (Bunani 2015). COD rejection efficiency for the two membranes was found to be on average 87-89.5%. A study conducted by Alzahrani and Mohammad analyzed the effectiveness of the removal of bacteria by RO and found an increase of 300% in coliform due to a lack of pretreatment and posttreatment (Alzahrani et al 2013). Alzahrani suggest that pretreatment and disinfestation of product water is needed to ensure the total removal of bacteria to prevent contamination (Alzahrani 2013). Feedwater TDS 854mg/L, permeate TDS 6.01mg/L<USEPA and WHO standards. Feedwater Turbidity 21 NTU, permeate <1 NTU. The removal efficiency percentages for TDS and Turbidity were found to be approximately 70% and nearly 100% respectively (Alzahrani 2013). A more recent study analyzing the water quality parameters of various membranes concluded that product water from RO membranes meet the legal requirements for the use of irrigation (Palma 2016). Ramiro Etchepare and Jan Peter van der Hoek concluded that the majority of the chemicals found in treated greywater would not cause appreciable human health concerns by being exposed to drinking water over a life-time period (Etchepare and Hoek, 2014). (needs more info, Hardness and BOD).Table 1 summarizes the findings of the literature search on existing technologies/projects.

Table 1 - Table comparing operating conditions of various existing PVRO systems.

Project (Author, year)	Pressure at feed (psi)	Feed Flow Rate (gpd)	Permeate Flow (gpd)	Feed TDS (ppm)	Permeate TDS (ppm)
H. Elsaad, et al; 2015 (Cistern)	55	2740	260	69	
(Well Water)	90	2740	260	2154	
H. Qiblawey, et al; 2011		989	241 to 178	340	
Bellona, et al; 2007	60 to 70	26208	21456		
D.Herold et al.; 1998	652 to 1015	5706	476 to 1109	Seawater SDI <1	<500
H. A. Shawky et al; 2015	142 to 491.7	8749	2726	1,000 to 25,000	<500
Gökçek & Gökçek, 2016	583	21112	6340	37864.4	434

This study is focused on demonstration of the feasibility of development and operation of a small decentralized water reuse system consisted of a MF, RO, and UV sections powered by solar power. The specific objectives of the study are to: a) validate operation of a small-scale decentralized MF/RO/UV water reuse unit and confirm the operating conditions are within industry's acceptable range; b) evaluate physical, chemical, and biological water quality parameters of product and reject streams; and c) assess energy consumption of each component of the decentralized MF/RO/UV unit and demonstrate the use of solar energy as the main source for operating the unit.

System Design and Configuration

In this effort, a solar-driven and off-grid water treatment system is fabricated, and tested. Figure 1 illustrates the configuration of the test setup. The hydraulic circuit of the system include the following components. A low pressure 12V DC pump (Seaflow 12V, 4.5 GPM Model No. SFDP1-045-040-41) is used to receive the raw water from the feed tank and pressurize it to about 75 psi, and send the water to an array of two micro-filtration(MF) units (Polystyrene Plastic, 4gpm, 5 microns), a ½ inch spring check valve is installed downstream of the low-pressure pump to prevent backflow. Pressure gauges are installed upstream and downstream of the MF configuration. A secondary high-pressure pump (PumpTec Model No. 350U) is installed downstream of the micro filters to increase the pressure beyond the osmotic pressure of the feed (maximum of 150 psi). Similarly, a check valve is installed downstream of the secondary pump to prevent backflow and damp potential vibration of the flow. An analog pressure gauge and a digital pressure transducer are installed downstream of the high pressure pump.

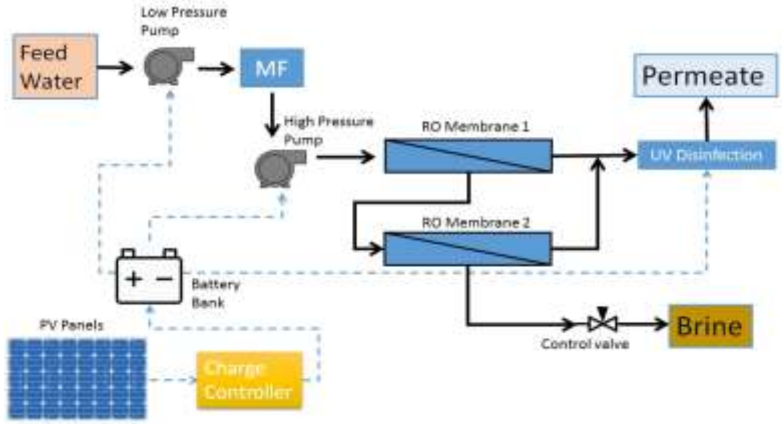

Figure 1: System Configuration and P&ID

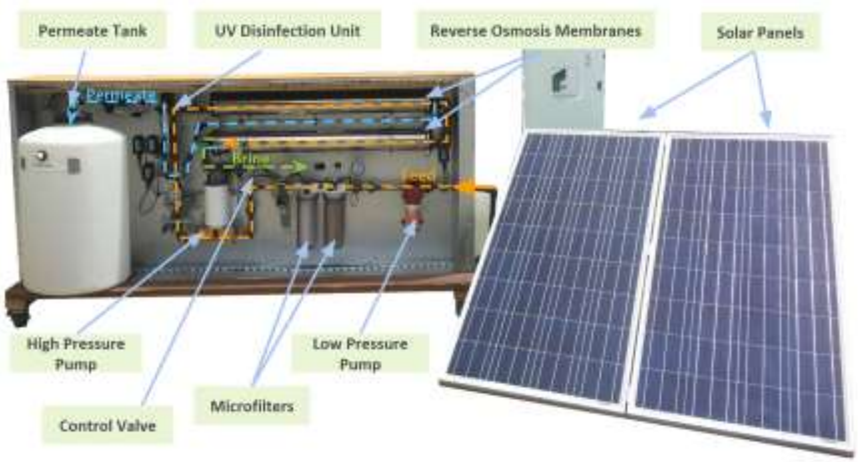

Figure 2 – Illustration of the system

The pressure of the water is regulated using a needle valve at the brine line. Both pumps and the UV disinfection unit is powered using solar power collected using two sets of Newpowa PV panels rated for 115 Whr, with an Everstart 115 amp-hr 12 DC battery serving as energy storage. The build for DROWT 1.0 can be seen in Figure 2 with the paths of the feed water, permeate, and brine. Two Uxcell flow sensors (Model No. FS300A) are placed in the system to monitor flow rates. One is placed along the permeate line, and another is placed at the brine line.

Experimental Procedure and Results

Data collection comprised of two processes. System performance was monitored using the following parameters: specific energy consumption (SEC) (kWh/kg), recovery rate (%), conductivity (μS/cm), hardness (mg/L), turbidity (NTU), and biological oxygen demand (BOD) (mg/L). The current at both pumps and the UV disinfection unit was recorded using an Extech AC/DC clamp meter (Model No. MA445). Through the use of Arduino and the two Uxcell flow sensors at the permeate and brine, the flow rate at both locations is recorded every second. The recovery rate is the ratio of water that is recovered to the amount of water that is fed into the system, and it is calculated using Equation 1.

$$Recovery\ Rate\ \% = \frac{Q_P}{Q_F} \times 100 = \frac{Q_P}{Q_P+Q_B} \times 100 \tag{1}$$

Q_F = *feed flow rate, gpm*

Q_P = *permeate flow rate, gpm*

Q_B = *brine flow rate, gpm*

SEC is the amount of energy consumed (kWh) per unit volumetric flow rate (kgal) and is found using Equation 2.

$$SEC\left(\frac{kWh}{kgal}\right) = \frac{1000\frac{gal}{kgal} \times I \times V}{1000\frac{W}{kW} \times 60\frac{min}{hr} \times Q_P} \tag{2}$$

I = *current, A*

V = *voltage, V*

Q_P = *permeate flow rate, gpm*

Water quality tests were performed on samples collected at each pressure setting. Turbidity is the cloudiness of a fluid from a large number of particles that are otherwise invisible to the naked eye. It was measured based on the sample's absorbance found using a HACH spectrophotometer then compared to a curve generated using the absorbance of HACH turbidity standards. Hardness (mg/L) is the calcium and magnesium content in water, which was found using a HACH hardness kit and colorimeter (Model No. DR/890).

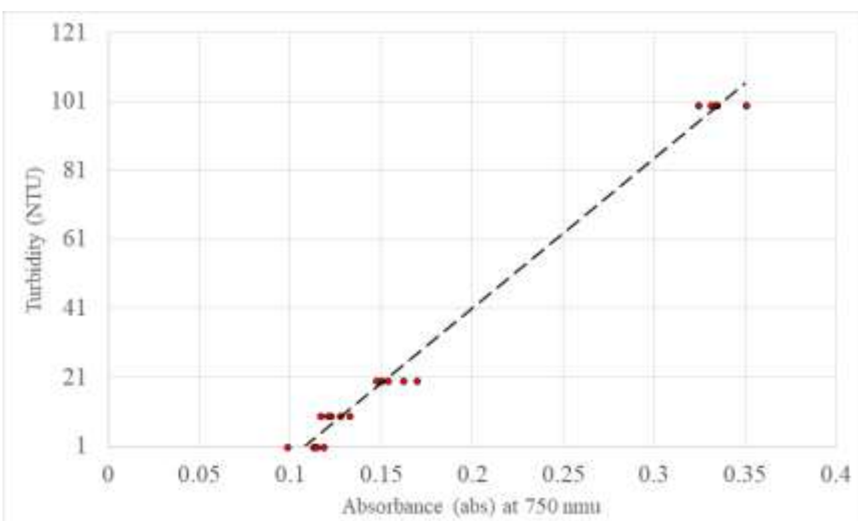

Figure 3 - Turbidity calibration curve used to interpret turbidity using absorbance at 750 nmu.

Figure 4 represents the energy consumption of systems similar to the DROWT system. It is noticeable that DROWT Version 1 has an average energy consumption of about 4kWh/kgal, which less than the energy consumed by similar systems. Figure 5 represents the average recovery rate curve and the energy consumption bars. The recovery rate ranges from 60% to 70% on average; whereas, the energy consumption averages around 4KWh/kgal. Figure 6 shows the conductivity (green curve) and the hardness (yellow curve) achieved by the system in different pressures. The dashed lines represent the acceptable hardness and conductivity for water reuse.

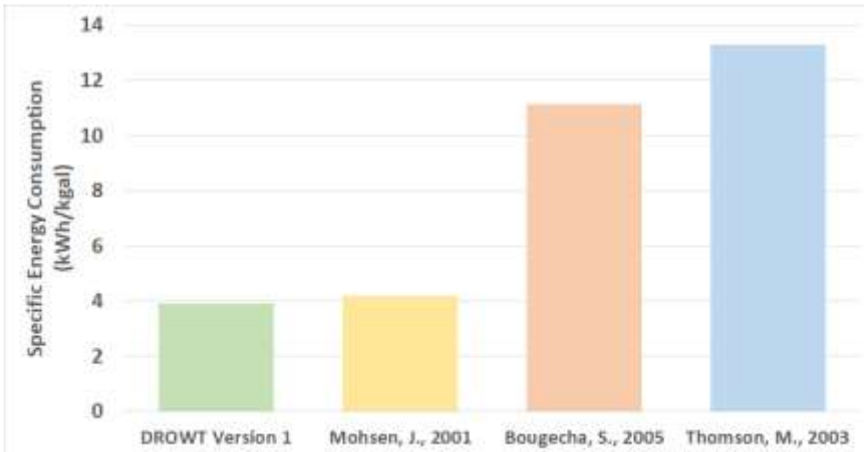

Figure 4 – Comparison of specific energy consumption of some decentralized water treatment units

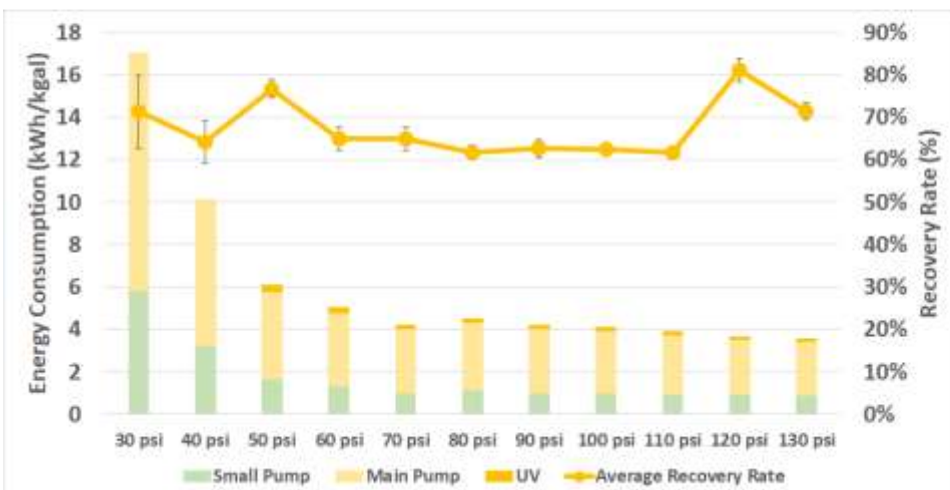

Figure 5 – Specific energy consumption and recovery rate of DROWT 1.0 in different operating pressures.

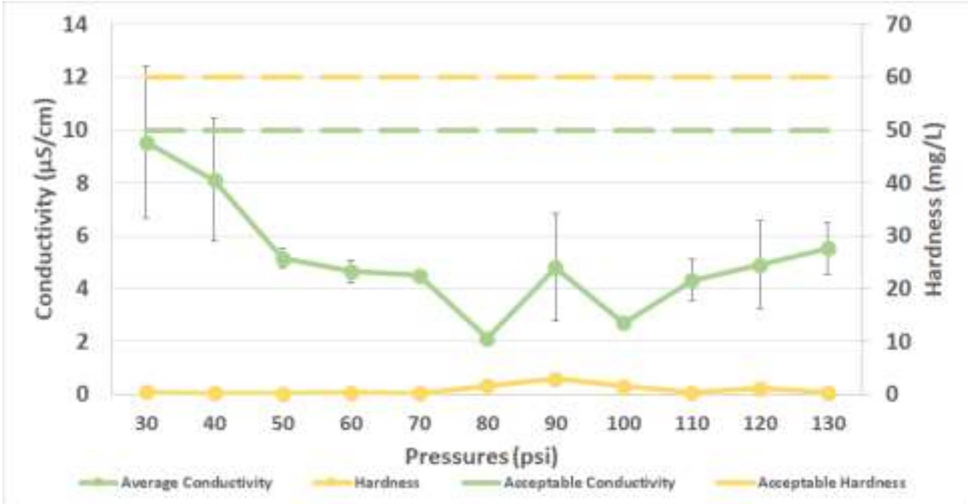

Figure 6 – Conductivity and hardness of permeate water generated by DROWT 1.0 at different operating pressures.

A significant finding resulting from the high feed pressure is the increased recovery rate. An increase in the feed water pressure increases the flow of the permeate water. On a micro level, water molecules are more likely to penetrate the membrane at a higher pressure; more water molecules strike the surface of the membrane per unit of time. An increase in recovery rate, increases the efficiency of the system. The highest recovery rate was found to be about 65% to 70%. By comparing this rate to the under the sink recovery rate systems, which happened to be about 30%, it is noticeable that the DROWT system is twice as efficient as those systems.

The energy consumption of the system varied by modifying the pressures. Since the energy consumption is calculated by dividing the power consumed by the flow rate of the permeate water, an increase in the flow rate lowers the energy consumption. Because the flow rate is directly proportional to the velocity, given that the cross sectional area is constant, the velocity was augmented by increasing the pressure, which hiked the flow rate, and minimized the energy consumption. With higher pressures, the system consumes more energy; however, the flow rate increase is more significant that the power consumed, which led to a minimum energy consumption of about 4kWh/Kgal at 100 psi. It could be considered that the optimal operating range for a minimum energy consumption ranges from 100 psi to 130 psi.

Appendix F (2018 ASME Conference Paper)

Proceedings of the ASME 2018 International Mechanical Engineering Congress and Exposition
IMECE2018
November 9-15, 2018, Pittsburgh, Pennsylvania, USA

IMECE2018-87090

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ABSTRACT

The decline of surface water sources along with periodic droughts has introduced new challenges for the state of California. In order to keep up with the increasing demand for water, the state is heavily relying on imported water from the north to Southern California as well as importing water from the Colorado River. The imported water has a large carbon footprint due to using grid power for water transport. Water reuse (reclaimed) is considered as one of the solutions to reduce the dependency of state on imported water. The research team at Cal Poly Pomona, is developing an off-grid solar-powered greywater treatment system for non-potable use in single households. Greywater is the drained water from bathroom sinks, showers, tubs, and washing machines; not including wastewater from toilets or kitchen sinks. Treating greywater on-site can provide significant water savings, and can reduce the carbon footprint of desalination using solar panels. The developed system is comprised of a three-stage treatment train: micro-filtration, solar-driven reverse osmosis, and ultraviolet disinfection. The end product of the project is capable of reclaiming 90-100 gallons of water per day which is about 60% of residential greywater waste. The system removes large suspended particles (particles of dirt, food, etc.) as well as organic and inorganic dissolved contaminants. It is demonstrated that the system can provide a permeate quality that agrees with recommended guidelines for reclaimed water. The system has a recovery rate of up to 62%.

NOMENCLATURE

C_{feed}	dissolved molar concentration of feed (mol/m^3)
C_{per}	dissolved molar concentration of permeate (mol/m^3)
K_w	Water permeability coefficient ($m^2.s/kg$)
P_{Hyd}	Hydrostatic pressure (Pa)
P_{Osm}	Osmotic pressure (Pa)
Q_w	Permeate Flow Rate (gpm)
R	Ideal gas constant (8.3144598 $kg\ m^2\ s^{-2}\ K^{-1}\ mol^{-1}$)
S	Wetted surface area of the membrane (m^2)
T	Feedwater temperature (K)

INTRODUCTION

Having access to clean water is a basic human need and right. According to United Nation's Human Development Report, about one in five people living in developing world do not have access to clean water [1]. Water crisis has been identified as one of the major challenges, facing human race in 21st century by World Economic Forum [2]. Many communities around the globe are experiencing new levels of water shortage. Cape Town (second most populous urban area in South Africa) is counting the days to reach "Day Zero" in which municipal water will stop flowing due to extreme drought condition and insufficient sources of fresh water [3]. The water crisis is not limited to the developing world. In the wake the most severe drought conditions in the history of California, as of April 2018, more than 58% of the Californians are living in water-stressed areas under drought condition [4].

Water reuse is one of the options available for the governments to reduce the need for fresh water. In California, water reuse has been utilized to reduce over-drafted ground and surface water supplies [5]. More than 37% of the reclaimed water is used for agricultural irrigation and about 12% of the reclaimed water is pumped to the aquifers for groundwater recharge. Although centralized wastewater treatment plants have been in operation for decades, decentralized and point-of-use water and wastewater treatment has not received enough attention.

Many of the decentralized membrane-based water treatment systems that are currently in operation are large scale and targeted at treating brackish water and seawater. Elsaad et al. [6] presented a decentralized water treatment system based on Reverse Osmosis to produce potable water for a village in Mexico. Elsaad's system treated groundwater and rainwater at a flow rate of 1.9 gpm. In a similar project, Qiblawey et al. [7] developed a photovoltaic-driven Reverse Osmosis (PV-RO) system that produces about 132 gallons per day of treated water. A softener unit is considered before the RO system as a pre-treatment step to remove sparingly soluble salts that cause ionic scaling. In addition to the softener, a 5-micron sediment filter and a granular activated carbon filter were used.

In a different and more recent effort, Gökçeks [8] developed a wind-driven RO system for remote locations in Turkey to desalinate seawater. They tested the RO system in conjunction with a variety of wind turbines, ranging from 6 to 30 kW. The excess power generated by wind turbines were exported to the local power grid. They demonstrated that their wind-driven system produces water at a rate of 4.4 gpm and at a slightly higher cost compared to a grid-tied desalination unit.

In a more recent study, Karavas et al [9], developed a decentralized and solar driven seawater desalination unit that was capable of producing up to 0.44 gpm of permeate flow at pressures as high as 740 psi. Unlike most PV-RO studies Karavas' system does not include a battery and employed DC micro grid concept along with mechanical and electrical energy storage methods such as hybrid capacitors and pressure vessels to remedy the intermittency of solar energy.

The current team previously designed, fabricated, and tested Decentralized Renewable Off-grid Water Treatment (DROWT) technology [10]. DROWT 1.0 was a solar driven RO filtration system that is designed to operate independent of the power grid. DROWT 1.0 was run by a DC pump and had a relatively large footprint. In this paper the second generation of DROWT products is presented. DROWT 2.0 has revolutionary differences with its predecessor including shorter footprint, ability to operate on- or off-grid, and more robust design and components. This paper discusses the design, fabrication, and testing of DROWT 2.0. The ultimate goal of the DROWT project is developing a water reuse technology for single-unit dwellings, remote areas, and disaster management.

REVERSE OSMOSIS THEORY

Reverse Osmosis is a membrane-based technology that is widely used for water and wastewater treatment. Raw water that may include suspended particles and dissolved contaminants, is pushed through a semi-permeable membrane. The membrane is only permeable to water molecules due to its small molecular size and impermeable to dissolved and suspended contaminants. The flowrate of the RO process product (permeate) is found by Eq. (1) [11]

$$Q_w = \left(\Delta P_{Hyd} - \Delta P_{Osm}\right) \times K_w \times S \qquad (1)$$

where Q_w is the permeate flow rate, ΔP_{Hyd} is the hydrostatic pressure across the membrane, ΔP_{Osm} is the osmotic pressure of the feed water, K_w is the water permeability coefficient, and S is the wetted surface area of the membrane. The hydrostatic pressure across the membrane must overcome the osmotic pressure of the feed water. The osmotic pressure of the feed water is found by Eq. (2)

$$\Delta P_{Osm} \approx RT\left(C_{feed} - C_{per}\right) \quad (2)$$

where R is the ideal gas constant (8.3144598 kg m^2 s^{-2} K^{-1} mol^{-1}), T is the temperature of feed water (K), and C_{feed}, C_{per} are molar concentration of dissolved species (mol m^{-3}) in feed and permeate flows, respectively. Since the concentration of the dissolved solids in the permeate flow is smaller than that of feed water (i.e., $C_{feed} \gg C_{per}$), the osmotic pressure of the feed water is almost linearly related to the concentration of dissolved solids in the feed water. The molar concentration of dissolved solids is commonly represented by Total Dissolved Solids (TDS) and the electrical conductivity of the feed water. The energy consumption of any RO system is directly proportional to the required feed pressure. Conclusively, desalinating water streams with high TDS (e.g., sea water) is much more energy intensive when compared to treating wastewater.

CONFIGURATION OF THE SYSTEM

DROWT 2.0 is designed and tested employing lessons learned from DROWT 1.0. The most significant difference between two versions is the addition of a third RO membrane in series and a third microfilter in the pretreatment step. The new design features a recycle loop that protects the RO membranes, enables higher recovery rates [7], and reduces the number of pumps from two in DROWT 1.0 to one in DROWT 2.0. Another major difference between the previous and new designs is the installation of a DC to AC inverter to power the pump and ultraviolet disinfection unit.

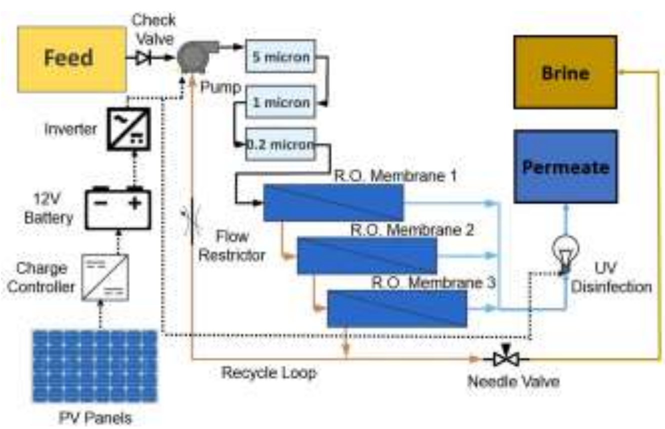

Figure 1 - Hydraulic Flow-diagram and Electric Circuit Schematic

Figure 1 shows the hydraulic and electrical circuit schematic for DROWT 2.0. Unlike DROWT 1.0, a plunger pump is no longer used on DROWT 2.0 and instead a vane pump is used due to its compactness and robust performance characteristics. Feed water is drawn from the feed tank by a positive displacement Procon Series 2 pump (Model No. 142A110S) rated at 112 gallons per hour. The pump is powered by a Marathon ½ hp split-phase carbonator pump motor (Model No. 871 YP). Feed water is conveyed in ½” outside diameter (O.D.) polyethylene tube and is mixed with flow from an integrated brine recycle loop before entering the suction side of the pump. A standard 304 stainless steel spring check valve is installed on the feedwater line upstream of the junction between the recycle line and feed before it is introduced to the suction side of the pump. A second spring check valve is installed downstream of the pump to eliminate potential backflow of water. An Ashcroft analog pressure gauge and a Kavlico pressure transducer, Model No. 1009 and P255, respectively were installed downstream of the second check valve to determine system pressure before the pretreatment stage in microfilters. In the pretreatment stage, water is passed through a series of microfilters with a successive reduction in porosity to reduce the filter maintenance expenses, i.e., 5-microns, 1-micron, and 0.2-micron. The pretreatment micro filters are Neo Pure Model No. PH-27097-05, PH-27097-1A, and HP-PESG-26100-0.2-B, respectively. The addition of a third microfilter was made to strategically step down the filtration in order to extend the life of the 0.2 micro filter; whereas, version 1 had similarly sized microfilters connected in series.

Service racks for both the microfilters and RO membranes were incorporated to better access the components when needed. Analog pressure gauges and pressure transducers were installed upstream and downstream of the 0.2-micron microfilter to monitor pressure drop across it for maintenance purposes, per manufacturer's specifications. After the pretreatment stage, feedwater is then directed through three Axeon 2.5" D x 21" L spiral wound reverse osmosis membranes (Model No. HF5-2521) connected in series. Permeate from each membrane is collected and directed to a Viqua Sterilight Ultraviolet Unit (Model No. SC1) for post treatment. The concentrate of the first and second RO membranes is passed through the subsequent membrane in series to enhance recovery rate. The concentrate of the third membrane is directed through a ⅜" Superlok needle valve (Model No. SINV4-F-6N-RS-S316) before disposal. The needle valve is used to regulate pressure in the system to desired test pressures. A tee fitting is installed upstream of the needle valve and a Neo-Pure one gallon per minute flow restrictor (Model No. FRSS-1-038FF) is connected to the branch side of the 3/8" O.D. Tee. The flow restrictor is used to allow a controlled portion of the 3rd membrane's concentrate to be recycled and mixed with feedwater and cycled through the system for treatment. Recycling the concentrate is necessary to increase the feed water that passes through RO membranes. Reduced feedwater flow rate in the RO membranes may cause excessive fouling and system failure.

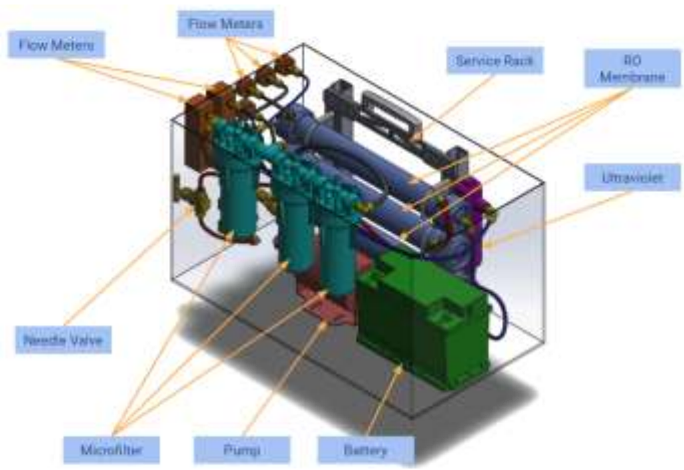

Figure 2 - SolidWorks Rendering of System Packaging and Hydraulic Circuit Configuration

The location of the components inside the enclosure was determined by developing a 3D CAD model in SolidWorks as illustrated in Fig. 2. Redundant flow meters were installed on the permeate and brine lines consisting of analog and digital meters. Digital flow meters are Uxcell ¼" hall effect water flow meters (Model No. A16042200UX0966) while the analog flowmeters are Hydronix panel mount (Model No. PMF-0202). A single digital flow meter was installed on the raw feed water so as to minimize head loss on the suction side of the pump. All fittings used were push-to-fit fittings compatible to the outside diameter of polyethylene tubing used for necessary changes in direction. Sizes in tubing and fittings varied to maintain a fluid flow velocity between 4 - 7 ft/s as recommended by [13] for schedule 40 pipe. Figure 3 shows the packaging and location of different parts of DROWT 2.0. The entire system was mounted and secured to a DeWalt portable tool chest (Model No. DWST38000) which has dimensions of 23" D x 24" H x 38" W. As shown in Figure 4 DROWT 2.0 has significantly smaller size and footprint compared to DROWT 1.0 presented in [10].

Figure 3 – DROWT 2.0 product packaging

Figure 4 – Comparison of DROWT 1.0 & 2.0 size and footprint

All electrical components are powered by a single 12V wet-cell lead acid battery with a 115 amp-hr rating. For off-grid purposes, two 115 W NewPowa solar panels in conjunction with a Windynation solar charge controller (Model No. P30L) are used to charge the battery. Power is passed through an Aims DC to AC power inverter (Model No. PWRINV20001212W) before distributing power to the pump and UV disinfection unit. The inclusion of an inverter allows for a wider variety of pump types and style readily available for AC applications at cost effective prices compared to those of DC circuits. This change was considered in designing DROWT 2.0 to allow for on- or off-grid functionality of the system. The inverter enables the user to plug the system into the grid in the event that it is desired to run the system beyond the capacities of battery and solar panels. Data acquisition from the flow meters and pressure transducers is accomplished via an Arduino Mega (Model No. 2560). Energy consumption of the pump and UV disinfection unit is evaluated by measuring the individual AC current withdrawn downstream from inverter via Extech AC line splitters (Model No. 480172) and recorded using and Extech Amp-meter (Model No. MA445).

EXPERIMENTAL PROCEDURE

Before testing, feed water was generated by dissolving sodium chloride (NaCl, 99% purity) into 20 gallons of DI water until the conductivity of the solution was 2000 µS/cm. The salinity of the feed water is in agreement with residential graywater and surface brackish water. Flow meters, pressure transducers, current sensors and conductivity probes were all calibrated before the beginning of testing. Pressure was varied by partially closing the needle valve located downstream of the reverse osmosis membranes (as shown on Figure 1) until the desired pressure was achieved. The performance of the system was tested at feedwatrer pressures in the range of 60-140 psi. The lowest operating pressure corresponds to a fully open needle and maximum pressure is dictated by the rating of the microfiltration housing. The system can be run by the power grid or entirely decentralized by utilizing solar panels. In order to perform more consistent data accusation and ensure a constant voltage output, data reduction was conducted while the system was run by the power grid.

Each test was characterized by turning on the pump and UV disinfection units and adjusting the needle valve to the desired feed pressure. Once the desired pressure had been achieved, the system was allowed to run for approximately two minutes to ensure steady state of all readings. After the stabilization period, data was collected for three minutes at each pressure setting. Pressure remained constant throughout each test. Flow rates of the feed, concentrate, and permeate lines were collected every second from digital flowmeters. Power consumption of the pump and UV disinfection unit was measured three times for each pressure setting. Three samples of permeate water were collected and the conductivity of the permeate was measured. Averages and standard deviation of all readings were calculated and plotted to describe the performance of the system and the random error associated with measurements.

RESULTS AND DISCUSSION

Feedwater and permeate flow rate as well as system recovery rate are plotted as a function of feed pressure in Figure 5. Feed flow rate decreases slightly with increased pressure due to the recovery loop. As predicted by Eq. (1) an increase in the hydrostatic pressure (ΔP_{Hyd}) across the RO membrane linearly increases the permeate flow rate. The results confirm the linear increase of permeate flow rate as a function of feedwater pressure. Unlike the permeate flow rate, the feedwater flow rate remains relatively constant at 1.2 gpm corresponding to 864 gpd which exceeds the generation of wastewater per household (i.e., 80-100 gpd/person). Figure 5 also shows that DROWT 2.0 is capable of recovering more than 62% of the feedwater at the maximum pressure setting. It should be noted that the achieved recovery rates exceed the recovery rate of available under-the-sink RO systems in the market (15% to 25%).

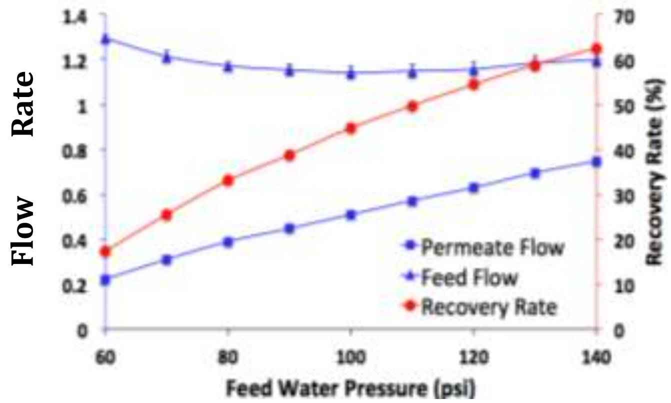

Figure 5 - Feed and permeate flow rates and recovery rate as a function of feed water pressure

The attention is now turned to the conductivity of the permeate flow and the salt rejection rate of the system as one of the most important characteristics of RO systems. Figure 6 shows the conductivity of the permeate flow at different pressure settings of the system. The conductivity of the permeate flow ranges from 154.6 µS/cm at 90 psi to 230 µS/cm at 140 psi. Taking the feed water conductivity of 2000 µS/cm into account, the salt rejection (i.e. TDS removal) rate for the system is between 88.5-92.3% for the tested pressures. The conductivity of the generated permeate agrees with the ideal conductivity of potable water (< 250 µS/cm).

The membranes used in designing the system are made of polyamide thin-film composite which is a hydrophobic material. The trend of the conductivity plot can be explained by the chemistry of hydrophobic material paired with the physics of membranes operating at high pressure. At low pressures the polyamide thin-film composite material provides a force that repels water from traveling through the membrane contributing to a low permeate flow rate. At low pressures, salt molecules are able to diffuse through the membrane which results in higher conductivities when combined with the small amount of permeate water. As feedwater pressure is increased, the water carries a larger force to pass through the membrane leading to more permeate water to be generated. The greater quantity of permeate water is able to dilute the salt particles passing through the membrane contributing to a decrease in conductivity. This trend only applies to a certain range of pressures because eventually at high enough pressures, salt molecules will start to be forced through the membrane along with water. Increasing the pressure to these levels will cause an increase in conductivity from the membrane failing to filter out the particles. With the specific membrane used in this study being rated for 80 psi, we can see in Figure 6 that the best quality water produced happened at this pressure.

The specific energy consumption of the system at different operating pressures is illustrated in Figure 6. The factors that affect the specific energy consumption are total energy consumption of the system and the amount of permeate water generated. The pump and the UV disinfection unit are the major energy consuming components of the system. The pump contributed to approximately 96% of the amount of total energy consumed. As shown in Figure 7, the total energy consumption of the system increases at higher feedwater pressures. The increase in permeate flow rate at higher pressures has a greater impact on the specific energy consumption, leading to a decreasing trend of specific energy consumption. The slope of the specific energy consumption plot in Figure 6 decreased with feedwater pressure. This behavior suggests that there is a minimum value for specific energy consumption of the system; however, this minimum value was not reached due to the limitations on the system pressure. In the study of DROWT 1.0, the minimum value of specific energy consumption was achieved and reported in [10].

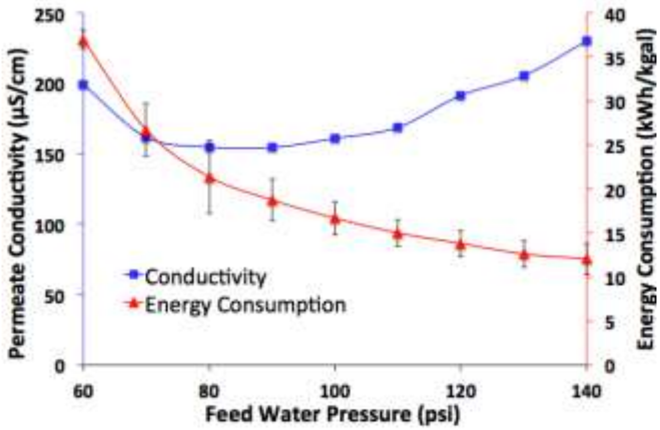

Figure 6 - Energy consumption per unit volume of product and conductivity of permeate flow as a function of feed water pressure. The feed conductivity is ~2000 µS/cm)

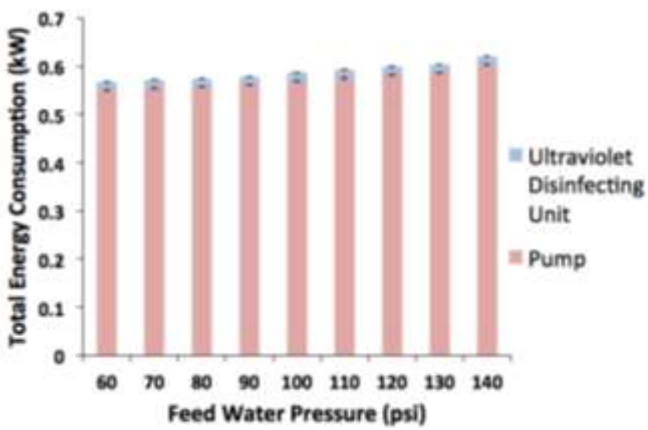

Figure 7 - Energy consumption of each component as a function of feed water pressure

Table 1 - Performance comparison between the two iterations of the system

	DROWT 1.0	DROWT 2.0
Optimal Pressure	120 psi	110 psi
At optimal pressure		
Recovery Rate	80 %	50 %
Conductivity	32 µS/cm	169 µS/cm
Specific Energy Consumption	3.5 kWh/kgal	17.2 kWh/kgal

As tabulated in Table 1, hydraulics and electrical upgrades implemented in DROWT 2.0 affect the performance of the system compared to DROWT 1.0. In order to simplify the hydraulic configuration as well as extend the lifespan of the RO membranes, the concentrate recycle loop has been introduced to the system at the expense of gaining lower recovery rates and having higher specific energy consumption.

The recycle water loop is considered to keep the velocity of feed and concentrate lines in the recommended range of the RO membranes. Moreover, due to blending of the feed with the recycled concentrate stream, the average feed conductivity before going into the first membrane is increased, thus the conductivity of permeate is also increased. The higher specific energy consumption in DROWT 2.0 is attributed to the reduced size of membranes and additional pretreatment steps.

THERMAL ASSESSMENT TEST

Since DROWT 2.0 is a highly compact design with major components working in a relatively small enclosure, overheating the electric motor and other electrical components of the system is a possibility. In order to assess the thermal characteristics of the design, the system was tested continuously on-sun with the lid closed. Infrared images of the components were taken at 10-minute intervals using a FLIR Thermal Camera (Model No. E8). Ambient temperature during the test was 21.1 ºC (70 ºF) in a fairly clear sky. Figures 8-1 and 8-2 show the initial and final thermal state of the system after 1.5 hours of continues operation. It was observed that the hottest component of the system after the test is the electric motor that runs the pump. The maximum temperature of the system is about 46.1 ºC (115 ºF) which is in the acceptable range of operation for all components of the system.

Figure 8-1 - Infrared image of unit before testing

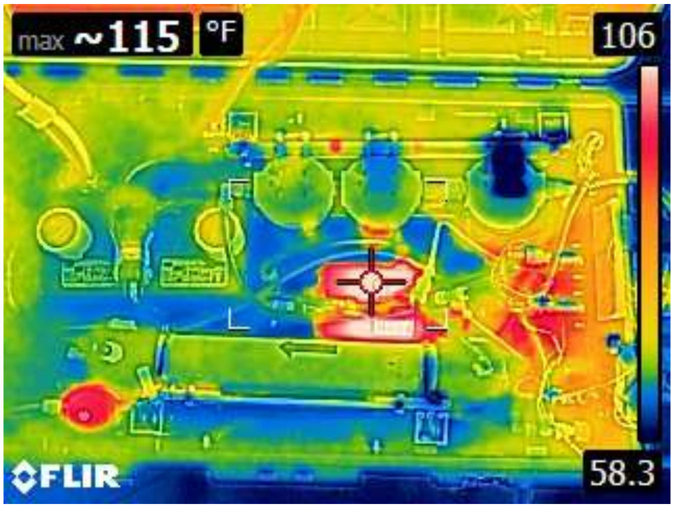

Figure 8-2 - Infrared image of unit after 1.5 hours of testing

CONCLUDING REMARKS

A solar-driven water treatment unit for off-grid applications was successfully designed and tested. The filtration process includes a pretreatment stage consisting of a three-stage micro-filtration, followed by a three-stage reverse osmosis and an ultra violet disinfection post-treatment. The designed system can be run on- or off-grid. In the off-grid operation, the system has zero operational carbon-footprint.

Tests of the system with a feed water conductivity of 2000 µS/cm yielded a recovery rates of 17-62% when tested at pressures ranging from 60-140 psi. The permeate flow rate during these tests ranged from 0.22-0.75gpm. Salt rejection at these pressures ranged from 88.5-92.3%. Specific energy consumption of the system ranged between 12-37 kWh/kgal of permeate water. The overall trend of energy consumption appears to approach a minimum value that is not achieved in the operating pressures of this study.

The performance of the two versions of DROWT system is compared and it was observed that DROWT 2.0 exhibits lower recovery rates and higher specific energy consumption due to its conservative design to reach higher lifetime of components.

FUTURE WORK

The Decentralized Renewable Off-grid Water Treatment (DROWT) team has its sights on developing a technology to be commercially available for consumers with a need for a decentralized, portable water filtration machine. In the next step, the performance of the system in treating synthetic graywater will be assessed. A user interface system will be developed to provide the user an easy way to operate and monitor the system remotely.

ACKNOWLEDGEMETS

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Appendix G (Endurance and Water Quality Tests of DROWT 2.0)

In order to monitor the performance of DROWT 2.0 operating at four different temperature points, water quality tests were conducted on the synthetic greywater feed water, as well as the brine and permeate produced by the system. The water quality parameters that were monitored are the following: conductivity (µS/cm), hardness (mg/L), turbidity (mg/L), and chemical oxygen demand (COD) (mg/L).

The tests were conducted by heating the feed synthetic greywater to 85℉, 90℉, 95℉, and 100℉ in that order. At each temperature point, 300 mL samples of the feed, permeate, and brine were collected.

Turbidity was measured using a spectrophotometer, the absorbance measured for all samples collected yielded very small numbers close to zero when converted to turbidity via a calibration curve generated using turbidity standards.

Figure 1 shows the conductivity of each sample taken after the water has reached each temperature point. The conductivity probe used was calibrated using 147 µS/cm conductivity standard solution. The conductivity of the brine is above 700 µS/cm at each temperature, always more than double the feed conductivity recorded for that sample. The permeate conductivity is seen as decreasing significantly from 90℉ to 95℉ and becoming steadier. This likely demonstrates the effect of a heated feed through the RO membranes.

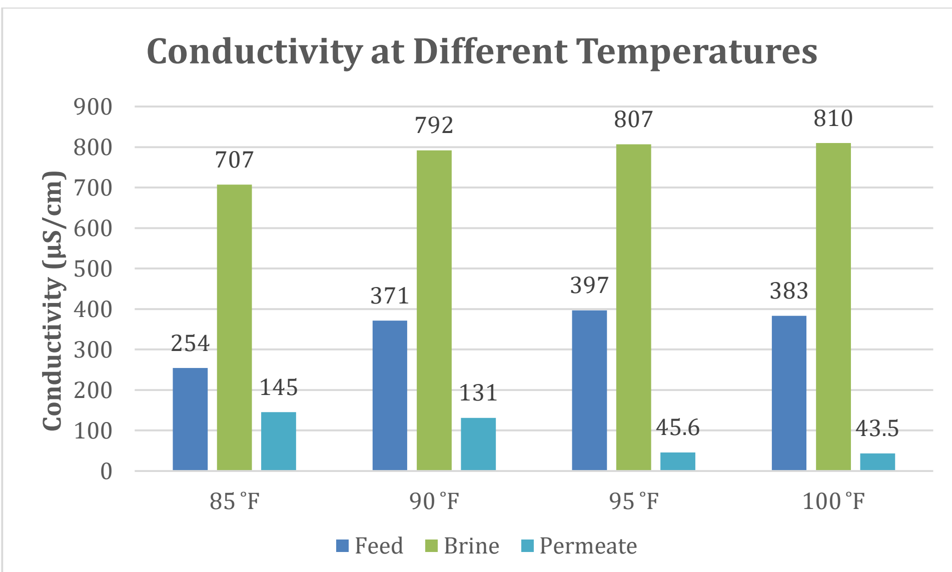

Figure 1: Conductivity of the Feed, Brine, and Permeate collected at 85℉, 90℉, 95℉, and 100℉.

Water is generally classified as soft if the hardness falls within the range of 0-60 mg/L. The hardness data shown in Figure 2 show that the water generated falls well into the lower range of soft water. The National Research Council states that drinking water contributes to human consumption of minerals, potable drinking water generally is moderately hard, that said the EPA does not have a specific number for acceptable hardness in potable water as it is not considered harmful to health.

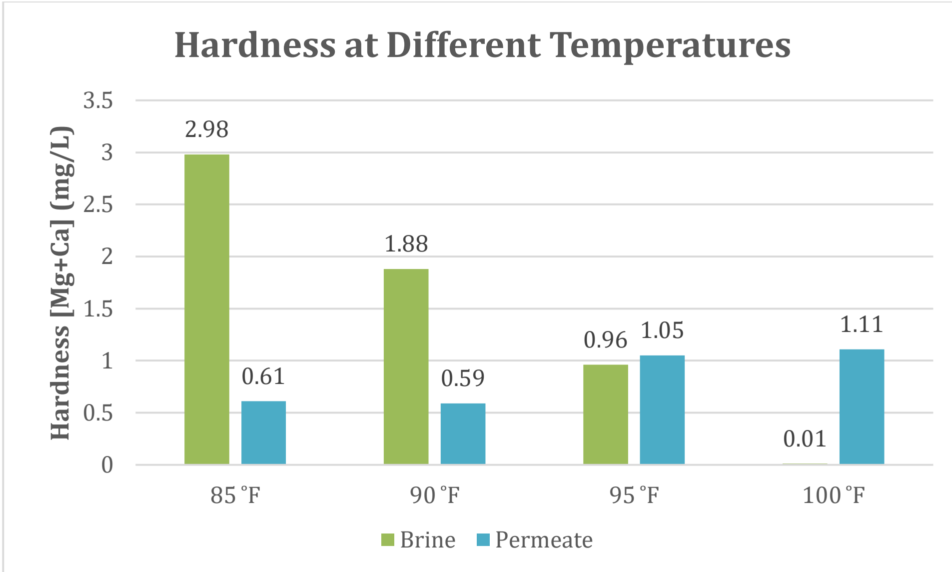

Figure 2: Hardness of the Brine, and Permeate collected at 85 ℉, 90 ℉, 95 ℉, and 100 ℉.

Figure 3 is a plot comparing the COD results across each temperature point. There is a lot of variation in the data. However, the COD of the permeate is consistently under 200 mg/L. COD of the 80 ℉ was out of range, and we were unable to secure a number for it.

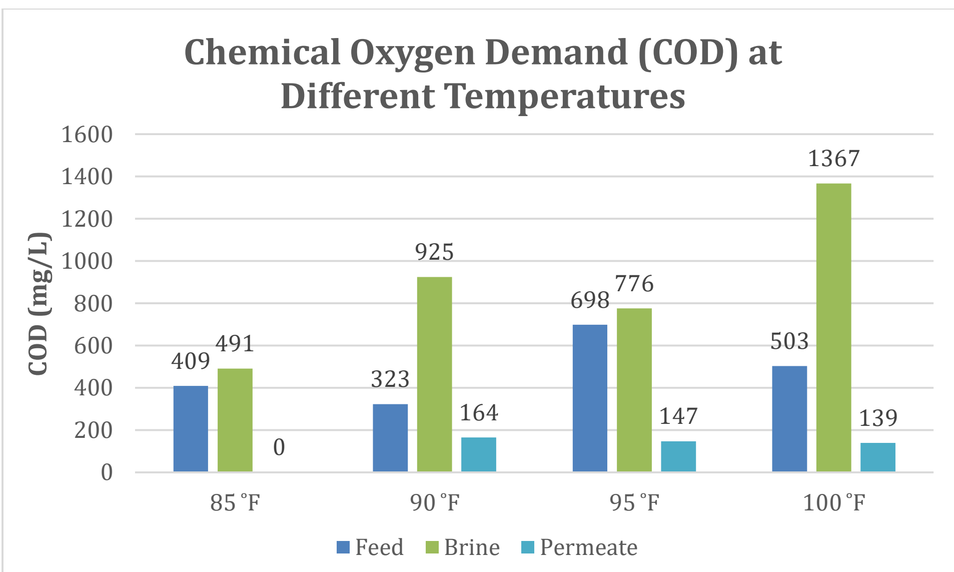

Figure 3: COD of the Feed, Brine, and Permeate collected at 85 ℉, 90 ℉, 95 ℉, and 100 ℉.

Four sets of 3-hour endurance tests were conducted on DROWT 2.0. These tests were conducted at 100 psi operating pressure while using synthetic greywater as feed water. The system was run on solar power until the power generated by the solar panels and continually stored in a 115 Ah 12 VDC battery was exhausted. Then the system was run on the wall for the rest of the duration of the test. While the system ran; samples of the feed, permeate, and brine were taken every 30 minutes to test for COD, conductivity, hardness, and turbidity. Flow rates at the feed and brine were collected every second for the entire duration of the tests.

The aim of these tests is to observe the performance of the DROWT 2.0 system in operation for longer periods of time. Our goal is to confirm that the system is able to operate for at least two hours on solar power and is able to produce at least 90 gallons of permeate water with consistent water quality.

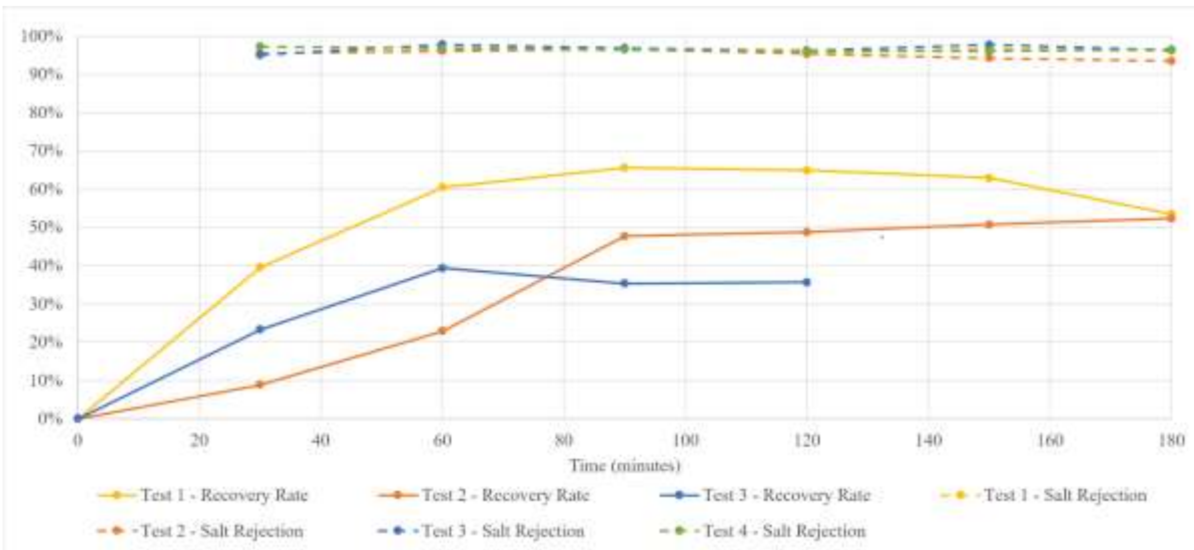

Figure 4: Recovery Rate and Salt Rejection Rate of each test over time.

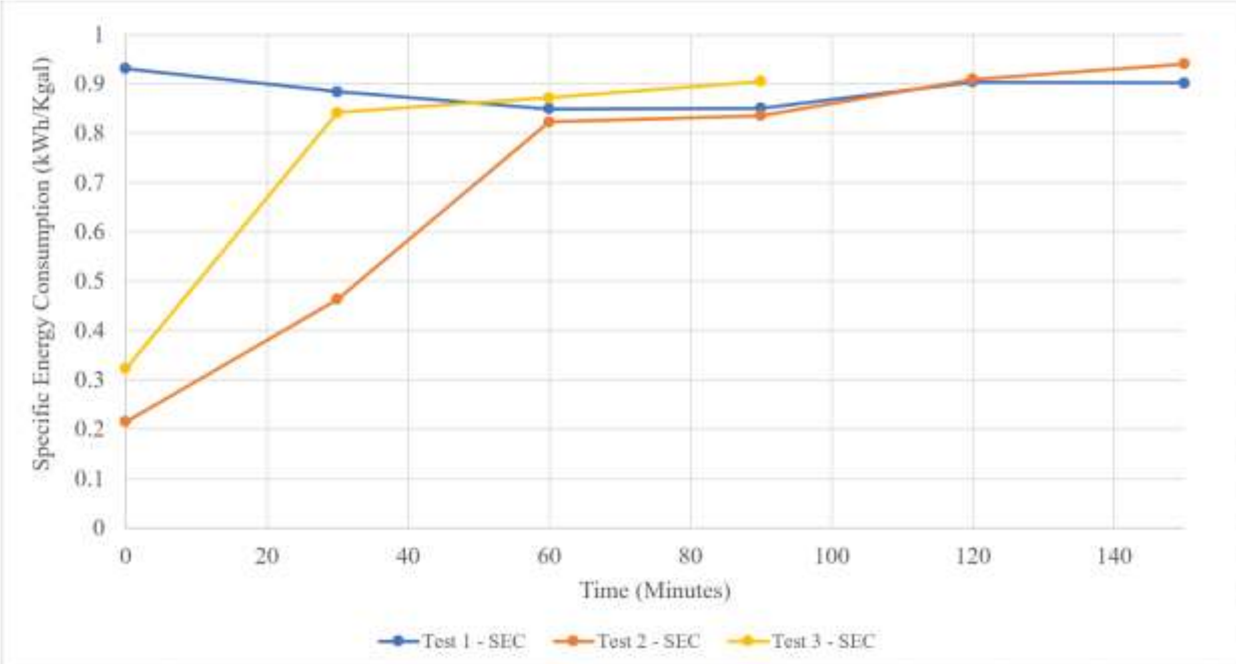

Figure 5: Specific Energy Consumption (SEC) of each test over time.

Figure 4 shows the recovery rates and the salt rejection rates of the DROWT 2.0 system over the course of 4 tests. There was an error in collecting flow rate data during Test 4, therefore it is lacking a line representing its recovery rate. While the recovery rate of the system varied, over among the days with the system hitting a steady rate ranging from 40% to around 65%, the salt rejection remained consistently above 90%. Even the specific energy consumption (SEC) shown in figure 5 is seen to hit the same levels consistently at around 0.9 kWh/kgal of energy consumed. It is important to note that Test 3 was cut short due to the onset of an overcast sky and rain that abruptly cut short our supply of solar power.

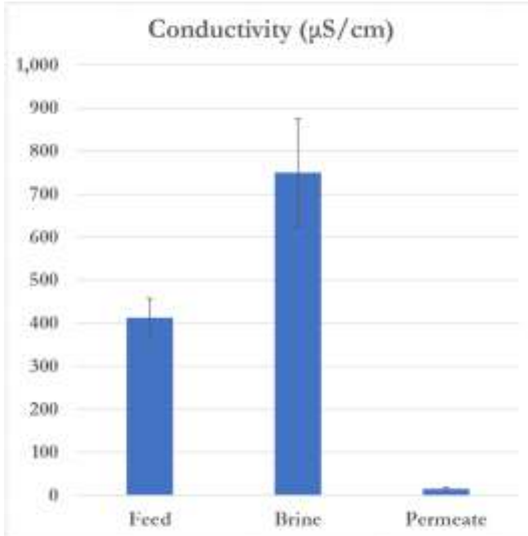

Figure 6: Average conductivity of the feed, brine, and permeate.

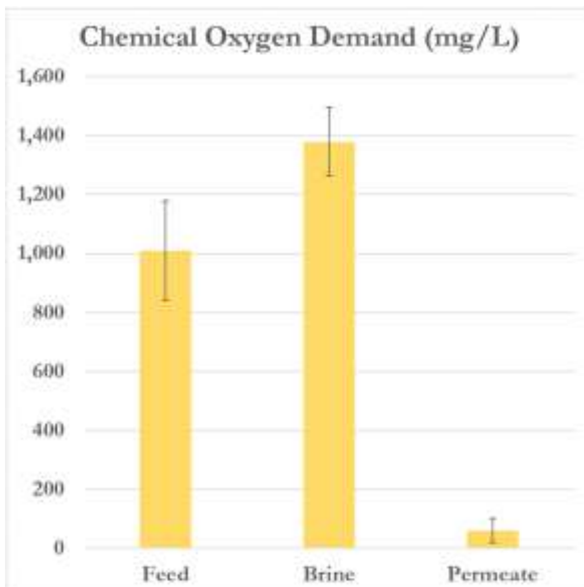

Figure 7: Average chemical oxygen demand (COD) of the feed, brine, and permeate.

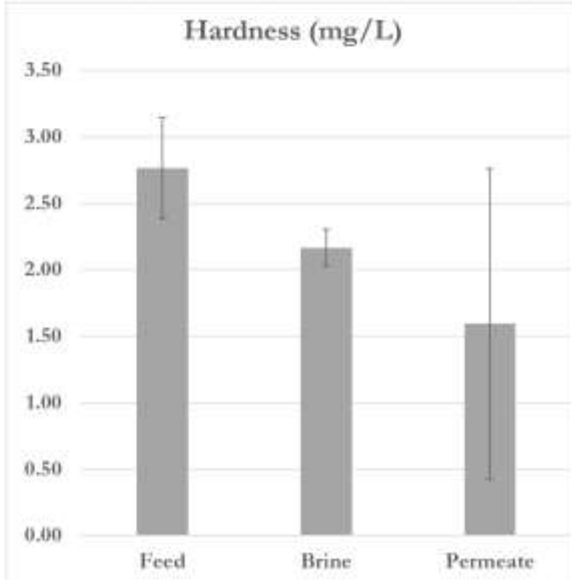

Figure 8: Average Hardness of the feed, brine, and permeate.

The water quality tests shown in figures 6, 7, and 8 show a drastic difference in water quality from feed to permeate. The values of which vary little as shown by the error bars. However, with Hardness, since the synthetic greywater had little hardness to begin with and is already considered soft by conventionally accepted hardness standards (60-120 mg/L). The values are actually very small in terms of hardness, therefore it is unlikely to drop drastically after having been run through DROWT 2.0, as it is already low.

Appendix H (Levelized Cost of Water Calculations)

The lifespan of the DROWT technology ranges from 10 to 20 years if operated in the allowable conditions. The solar photovoltaic systems are expected to operate more than 20 years. The reliability of the DROWT technology is boosted by implementing a smart electronic control system that ensures the system does not cross the boundaries of safe operation. The system will require replacement of Reverse Osmosis membranes and filters every 3-5 years depending on the quality of the feed water. For the sake of this calculation several assumptions were made, the assumptions are listed below:

- 10 year useful life of the device.
- Inflation rate selected based on the USDA inflation rate forecast from 2019-2029: 2.3%.
- Discount rate selected to be 3% based on the Federal Reserve Board of Governors.
- The RO membranes are assumed to be changed every 4 years.
- The microfilters are assumed to be changed as follows: 0.5 micron filter changed every 3 years, 1 micron filter changed every 2 years and 5 micron filter changed every year.
- Mass production cost is assumed to be 40% of the total current cost.
- Repair and replacement costs is assumed to be 10% of the device cost on average.
- Two LCOW values calculated a low value based on operating the device for 2 hours daily and a high value based on operating the device for 4 hours daily.

The methodology of calculating the LCOW is based on the guidelines provided by The Pacific Institute in their study titled "The Cost of Alternative Water Supply and Efficiency Options in California, 2016". The following equations were utilized:

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

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

The LCOW calculation yielded a low value of \$1466.25/acre.ft (¢0.45/gallon) based on 4 hours of daily operation, and a high value of \$2929.17/acre.ft (¢0.902/gallon) based on 2 hours of operation daily. In the same study, The Pacific Institute provides data on water recycling and reuse cost for non potable water facilities, the data is based on a sample size of 7 facilities and included the cost of water distribution. Based on the data, for non-potable water reuse, the low cost is \$1500/acre.ft and the high value was \$2100/acre.ft.