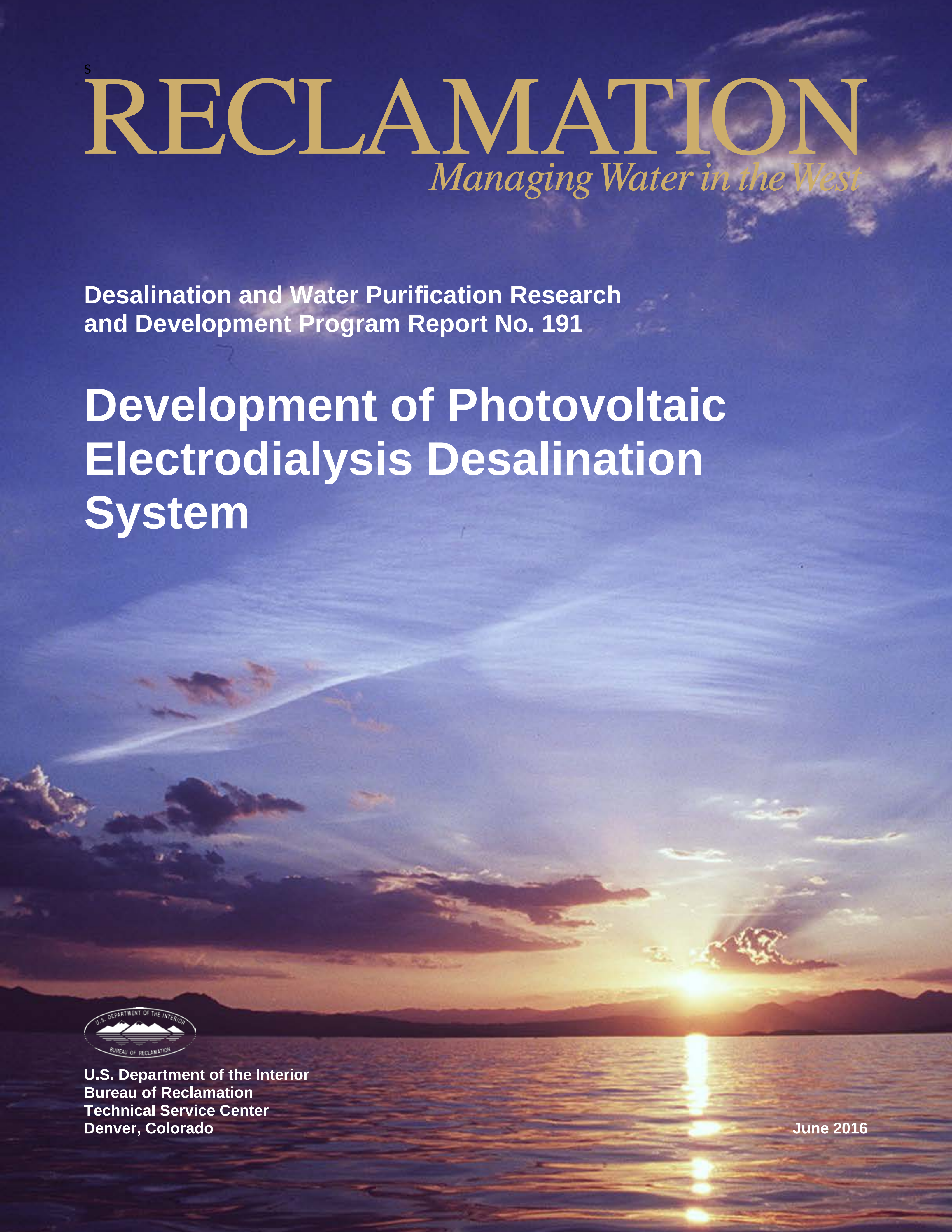


s

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research
and Development Program Report No. 191

Development of Photovoltaic Electrodialysis Desalination System

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

June 2016

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
25/05/2016	Final	September 2014 to May 2016

4. TITLE AND SUBTITLE
Development of Photovoltaic Electrodialysis Desalination System

5a. CONTRACT NUMBER
Agreement No. R14AP00155

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ali Sharbat, PhD, PE

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cal Poly Pomona Foundation, Inc.
3801 West Temple Avenue, Building 55
Pomona, California 91768

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)
Reclamation

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DWPR Report No. 191

12. DISTRIBUTION/AVAILABILITY STATEMENT
Online at https://www.usbr.gov/research/dwpr/DWPR_Reports.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The declining supply of drinking water for an increasing world population is a global concern with impacts on public health as well as micro and macro economies. A Photovoltaic Electrodialysis (PV-ED) unit is designed and constructed. The unit consists of a direct current power supply that charges batteries to provide a constant current to the unit. This includes an electrodialysis stack (desalinization unit), circulation pumps, a concentrate discharge unit, and a control unit to communicate between the photovoltaic and electrodialysis systems. The controller unit in conjunction with several sensors to monitor flow, conductivity, pressure, water elevation levels, and temperature creates a closed loop feedback system. The logic used in the control system was developed after physical construction of the unit. A closed loop feedback system allows battery charging, power regulation, and product water parameters to be precisely controlled while maintaining maximum efficiency. Based on the experience obtained during this research, the team at Cal Poly Pomona has estimated that this small PV-ED unit can be manufacture with a unit cost of $4,000. The Cal Poly Pomona team is looking into opportunities for implementation of this decentralized PV-ED unit in a disadvantaged community (DAC) in California.

15. SUBJECT TERMS
Desalination, Electrodialysis, Photovoltaic

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Yuliana Porras-Mendoza
a. REPORT	b. ABSTRACT	THIS PAGE	U	108	19b. TELEPHONE NUMBER *(Include area code)*
U	U	U			303-445-2265

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Desalination and Water Purification Research and Development Program Report No. 191

Development of Photovoltaic Electrodialysis Desalination System

Prepared for the Bureau of Reclamation Under Agreement No. R14AP00155

by

Ali Sharbat, PhD, PE

Cal Poly Pomona Foundation, Inc.
3801 West Temple Avenue, Building 55
Pomona, California 91768

U.S. Department of the Interior
Bureau of Reclamation
Denver, Colorado

June 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

The views, analysis, recommendations, and conclusions in this report are those of the authors and do not represent official or unofficial policies or opinions of the United States Government, and the United States takes no position with regard to any findings, conclusions, or recommendations made. As such, mention of trade names or commercial products does not constitute their endorsement by the United States Government.

Acknowledgments

We would like to thank our project sponsor, Desalination and Water Purification Research and Development Program in the Bureau of Reclamation, and especially Yuliana Porras Mendoza and Saied Delagah for providing their oversight and productive feedback for this effort. Also, we thank our 2014-2015 Senior Project cohort, Michael Lepore, Tiffany Lai, Westley Harijanto, Terrance Gaines, Kalvin Lam, Lucas Townsend, Ik-hyoun Kim, Natalie La, Deanna Lestina, Christine Zheng and Yaochituati Bourdon, in the Civil Engineering department at Cal Poly Pomona for their hard for working on the project in various phases and development of this report.

Acronyms and Abbreviations

AC	alternating current
ADC	analog to digital converter
BGNDRF	Brackish Groundwater National Desalination Research Facility
DAC	disadvantaged community
DC	direct current
DI	deionized
ED	electrodialysis
EDR	electrodialysis reversal
ETC	Evacuated tube collector
FPC	Flat plate collector
GOR	Gain output ratio
HD	humidification-dehumidification
HPC	High pressure condenser
LCD	liquid crystal display
MED	multi effect distillation
MOSFET	metal–oxide–semiconductor field-effect transistors
MPPT	maximum power point tracker
MSF	multistage flash evaporation
MVC	mechanical vapor compression
NF	nanofiltration
PR	Performance ratio
PTC	Parabolic trough collector
PWM	pulse width modulation
PV	photovoltaic
Reclamation	Bureau of Reclamation
RO	reverse osmosis
RR	recovery ratio
SD	secure digital
SEC	Specific Energy Consumption
SR	salt rejection
TBT	top brine temperature
TDS	total dissolved solids
TVC	thermal vapor compression
VC	vapor compression
VVC	vacuum vapor compression

Measurements

°C	degree Celsius
A	amp
Ah	amp hour
cm	centimeter
cm2	square centimeter
equiv/L	normality
g/mol	grams per mole
gpd	gallon per day
gph	gallon per hour
gpm	gallon per minute
kg	kilogram
Kva	kilo-volt-ampere
kW	kilowatt
kWh	kilowatt hour
L	liter
$l/d/m^2$	liters per day per square meter
L/day	liter per day
L/min	liter per minute
L/s	liter per second
m2	square meter
m3	cubic meter
m3/d	cubic meter per day
m3/h	cubic meter per hour
mgd	million gallons per day
mg/L	milligram per liter
ml	milliliter
mL/s	milliliter per second
mm	millimeter
mol/L	moles per liter
Mpa	megapascal
mS/cm	milliSiemen per centimeter
S/m	Siemen per meter
ppm	part per million
psi	pounds per square inch
W	watt
W-hr	watts per hour
V	volt
µS/cm	microSiemens per centimeter

Contents

Appendices

Figures

Tables

1. Executive Summary

The declining supply of drinking water for an increasing world population is a global concern with impacts on public health as well as micro and macro economies. Recent evaluations of brackish and saline groundwater resources show many regions have an abundance of brackish groundwater where fresh water is lacking. In the Western United States, many rural and remote communities have limited access to fresh water sources. However, studies show that underground brackish water is available. High energy requirements and the lack of a connection to a centralized drinking water treatment system in remote rural areas are two issues for using brackish groundwater as a new source for drinking water.

Developing robust decentralized brackish water desalination systems that use solar energy to eliminate the dependence on grid power could be a path to use these brackish water sources as a new source for drinking water for rural and remote communities. Decentralized solar desalination eradicates the dependence on a centralized water treatment and distribution system as well as grid power while minimizing the carbon footprint of operation desalination processes.

Determining the viability of various desalination processes currently in requires evaluating the cost of product water, energy efficiency of desalination, salt removal rate, recovery rate of water, system capacity, and power source type (for renewable-energy-dependent processes). An electrodialysis (ED) unit can control flow rate according to the amount of available energy and is suitable for inland desalination applications. ED does not require high pressure to produce fresh water like pressure-driven desalination processes (e.g., reverse osmosis [RO] technology).

In this project, we designed and constructed a photovoltaic (PV) electrodialysis unit. The unit consists of a direct current (DC) power supply (PV) that charges batteries to provide a constant current to the unit. This includes an ED stack (desalinization unit), circulation pumps, a concentrate discharge unit, and a control unit to communicate between the photovoltaic and electrodialysis systems. The logic used in the control system was developed after physical construction of the unit. The controller unit in conjunction with several sensors to monitor flow, conductivity, pressure, water elevation levels, and temperature creates a closed loop feedback system. A closed loop feedback system allows battery charging, power regulation, and product water parameters to be precisely controlled while maintaining maximum efficiency.

A recovery rate of 75 to 80% is targeted from feed water with a total dissolved solids (TDS) concentration ranging from 1,000 to 6,000 milligrams per liter (mg/L). The PV-ED desalinization unit is able to effectively produce about 100 gallons per day (gpd) (400 liters per day [L/day]) of product water, which is enough fresh water for daily consumption of one single family is dwelling. Because there are typically 5 to 8 hours of usable sunlight per a day to obtain a sufficient amount of power, the unit will operate at about 0.25 gallons per minute (gpm) (1 liter per minute [L/min]). Portability and ease of implementation makes PV-ED units ideal for emergency response situations to produce drinkable water with solar energy and enables desalinization in remote areas where fresh water sources are scarce.

We used facilities at the Brackish Groundwater National Desalination Research Facility (BGNDRF) for a comprehensive set of testing using various brackish feed water chemistries during the summer 2015. Thirteen Civil Engineering students worked on this project and eleven have already graduated, spending one (1) academic year working on this project as their senior project. A number of presentations have been made in different technical local and national settings. The topic received the Best Paper Award at the 2015 WateReuse California Annual Conference.

A patent application has been submitted. Based on the experience obtained during this research, the team at Cal Poly Pomona has estimated that this small PV-ED unit can be manufactured with a unit cost of $4,000 U.S.. The Cal Poly Pomona team is looking into opportunities for implementing this decentralized PV-ED unit in a disadvantaged community (DAC) in California.

2. Problem

Projected demands for required water resources corresponding to the world population growth will surpass the available conventional water resources and become a global predicament, impacting local, national, and global economies as well as public health. More than one billion people in the world still do not have access to clean drinking water (Bilton et al. 2011). The growing demand for freshwater sources and the environmental stresses occurring around the world from droughts have increased concerns and driven movements from water conservation to industrial processes such as technological advancements in water reuse and desalination (Ali et al. 2011). However, desalination requires excessive amounts of energy and the use of non-renewable energy can be expensive and harmful to the environment.

2.1. Desalination Around the World

Over the past half-century, developing desalination technologies have become an increasingly vital resource for producing drinking water. Consequently, there has been a consistent growth in seawater and brackish water desalination plants worldwide since the 1970s as seen in Figure 1.

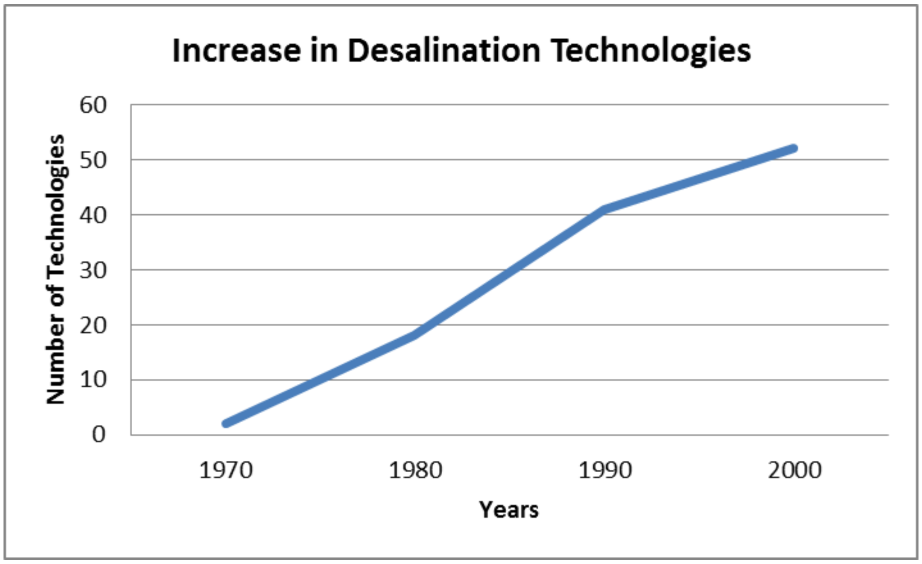


Figure 1. Increase in desalination technologies since 1970.

About 65% of currently installed desalination plants primarily treat seawater while 35% treat brackish water. Today, the global capacity of desalted water production is over 16 billion gpd. This number will increase as investments in new desalination plants worldwide is projected to increase.

Current desalination technologies implemented in these plants are divided into two categories: phase-change thermal and single-phase membrane processes. Phase-change thermal processes consist of three types: multistage flash evaporation (MSF), multi-effect distillation (MED), and vapor compression (VC). Meanwhile, single-phase membrane processes are comprised of reverse osmosis (RO) and electrodialysis (ED). Figure 2 lists the various types of desalination technologies.

Thermal desalination and desalination membrane processes have been advancing for the last 60 and 40 years, respectively. However, membrane desalination processes such as RO and ED have been more successful than thermal desalination because they require less energy than thermal processes. Currently, RO is the most commonly used for new desalination plants and is responsible for 44% of desalination production capacity internationally. There are over 15,000 desalination plants globally, and 80% of these plants use RO. Implementing membrane desalination has continued to increase due to membrane advancements, resulting in lower start-up costs and higher quality product water in a lesser amount of time.

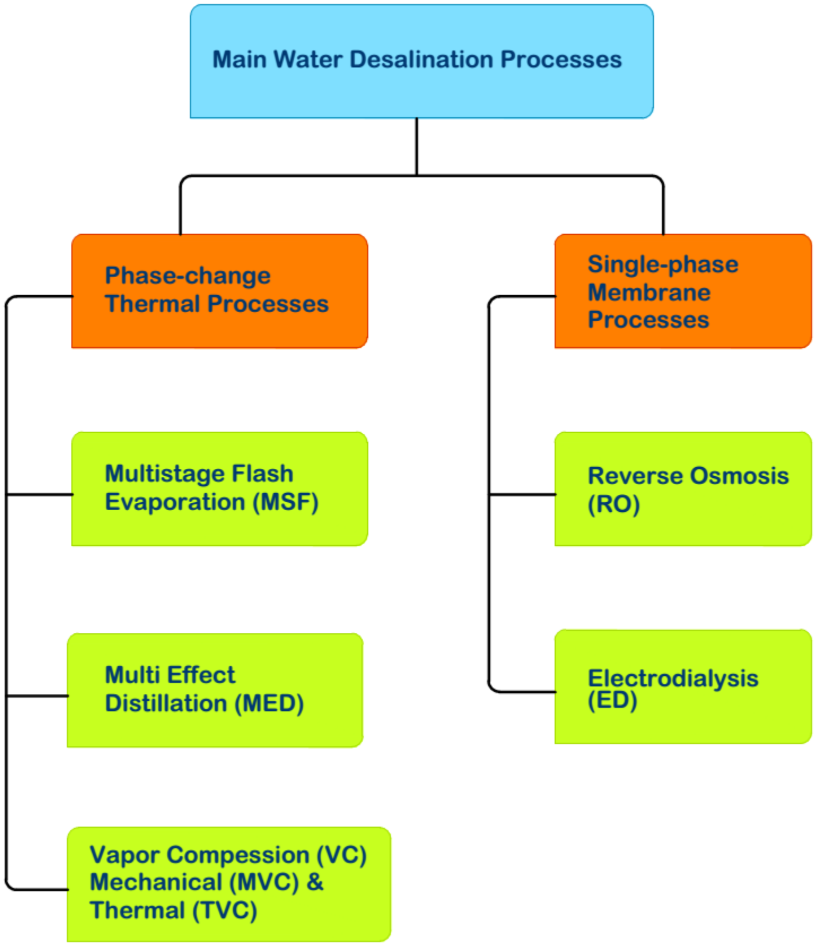


Figure 2 Types of desalination processes.

2.2. Desalination Challenges

Currently, desalination plant operations are expensive, particularly for energy and brine disposal. High energy consumption of fossil fuels creates a large carbon footprint impact on our environment. Furthermore, desalination can result in detrimental effects on the environment Pumping large volumes of seawater into desalination plants can harm small fish and plankton, impacting the marine ecosystem and food chain. Disposing brine concentrate back into the ocean can result in similar environmental outcomes.

2.2.1. Energy Consumption

Large amounts of energy are required to power the desalination of seawater and brackish water, resulting in high costs. In thermal desalination processes, typical sources of energy consist of fossil fuels, solid waste, nuclear, and solar.

Membrane processes require electricity. For any process, electricity is needed in desalination plants to power electrical components such as pumps.
Product water costs through desalination processes are primarily determined by costs for energy, operations and maintenance, and capital investment. Energy costs account for approximately 50% of the product water cost.

Conventional sources of energy are expensive and detrimental to the environment. Using fossil fuels results in carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions as well as the thermal pollution of seawater, harming the environment. In addition, fossil fuel prices continue to increase due to high demand and little supply. As a result, renewable energy systems have been integrated into desalination processes to mitigate costs and environmental hazards. These renewable energy systems include solar thermal, solar photovoltaic, wind, and geothermal technologies. Renewable energy desalination continues to become more economically viable as renewable energy technology advances.

2.2.2. Concentrate Disposal

The increase in membrane desalination processes also has its environmental challenges such as brine discharge. Using desalination to treat large volumes of water results in a correlating equivalent amount of brine concentrate discharged from the system. The most common method of brine disposal for seawater desalination plants consists of discharging brine back to the sea by using pipelines, which could harm the marine life and ecosystems. In accordance with the EPA's Guidelines for Water Reuse (EPA 2012), these actions are permitted as there are no Federal mandates against brine disposal to the ocean. However, in some states, such as California, toxicity standards are set regarding concentrate disposal and violation of these standards result in fines and penalties. Methods to mitigate these effects and protect the ecosystem include various solutions such as diluting the brine concentrate to acceptable levels specifically for the concentrate stream to remove the harmful contaminants within the brine and minimize the impact on the receiving environment.

In addition, brine disposal is costly and varies according to the concentrate quality, pre-disposal treatment level, disposal method, and volume of concentrate. Inland desalination plants experience higher desalination costs than those that discharge brine into the sea. Inland brine disposal options include deep well injection, evaporation ponds, irrigation of high-salinity tolerant plants, discharge into surface waters, and disposal into sewers. To reduce environmental risks and high costs of concentrate disposal, many are turning to options such as evaporation ponds and renewable energy. Expanding development and implementation of desalination processes is essential to refining a viable alternative source for drinking water production.

2.3. Project Objectives

This project investigates methods to use renewable energy desalination to address current challenges regarding costs and environmental concerns stemming from energy consumption and brine disposal. By using solar energy through photovoltaics (PV), the membrane desalination process, ED, can be satisfied without leaving a carbon footprint by mitigating the losses associated with converting alternating current into direct current and lowering the power consumption and operation costs.

3. Technology Background

3.1. Reverse Osmosis Powered by Renewable Energy

RO is a membrane process and, along with electrodialysis, is considered one of the most favorable technology to desalinate seawater or brackish water (Al-Karaghouli and Kazmerski 2011 and Ali et al. 2011). RO is a pressure-driven process applied to a saltwater stream that flows under high pressure through a semipermeable hydrophilic membrane. Water passes through the membrane when the applied pressure is higher than the osmotic pressure, while salt is held behind. As a result, a low salt concentration permeate stream is obtained and a concentrated brine remains at the feed side. The high-pressure brine passes through an energy recovery device, such as a pressure exchanger or turbine, to recover the useful energy in the brine before it exits the system. However, since RO membranes are susceptible to fouling and scaling, the necessary pre-treatment results in higher maintenance costs (Ali et al. 2011). To mitigate energy costs, RO systems can be connected to renewable sources of energy such as photovoltaic panels.

A general schematic system of the photovoltaic reverse osmosis system is illustrated in Figure 3 that consists of PV solar panel, charge regulator, batteries, direct current/alternating current (DC/AC) invertor, high pressure pump, pre-treatment tank, reverse osmosis membrane unit, turbine, and post-treatment. PVRO technology is especially used in semi-arid and remote areas (Al-Karaghouli and Kazmersk 2011).

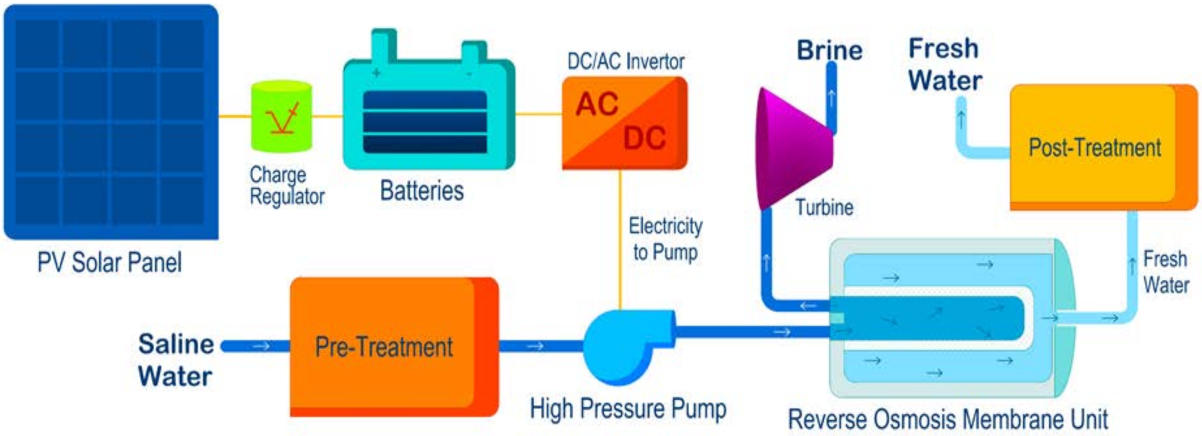


Figure 3. General schematic of PVRO.

Small, medium, and large scale PVRO plants have been built successfully since the 1980s in different locations around the world (Al-Karaghouli and Kazmerski, 2011) as seen in Table 1, which illustrates an extensive but still partial list of PVRO installations. This list describes available documented information about the capacity, energy consumption, Specific Energy Consumption (SEC), cost of energy per cubic meter, and any particular description of the plants.

As early as 1980, a PVRO plant was commissioned in Concepcion del Oro, Mexico with a capacity of 396 gpd (1.5 cubic meters per day [m^3/d]) which treated brackish water with a TDS concentration of 3,000 parts per million (ppm) and involved an SEC of 6.9 kilowatts per cubic meter (kW/m^3) (Ali et al. 2011).

A commercial scale PVRO plant was commissioned in Jeddah, Saudi Arabia in 1981. The system effectively desalinated seawater with salt concentrations from 42,800 ppm at a production rate of 845 gpd (3.2 m^3/d). The SEC ranged from 16.1-19.7 kW/m^3 without energy recovery devices (Ali et al. 2011).

An automatic PVRO plant was assembled at the University of Almeria in Spain. The plant had a capacity of 655 gpd (2.48 m^3/d) and treated brackish water with a saltwater concentration equivalent to 2,690 – 4,030 ppm, which was reduced after treatment to 6.4 - 166 ppm. The efficiency factor of the PV plant was about 7.4%. The plant operated on average of 4.9 hours per day instead of the originally projected 20 hours per day. This plant experienced problems such as frequent maintenance requirements for filters and cleaning membranes, which would not allow the plant to operate completely automatically. The concentrate was disposed back into the sea (Ali et al. 2011).

In Keratea, Greece, a seawater desalination plant using an RO connected to a PV and a wind source of energy was installed in 2003. The system consisted of manually adjustable tilt PV panels with 3.96 kW and a 900 watt (W) wind turbine.

The PV and wind turbine systems were linked to a battery bank of 44.4 kilowatt hours (kWh) of electrical storage. The system produced 824 gpd (3.12 m^3/d) with energy consumption of 16.5 kWh/m^3. No energy recovery device was installed to cut costs. Water costs from the unit were estimated to range from $23 to $27 U.S. per cubic meter (Ali et al. 2011).

The smallest PVRO seawater desalination plant was commissioned in Pozo Izquierdo (Gran Canada Island) in Spain and orchestrated by the Aachen University of Applied Sciences and the Energy and Water Research Center of the Canary Islands Technological Institute. The average daily drinking water production was 211 to 792 gpd (0.8 to 3 m^3/d) and a total of potable water with TDS of 480 ppm. The plant was supplied by a PV 4.8 kW with battery storage of 60 kWh. In addition, energy recovery systems can affect efficiency up to 98% and reduce the energy consumption of the high pressure pumps (Herold and Neskakis 2001).

The Bureau of Reclamation (Reclamation) has performed studies and demonstrated the practicality of powering up an RO system with PV panels and promising results have been published recently.

PVRO systems efficiently desalinate seawater and brackish water. Pre-treatment is necessary to prevent major problems with RO membranes which are susceptible to fouling and scaling. Thus, the constant maintenance and operation required would increase the cost. Expenses of PV panels, batteries, and energy recovery methods also contribute to the increase in cost for these systems. Today, small-scale PVRO systems that desalinate brackish water are commercially available.

Table 1. Partial List of Documented PV-RO Systems

Location	Capacity (m^3/day)	Treated water	Concentration (ppm)	PV Energy supply (kW)	SEC (kW/m^3)	Cost (US$/$m^3$)	Particular Characteristics	Year
Conception del Oro, Mexico[1]	1.5	Brackish water	3,000	2.5	6.9		RR 37%, total area 30m^2	1980
Las Barrancas, Mexico[1]	20	Seawater		250				1980
Giza, Egypt[2]	6	Brackish water		7			No energy recovery, batteries	1980
Jeddah, Saudi Arabia[1]	3.2	Seawater		8	16.1-19.7		Batteries 45.56(kWh), RR 22%	1981
Perth, Australia[1,2]	0.4-0.7	Brackish water		1.2	4-5.8		No energy recovery, battery 4.3 (kWh)	1982
Cituis, Indonesia[1,2]	12	Brackish water	3500	25.7	8	3.68	Batteries 136.8 (kWh) for pump & control, 25.72 (kW) for pump & control, RR 35%	1983
Vancouver, Canada[1]	4	Seawater	3300	4.8	<4	9	Price estimate for variable speed pump w/o battery and with energy recovery	1984
El Hamarawein, Egypt[1,2]	53	Brackish water	3500	18.5	0.89		9.84 kW (pump) 0.64 kW (control equipment) PV 208 kWh battery RR 51%	1986
Hassi Khebi, Algeria[1]	24	Brackish water	3000	2.59	1.38-2.77		Battery 60 kWh RR 24-40%	1988
Doha, Qatar[1]	5.7	Seawater	3500	11.2		10.6		1988

Location	Capacity (m^3/day)	Treated water	Concentration (ppm)	PV Energy supply (kW)	SEC (kW/m^3)	Cost (US$/$m^3$)	Particular Characteristics	Year
University of Almeria, Spain[1]	2.48	Brackish water	2,690 to 4,030	23.5			2,240 Ah 190 to 254 V battery	1988
Lempedusa Island, Italy[1,3]	40	Seawater	1,600	100	5.5	9.75	Batteries 880 kWh An energy-recovery turbine of modest efficiency	1990
Gillen Bore, Australia[1,2]	1.2	Brackish water	1,600	0.52			No energy recovery batteries	1993
Sadous, Saudi Arabia[1,2]	5.7	Brackish water	5,800	10.1	<18	3	Batteries 264 kWh) Solar still added 1,449 m^2 area	1995
St. Lucie Inlet State Park, Florida, USA[1]	0.64	Seawater	3,200	2.7	13		RR 10% and diesel generator	1995
Heelat Ar Rakah, Oman[1,2,4]	5-7.5	Brackish water	1,000	3.25	2.45	6.25	Batteries 9.6 kWh No energy recovery	1995
Megan, Israel[5]	3	Brackish water	4,000	13.5		11.6	600-kW wind turbine, 3.5-kW diesel generator High cost Wind turbine is more maintenance than PV	1997
Mudroch Universtity, Australia[1]	0.4	Brackish water	5,000	0.12		3.6	Batteries 9.6 kWh RR 16 -25% Venco manufacturer	1997
Lipari Island, Italy[1]	2	Seawater		63				1998

Location	**Capacity (m^3/day)**	**Treated water**	**Concentration (ppm)**	**PV Energy supply (kW)**	**SEC (kW/m^3)**	**Cost (US$/$m^3$)**	**Particular Characteristics**	**Year**
Canary Islands, Spain[1,2,6]	5	Seawater	35,000	4.8	18-19	16-17	1.8 m^3/day (at a pressure of 45 bar and a motor 1.8m^3/day 8.5 A) to 4.2 m^3/day (70 bar and 13 A) Batteries 60 (kWh), RR 14%	1998
Lisbon, Portugal[1,2]	0.08	Brackish water	2,000 to 5,000	0.15	25.6-32.4		RR 1.8-2.4, SR 90-94% No batteries	2000
Haifa, Israel[1]	3	Brackish water	4,000	3.5			0.6 kW wind 36 kWh battery RR 50%, SR 98%	2000
Ceara, Brazil[1]	6	Brackish water	1,200	1.1	3	12.76	9.6 kWh battery RR 27%	2000
Massawa, Eritia[1,2]	3	Seawater	40,000	2.4		3	PV with single-axis tracking Spectra Clark pump energy recovery	2001
White Cliffs, Australia[1,2]	0.5	Brackish water	3,500	0.34	8		RR 10-25% SR 93-95%	2002
Mesquite, Nevada[2]	1.5	Brackish water	3,500	0.54		3.46	No energy recovery No batteries	2003
Keratea, Greece[1]	3.12	Seawater	37,700	3.96	16.5	23-27	0.9 kW wind 44.4 kWh battery RR 13%	2003
Baja California Sur, Mexico[1]	19	Seawater			2.6		Tested Spectra Clark pump Pressure exchanger and Danfoss axial piston motors	2003

Location	**Capacity (m^3/day)**	**Treated water**	**Concentration (ppm)**	**PV Energy supply (kW)**	**SEC (kW/m^3)**	**Cost (US$/$m^3$)**	**Particular Characteristics**	**Year**
Coite´– Pedreiras, Brazil[2]	0.55	Brackish water	1,200	1.1		12.76	Batteries 9.6 kWh No energy recovery	2004
Canary Islands, Spain[1]	10	Seawater	35,000	5.6	2.54		PV with tracking 41 kWh battery Pressure Exchanger RR 36%	2004
University of Athens, Greece[1]	2.2	Seawater	35,000	0.846	3.3-5.2	8-11	1 kW wind 7.56 kWh battery RR 10%, SR 99%	2004
Amman, Jordan[2]	0.1	Brackish water	400	0.07			No energy recovery, no batteries	2005
Hammam Lif, Tunisia[2]	0.05	Brackish water	2,800	0.59		8	No energy recovery, no batteries	2005
Canary Islands, Spain[1]	1	Seawater		0.6	3.74		0.89 kW wind 21 kWh battery Energy recovery device RR 18%	2005
North West of Sicily, Italy[1]	36	Seawater		125	4.86		Pelton turbine recovery 160 kVA diesel generator	2005
Cooper Pedy, Australia[1]	0.764	Brackish water	74,000	3.2	3.2		RR 17.5%, SR 96%	2005
Rajasthan, India[1]	3.6	Brackish water	6,000	2.5			SR > 95%	2006
Solarflow, Australia[1,5]	0.4	Brackish water	1,500 to 5,000	0.12		7.75	Day time operation only 15% water recovery.	2006

Location	Capacity (m^3/day)	Treated water	Concentration (ppm)	PV Energy supply (kW)	SEC (kW/m^3)	Cost (US\$/m^3)	Particular Characteristics	Year
University of Athens, Greece[1]	0.8-0.9	Seawater	35,000	0.846	4.3-4.6	7.8 (w/o battery), 8.3 (with battery)	7.56 kWh battery Energy recovery by Clark type pump RR 8%, SR 99.2%,	2006
Ras Ejder, Lybia[1]	300	Seawater	42,000	50	4.3	3	275 kW wind Grid back up Energy recovery by PX, RR 35%	2006
Ksar Ghilene, Tunisia[1]	50	Brackish water	3,500	10.5	8		72 kWh battery Building containing desalination unit and control equipment is half-buried and uses solar panel shade to provide passive cooling RR 70%	2006
Irbid, Jordan[1]	0.192	Brackish water	720	0.136	1.3 (w/o battery), 2.7 (with battery)	10 (w/o battery), 13 (with battery)	RR 37%, SR 98%,	2007
Fethiye Area, Turkey[1,]	2	Brackish water		6	15	25	4.8 kWh battery RR 15%	2007
Pine Hill, Australia[2]	1.1	Brackish water	5,300	0.6			Energy recovery, no batteries	2008
Athens, Greece[2]	0.35	Seawater	40,000	0.85		11.45	Energy recovery, no batteries	2008
Tangarfa, Agadir, Azla and Marrakech, Morocco [1]	8	Brackish water	2,500-8,700	4			4 systems were installed	2008

Location	Capacity (m^3/day)	Treated water	Concentration (ppm)	PV Energy supply (kW)	SEC (kW/m^3)	Cost (US$/$m^3$)	Particular Characteristics	Year
Alexandria University, Egypt[1]	30	Brackish water	10,000	7.6			5kW wind 5 kVA diesel generator	2009
Boston, MA[2]	0.4	Seawater	35,000	0.23			Energy recovery, no batteries	2010
Umm Qasr, Iraq[7]	2000	seawater	35,000 to 45,000		2.97	0.986	RO, product water 279 ppm	
RO unit from Aguapuro equipments[8]	0.38-1.145		1,000	24V	50W	6.84	Commercial unit	2014
Ksar Ghilène, Tunisia[9]	7.25	Brackish water	4,503	3.57	2.5		Dessol, Commercial unit	2006
DWC, renewable powered desalination system[10]	3.5	Brackish water, Seawater	40,000	650			Commercial unit, DWC DecRen Water Consult	2014

[1] Ali et al. 2011
[2] Lienhard 2012
[3] Alkhatib, 2014
[4] Suleimani and Rajendran 2000
[5] Cheah 2004
[6] Herold 1998
[7] Al-Karaghouli and Kazmerski
[8] Aguapuro Equipments LTD is a website for water & wastewater treatment technology (http://www.mineralwaterplants.net/reverse-osmosis-systems.html);
[9] Instituto Tecnológico de Canarías is a website for desalination by PVRO dessol unit (http://www.itccanarias.org/web/tecnologias/agua/dessol.jsp?lang=en);
[10] DWC is a website for water consultant for renewable solutions of water supply and waste water treatment (http://www.dwc-water.com)
A= amp,Ah = amp hour, kVA = kilo-volt-amp, RR = recovery ratio, SR = salt recovery

3.2. Electrodialysis (ED)

Electrolysis (ED) is an electrochemical membrane process that reduces salt concentration from salt water by a direct current and has been used commercially for desalination of brackish water since the 1970s, predominantly for small and medium scale systems in the range of 500 gallons to 1 million gpd (1.89 m^3/day to 378 m^3/day) (Ali et al. 2011 and AlMadani 2003). Due to its use commerciality, ion exchange membranes are produced globally (Valero and Arbós, 2010) and Table 2 provides a list of the main manufacturers.

Table 2. Main Manufacturers of Ion Exchange Membranes

Manufacturer/Reference[1]	**Commercial brand**	**Country**
Asahi Chemical Industry Co.	Aciplex	Japan
Asahi Glass Col. Ltd	Selemion	Japan
DuPont Co.	Nafion	USA
FuMA-Tech GmbH	Fumasep	Germany
GE Water & Process	AR, CR,..	USA
LanXess Sybron Chemicals	Ionac	Germany
MEGA a.s.	Ralex	Czech Republic
PCA GmbH	PC	Germany
Tianwei Membrane Co.Ltd.	TWAED	China
Tokuyama Co-Astom	Neosepta	Japan

[1] Valero et al. 2010

Electrodialysis occurs when feedwater flows into an ion exchange chamber that consists of cation and anion exchange membranes positioned alternatively between two electrodes: the cathode and the anode (Namboodiri and Rajagopalan, 2014 and Ortiz et al. 2008). Electrodes are typically constructed from niobium or titanium with a platinum coating (Al-Karaghouli et al. 2010). When an electrical force is applied to the electrodes, the cations (positively charged ions) travel toward the cathode and anions (negatively charged ions) travel toward the anode. The cations pass through the cation membrane and are held back by the anion exchange membrane. The anions pass through the anion exchange membrane and are held back by the cation exchange membrane. Figure 4 illustrates this process (Ortiz et al. 2008). At the end of this process, concentrated cations and anions flow to the brine residue stream (Ortiz et al. 2008, Valero and Arbós 2010, Ali et al. 2011, Uche et al. 2013, Namboodiri and Rajagopalan 2014, and Sharon and Reddy 2015).

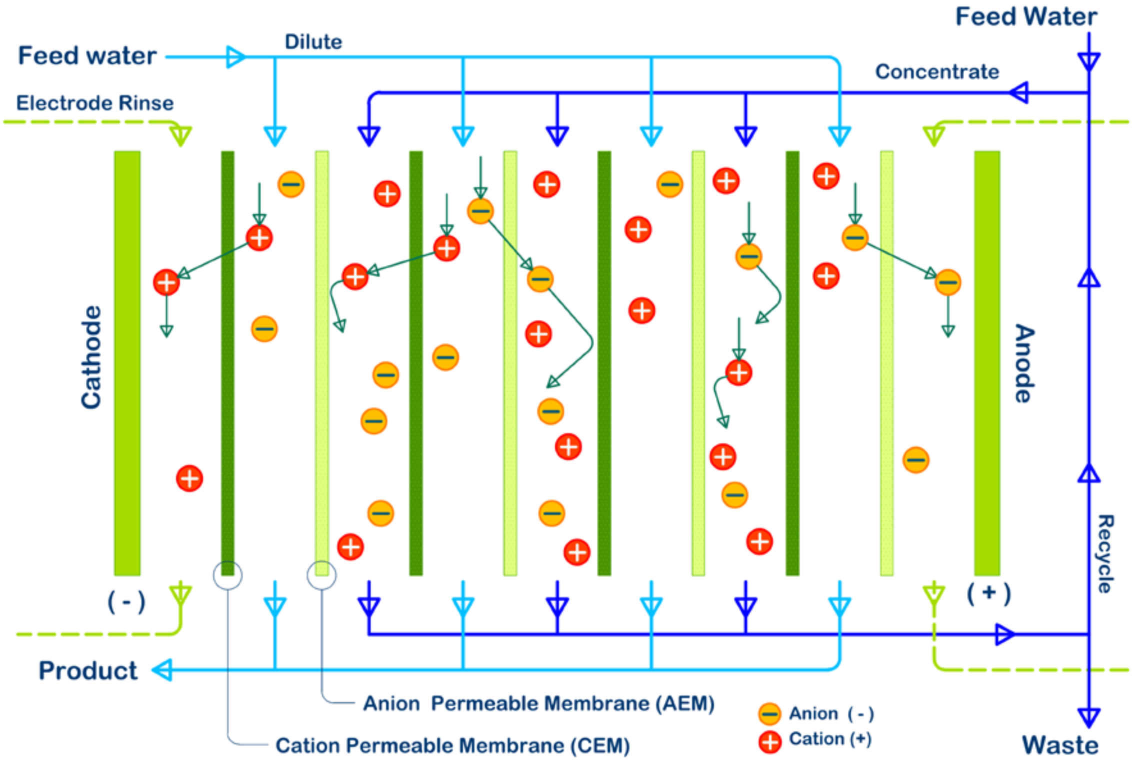


Figure 4. Ion exchange chamber in electrodialysis.

Desalination of seawater from 36,000 to 800 mg/L salt requires at least 26 kWh/m^3. This energy demand surpasses energy capabilities of RO systems. Electrodialysis is capable of treating water with high concentrations of salt at a lower watt per unit volume than RO.

3.3. Electrodialysis Theory

The four primary operating principles controlling ED to be considered for a design are: the dissociation of salts in water, membrane properties, Faraday's law, and Ohm's law. Dissociation refers to ions formation by the dissociation of salts, mineral, alkalis, and acids in water. Membrane properties are based on the quality of the raw or source water as well as ion exchange membranes that have low electrical resistance and consume less energy, which increase efficiency in the system. As concentration of the solution increases, the resistance decreases. Another important factor to consider is organic content, because organic acids commonly present in brackish water can decrease membrane efficiency.

Faraday's law is the basis for determining the amount of electrical current needed in an ED process to transfer a specific quantity of salt. Faraday's law is given as Equation 1:

$$I = \frac{F \cdot Q_d \cdot \Delta N}{e \cdot c_p} \tag{1}$$

Where:

I =the amount of electrical current in Amps (A)
F = Faraday's constant $(96500\frac{A \cdot s}{equivalent\ cell\ pair})$

Q_d = the flowrate of the demineralized stream through the membrane stack in liters per second (L/s)
ΔN= the change in normality of the demineralized stream between the inlet and outlet of the membrane stack
e = current efficiency
c_p = the number of cell pairs

Ohm's law dictates that the potential E of an electrical system is equal to the product of current *I* and the system resistance *R* as shown in Equation 2:

$$E = I \times R \tag{2}$$

Where:

E=Voltage in Volts (V)
I =the amount of electrical current in Amps (A)
R=resistance in Ohms (Ω)

To calculate the resistivity with the measured current according to Ohm's law, Equation 3 is used:

$$R = \frac{U}{I} = constant \tag{3}$$

Where:

R=resistance in Ohms (Ω)
U = Voltage in Joules per Coulomb
I =the amount of electrical current in Amps (A)

Conductivity and resistance can also vary by other factors including temperature, ionic species, and ionic concentration temperature. Elevated temperatures and solution concentrations drop the solution resistance as well as the stack resistance. Typically, voltage requirements for an ED or electrodialysis reversal (EDR) system depend on current, resistance, and hydraulic capacity.

Electrodialysis can be designed in three different modes: batch, continuous, and feed-and-bleed flow systems (Tanaka 2014 and Tsiakis and Papageorgiou 2005). The batch operation was the first commercial available (Valero and Arbós 2010) and is a simple and easy process to set up. Batch operation consists of desalted liquid recycled through a batch tank (Tanaka 2010). The liquid in the circulation tank is steadily desalted and ultimately discharged from the tank (Tanaka 2014). The batch process for an ED system requires large amounts of feed solution to be constantly circulated through the ED unit. By doing so, the effluent stream is manipulated to recirculate back to a feed holding tank. In-line water quality testing must also take place on the downstream side of the ED unit. Figure 5 illustrates a batch process. A batch operation is suitable for a small-scale unit (Tanka 2014).

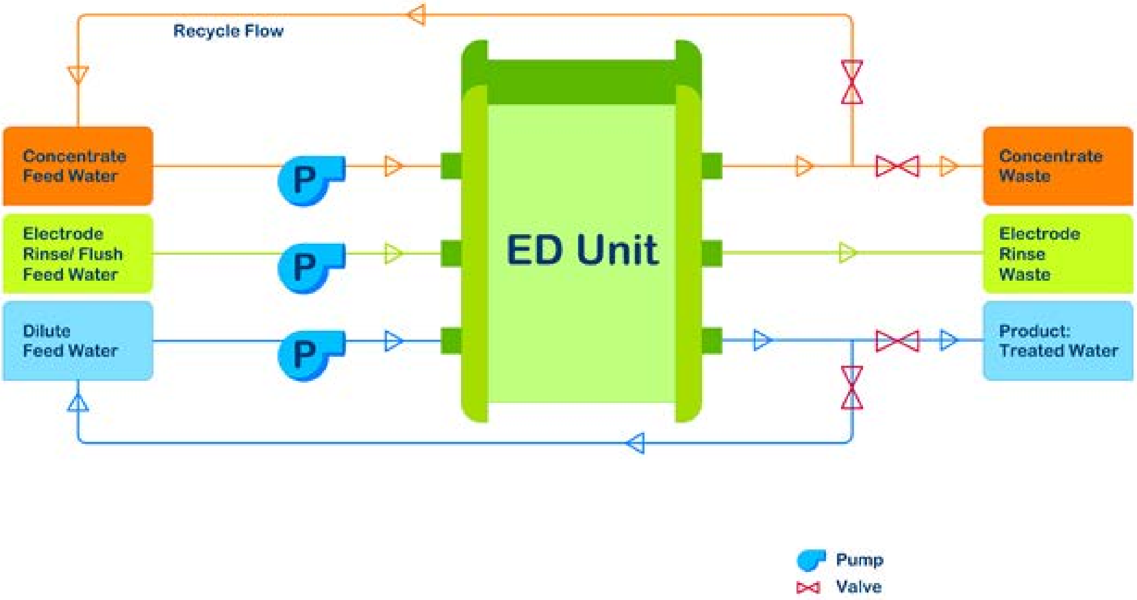


Figure 5. Batch process for ED.

In a continuous operation, the feeding solution flows from feed water to a product treated tank continuously at the same rate. The ED stack is configured in multiple hydraulic stages (Tanaka 2014 and Valero et al. 2010) to help improve the desalting ratio. The concentrate stream is partially recycled to reduce wastewater volume and is injected with acid to prevent scaling. The major issue with this type of system is that the operator has little control over the consistency of the product since the influent feed conditions can change (Kesner 2001). Figure 6 details a basic continuous system model for an ED system. This configuration is suitable for large-scale operations (Uche et. al. 2013).

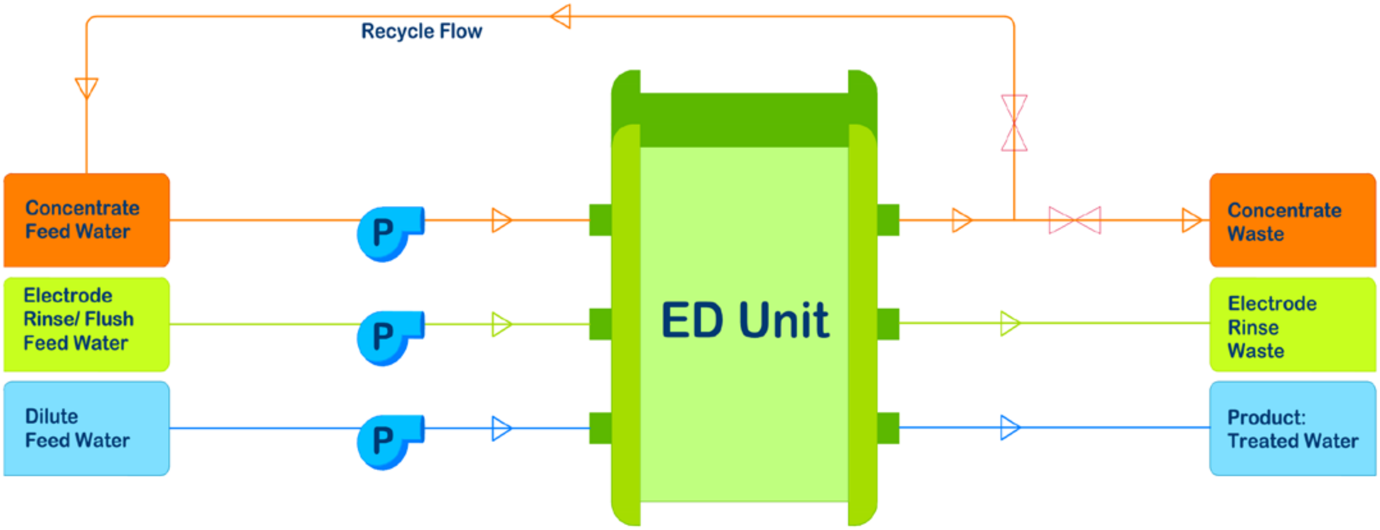


Figure 6. Continuous process for ED.

In a feed and bleed operation, the resulting product is recycled directly to the dilute feed inlet for reprocessing to ensure that the final product is of the desired salinity. The recycle rate for the dilute is determined from the anticipated concentration of the feed water (Tanaka 2010). This type of process combines the idea of the batch and continuous process into one (Kesner 2001) as seen in Figure 7. Like a batch system, some re-circulation of both the concentrate and the dilute is recycled directly back through the ED unit (Kesner 2001 and Tanaka 2010). This configuration is suitable for middle or large-scale units (Tanaka 2014).

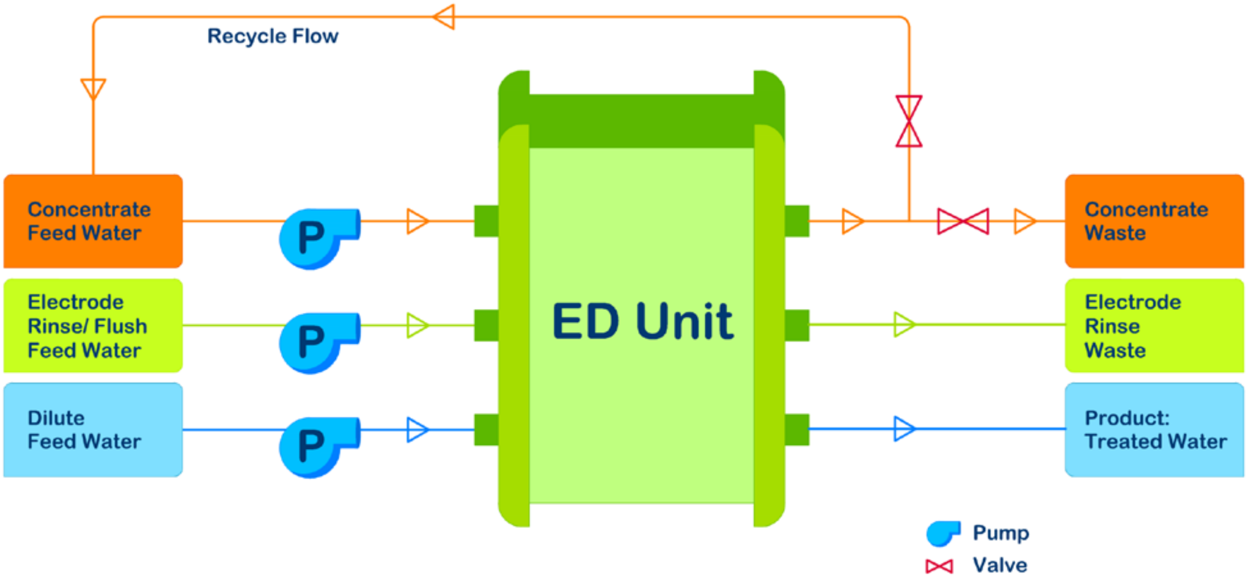


Figure 7. Feed-and-bleed process for ED.

Batch operation is ideal for small-scale desalination, while continuous operation is ideal for large-scale desalination. Feed-and-bleed operations can be used in all scales of desalination but work optimally in a small or medium-scale (Tanaka 2014). Each of these operations can be applied to different scenarios based on water needs and demands. ED systems have various benefits, including long operating life of membranes due to a developed chemical and mechanical stability as well as robust operation and low maintenance operation requirements (García-Rodríguez 2003). Other advantages include superior salt and mineral removal from wastewater or reused water, minimal feedwater pretreatment, and cost effective hydraulic recovery (Valero et al. 2010), lack of biofouling (Ortiz et al., 2008), lower residues, and accessible startup and shutdown for intermittent operation process (Ortiz et al. 2007 and Tsiakis and Papageorgiou 2005).

Disadvantages associated with ED are additional expenses from energy demands due to elevated salt content in feedwater as well as the need for post-treatment to mitigate the threat of microorganisms (Valero et al. 2010). To reduce energy costs, ED systems can be powered by renewable energy (Ma and Lu, 2011).

3.4. Electrodialysis Powered by Renewable Energy

Several pilot systems across the globe have been tested using various forms of renewable energy. Two of the most common energy sources are wind and solar power.

In Gran Canaria Island, Spain, a team conducted on-grid tests to identify the most suitable desalination systems for connecting to the medium sized off-grid wind farm. The capacity range of this ED plant was 0.02 to 0.05 million gallons per day (mgd) (72 to 192 m^3/d) (Veza et al. 2001). The product water flow rate was from 793 to 2,200 gallons per hour (gph) (3 to 8.5 cubic meters per hour [m^3/h]) with power requirements ranging from 4 to 19 kW. The desalination unit demonstrated decent flexibility and easily adapted to abrupt fluctuations in the wind power energy supply (Veza et al. 2004).

As an alternative to wind, ED can be powered by photovoltaic (PV) energy. Solar energy is nonpolluting, silent, decentralized, free, interminable, and durable. The low maintenance cost of these systems is also another positive factor since solar energy is accessible throughout the year (AlMadani 2003 and Ortiz et al. 2007).

Solar power is an appealing alternative to conventional energy sources, particularly in remote and dry locations (Al Suleimani and Nair 2000 and Sharon and Reddy 2015). PV cells, or solar panels, convert solar energy directly into electricity (Ortiz et al. 2008). A typical PV system consists of several solar cells, batteries, a regulator or controller, an inverter for AC, and an electrical load (Figure 8). The PV modules can be connected in series and/or parallel, depending on the power requirements. The solar radiation on the surface of the PV array is transformed into electric energy (direct current) (Ortiz et al. 2008). The controller in the PV system regulates voltage and current flow. It has both voltage and current sensors that monitor the PV system's output. The sensors are programmed to regulate the voltage and current entering the battery and the ED system.

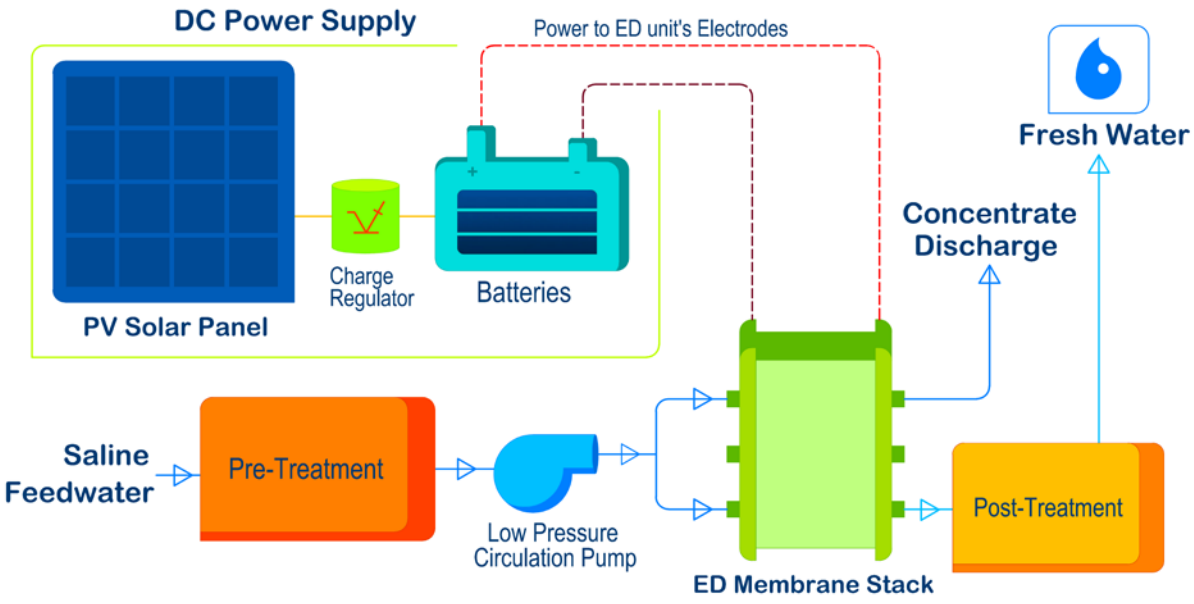


Figure 8. Schematic diagram of a PVED system.

In different locations around the world, PVED pilot units have been built successfully (Table 3). This list describes available documented information about the capacity, energy consumption, SEC, cost of energy per cubic meter, and plant descriptions.

The first documented PV-ED unit to treat brackish water was in La Luz, Mexico. Commissioned in 1979, the unit had a capacity of 4,000 gpd (15 m^3/day) and used 5 kilowatt (kW) (Al-karaghouli and Kazmerski, 2011).

Another ED-PV unit was commissioned in 1986 at Spencer Valley, New Mexico. The unit used two separate PV arrays: two tracking flat-plate arrays (1 kW power, 120 V) with DC/AC inverters for pumps and three fixed arrays (2.3 kW, 50 V) for ED supply. The ED unit produces 750 gpd (2.83 m^3/day) of product water from feedwater with about a 1,000 ppm TDS concentration. Unit energy consumption is about 0.82 kWh/m^3 with a cost of $16 US per cubic meter (Al-Karaghouli et al. 2011).

A small experimental PVED unit in the city of Tanote, in Rajasthan, India has a PV system capable of providing 450 W. The ED unit includes three stages and produces 264 gpd (1 m^3/day) of water from brackish feedwater with a 5,000 ppm TDS concentration. The unit energy consumption is 1 kWh per kilogram (kg) of salt removed (Al-Karaghouli and Kazmerski, 2011).

An alternative system to desalinate seawater in Oshima Island, Japan, uses PV technology with an ED system. It was commissioned in 1986. The solar field consists of 390 PV panels with a peak power of 25 kW. The ED stack has 250 cell pairs with a capacity of 2,600 gpd (10 m^3/day) and the quality of the product water is below 400 ppm TDS (Al-Karaghouli and Kazmerski, 2011).

In 1990, the largest solar powered ED plant was installed in Fukue City, Japan with average fresh water production of 52,800 gpd (200 m^3/d) and consisted of a 65 kW PV array with 1.2 Ah of storage. The fresh water production ranged from 34,300 to 97,700 gpd (130 to 370 m^3/day) with energy consumption of 0.6 to 1 kWh/m^3 (Al-Karaghouli and Kazmerski 2011 and Sharon and Reddy 2015). The PV system efficiency and overall system efficiency varied between 6.8 to 10.5% and 6.0 to 8.2%, respectively. The water production varied between 52,800 gpd (200 m^3/day) and 99,100 gpd (375 m^3/day). The electric power consumption per cubic meter of water produced was lower than the designed value of 1.92 kWh/m^3 (Sharon and Reddy, 2015).

A small-scale commercial electrodialysis stack powered by photovoltaic cells was commissioned in University of Bahrain with a production rate of 300 gpd (1.14 m^3/day) achieved with a salt removal greater than 95%. The stack consisted of 24 cell pairs arranged in four hydraulic stages and two electrical stages. Feedwater with TDS concentrations ranging from 1,000 to 5,000 ppm for salt (NaCl) solutions and brackish water, temperatures ranging from 10 to 40 degrees Celsius (°C), and product flow rates ranging from 50 to 300 gpd (0.2 to 1.1 m^3/day) were tested. It was concluded that increasing the feedwater temperature results in higher salt removal and the quality of the product (dilute) was substantially improved at low product flow rates (Ali et al. 2011 and AlMadani, 2003).

At the University of Alicante in Spain, the effect of variation in PV power on ED process was researched (Ali et al. 2011). Using a mathematical model, the characteristics of the experimental treatment system were determined. Characteristics include the electrodialysis size and the number and configuration of PV modules for the desalination of brackish water without batteries. This small PV-ED unit capacity averaged 350 gpd (1.32 m^3/day) (Charcosset 2009 and Ortiz et al. 2007). The ED stack has 70 cells. The active membrane area per cell is 500 square centimeters (cm^2) and the overall effective surface area is 3.5 square meters (m^2). There are 451 tilt panels in the south-facing PV array. The TDS concentrations of the feedwater ranged from 2,300 to 5,100 ppm. The electrical consumption ranged from 0.7 to 1.7 kWh/m^3 and the cost varied from $0.22 to $0.15 U.S. per cubic meter (Ortiz et al., 2008).

A recent experiment with a PVED batch pilot was commissioned at the University of Zaragoza in Spain in 2010, and the unit is still being tested (Uche et al. 2013). The capacity of the system is 1,140 gpd (4.32 m^3/day) and can produce 77 gph

($0.29\ m^3/h$) of fresh water. The ED unit consisted of ten $0.02\ m^2$ membrane stacks involving NEOSEPTA cell pairs and an on-grid connection to the ED stack. Flows are controlled by rotameters. The main innovation in the PV generator proposal is its flexibility to change the operating conditions by changing the number of connected cells, in addition to a maximum power point tracker (MPPT) to operate the PV array. The ED unit could also be connected to the grid with a controlled rectifier. A very competitive specific energy consumption (SEC) of about 1 kWh/m^3 was obtained (Uche et al. 2013), which is similar to other PVED systems listed in Table 3.

A PVED system is efficient and effective in treating brackish water with TDS concentrations of 1,000 to 5,000 mg/L as well as seawater. Also, it is significantly efficient with elevated temperatures and lower flow rates in the feedwater stream. Since 1986, the cost has decreased from $5.30 to $0.15 U.S. per cubic meter. It is also an alternative solution to provide potable water for barren, semi-arid, and remote regions. However, other desalination technologies have been implemented globally for decades.

Table 3. Partial list of Documented PVED Systems

Location	Capacity (m^3/day)	Treated water	TDS (ppm)	Energy supply	SEC (kW/m^3)	Cost ($US/$m^3$)	Particular characteristics	Year
La Luz, Mexico[1]	15	Brackish Water			5 kW			1979
Spencer Valley, New Mexico, USA[2]	2.8	Brackish Water	1,000	2.3	0.82	16	1 kW PV with tracking, two separate PV arrays: two tracking flat-plate arrays with DC/AC inverters for pumps, three fixed arrays)	1986
Tanote in Thar desert Rajasthan, India[2]	1	Brackish Water	5,000	0.45	1 kWh/kg of salt removed	5.8	42 cell pairs; three stages	1986
Oshima Island (Nagasaki), Japan[1,2]	10	Seawater		25		5.8	250 cell pairs; product water TDS 400 ppm levels	1986
Fukue City, Japan[2,3]	200	Brackish Water	700	65	0.6-1	5.8	1.2 Ah battery storage	1990
University of Bahrain, Bahrain[2,4]	1.14	Brackish Water	1,000 - 5,000	0.132			Stack of 24 cell pairs in 4 hydraulic stages and 2 electrical stages, feed pump, SR 30-50%	2002
University of Alincante, Spain [5]	1.32	Brackish Water	2,300 - 5,100	0.272	0.7 - 1.7	0.15-0.22	70 cells. 3 experiments using different concentrations, total cost of investment ranged from $7,000 to $17,000 U.S.	2006
Zaragoza, Spain[6]	4.32	Brackish Water	3,000 - 5000	1.24-1.9	1		On-grid and off-grid connections, batch-ED technique pilot unit, 99.9% purity NaCl use as solution	2010

[1] Al-Karaghouli & Kazmerski; [2] Ali ,2011; [3] Lienhard; 2012, [4] AlMadani, 2003; [5]Ortiz et al, 2008; [6] Uche, 2013

3.5. Other Desalination Technologies

Other desalination technologies are thermal processes; thermal processes are mainly used in the Middle East because of the lower cost of fossil fuel. These technologies include multistage flash evaporation (MSF), vapor compression in the form of ejectors/thermo, mechanical, and vacuum (vapor compression [VC], thermal vapor compression [TVC], mechanical vapor compression [MVC], and vacuum vapor compression [VVC]), and multi-effect distillation (MED).

Thermal processes differ from other technologies as salt is separated from water by evaporation and condensation. MSF is one of the most widely used and important methods of thermal desalination. The MSF process uses a series of flash chambers where steam is generated from seawater at a progressively reduced pressure. The different stages are: water abstraction and pretreatment, flash and heat recovery, heating, post-treatment, and brine outlet and fresh water delivery for the MSF process (Figure 9).

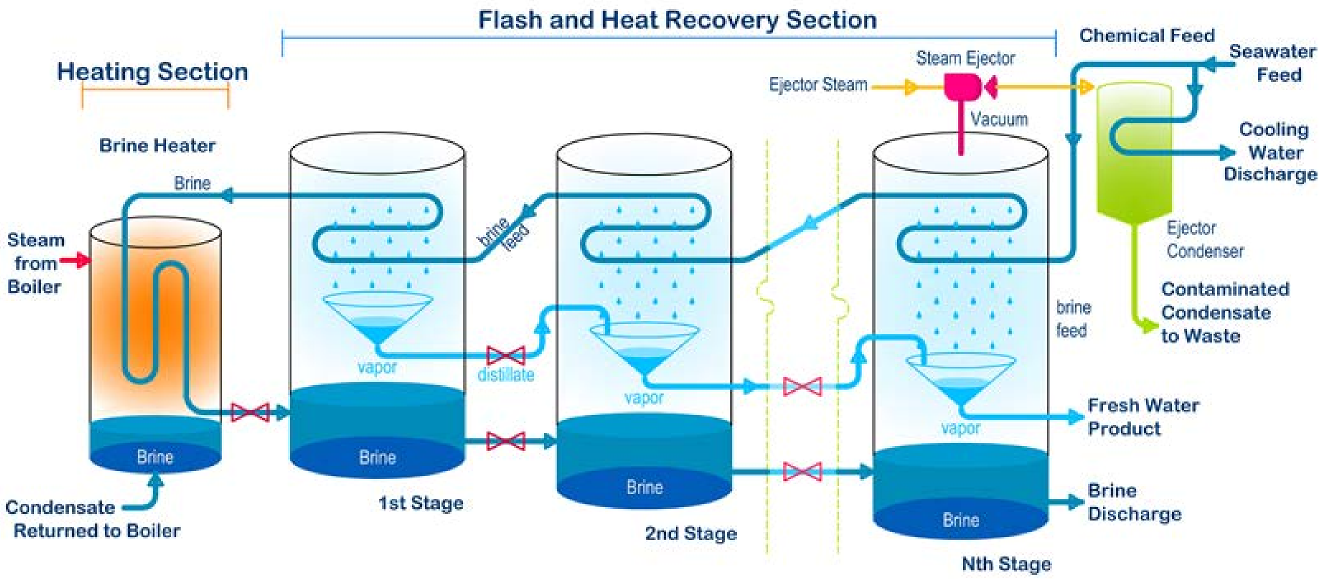


Figure 9. MSF process.

MED, another thermal process, was the first process developed for desalination. MED consists of using heat transported from condensing steam to seawater through a series of stages used to evaporate the water—leaving the salts behind. The evaporated water is then later condensed back into a liquid (Figure 10).

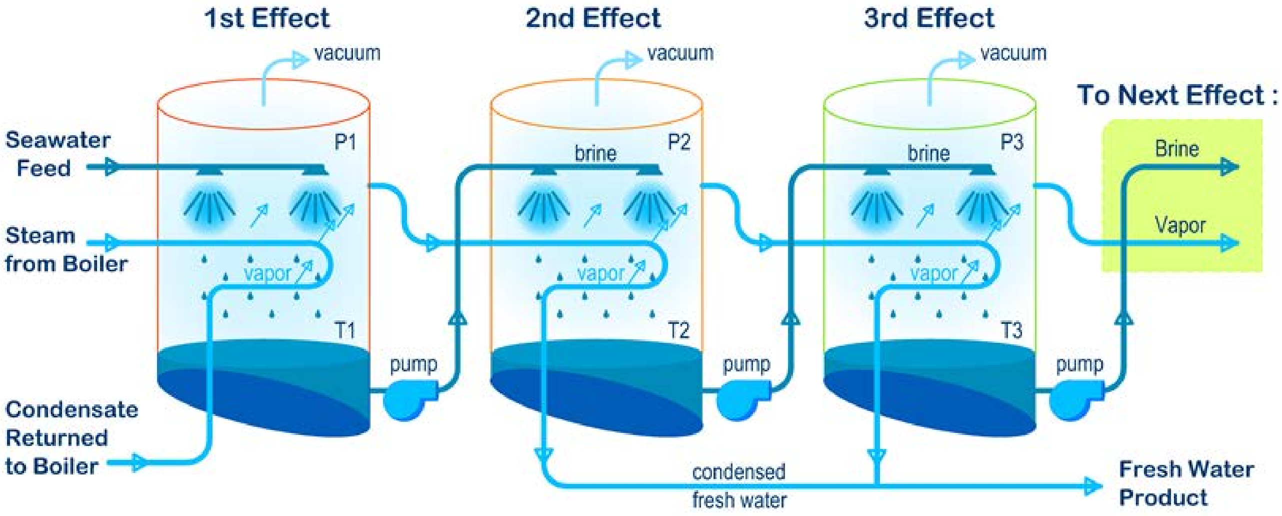


Figure 10. MED process.

In VC, another thermal process, vapor is produced and then recompressed to a higher pressure. Recompressing can be accomplished using various technologies such as a compressor or heat chambers. Ejector/thermo (TVC), mechanical (MVC), and vacuum (VVC) recompression processes are currently used in industry and are available for purchase. VC units are for smaller scale desalting units.

Other technologies have surpassed thermal methods in the past 40 years because of thermal processes' high energy demands, lower recovery factors, and higher desalted water costs. However, thermal processes are still being installed in plants, mostly in the Middle East. To reduce the energy cost of these plants, they use renewable energy systems such as solar panels, wind turbines, and solar ponds. Figure 11 illustrates a solar greenhouse effect. Table 4 compares thermal desalination processes with typical RO membrane processes.

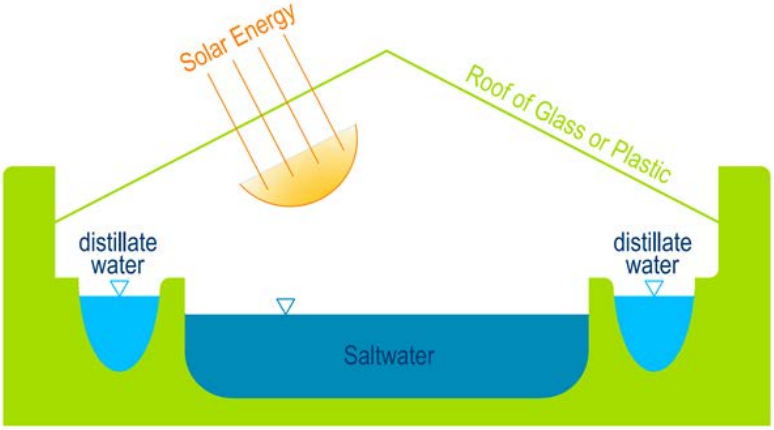


Figure 11. Solar greenhouse effect.

Table 4. Comparison of Operational Data of Membrane and Thermal Based Desalination (Macedonio et al., 2012, reprinted with permission)

	Thermal processes (MSF, MED, VC)	Membrane processes (RO)
Typical salt content of feedwater (ppm)	30,000 - 100,000	1,000 - 45,000
Desalted water with low total dissolved solids concentrations (ppm)	10.0 - 20.0	100 - 550
Thermal energy consumption (kWh/m^3)	12	0
Energy consumption (kWh/m^3)	17 - 18	2.2 - 6.7
Recovery Factor	40%	40 - 60%
Capital costs	high	low
Operating costs	high	low
Desalted water cost (\$/m^3)	0.9 - 1.4	0.50 - 0.70

Table 5 lists where thermal processes have been used, year the plant was built, type of processes being used, energy consumption, and how they get the energy (if other than the power grid), and the cost of the produced water.

Table 5. Partial List of Documented Other Desalination Technologies

Location	Capacity (m^3/d)	Treated water	TDS (ppm)	Energy supply	SEC	Cost ($US/$m^3$)	Particular characteristics	Year
Takami Island, Japan[1]	20	Seawater		336 m^2 ETC 185 m^2 FPC 38 m^3 stratified hot water storage 25 m^3 mixing type water storage			16 effect horizontal tube air-bubbling type ED ETC used for MED and FPC for ED RR 24.5%	1977
La Paz, Mexico[2]	10	Seawater		PTC-FPC	194 m^2 FPC 160 m^2 PTC with 2-axis tracking <144 kWh/m^3		10 stage	1980
Las Barracas, Mexico[1]	20	Seawater		PTC-FPC	550.8 m^2 PTC 1,540 m^2 HPC 16 m^3 hot oil storage 114 m^3 hot water storage			1980
Safat, Kuwait[2]	10	Seawater		PTC	220 m^2 PTC 7 m^3 hot water storage 81-106 kWh/m^3		12 stages GOR 6.5-8 RR 6% 10 times output of solar still of same collection area	1983
Abu Dhabi, UAE[1]	80	Seawater		ETC 1,862 m^2 300 m^3 of stratified hot water storage	50 kW/m^3		18 effect with preheating in each stage GOR 12.4 RR 12% 24 stages falling film MED	1984

Location	**Capacity (m^3/d)**	**Treated water**	**TDS (ppm)**	**Energy supply**	**SEC**	**Cost ($US/$m^3$)**	**Particular characteristics**	**Year**
El Paso, USA[1]	2.35-7.2	Seawater		220 m^3 PTC 7 m^3 hot water storage	81 - 106 kW/m^3		12 stages GOR 6.5-8 RR 6% 10 times output of solar still of same collection area Multi-effect multi-stage spin flash, brine concentration recovery system for testing zero discharge concept PR 1.7-3.3	1987
University of New South Wales, Australia[1]	0.05	Seawater		3 m^2 FPC	55.6 (thermal and electric combined)		Process efficiency 17 l/d/m^2 of collector area	1991
Island of Ibiza, Spain[1]	2	Seawater		51 m^2 ETCC 10 m^3 hot water storage	150 – 200 kW/m3		RR 5%	1993
Doba and Al-Waijh, Saudi Arabia	227.1	Seawater		MSF				1928
University of Alcona, Italy[1]	30	Seawater		solar pond 625 m^2 with 3.5 m depth	8 (electric) 194 (thermal) for MED 2.5 (electric) 111(thermal) for TVC		GOR 5.73 for TVC RR 5.7% for MED and 11.4 for TVC	1997
Island of Cape, Verde[2]	5	Seawater		solar pond			Atlantis (Auto flash) 30-95 °C TBT	1999

Location	Capacity (m^3/d)	Treated water	TDS (ppm)	Energy supply	SEC	Cost ($US/$m^3$)	Particular characteristics	Year
Gaza, Palestine[2]	0.2	Brackish water		FPC-PV	5.1 m^2 FPC, PV with battery storage		4 stage MSF thermo-siphoning from FPC experimental, batch process PV for vacuum pump and controls	1999
El Paso, USA[1]	0.4	Seawater	35,000	3,000 m^2 solar pond with 3.75m depth				1999
Canary Island, Spain[1]	0.08	Seawater	35,000	6 m^2 FPC 0.08 - 0.096 kW PV	144 kW/m3		1 membrane module with high internal heat recovery	2003
Plataforma Solar De Almerica, Spain[2]	72	Seawater		CPC	500 m^2 gas boiler back up with 30% continuous operation. 3.3-5 (electric), 57.2-70.4 (thermal)	2.86	14 stages double-effect absorption heat pump to enhance system efficiency hydro-ejectors vacuum system PR 11%	2004
Suez, Egypt[2]	0.009			FPC	2.39 m^3 FPC		PR 0.7-0.9 40-60 C TBT RR 0.6%	2005
Alexandria, Egypt[1]	0.064	Brackish water	670	5.73m^2 FPC	647 kW/m^3		Single-loop system SR 99.5% process efficiency 90%	2005
Gran Canary, Spain[1]	0.15	Seawater	35000	90 m^2 FPC 4 m^3 hot water tank 1.92 kW PV no battery	100-200		5 membrane module PV for pumps 2 loop system double glass collector with anti-reflective coating RR 3.6%	2005

Location	Capacity (m^3/d)	Treated water	TDS (ppm)	Energy supply	SEC	Cost ($US/$m^3$)	Particular characteristics	Year
Irbid, Jordan[1]	0.1	Brackish water		5.73 m^2 FPC 106 kW PV	200-300		1 membrane module with high internal heat recovery RR 1-4% GOR 0.3-0.9	2005
Aqaba, Jordan[1]	0.44	Seawater	55000	72 m^2 FPC 1.44 kW PV 3 m^3 water storage battery storage	200-300		4 membrane modules PV for pumps GOR .4-0.7 2 loop system RR 3-4.5%	2006

[1] Ali 2011; [2] Gude 20102, [3] Al-Mutaz 1996

Humidification-dehumidification (HD) desalination integrates the functions of solar collection, water heating, evaporation, and condensation to desalinate seawater. HD desalination separates components for each of the thermal processes, allowing for greater flexibility in designing the thermodynamics of the cycle for vaporizing water. The concept of the system is to collect moist air such as morning dew and condense it over a cool surface to obtain the water. The process is very attractive because it requires low temperatures and uses a simple design. It can also be manufactured locally and is non-corrosive. However, its thermal energy requirements are still high compared to other technologies.

Other desalination technologies also include nanofiltration (NF). NF is similar to RO in that it uses a membrane to separate ions from the water. However, in nanofiltration, the membrane allows larger ions to pass through it. NF membranes only target divalent and larger ions to remove. Ions such as sodium and chloride will pass through the NF membrane.

Solar stills are another way to distill water. Salty water is collected in an air-tight basin made of concrete, galvanized iron sheet, or fiber reinforced plastic. The salty water is blackened to increase its solar energy absorption. Water in the basin evaporates from thermal heating and condensates on the glass or plastic cover over the basin. The condensation of distilled water is then collected at the lower end of the cover. These systems are classified as either passive or active based on their heating principles (Ali et al., 2011). Solar stills may be inefficient, can have a high capital cost, and may require large installation areas that do not experience extreme weather conditions.

With these different processes, energy demands can be met in different ways. Traditional sources such as fossil fuels can be used, but renewable energy is becoming increasingly popular because of its cost-effectiveness and minimal carbon footprint.

3.6. Photovoltaic

Solar energy is a free and continuous source of energy, making it an attractive energy supply over the past decades as resources become scarce. Solar power is an attractive alternative to conventional sources, particularly in remote locations. The photovoltaic (PV) generation of electricity is the most widespread and studied (Ortiz et al. 2008). In addition, PV cells or solar panel devices convert solar energy directly into electricity, leaving no greenhouse emissions nor carbon footprint (Ortiz et al. 2008). Photovoltaics have many advantages such as free and abundant energy as well as simple operation and low maintenance (Ortiz et al. 2008).

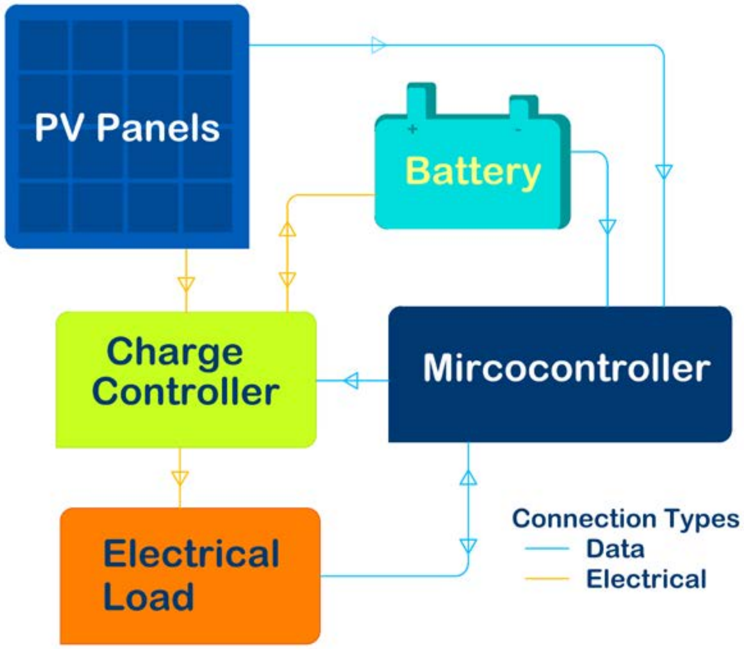


Figure 12. General schematic of PV and control systems.

Generally, a PV system consists of several stacks of PV modules, batteries, a regulator or controller, an inverter or direct DC, and electrical loads (Figure 13). The PV modules can be connected in series and/or in parallel. The solar radiation interacting with the surface of the PV array is transformed into electric energy (direct current) (Ortiz et al. 2008). The controller in the PV system regulates voltage and current flow. It has voltage and current sensors that monitor the PV system's output and is programmed to regulate the voltage and the current entering the battery or the ED system.

A general schematic of the ED (Figure 13) consists of: a pretreatment system, a membrane stack, a low-pressure circulation pump, a power supply for DC (rectifier or PV system), and a post-treatment system.

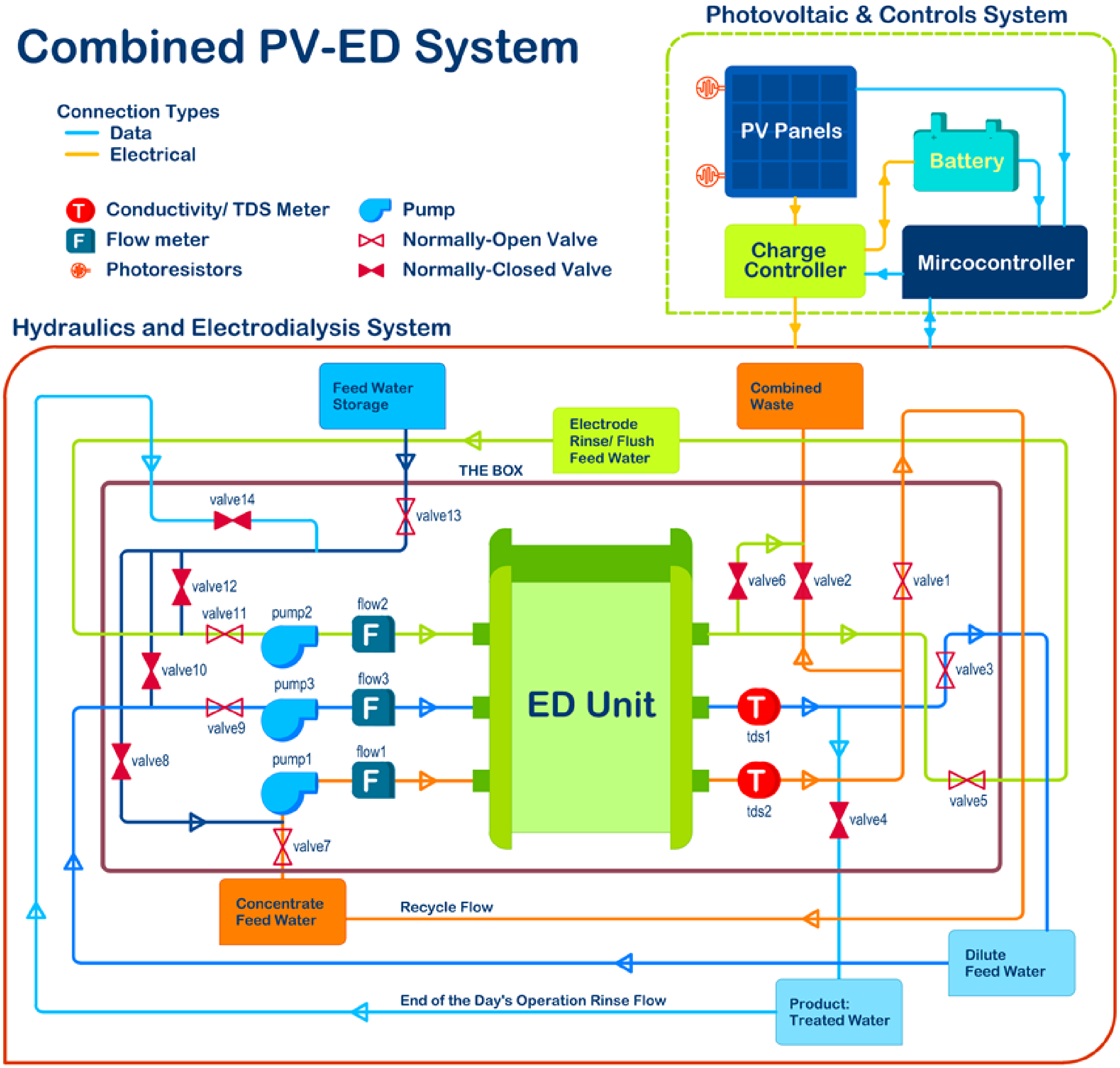


Figure 13. Schematic of PV-ED system.

3.7. Comparison of Desalination Technologies

Table 6 provides a comparison of desalination by showing the average values from Table 1, Table 3, and Table 5. PVRO capacity was 0.015 mgd (55.90 m^3/d), which is higher than ED-PV and other technologies. This is expected because PVRO plants have greater capacities and are widely commissioned.

Other technologies treat feedwater with higher TDS concentrations (>35,000 ppm) than PVRO and PVED. Other technologies are used primarily to treat seawater as was PVRO, for which feedwater TDS concentrations average

14,892.7 ppm. PVED units mostly treat brackish water with lower TDS concentration.

Specific Energy Consumption (SEC) for other technologies was 178.8 kW/m^3, which is higher than RO and ED. This is expected because thermal technologies use more energy than RO (7.9 kW/m^3) and ED (1.08 kW/m^3).

The cost for PVED is $5.62 US/m^3, which is lower than $9.76 US/m^3 for PVRO, because PVRO is associated with greater maintenance and operation costs.

Seawater Recovery Ratio (RR) for PVRO is 9.76% and 10.15% for other technologies. Brackish water RR for PVRO is 14.99% and 2.5% for other technologies. Recovery Ratio for PVRO appears to correlate with TDS concentration; if TDS concentration is higher, than the RR is lower and vice versa as lower TDS concentrations have higher RR.

Table 6. Operational Parameters of Desalination Technologies

Technology	PVRO	PVED	Other Technologies
Capacity (m^3/d)	55.90	27.92	23.19
TDS concentration (ppm)	14,892.7	3,122	>35,000
SEC (kW/m^3)	7.9	1.08	178.8
Cost ($US/m^3)	9.4	5.62	Not enough data
Recovery ratio % (seawater)	9.76	Not enough data	10.15
Recovery ratio % (brackish water)	14.99	Not enough data	2.5

4. Project Objectives

This project’s goals were to develop a renewable energy desalination system that is independent of the power grid, uses an automated system, and can treat brackish water to potable water. Independence of the power grid allows for the ability to treat brackish water in remote areas. Automation and portability allow for usability and ease of implementation for any user. The automatic electrodialysis (ED) unit is powered by photovoltaic (PV) cells. Treatment objectives consist of treating the brackish water, which contains concentrations of total dissolved solids (TDS) ranging from 1,000 to 6,000 mg/L, to Environmental Protection Agency (EPA) secondary standards of 500 mg/L of TDS.

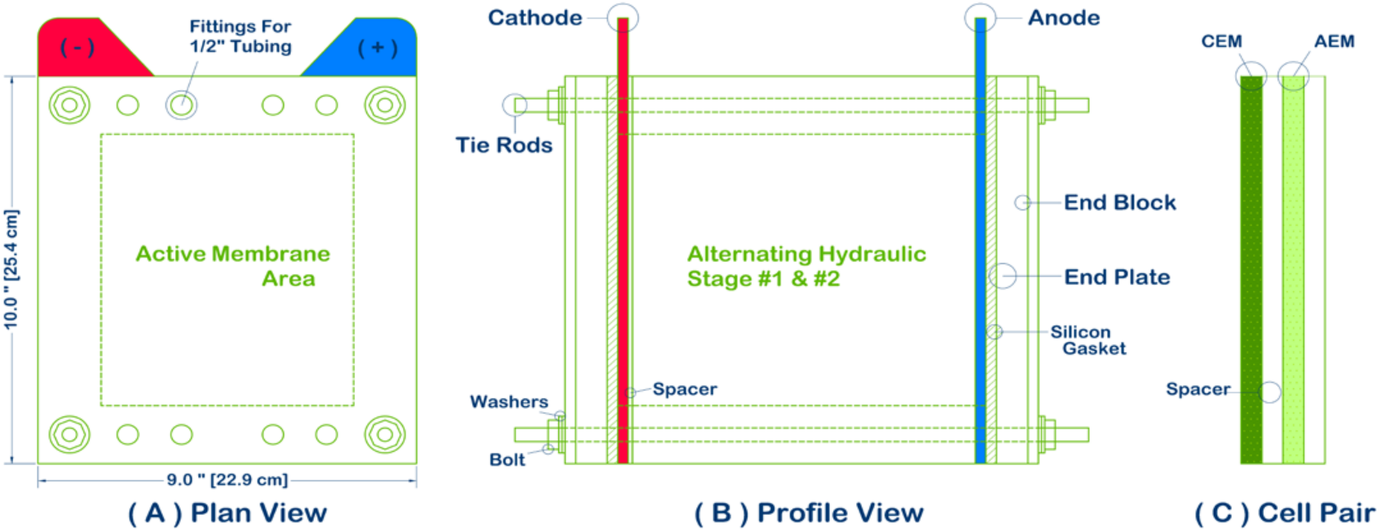
We developed a pilot system that met these objectives and provided a 78% recovery rate as well as a 20% removal rater per pass in the batch system. The unit consists of four subsystems: electrodialysis, hydraulics, photovoltaic panels, and automatic controls.

5. Methodology

5.1. Electrodialysis (ED)

5.1.1. Design approach

To meet EPA’s secondary standard recommendation of 500 mg/L of TDS, a feed-and-bleed electrodialysis unit was designed to treat 0.3 gpm (1.1 L/min) of dilute feedwater. The water is processed through an ion membrane stack consisting of: 20 AR204 anion exchange membranes (AEM), 20 CR67 cation exchange membranes (CEM), and 41 screen spacers (General Electric, Fairfield, Connecticut) as seen in Figure 14: (c) Cell Pair.



(A) Plan View (B) Profile View (C) Cell Pair

Figure 14. ED unit schematic layout. The schematic is not drawn to scale.

First, a computer simulation model of Faraday’s Law was developed to predict the behavior of the ion membrane stack and determine the preliminary current through the stack. The following assumptions are used as input parameters in the computer simulation model: an estimated 0.04 M normality and 100% current efficiency within the design flow and cell pairs. As a result, the preliminary current through the stack was determined as 7.12 A.

Assembly of the initial ED stack consisted of items included in GE’s Stack Hardware Kit shown in Figure 14: (b) Profile View depicts a schematic diagram of two hydraulic stages (consisting of 20 cell pairs) sandwiched between two electrodes: one coated titanium anode and one hastealloy cathode. The electrodes sit between two end plates and two end blocks, which are fastened together by four tie rods and securing hardware (bolts on each tie rod end with two washers). An additional layer of $^{1}/_{32}$-inch 70 A Durometer silicon gasket (SmallParts or AmazonSupply, Seattle, Washington) was inserted between each electrode and end plate to mitigate leaking. Figure 14: (a) Plan View shows fittings for ½-inch (12.7 millimeter [mm]) flexible tubing where flow will enter and exit the ED unit. The nominal size of the membranes and spacers are 9 x 10-inch (22.9 x 25.4 centimeters [cm]) with an active membrane area of 43 square inches (272 cm^2).

The flow within the membrane stack is controlled using screen spacers to create four separate flow patterns: dilute-hydraulic stage #1, electrode flush, dilute-hydraulic stage #2, and concentrate. Each spacer contains one inlet and one outlet. The resulting flow patterns are determined by varying the alignment of the inlet and outlet of each spacer as shown in Figure 15. A flexible pipe is used to connect hydraulic stage #1's outlet to hydraulic stage #2's inlet as indicated by the dashed line in Figure 15. A 2:3 ratio between hydraulic stage #2 to hydraulic stage #1 is implemented in the design, which is a common industry standard used to equalize the voltage drop throughout the system.

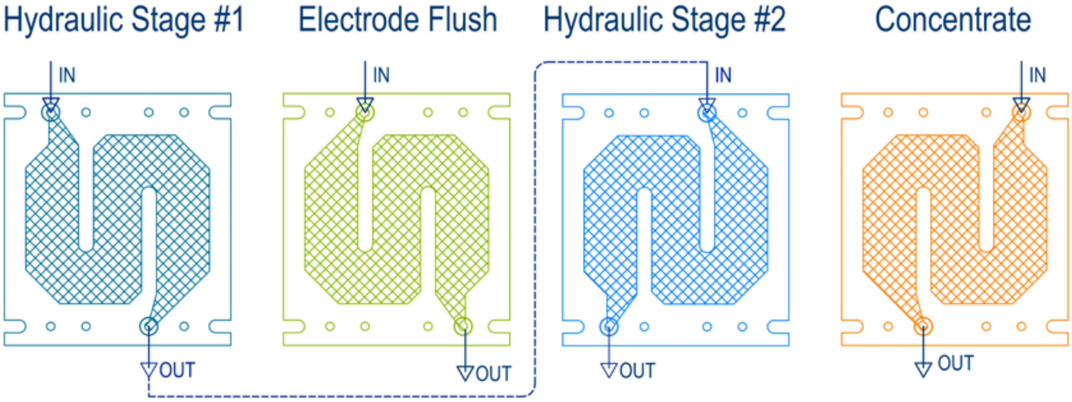


Figure 15 Flow Patterns Alignment of Spacers

5.1.2. Construction Process

The construction process for assembly of the ED unit was:

1. The flow patterns for dilute (hydraulic stage #1 and #2), concentrate, and electrode flush streams are initially assigned individual input and output locations on the ED unit. The designation of these streams dictated the orientation of the spacers. The resulting flow pattern directions are shown in Figure 15.

2. The stack was then carefully assembled in order from: the first end plate and block, a silicon gasket layer, the titanium anode, the pattern configuration of alternating spacers and membranes, the hastealloy cathode, a second silicon gasket, and the second end plate and block. This assembly pattern is shown in Figure 16. In later development of the stack, this assembly pattern was adjusted so the hydraulic #1 and #2 were arranged together on opposite sides of the ED unit rather than alternating

stages for more efficient use of power to the unit. It is critical that no errors are made when assembling the pattern configuration—misplaced spacers will disrupt salt removal within the stack. In the initial design, GE’s ½-inch fittings were attached to the second end plate before placing the proceeding block atop.

3. The ED unit is bolted together using four tie rods with double washers and bolts at each end to compress the membrane stack to limit leakage. An assembled ED unit is shown in Figure 17.

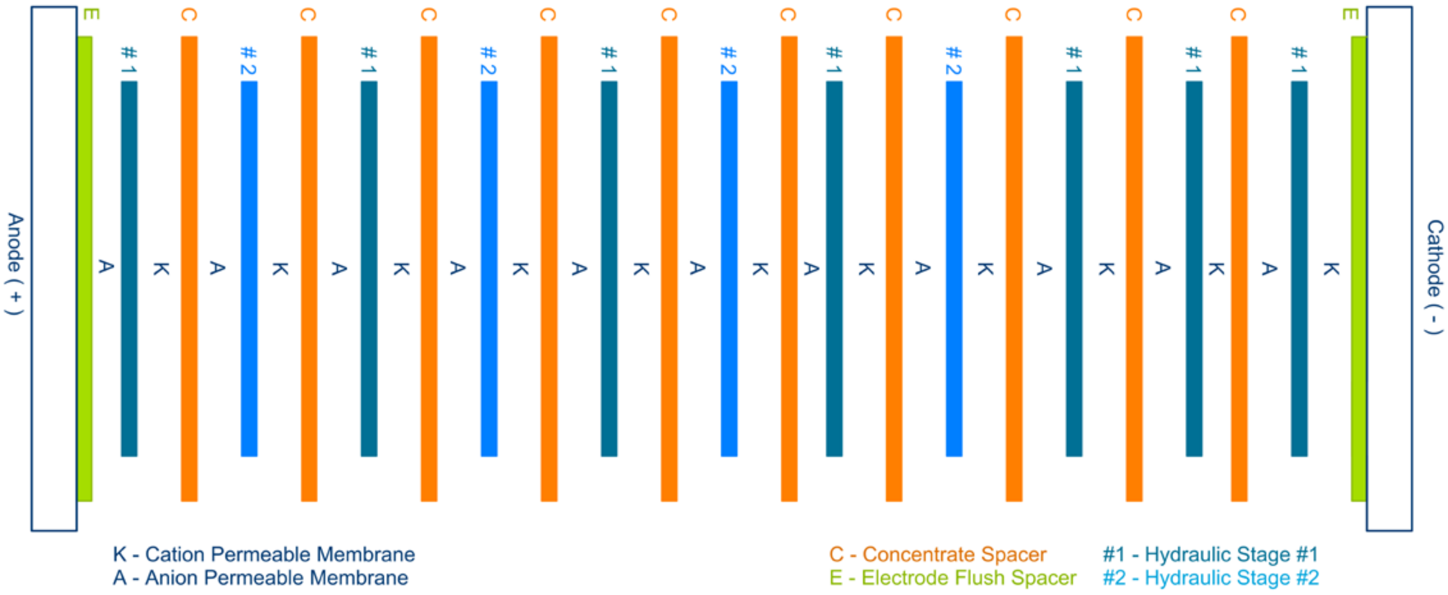


Figure 16. Order of the ED stack’s assembly.

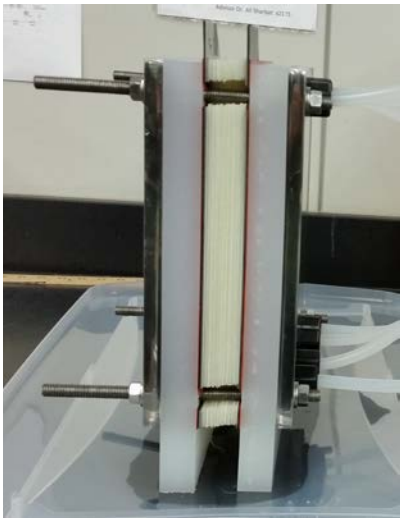


Figure 17. Assembled ED unit.

5.1.3. Design Procedures

The electrodialysis unit's efficiency was determined by comparing the amount of wattage used to the percent of constituents removed. The limiting current test was conducted to further evaluate the relationship between current and salt removal during the ED stack operation. The developed computer simulation model was used to calculate the minimum current for the test using Faraday's law. A conductivity meter was selected to proportionally measure how much TDS is removed after the electrodialysis process.

5.1.3.1. Conductivity to TDS

Conductivity tests were conducted to determine the TDS of a sample. When only ions were present in the water, conductivity was directly proportional to TDS. Conductivity measurements vary with temperature. However, the resulting varying conductivity was accounted for in the controller software, as described in Section 5.3. Controller. TDS concentrations were used as an indicator to identify salt content and to determine the efficiency of salt removal. A conductivity meter was used to confirm the rate the electrodialysis unit removed salts. The physical unit for conductivity was given by the unit, Siemens per meter (S/m). A conductivity meter was used to test the influent and effluent water, determining if TDS is efficiently being removed by the electrodialysis process.

For initial testing of the ED unit, salt water was produced with NaCl salt (United Salt Corporation, Houston, Texas) and deionized (DI) water for feedwater. The relationship between conductivity and TDS (composed of primarily the table salt's sodium and chlorine ions) was measured using an EcoTestr EC High pocket conductivity meter (Oakton Instruments, Vernon Hills, Illinois). From this lab's data, an equation was obtained to determine the amount of table salt concentration needed to replicate desired conductivity levels found within brackish water ranging from 2,000 to 20,000 microSiemens per centimeter (µS/cm). The performed lab procedures are:

- Fill one beaker to 100 milliliter (ml) of DI water.
- Place 180 grams of salt into beaker and mix well with a magnetic stirrer.
- After five minutes of mixing, test and record the conductivity of the water using the EcoTester conductivity probe.
- Repeat steps 1 to 3 with 360 grams of salt.
- Fill two beakers with 500 ml of DI water. Add 180 grams of salt in one beaker and add 360 grams of salt in the other.

- Using the magnetic stirrer, mix the beakers for five minutes. Then, test and record conductivity for each.

- Repeat steps 5 to 6, but fill the beakers to 1,000 ml of DI water. All data was recorded in Table 7.

Table 7 Conductivity Pen to TDS Ratio Results.

Test	Added Salt (mg)	Water (mL)	Concentration (mg/L)	Conductivity (mS/cm)	(μS/cm)	Ratio (mg/L)/(μS/cm)
1	183	100	1,830	3.7	3,700	0.495
2	360	100	3,600	6.8	6,800	0.529
3	181	500	362	0.8	800	0.453
4	363	500	726	1.5	1,500	0.484
5	179.5	1,000	179.5	0.4	400	0.449
6	364	1,000	364	0.8	800	0.455

mS/cm = milliSiemens per centimeter

- Calculate the ratio of concentration over conductivity for each test using Equation 4:

$$Ratio = \frac{Concentration\ (\frac{mg}{L})}{Conductivity\ (\mu S/cm)} \tag{4}$$

Sample Calculation: Using Test 1 from Table 7

$$Ratio = \frac{1830\ (\frac{mg}{L})}{3700\ (\mu S/cm)} = 0.495$$

- The ratios were averaged to discover that the TDS of table salt water (mg/L) is 0.477 times the measured conductivity (μS/cm).

From this relationship, the TDS concentration of table-salt water was directly calculated from the measured conductivity and vice versa. This was used to control the conductivity and the TDS concentrations of sample water batches for later electrodialysis unit testing. Future electrodialysis unit testing is currently in planning with the use of natural water from Brackish Groundwater National Desalination Facility's Well 1. The relationship between TDS and conductivity of the well water would have to be determined due to different ion and salt composition of the water.

5.1.3.2. Computer Simulation

Most equations used to determine the operation parameters for the electrodialysis depend on each of the individual ions in the water. Individual chemical properties such as valence charge and molecular weight are calculated for each ion. To adapt to varying water chemistry, an Excel 2007 sheet (Microsoft, Redmond, WA) was programmed to accurately calculate the electrodialysis stack's current through Faraday's law.

In Faraday's equation, the change of normality is the ion-dependent parameter. The parameter is based on the different concentration, molecular weight, and valence charge for each specific cation and anion in the water.

Normality (N) for each ion can be calculated by using Equation 5:

$$N = (concentration\ mg/L)\ /\ (molecular\ weight\ g/mol) * (valence\ equivalent/mol) \quad (5)$$

Calculations for the change of normality are shown in Equation 6:

$$\Delta N = N(feed\ water) - N\ (treated\ dilute) \quad (6)$$

For this project, N (treated dilute) was approximated as zero normality. The normality of feedwater is the sum of each normality from either anions (-) or cations (+). Both sums should be the same for total normality due to the electro-neutrality principle (i.e., for every negative charge in water there is a positive charge). The average normality between the anion and cation sums was used as the initial normality of the feedwater. Faraday's law calculated with flow, cell-pair, and efficiency inputs.

This is a brief overview of how the developed computer simulation model operates; the Excel program was made by:

1) Formatting the Excel file first. On the first sheet, water chemistry is inputted while a separate Faraday's Law calculation sheet references this data for varying ions in the water. The anions (-) and cations (+) are grouped separately.

2) Calculating the normality for each ion parameters using the cell arrangement in Table 8. Few ion parameters were adjusted for their calculations of normality as listed below Table 8.

Table 8. Excel Arrangement for Calculating Normality

Name	**Unit**	**Data**	**Ion**	**Valence (e-)**	**M.W. (g/mol)**	**Molarity (mol/L)**	**Normality (equv/L)**
A	mg/L	B	C	D	F	G=B/F*10^{-3}	H=G/D
Barium	mg/L	0.038	Ba^{+2}	+2	137.3270	2.77E^{-07}	5.53E^{-07}

g/mol = grams per mole
mol/L = moles per liter

Omitted and uncalculated normalities were:

- Total Alkalinity
- P-Alkalinity
- Nitrate + Nitrite
- Iron (Dissolved) and Manganese (Dissolved).

Assumed Valences were:

- +2 for cobalt, copper, lead, mercury, nickel and molybdenum
- +4 for silicon dioxide
- +4.5 for chromium

For iron (Total) and manganese (Total), a weighted valence between the dissolved (+2) valence and non-dissolved (+3) valence. Due to varying reporting units, the molarity calculations below are adjusted as shown:

$[HCO_3^-] = 1.22* (HCO_3^- \text{ as mg/L } CaCO_3) / (HCO_3^- \text{ g/mol}) * (\text{g/1,000 mg})$
$[CO_3^{-2}] = 0.6 * (HCO_3^- \text{ as mg/L } CaCO_3) / (HCO_3^- \text{ g/mol}) * (\text{g/1,000 mg})$
$[OH^-] = 0.34 * (HCO_3^- \text{ as mg/L } CaCO_3) / (HCO_3^- \text{ g/mol}) * (\text{g/1,000 mg})$
$[NO_3^-] = 4.4268 * (NO_3^- \text{ as mg/L N})/ (NO_3^- \text{ g/mol})* (\text{g/1,000 mg})$
$[NO_2^-] = 3.2845 * (NO_2^- \text{ as mg/L N})/ (NO_2^- \text{ g/mol}) *(\text{g/1,000 mg})$

Valence charges for uranium varies in brackish water depending on pH, so its normality calculations were adjusted by the predominant charge of a single uranium ion.

Phosphorus was underdeveloped for its calculations. Adjustments have yet to been made for the many compounds with varying valences found in water. This program is only applicable for water chemistry with zero amounts of phosphorus such as sample water from BGNDRF.

3) Summing the normality of all the cations and all the anions separately. Average these sums to obtain the initial feedwater normality.

4) Calculating Faraday's Law with flow, cell pair, and current efficiency parameter for design.

The computer simulation performed well enough to estimate the current for BGNDRF's Well 1 water by Faraday's law from the normality sum of the anions. All present parameters were adjusted and calculated correctly. This full excel calculation is in Appendix A. The program is currently only applicable for water chemistry with zero amounts of phosphorus.

Additionally, attempts were done to adjust this Faraday's Law calculation to accurately predict the required current through the stack when compared to laboratory tests results. This was though proven unsuccessful due to possible inaccurate measurements during experiments such as conductivity which related to normality as well as not enough data.

5.1.3.3. Limiting Current Test:

Limiting current is defined as the maximum current level at which the percent of salt removal will no longer significantly increase. Conductivity was measured as substitute to its directly-proportional TDS for practical time to perform lab work. The experiment was set up as shown in Figure 18 and Figure 19, where the concentrate and dilute stream are recirculated into the same tank to maintain the same conductivity. This allows the dilute stream to be tested at varying current with constant flow.

The first three experiments were performed on a 10-cell pair stack consisting of six hydraulic stage #1 and four hydraulic stage #2 with a HACH conductivity meter (Hach, Loveland, Colorado). Later experiments were performed on a 20-cell pair stack of the same 2:3 hydraulic stage ratio either the HACH conductivity meter or an EcoTester EC High pocket conductivity tester (Oakton Instruments, Vernon Hills, Illinois). Data from these experiments are shown in Appendix B.

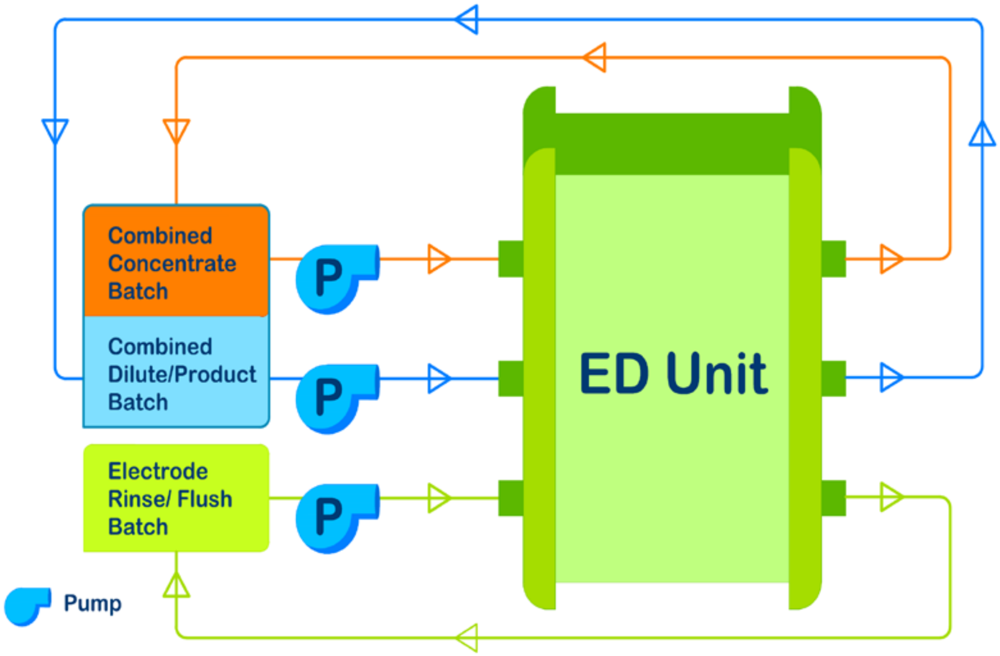


Figure 18. Limiting current test schematic.

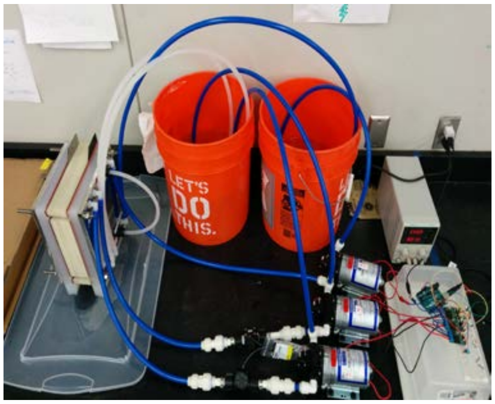


Figure 19. Limiting current test set up.

Limiting current test procedures:

1) Fill one fourth of a 5-gallon bucket with DI water

2) Place some salt in the water and mix well. Note: an estimated amount of salt and water was combined into the bucket during testing because this experiment's goal was to observe salt and conductivity removal.

3) Measure and record this initial conductivity of water in the bucket.

4) Place inlet and outlet lines of the dilute and concentrate stream into this 5-gallon bucket. This creates a circulating system that maintains the same conductivity level as the salt removed from dilute is returned as the salt taken into the concentrate. Place the inlet and outlet of the electrode flush into a separate bucket of lightly salted DI water.

5) Turn the pumps on. After a steady flow is established, measure dilute flow rate. This was done by filling a graduated cylinder through the dilute steam's outlet flow where flow rate was the measured volume divided by the time to fill it.

6) Set the digital-control DC power supply (Korad, P.R. China) to a fixed current and run system for 10 seconds. Record the operation's current and voltage applied to the unit.

7) Take a sample directly from the dilute outlet and test and record its conductivity. Concentrate's conductivity may also be recorded as double check for salt removal if it increases.

8) Repeat step 6 and 7 at varying current as the next trial. However, many number of trials of the same initial conductivity and flow rate made up one data set (Table 9).

Table 9. Sample Data for Limiting Current Test (Taken January 30, 2015)

Trial No.	Amp (A)	Voltage (V)	Concentrate (μS/cm)	Product (μS/cm)	Initial (μS/cm)	% Removal	Q (gpm)
1	0.6	18.00	2,690	2,450	2,680	8.58	0.6
2	0.8	10.74	2,780	2,430	2,680	9.33	0.6
3	1.0	12.45	2,760	2,350	2,680	12.31	0.6
4	1.4	17.40	2,840	2,330	2,680	13.06	0.6
5	1.8	20.00	2,940	2,260	2,680	15.67	0.6
6	2.0	21.10	2,990	2,220	2,680	17.16	0.6

9) Calculate the percent removal for each trial using Equation 7:

$$Percent\ Removal\ (\%) = \frac{Initial\ \left(\frac{\mu S}{cm}\right) - Product\ \left(\frac{\mu S}{cm}\right)}{Initial\ \left(\frac{\mu S}{cm}\right)} * 100\ \% \qquad (7)$$

Sample Calculation: Using Trial 1 on Table 9:

$$Percent\ Removal\ (\%) = \frac{2680\left(\frac{\mu S}{cm}\right) - 2450\ \left(\frac{\mu S}{cm}\right)}{2680\ \left(\frac{\mu S}{cm}\right)} * 100 = 8.58\ \%$$

10) Graph percent removal and current (Figure 20). The limiting current is found at the point where the slope of the percent salt removal versus the current becomes quite flat.

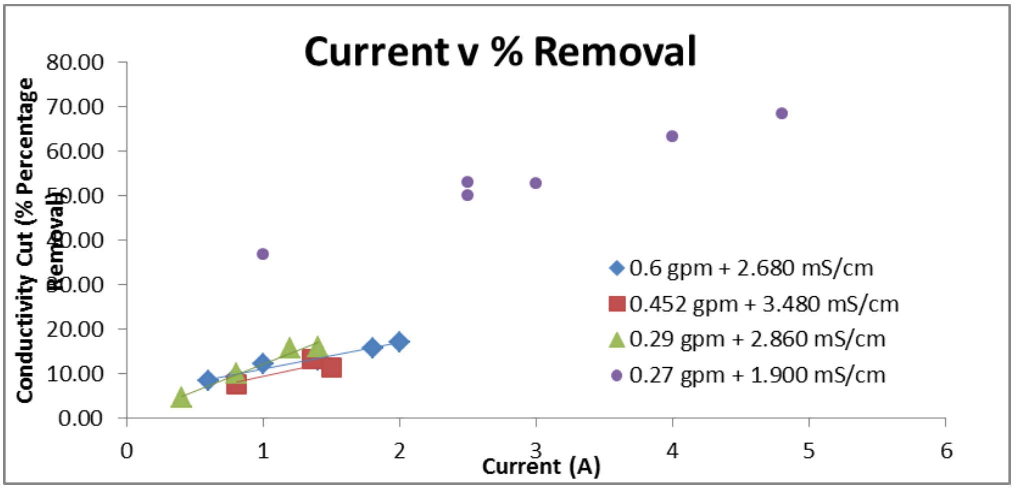


Figure 20. Percent salt removal versus current.

Limiting currents were not reached during testing due to the design's practical applied current. The design's practical applied current is a maximum of 2 A to prevent potential electrical hazards from the experiment's configuration. Because of this, testing did not exceed currents of 2 A.

We predicted the behavior of the ED stack using the computer simulation model and confirm this through testing. Data sets of similar conductivity (2.680 mS/cm and 2.860 mS/cm) were observed (Figure 20). We concluded that the greater the flow rate, the lower the salt removal per current; which is observed through the milder slope. The lower flow causes water to spend more time between the membranes, allowing the electrodes to draw more anion and cations from the dilute stream. Additionally, by comparing the data sets of similar flow (0.29 gpm and 0.27 gpm), we concluded that salt removal per current is lower when the initial conductivity and salt content is higher.

The ED unit was operated in a modified-batch mode at varying flowrates and current to determine the amount of percentage removal for each case. This achieved by using a bench power supply, which permitted a constant current to be delivered to the electrodes during testing. The initial goal was to determine the limiting current through these tests. However, due to facility safety regulations, it was not possible to determine the limiting current. These experimental results can be found in Appendix B.

5.1.3.4. Batch Test

We also ran the ED system in batch mode to test its desalination performance. This experiment was set up as shown in Figure 5 where the concentrate and dilute are recirculated in separate tanks so that salt removal in the dilute batch tank could be observed over time.

We performed four batch tests on a 20-cell pair stack consisting of six hydraulic stage #1 and four hydraulic stage #2 with a HACH H170 pH/Conductivity meter (Hach, Loveland, CO) and under a constant 1.0 A current. Data from these experiments are shown in Appendix C.

Batch Test Procedures:

1) Fill three buckets with DI water. Measure the amount of water (gallons) in the concentrate and dilute bucket.

2) Place some salt in the buckets and mix well. For the electrode flush bucket, add only a bit of salt to avoid hydrolysis in this stream. Note: an estimated amount of salt and water was combined into the bucket during testing because of this experiment's goal to observe salt and conductivity removal.

3) Measure and record this initial conductivity of water in all the buckets.

4) Place inlet and outlet pipes to their corresponding buckets for a batch system.

5) Turn the pumps on. After a steady flow is established, measure dilute flow rate. This was done by filling a graduated cylinder through the dilute steam's outlet flow where flow rate was the measured volume divided by the time to fill it.

6) Set the digital-control DC power supply to a fixed 1.0 A current. Apply power to the stack's electrode and began timer. Take the first data set at time zero (0 min) according to step 7.

7) Record the operation's voltage applied to the unit. For the dilute and concentrate, take a sample directly from the outlet (tube) and from the batch bucket (tank), and test and record their conductivity.

8) Pour all sample water back into the original bucket.

9) Repeat step 7 and 8 about every two minutes as constantly as possible until the entire dilute batch has reached drinking water standards (TDS ≤ 500 mg/L) which is about 1,000 µS/cm for table-salt water or nearly 30 V applied to the ED stack was reached due to maximum 30 V limit of the power supply. A sample data set is shown below in Table 10.

Table 10 Sample Data for Batch Testing (Taken March 2015)

Trial 4	Current	1	A	Volume Dilute		2.1	gallons		
	Flow rate	0.201	gpm	Volume Concentrate		2.43	gallons		
Time (min)	**Dilute**		**Concentrate**		**Flush**	**Voltage (V)**	**% Removal Tank to Tube (per Pass)**	**Overall % Removal (from Dilute Tank)**	**Dilute Difference (µS/cm)**
	Tank	**Tube**	**Tank**	**Tube**					
0	3,090		4,680		-	13			
1	3,030	1,523	4,810	6,080	-	16.53	49.74	30.50	1,507
3	2,720	1,214	5,120	6,470	-	20.72	55.37	37.61	1,506
5	2,410	824	5,440	6,680	-	27.33	65.81	44.72	1,586
								AVG:	**1,533.00**

10) Turn off the power supply and pumps.

11) Calculate percent removal per pass through the ED stack and overall dilute batch tank was calculated for each trial using Equation 8:

$$Percent\ Removal\ (\%) = \frac{Initial\ \left(\frac{\mu S}{cm}\right) - Outlet\ \left(\frac{\mu S}{cm}\right)}{Initial\ \left(\frac{\mu S}{cm}\right)} * 100\ \% \qquad (8)$$

For percent removal per pass, the initial conductivity is measured from the dilute batch tank per trial, and the outlet conductivity is directly measured from the ED's stack outlet tube of the same trial. For percent removal for the overall dilute batch tank, the initial conductivity is measured from the dilute batch at zero minutes, and the outlet conductivity is measured from the dilute batch tank per trial.

Sample Calculation: Percent removal per pass at 1 minute on Table 10:

$$Percent\ Removal\ (\%) = \frac{3030\left(\frac{\mu S}{cm}\right) - 1523\ \left(\frac{\mu S}{cm}\right)}{3030\ \left(\frac{\mu S}{cm}\right)} * 100 = 49.7\ \%$$

Sample Calculation: Percent removal for overall dilute batch tank at 1 minute on Table 10:

$$Percent\ Removal\ (\%) = \frac{3090\left(\frac{\mu S}{cm}\right) - 3030\ \left(\frac{\mu S}{cm}\right)}{3090\ \left(\frac{\mu S}{cm}\right)} * 100 = 30.5\ \%$$

12) The amount of conductivity removed per pass of the dilute flow was calculated as shown using Equation 9:

$$Conductivity\ Removal\ per\ Pass\ \left(\frac{\mu S}{cm}\right) = Conductivity\ In\ \left(\frac{\mu S}{cm}\right) - Conductivity\ Out\ \left(\frac{\mu S}{cm}\right) \qquad (9)$$

The "conductivity in" is measured from the dilute batch tank per trial and the "conductivity out" is directly measured from the ED's stack outlet tube of the same trial.

Sample Calculation: Percent removal for dilute difference at 1 minute on Table 10:

$$Conductivity\ Removal\ per\ Pass\ \left(\frac{\mu S}{cm}\right) = 3030\left(\frac{\mu S}{cm}\right) - 1532\left(\frac{\mu S}{cm}\right) = 1507\ \left(\frac{\mu S}{cm}\right)$$

Chart three graphs:

(1) Time and percent removal per pass for batch removal
(2) Time and dilute tank conductivity
(3) Voltage and dilute (tube) conductivity

Three out of the four batch tests were graphed. The omitted batch test (Trial 1) did not have enough measured data for proper analysis (see Appendix C).

Figure 21 shows operating the ED stack in batch has an increased removal per pass when the flow rate is slower due to greater contact time between the dilute water, electrodes and membranes in the ED stack. Additionally, the percent removal per pass generally non-linearly increases over time as the dilute conductivity decreases though the conductivity removed per pass remains approximately the same by a constant current as observed in the dilute difference columns for each batch test in Appendix B.

Operating under batch mode at constant current will remove salts at a relatively steady rate from above graphed linear slopes (Figure 22). This graph also demonstrates that under the same operating batch system for brackish water with greater initial conductivity will take longer to treat.

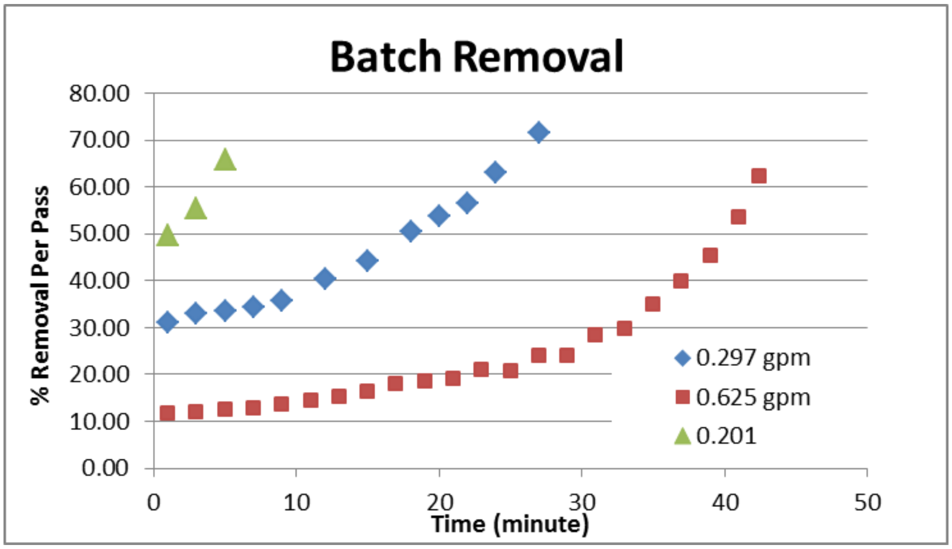


Figure 21. Time and percent removal per pass for batch removal.

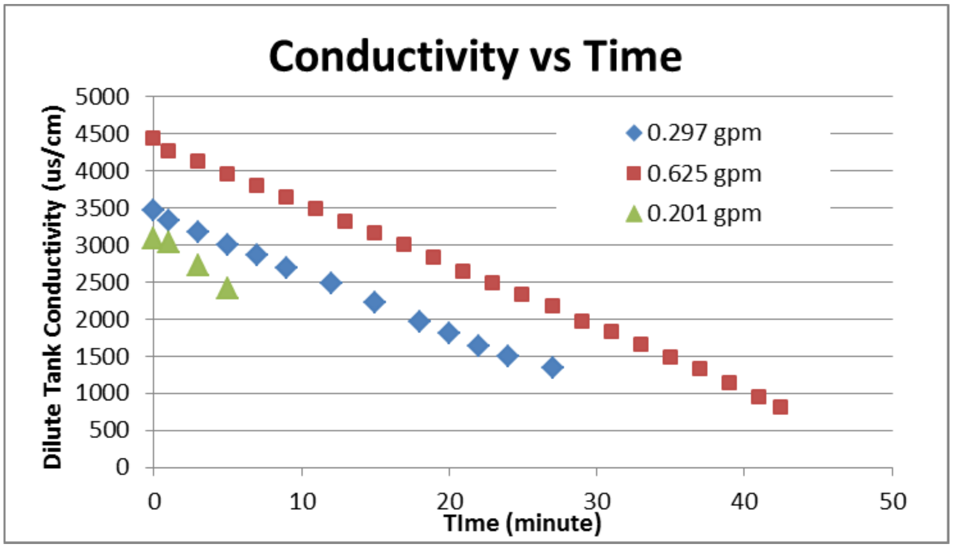


Figure 22. Time and dilute tank conductivity.

Figure 23 shows that as the dilute conductivity decreases, voltage through the ED stack increases non-linearly. This demonstrates that as the dilute batch is treated towards drinking water standards, more power from the solar panel is required to continue treatment. The voltage increase also appears slightly less drastic for higher flow rates as observed that at the same dilute conductivity, less voltage is required.

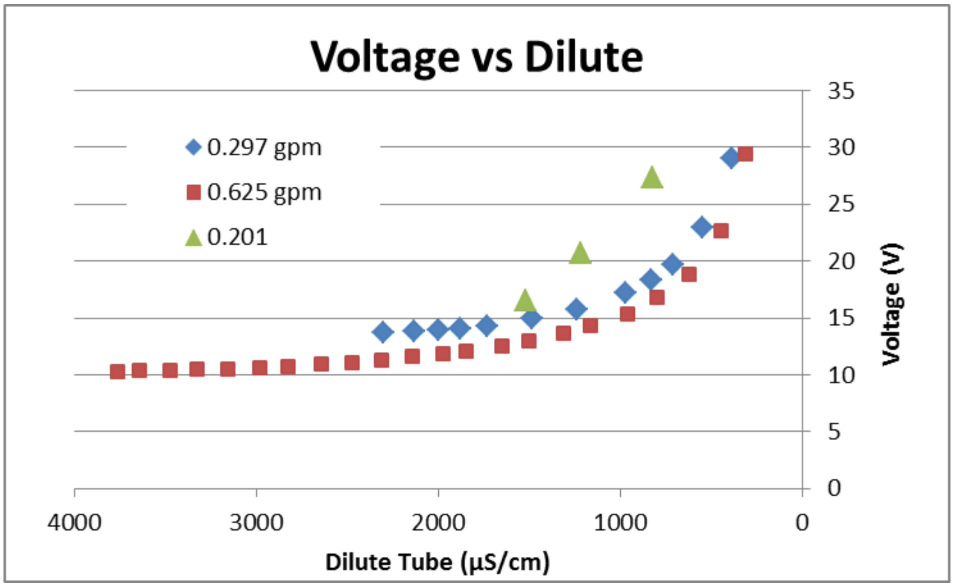


Figure 23. Voltage and dilute (tube) conductivity.

Overall, it was concluded that treatment time of the batch is independent of flow rate as shown in Figure 22. This may be due to that for greater flow rates although there was lower percent removed per pass, there were also more passes per time and the vice-versa for slower flow rates, so the overall treatment of batch would have remained quite similar. Under batch operations, it was shown that more time is needed to treated water with a greater initial conductivity (salt) level.

5.1.4. Hydraulics

5.1.4.1. Design Approach

The general parameters considered in designing the feed-and-bleed hydraulic system include: the feed solution flow rate, pressure, and the efficiency of salt removal. These parameters also dictate the design of the hydraulics of the system. However, the hydraulic system is based on a batch design.

5.1.4.2. Design Requirements

In addition to having a product flow of approximately 100 gpd (gallons/day), it is also important that the ED unit is supplied with an adequate pressure. As suggested by General Electric (Fairfield, Connecticut), there is an expected 20 pounds per square inch (psi) (0.14 megapascals [Mpa]) pressure drop through the ED unit. Along with the flow parameter, the pressure requirement aids in selecting pumps for the system.

The initial design of the pipes and pumps is based on a daily product water output of 100 gpd (400 L/day), expected amount of sunlight, and the ED stack limitations (which include physical flow capacity and efficiency of salt removal). A simple conversion equates the daily product output to 0.0917 gpm (0.347 L/min). However, with only 8 hours of daylight to power the solar energy operation system, the required minimum flow increases by a factor of 3, to 0.275 gpm (1.04 L/min). Because the system will cycle the feed solution multiple times through the ED stack, the actual flow rate of the solution through the ED unit will be greater than 0.275 gpm (1.04 L/min). The average product stream must equate to 0.275 gpm (1.04 L/min), and thus yields the required 100 gpd (400 L/day) of product water. The exact flow rate of the dilute stream through the ED unit itself will need to be determined during the testing phase.

The system also includes flush and concentrate streams with parameters dictated by the hydraulic system design. The required product outflow dictates the necessary hydraulic system, and the hydraulic system dictates how the flush and concentrate streams will work. Flush and concentrate stream specifics were developed through testing. They were based on the effectiveness of the ED unit, and thus based on the specified flow rate of the dilute stream that the ED unit requires.

5.1.4.3. Design Procedures

The selected hydraulic process is a batch system. During this process, downstream flow conductivity is monitored continuously. Dilute stream effluent is measured by a conductivity meter. Conductivity is measured rather than directly measuring TDS concentrations because conductivity can quickly be measured and related to the TDS concentrations. Directly measuring TDS can be a long process, which includes evaporating water from a dish and then directly weighing the amount of solids left behind. With a conductivity measurement, we can indirectly measure TDS by multiplying a ratio factor to our conductivity. EPA recommends a TDS level of 500mg/L for drinking water; however, this is only a secondary standard, and is not enforceable (EPA, n.d.). For this project, it is desirable to fall below this limit. If the dilute stream effluent is not below this 500mg/L limit, it proceeds to recirculation tank, where is pumped back through the ED unit once more.

Once the effluent is measured at the appropriate level, the control system will switch to a “dumping” mode, to pass the entire batch through the ED stack once more and drain to a product tank. We called this a modified batch system. The conductivity testing takes place in line with the product stream effluent—not the recirculation tank. Testing concluded that treating the entire batch to the required TDS level was implausible, if not impossible. This is because the ED stack experiences a voltage spike around 800 to 900 µS/cm conductivity, as testing data shows in our ED methodology section. When trying to treat the entire batch, effluent conductivity levels inevitably fall below these levels, causing the voltage spike. This leads to an overall spike in power consumption. For the sake of efficiency, this power spike is not wanted—and therefore avoided with this type of system.

Because the system needs to be totally enclosed in the provided containment box, we needed to design a system where the entire hydraulic system could be contained and operated in the box. This system consists of a series of valves, conductivity meters, and flow meters which monitor and control the direction of flow. The influent pipes rely on a system that can pull water sources from their respective batch tanks (dilute, concentrate, flush), or from the larger storage feed tank to fill their own respective tanks after those tanks are drained to product or waste. The effluent system is fairly simple: with each ED stack path either flowing to the final storage tanks or back to the initial batch recirculation tanks.

Like other hydraulic systems requiring piping, calculating pressure losses associated with the friction of the pipe (major head losses) is necessary. This critical step determines the proper pump selection using the Darcy-Weisbach head loss equation to calculate system pressure loss due to friction. Knowledge of pressure parameters helps to select adequate pumps to ensure sufficient pressure head as shown in Equation 10.

$$h_f = f\frac{L}{D}\frac{V^2}{2g} \qquad (10)$$

Where:
V is velocity
L is length of pipe
D is diameter of pipe
f is the friction factor

As described by Equation 10, the head losses that the pump will have to overcome are directly related to the size of piping of the system. In selecting the pipe size, normally head loss and velocity criteria are standardized by a governing agency. For this project, pipe sizing was done by choosing a pipe size and calculating the head loss. If it were determined that the pump selected could overcome the head losses, then the pipe sizing was adequate. Specific head loss and velocity criteria were not created. Another pipe sizing factor was simply the relative ease and accessibility of different pipe sizes. After a few calculations with the equation, we found that the head losses through the pipes would not affect the piping choices as much as expected. Instead, the main factor in the frictional losses of the system would simply be the losses associated with the water passing through the stack. As stated before, GE recommended an assumption of roughly 20 psi losses through the stack. Through testing, we found that we averaged around 15 psi losses through the stack.

Pump selection for this system was based on the pressure requirements for the ED stack, the pressure losses from the pipes, and the desired flow rate. Pump selection was further based on the system requirements and retail pump outputs. Pumps were selected using simple comparisons of the requirements and the pumps capabilities listed. Because the system runs on photovoltaic cells, the voltage, amperage, and wattage requirements of the pump played a role in the pump selection. To keep the electrical demands low for the PV cells, we balanced selecting pumps that required the least amount of power with providing adequate water pressures. Once the pump was selected, we tested the pumps to properly calibrate the selected pump, such that the pump outputs the required flow rate.

The preliminary design required four Liquid Flow Meters (Adafruit, New York City, New York), which are mounted in line with the water flow and use a pinwheel sensor to measure the water that flows through the system (Figure 13). Adafruit specifies that this particular flow meter has a ten percent precision, with a flow rate of 0.26 to 7.93 gpm (0.984 to 30.0 L/min), which works perfectly for the required range. The SHURflo pump (PENTAIR/SHUFLO, Costa Mesa, California) has a maximum flow rate of 1.4 gpm (5.3 L/min) and a maximum pressure of 45 psi (0.310 MPa). This pump is ideal for this particular design because it can run dry without damage. The design also incorporates the $^{1}/_{2}$-inch (12.7 mm) OD LLDPE polyethylene tubing (Freshwater Systems, Greenville, South Carolina). According to the manufacturer, this type of tubing is ideal for either cold or intermittent hot water and provides a good resistance to environmental stress cracking. The design also required six valves, which connect to the tubing. Valves incorporated in the experiment were a Plastic Water Solenoid Valve at 12V (Adafruit, New York City, New York). In addition, a minimum pressure requirement of 3 psi (0.02 MPa) must be maintained throughout the valve.

5.2. Photovoltaics (PV)

5.2.1. Design Approach

Solar panel selection depends on the amount of power required in a system, the time the system will be running, and the battery required to regulate power in the system.

5.2.2. Design Requirements

In designing a solar-battery system, the power requirements of the load must be known. Based on preliminary computer modeling, the ED unit consumes a maximum of 80 W at optimal flow rate. The estimated operating voltage of the ED unit is 38 V running at about current 2 A of current. The battery bank mets these power requirements, and the solar charging system exceeded these values to simultaneously charge the batteries and power the load if needed. The electrical hardware had to be capable of stepping up the voltage from 12V to 38V to regulate current in the ED stack. The photovoltaic panels had to be sized appropriately to provide the required power to charge the battery bank and power to operate the electrical load.

5.2.3. Design Procedures

Photovoltaic panels convert sunlight energy into a direct electron flow (i.e., electric power) to power the electrodialysis (ED) unit. A load calculation is also essential in selecting the appropriate battery and panel size. The two parameters in calculating the load are the power of the unit and the amount of time the unit operates. Once this information is gathered, a watt-hour calculation can be done for each electrical component by multiplying the power by the amount of time the system will be running. These values are summed together to determine the total load which the battery and panels are sized from as shown in Equation 11.

$$\begin{gathered} P\ (Watts) = V * I \\ Load\ (Watt\ Hour) = (Watts) * (time\ of\ run) \end{gathered} \tag{11}$$

The ED unit and electronics require a constant input voltage which a solar panel does not provide. A panel’s voltage fluctuates depending on the light conditions, which can disrupt the system. A deep cell rechargeable battery is essential in regulating voltage and powering the system when sunlight is not available. Batteries are sized as a function of voltage and ampere hour as given in Equation 12:

$$Capacity\ of\ Battery = Load/Voltage \tag{12}$$

Once the constant voltage of the system is determined, a battery can be selected by calculating the required capacity. This is computed by dividing the total watt hour by the required voltage of the system. Since batteries are not completely efficient, this value is divided by the estimated or given efficiency of the battery (typically 80% efficiency) as shown in Equation 13:

$$Capacity\ of\ Battery\ (efficiency) = \frac{(Total\ Amphere\ hour)}{(\%\ of\ efficency)} \qquad (13)$$

After the battery is sized, the panels can be selected. Panels are selected by the amount of power required (total W) and the voltage it will be providing to the unit as shown in Equation 14. For example, a 125W power requirement needs a 12V solar panel.

$$Total\ Power\ Output\ of\ Panels\ (Wh) = \ Capacity\ of\ battery\ (Ah) * \ (Battery\ Voltage)$$
(14)

An estimation of how much “effective sunlight” is produced is made to calculate the most efficient size of the panel. Dividing this value by the amount of effective sunlight hours gives the overall power required. A panel can be selected after the voltage and total power required in the system is determined. The more power required, the larger the panel that is needed as shown in Equation 15.

$$Total\ power\ of\ solar\ panel\ size\ (W) = \frac{Total\ Power\ Output\ of\ Panels\ (Wh)}{(estimated\ hours\ of\ sunlight)}$$
(15)

To meet the design requirements, the ED unit requires a battery bank. Deep cell batteries, similar to batteries found in boats and camper trailers, were used for their ability to greatly discharge without damage, unlike lead-acid car batteries. Deep cell batteries typically come in nominal voltages of 12 V and 24 V. To power the various pumps, sensors, and electronics, two additional buck converters are needed. The pumps and flow valves require an operation voltage of 12 V while the control electronics run on 5 V. The battery bank capacity was determined after the exact power requirements of the unit were found through testing. The capacity of the battery was based on the total power drawn from the system and anticipated run time without solar power.

5.3. Automatic Control System

5.3.1. Design Approach

A fully functional, autonomously operated ED-PV unit requires a control system to control the numerous components functioning with the unit. These components need a system to communicate and operate the system efficiently and automatically. Figure 24 shows the initial design of the PV regulator, battery charger and Load controller system.

Each parameter monitored has a specific purpose in making the unit fully functional.

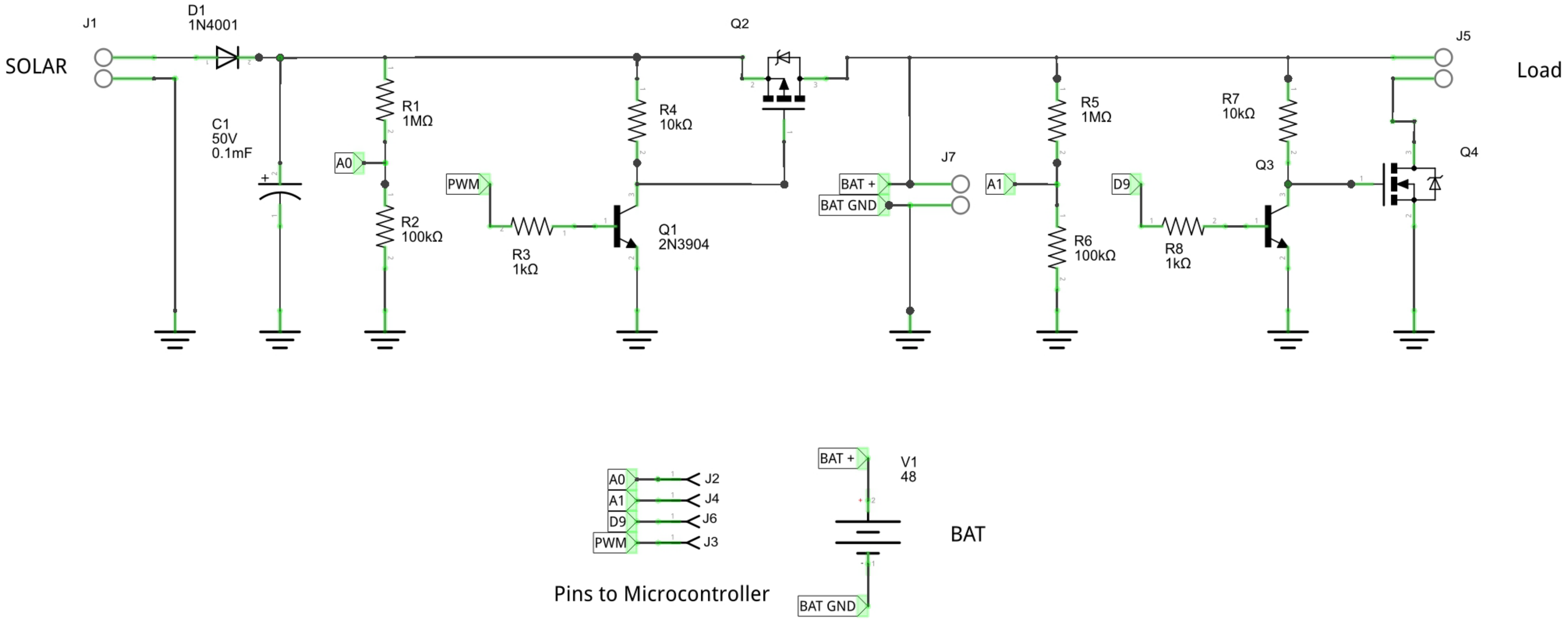


Figure 24. Controller schematic.

The control system measures two types of parameters: displayed measurements and parameters measured to communicate with the system.

The displayed measurements include: the total wattage the system is using, flow rates, and TDS concentrations of the treated water. These measurements will be displayed onto a small liquid crystal display (LCD) screen. These values are key for the initial testing and inspection of the unit's operation and reveal the overall functionality of the unit.

All of the measured and calculated parameters are stored on a secure digital (SD) card. The controller unit logs each parameter onto the SD card with a corresponding time stamp. The data log provides a means of keeping track of the overall performance of the system and aid in troubleshooting. Data logging was handled by an Arduino data logging shield (Adafruit, NYC, New York). For more information on data logging see Section 5.4.6. Coding. The solar panel's voltage and current is monitored to control the amount of power going into the unit or battery. Photo resistors on the sides of the solar panels log outputs so the panels may track the sun efficiently. An installed solar tracker limit switch establishes a starting point for the panels on start up. The batteries voltage and current is monitored and adjusted depending on the charge level and discharging is appropriate. The ED unit and pumps' current load ensures the most efficient system. The input, output, and concentrate flow rates are measured to monitor the efficiency and operation of the pumps. A comparison of the input conductivity with the output conductivity determines the quality of water the unit is producing. The conductivity measurements are converted into levels of TDS. The battery, unit, and water temperature are monitored to prevent overheating and retrieve appropriate data for water quality testing. Water pressure meters are installed and logged to monitor the pipes efficiency and quality. Water level meters are installed into the tanks to measure the amount of water in the tanks. All these parameters are logged onto an SD card and linked to the Atmel microcontroller, which acts as the controller for each parameter. A specific code is developed and programmed onto the Atmel for each parameter to communicate with the system.

5.3.2. Measuring Parameters

Each of these parameters are logged, controlled, and connected to the Arduino circuit board. Each meter and component are wired to the Arduino circuit board and read in one of three different ways. Most of the meters are read as an analog voltage. The code analogRead interprets and reads the measurements in a voltage from 0 to 5 V. Figure 25 shows how current data are converted into an analog signal. The Digital High and Low read the measurements as either "on" or "off." The Interupt mode logs continuous readings in the background and the program calls the data when necessary. The flow meter, a pinwheel meter sending out electrical pulses, is the only parameter measured in "Interrupt mode". The Digital High and Low inputs are connected to the Solar Tracker limit switch and the tank level meter. All other parameters are read as an Analog Read Voltage.

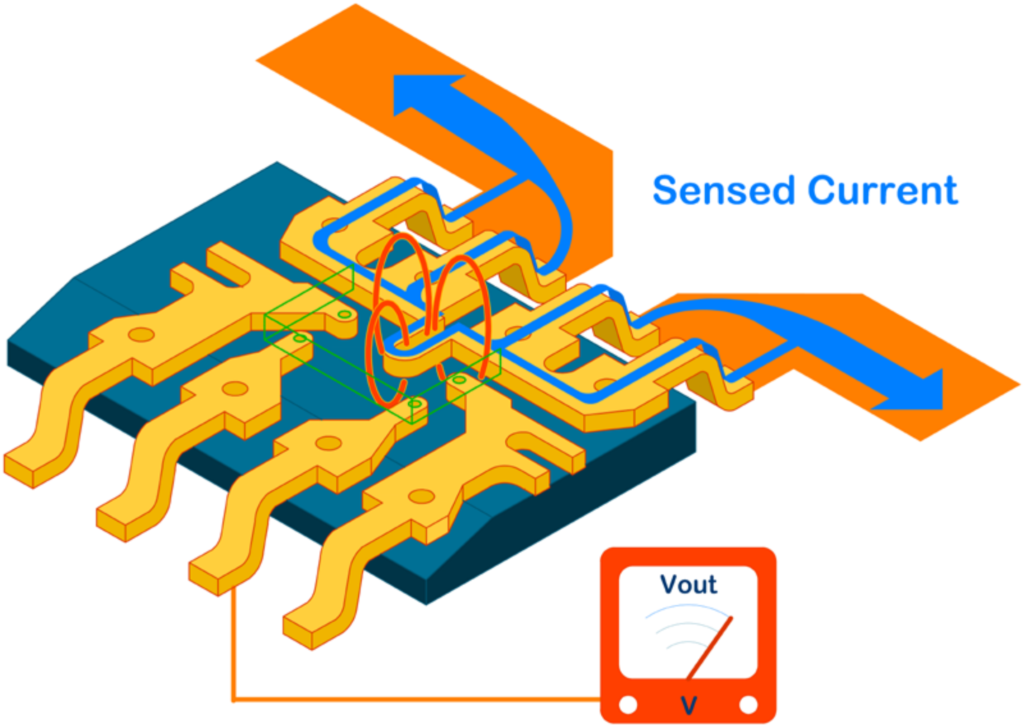


Figure 25 Current sensor.

Each of these sensors and meters need to be calibrated and adjusted within a code to be read in its proper units. Procedures were developed and tested to read each parameter as the PV ED unit development progressed. Extensive coding was developed and programed into the circuit board to read the parameters in their appropriate units.

5.4. Controller

5.4.1. Design Requirements

The overall purpose behind the controller system is to provide an automatic and efficient system to control, monitor, and link the various components required in the system. The controller system runs without user input and at maximum efficiency. The controller system monitors and regulates solar power generation as well as battery charging and discharging. In addition, the controller manages product and concentrate flow, operates valves and pumps, and tests product water parameters such as TDS and conductivity.

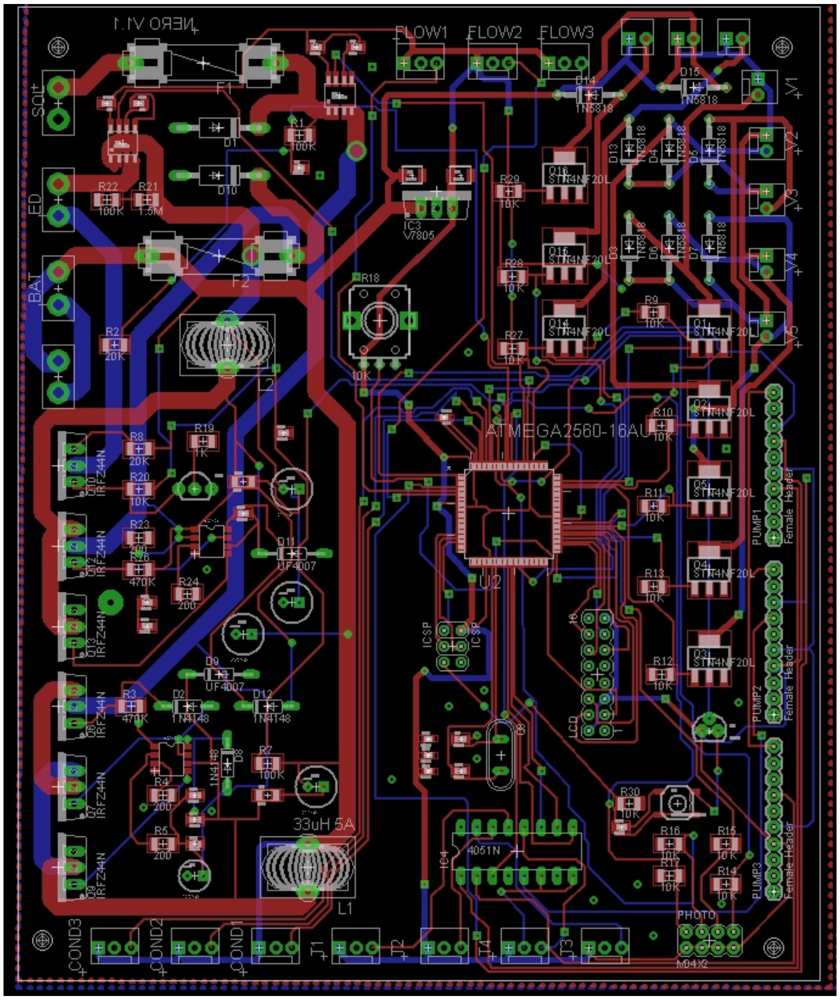


Figure 26 Control Board

5.4.2. Design Description

A microcontroller is used to operate the ED system. The controller board was based around the 8-bit Atmega2560 microcontroller consisting of 54 digital input/outputs and 16 analog inputs. The controller board consists of three man sections: power control, inputs, and outputs.

5.4.3. Power Control

Testing revealed the electrical behavior of the ED unit. While doing tests under constant current, we found that as the water quality increased, the amount of voltage required increased. This is due to the nature of the ions helping the water conduct electricity. As the ions are removed, the water’s resistance increases, requiring the need for more voltage due to Ohm’s Law. To combat this issue, a buck regulator circuit was added to allow the microcontroller to adjust the voltage to the ED unit. A buck regulator is a circuit consisting of two metal–oxide–semiconductor field-effect transistors (MOSFET), a MOSFET driver, an inductor, and a capacitor. The buck regulator allows the voltage to be dynamically changed to keep the current through the ED unit constant. A design change was made at this point to use 12 V batteries and use a voltage step up instead of a 48 V battery bank. This design change reduced the number of batteries and panels required for the ED unit—saving cost and space.

A second buck regulator circuit is used in a different fashion to achieve maximum power point tracking. Since photovoltaic panel energy production depends on the resistance of the attached load, a buck regulator is needed to simulate a load on the solar panel output. This circuit maximizes the power produced by the solar panel. The output of the buck regulator is used to charge the unit's batteries. The batteries are charged in the typical trickle charge method: where the battery receives full current until it is 80% full and then is charged slowly up to 100%.

5.4.4. Inputs

The microcontroller system can monitor several input parameters of the ED system, including: solar current, solar voltage, battery current, battery voltage, ED voltage, ED current, solar tracking photo-resistors, pump current draw, product flowrate, concentrate flowrate, electrode rinse flowrate, product conductivity, concentrate conductivity, and tank levels. These inputs are read with an analog to digital converter (ADC) inside the microcontroller. The ADC converts the analog voltage ranging from zero to five volts to a 10-bit digital signal. The input data are processed and used to make decisions on how to alter the systems parameters such as salt removal, and flowrate.

5.4.5. Outputs

The microcontroller's outputs are used to control parameters of the ED system as well as to display information. The controlled outputs are used for pump control, valve control, ED stack voltage and current control, and LCD display control. The pumps are controlled by a constant current motor driver integrated circuit. By varying the pulse width modulation (PWM) frequency, each of the pump flow rates can be independently altered. The voltage to the ED stack is controlled by the frequency of the PWM output to the MOSFET driver integrated circuit, which controls the buck regulator. Battery charging is controlled in a similar way using a separate buck regulator circuit.

5.4.6. Coding

The final code for the ED system is shown in Appendix C. The code is broken into void modules: each module has a specific task. The main void modules are: battery charging, solar tracking, read data, write data, stack control, and flow control. When each void module is called, it performs a specific function, for example, the Read data void function cycles through all of the analog and digital inputs and updates the appropriate variable associated with each input. These data are then stored for use by the other modules in the code.

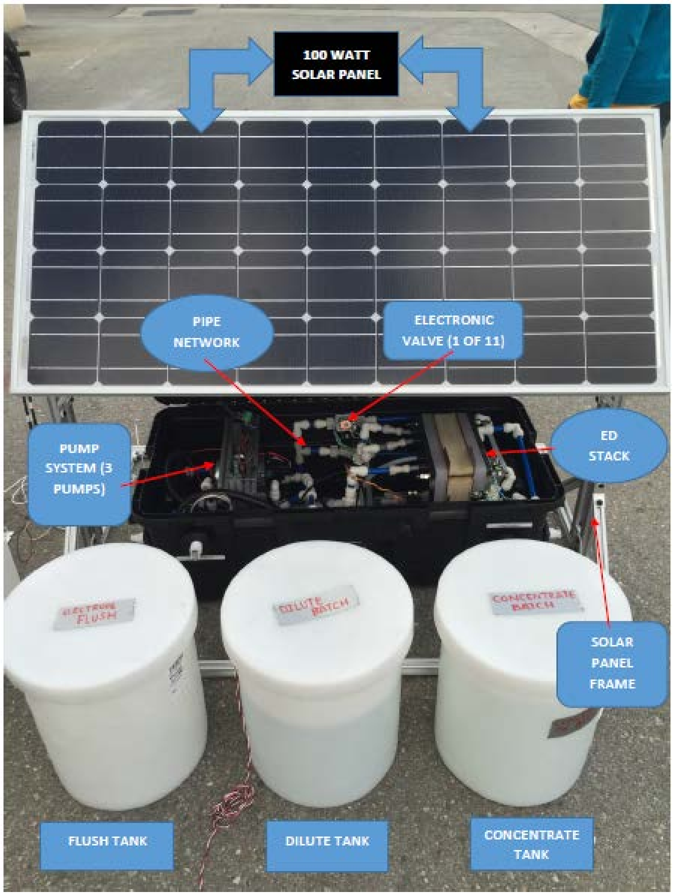


Figure 27. System components.

5.5. System Components

Figure 27 defines the various components of the system. Items not included in Figure 27 are:

- Fabricated circuit board
- 2 inline conductivity meters
- 2 flow meters
- Product tank
- Feed tank
- Tank sensors
- Solar tracker motor
- Solar tracker gear mount
- MPPT solar charger
- Solar battery

6. Testing at Brackish Groundwater National Desalination Research Facility

6.1. Unit Testing (July 1, 2015 – September 10, 2015)

The PV ED system was transported from Cal Poly Pomona, Pomona, California to BGNDRF in Alamogordo, New Mexico. The unit was tested with brackish groundwater from an underlying aquifer through three different wells within the facilities grounds. The brackish groundwater ranged in quality from 1,500 to 6,000 µS/cm. During July 1, 2015 through September 10, 2015, the unit was tested with Well #1 and Well #2 water, containing a water quality of 1,500 to 4,000 µS/cm. BGNDRF well data can is in Appendix D: BGNDRF Groundwater Data.

We tested the unit in four phases:

- Phase 1: Water Quality Variation
- Phase 2: ED Stack Voltage Variation
- Phase 3: Pump Flow Variation
- Phase 4: Percent Recovery

In the first three phases, the unit production rate, overall average power into the unit, and salt recovery percentage were recorded and analyzed. The unit operated in batch mode during each testing phase, producing product water with a quality ranging from 400 to 1,000 µS/cm and a concentrate waste ranging from 8,000 to10,000 µS/cm.

Figure 28 through Figure 30 show components of the ED unit.

Figure 28: System set up in BGRNDRF bay area.

Figure 29. Feed tank, product tank, waste tank.

Figure 30. Batch tanks: dilute, concentrate, electrode flush.

Along with testing the unit and solar panels (Figure 31), the solar tracking system was completed and operational during testing, increasing the unit's efficiency. The tracking motor was powered from its own 12 V battery throughout unit operation (Figure 32).

Figure 31. Solar panel and frame.

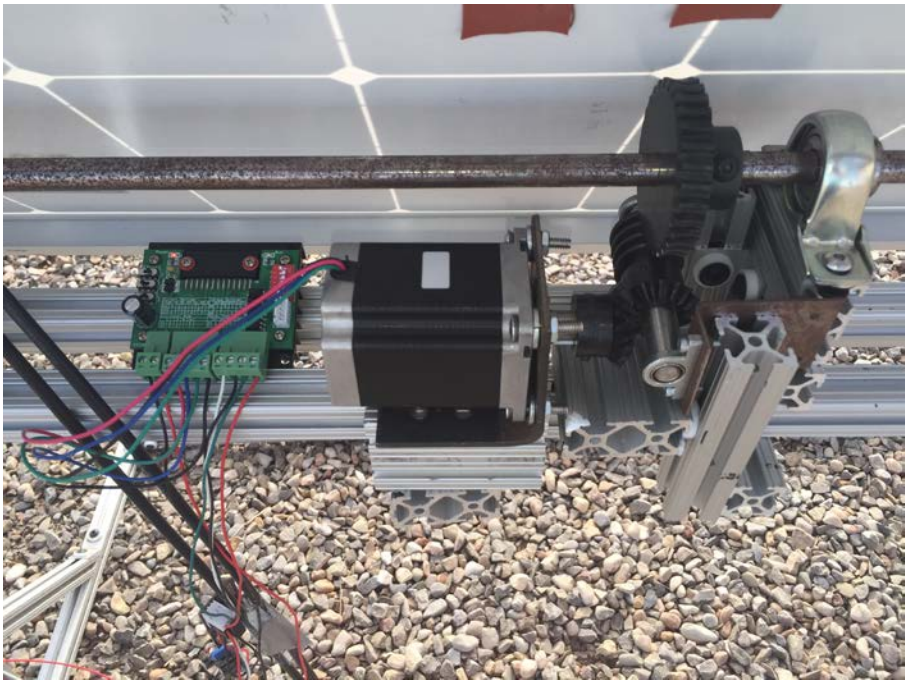


Figure 32. Solar tracking motor.

6.2. Unit System Troubleshooting

The system experienced minor operational flaws during initial testing. A flow and suction issue occurred in the unit's piping system, resulting in the mixture of the flush and concentrate lines. This issue caused the dilution of the concentrate batch during testing, which may have slightly skewed the data.

As an ED system operates in batch mode, each flow line must be independent from one to optimize the system's performance. However, the pilot system experienced scenarios in which the concentrate tank volume increased as the flush tank decreased or vice versa. This issue suggests that the flow line from the concentrate flow and the electrode flush flow were mixing within the hydraulics system. Another indication was speculated that the flow lines were mixing within the stack. The flush flow path travels through the ends and middle of the stack as described in the Methodology section of the report. The flow path stacked next to the flush is the concentrate. Therefore, any corrosion or tears in the nylon flow spacers between the membranes may have caused a mixture of the flow lines. As the unit operates in batch, the concentrate flow line begins to gain concentration of salt over time.

The electrode flush flow line's purpose is to prevent the electrode metal plates from being scaled. No ions should enter the electrode flush line; therefore, the flow path should remain at the initial salinity levels and not fluctuate over time. As the electrode flush flow path enters the concentrate flow path, the concentrate salinity levels become diluted from the electrode flush flow. This provides an extended, inaccurate testing of the time it takes to waste the concentrate batch. Also, as the concentrate tank is diluted, the dilute flow line may lose ions at a more rapid rate. These flaws were identified while the system was under testing and proper troubleshooting was performed on the hydraulics of the system.

6.3. Unit Testing Procedure

During each Phase 1, Phase 2, and Phase 3 of testing the production rate, product volume, energy intake, salt removal percentage, operation time, dilute line conductivity, concentrate line conductivity, and flush line conductivity were recorded during each batch. One batch refers to a period of time which the ED unit brings initial quality below 1,000 µS/cm, dumps the dilute tank water into the product tank, and refills the dilute tank from the feed water line for the next batch.

Every 5 to 10 minutes during system batch operation, the overall unit energy, stack energy, flowrate, dilute line conductivity, flush line conductivity, and Concentrate line conductivity were recorded for analysis. After the completing a batch, the product volume, product conductivity, concentrate conductivity, total time of batch, and entering feed water conductivity were recorded for analysis. The first batch data of each day of testing was labeled as the “ripening batch.” During the initial operation of the unit each day, the water quality and energy were not behaving consistently with the remaining batches. Therefore, all initial batch data points were removed from the graphical analysis.

An average of the overall unit energy and stack energy consumption was calculated and recorded. The salt removal percentage for each batch was recorded for analysis. Solar panel operations were monitored by weather recordings every 5-10 minutes described as sunny, partly cloudy (PART CL), and cloudy.

6.3.1. Phase 1: Water Quality Variation

The water quality test was performed to analyze the efficiency of the PVED system operating at various water qualities.

During Phase 1 of testing, the system operated at a constant stack voltage intake and flowrate throughout the week. Water from Well 1 and Well 3 was used for water quality variation testing. BGNDRF well data can be viewed in Appendix D: BGNDRF Groundwater Data. Each day, a different feed water quality was introduced into the system, ranging from 2,000 to 4,000 µS/cm. Each batch produced product water ranged from 500 to 1,000 µS/cm.

Water quality variation testing lasted two weeks (July 6, 2015 to July 17, 2015). The first week, the stack was introduced to 12 V. The dilute, concentrate, and flush flow lines operated at 30 milliliters per second (mL/s). Three water qualities (1,500 µS/cm, 2,000 µS/cm, and 3,000 µS/cm) were introduced into the system and treated to a quality below 1,000 µS/cm. The second week, the stack’s voltage was doubled at 24 V. The dilute, concentrate, and flush flow lines continued to operate at 30 mL/s. However, the initial qualities introduced into the system were lower quality (higher conductivity) at 1,200 µS/cm, 2,600 µS/cm, 3,000 µS/cm, and 4000 µS/cm and treated to a quality below 1,000 µS/cm (Table 11).

Table 11. Phase 1. Water Quality Variation Results

Week 1 (July 6, 2015 – July 10, 2015):

Constant System Parameters	Values	Varying System Parameters	Values
Stack Voltage	10-12 V	Initial Feed Water Quality	1,500 µS/cm 2,000 µS/cm 3,000 µS/cm
Flow Rates	30 mL/s		
Product Water Quality	<1000 µS/cm		

Week 2 (July 13, 2015 – July 17, 2015):

Constant System Parameters	Values	Varying System Parameters	Values
Stack Voltage	24 V	Initial Feed Water Quality	1,200 µS/cm 2,600 µS/cm 3,000 µS/cm 4,000 µS/cm
Flow Rates	30 mL/s		
Product Water Quality	<1000 µS/cm		

The data acquired from Phase 1 testing suggests that the PVED system operates more efficiently with a lower salinity concentration in the feedwater. As the system operates in batch mode, the dilute flow line requires more passes through the ED stack at higher concentrations of initial feed water. The higher the conductivity in the initial feed introduced to the system, the longer the batch will last to produce water at a quality below 1,000 µS/cm. Therefore, the higher concentrations of salinity in the feed water require more overall energy (watts per hour [W-hr]) introduced into the system. Graphical representations describing the relationship of initial feed quality versus the time required for a batch production is provided. Each point represents the time it took a single batch to produce a volume of product water at a quality under 1,000 µS/cm, starting at an initial feed conductivity. The x-axis represents time (minutes) and the y-axis represents the initial water quality (µS/cm). The positive slope in Phase 1 graphs describes the characteristics of the ED unit operation at different initial feed qualities (Figure 33 and Figure 34). The points gradually increase in conductivity over time. This relationship describes the efficiency of the ED-PV unit under different initial feed qualities.

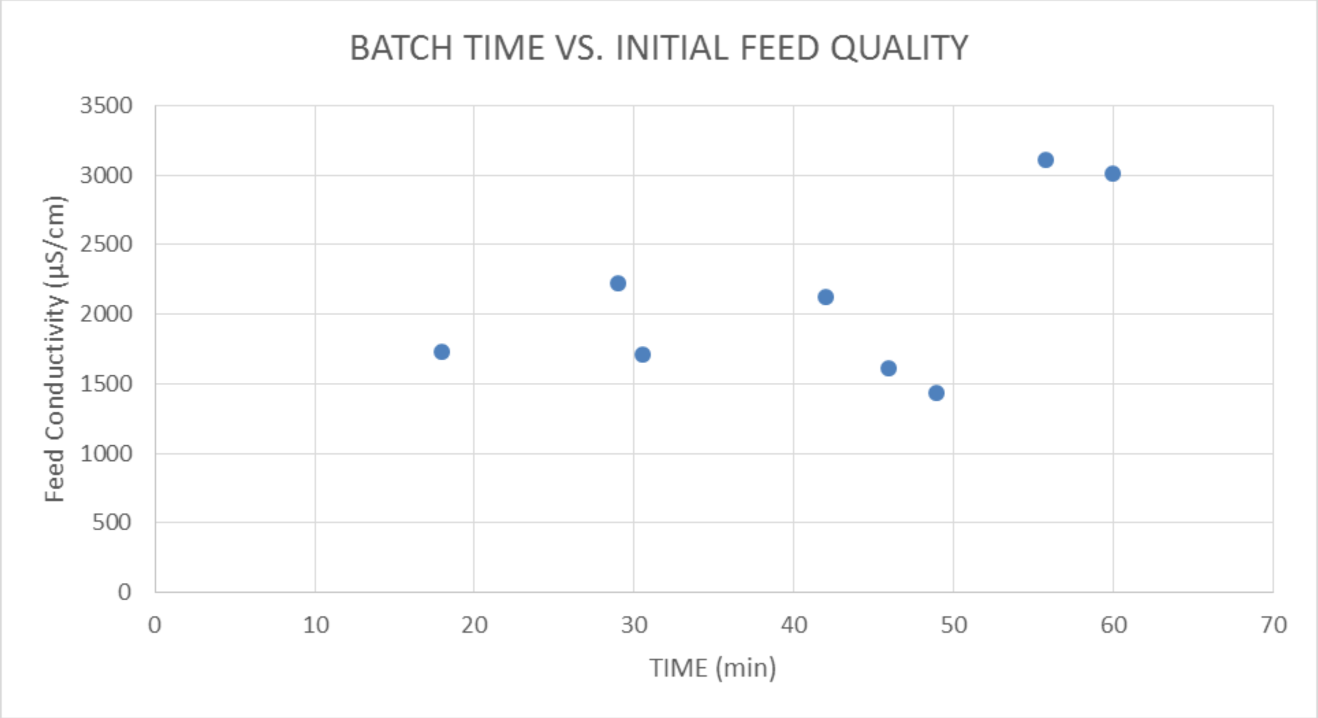


Figure 33. Week 1: Feed water quality versus initial feed quality.

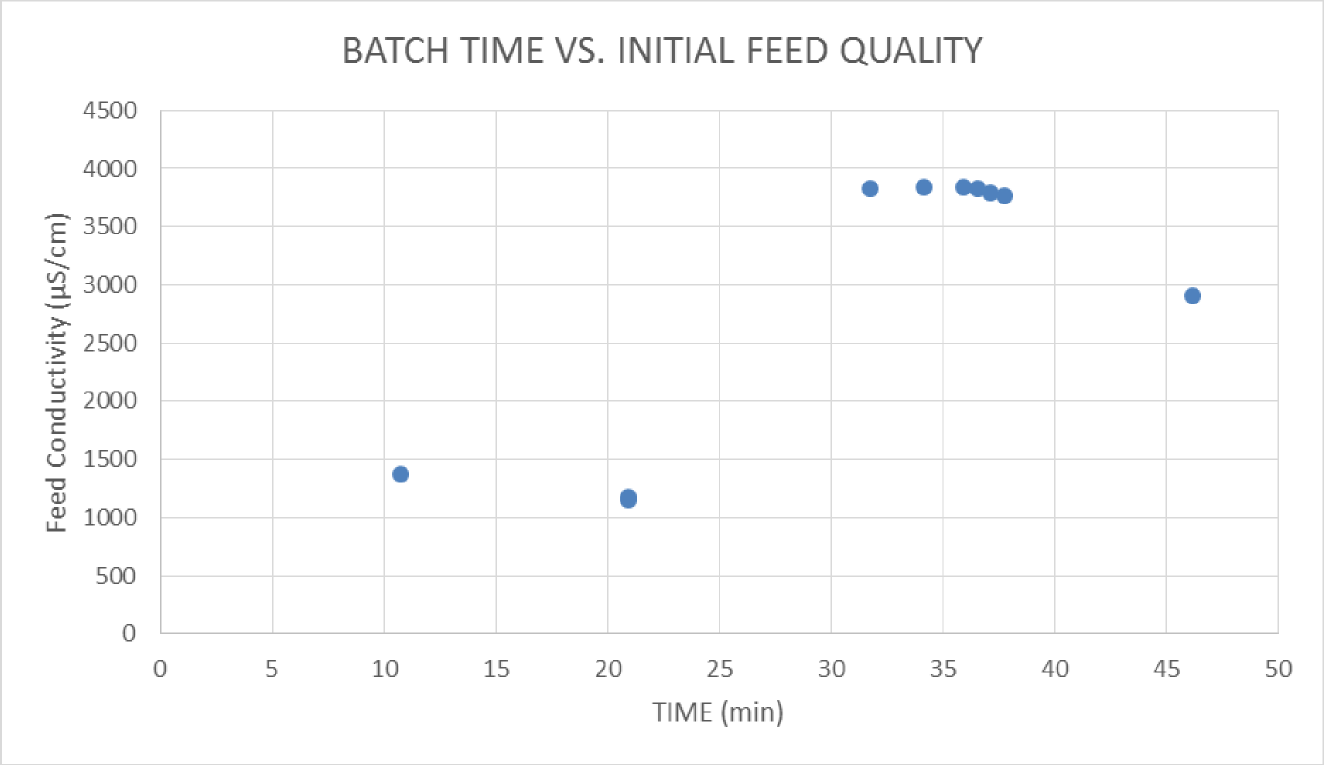


Figure 34: Week 2: Feed water quality versus initial feed quality.

6.3.2. Phase 2: ED Stack Voltage Variation

To analyze the energy dynamics of a ED-PV system, we conducted the Stack Variation test in Phase 2 by providing various levels of energy into the ED stack.

The test was conducted in batch mode over two weeks (July 27, 2015 to July 31, 2015). During week 3, stack variation testing, the initial feed water quality remained at a constant average of 3,000 µS/cm. Well 3 groundwater was used during Phase 2 testing with a conductivity ranging from 2,500 to 4,000 µS/cm. Phase 2, week 4, stack variation testing, a 30% Well 3 to 70% Well 1 mixture was introduced as the feed water into the system. This mixture produced a conductivity from 1,500 µS/cm to 2,500 µS/cm. BGNDRF Well 3 and Well 1 data may be viewed in Appendix D: BGNDRF Groundwater Data. The three different flow rates remained constant each at 25 mL/s. All product water produced was treated to a conductivity below 1,000 µS/cm. The voltage into the stack was controlled by a manual voltage step up and a buck converter, with voltage into the ED stack varying from 12 to 30 V.

The initial testing (July 27, 2015 to July 31, 2015) of Phase 2 consisted of putting 12 V, 17 V, and 24 V into the ED tack and analyzing the unit at the three different energy levels. We found that as dilute water passes through the stack, salt ions are removed—resulting in lower conductivity. As the salinity concentration levels lower, the current drawn into the stack lowers over time. Therefore, the final week of Phase 2 testing (August 3, 2015 – August 7, 2015), the voltage into the stack was increased during each batch starting from 12 V and ending at 30 V. As the voltage increased over a batch cycle, the current remained relatively higher which provided a higher overall average ED stack energy consumption (Table 12).

Table 12. Phase 2. ED Stack Voltage Results

Week 3 (July 27, 2015 to July 31, 2015):

Constant System Parameters	Values	Varying System Parameters	Values
Initial Feed Water Quality	3000 µS/cm (average)	Stack Voltage	12V to 30V per batch
Flow Rates	25 mL/s		
Product Water Quality	<1000 µS/cm		

Week 4 (August 3, 2015 to August 7, 2015):

Constant System Parameters	Values	Varying System Parameters	Values
Initial Feed Water Quality (Well 1 and Well 3 mix)	2000 µS/cm (average)	Stack Voltage	12 V 17 V 24 V
Flow Rates	25 mL/s		
Product Water Quality	<1000 µS/cm		

As more voltage is introduced into the ED stack, more current flows through the stack during the batch operation. Therefore, more salt ions are being removed from the dilute stream. Phase 2 testing suggested that the more voltage is provided into the stack, the less amount of time is needed for a batch completion.

Figure 35 and Figure 36 illustrate the relationship of voltage into the stack versus the time required for a batch production. This relationship describes the dynamics of power consumption within the overall system. The x-axis represents time (minutes) and the y-axis represents the initial water quality (average ED stack energy). As expected, the points are presented in a negative orientation. As the average ED stack wattage decreases, the more time it takes the unit to produce a batch. This relationship proves when the ED stack is introduced to a higher voltage, it provides a more efficient batch operation.

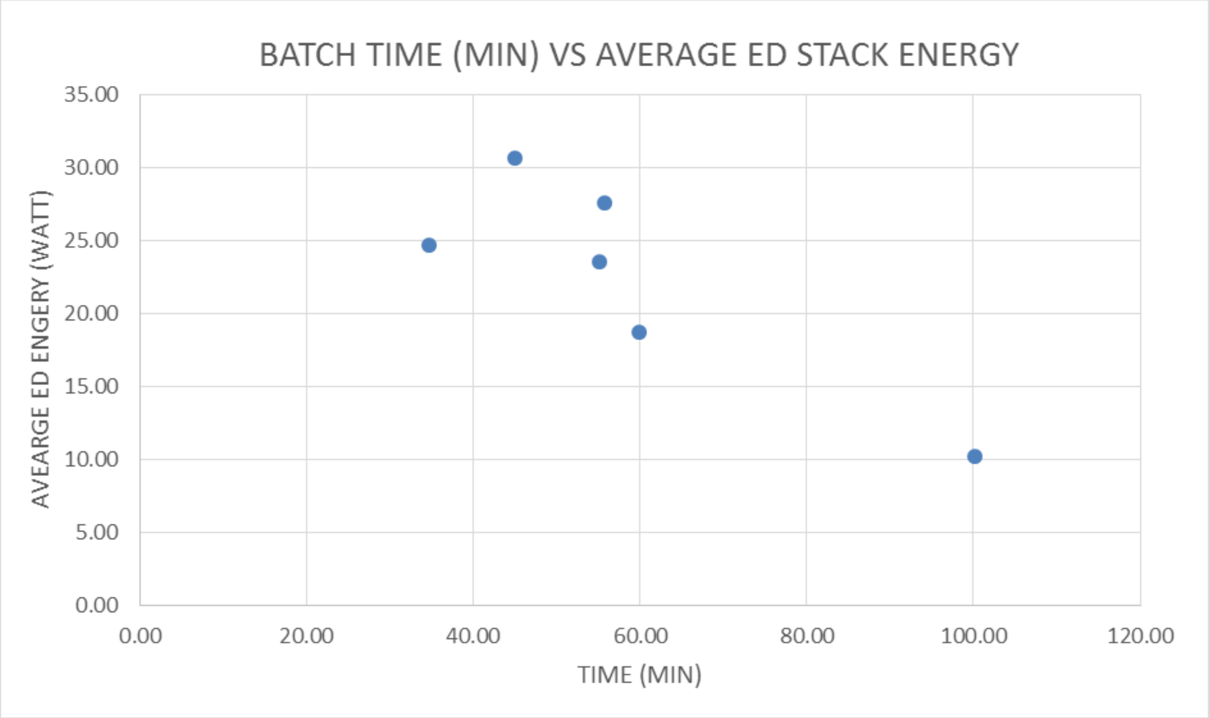


Figure 35: Week 4: Time vs. ED stack energy.

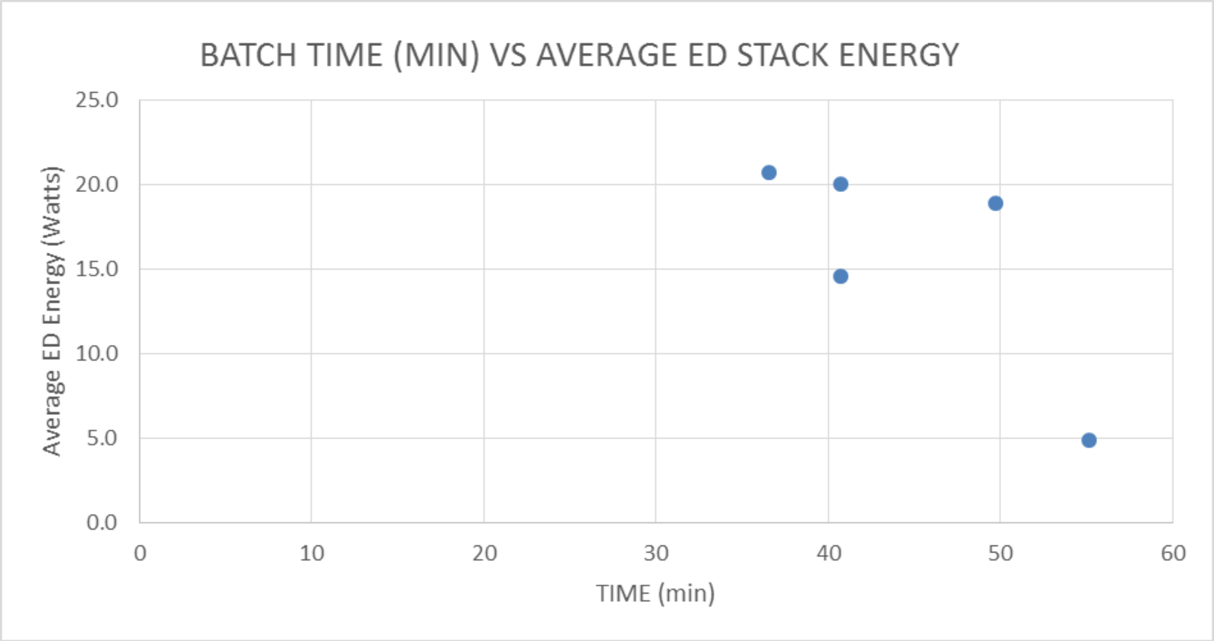


Figure 36: Week 5: Time vs. ED stack energy.

6.3.3. Phase 3: Pump Flow Variation

Phase 3 testing consisted of the system operation at various flow rates.

The testing lasted two weeks (August 10, 2015 to August 21, 2015). The unit operated in batch mode with flow rates ranging from 11 to 35 mL/s. The dilute pump, concentrate pump, and flush pump ran at the same flow rate throughout each test. The Phase 3 initial feed water quality introduced averaged 3,000 µS/cm during week 5 (August 10, 2015 to August 14, 2015) and 2,500 µS/cm during week 6 (August 17, 2015 to August 21, 2015). The stack operated at 24 V and provided a product water quality of 1,000 µS/cm.

The initial testing (August 10, 2015 to August 14, 2015) of Phase 3 consisted of observing the system flow operation at 17 mL/s, 21 mL/s, and 25 mL/s. The unit operated at a flow of 11 mL/s, 16 mL/s, 26 mL/s, and 30 mL/s during Phase 3, week 6 testing (Table 13).

Table 13. Phase 3. Pump Flow Variation Results

Week 5 (August 10, 2015 August 14, 2015):

Constant System Parameters	**Values**	**Varying System Parameters**	**Values**
Initial Feed Water Quality	3,000 µS/cm (average)	Flow Rates	17 mL/s 21 mL/s 25 mL/s
Stack Voltage	24 V		
Product Water Quality	<1,000 µS/cm		

Week 6 (August 17, 2015 – August 21, 2015):

Constant System Parameters	Values	Varying System Parameters	Values
Initial Feed Water Quality	,2500 µS/cm (average)	Flow Rates	11 mL/s 16 mL/s 26 mL/s 30 mL/s
Stack Voltage	24 V		
Product Water Quality	<1,000 µS/cm		

Phase 3 testing was conducted to analyze the system's operation and efficiency at various flow rates. Theoretically, as the flow increases through the stack, the less amount of time it should take for a batch to finish. However, originally the ED-PV system did not operate as expected. The preliminary rough data were scattered and no conclusion could be made.

Further detailed tests were conducted under the same described testing conditions with a constant 2,000 µS/cm of feed conductivity at Cal Poly Pomona to compare the amount of energy required to complete a batch. Overall, the faster the flowrate, the less energy was required to produce the same volume of water. A table of various flow rate values along with the average energy used by the system was compiled and used to distinguish the change in the systems energy usage within each flow rate (Table 14).

We compiled table of various flow rate values along with the average energy used by the system to distinguish the change in the systems energy usage within each flow rate. Through each flow rate, it was evident that as flow rate increased, the amount of energy needed per volume of water decreased. The amount of product water produced within each flow rate stayed constant at approximately 10 L; however, energy per volume of water witnessed a decrease at higher flow rates.

A flow vs. energy graph was plotted encompassing the change in flow rate and amount of energy needed to desalinate the initial feed water (Figure 37). Results depicted what appears to be a linear decrease in energy as the flow rate through the ED-PV system was increased.

Table 14. Energy Consumption Per Unit of Water in Various Flow Rates

Flow (mL/s)	Avg. Watts (W)	Avg. Product Water (L)	Avg. Batch Time (hr)	Average Product Water (Gallons)	Energy Per Volume of Water (Kwh)/(Gal)	Energy Per Volume of Water (W-hr/Gal)	Energy Per Volume of Water (kwh/m^3)
10	15.71	10	0.81	2.64	4.79E-03	4.79	1.26
13	19.04	10	0.69	2.64	4.96E-03	4.96	1.31
16	19.63	10	0.67	2.64	4.95E-03	4.95	1.31
21	18.33	10	0.58	2.64	3.99E-03	3.99	1.05
24	15.26	10	0.70	2.64	4.07E-03	4.07	1.07

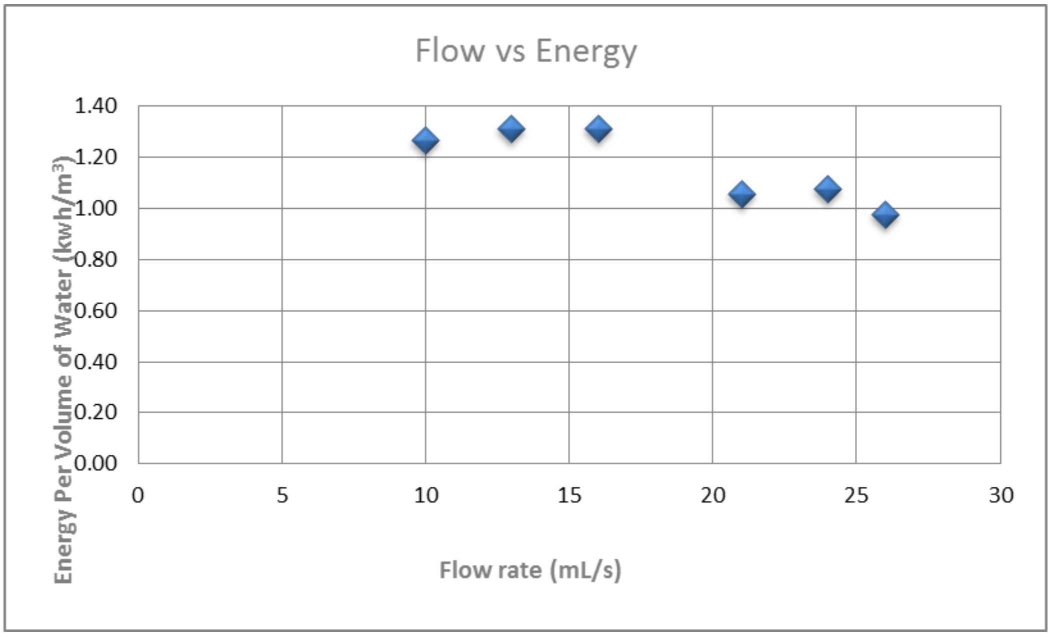


Figure 37. Energy per volume of produced water in different flowrates.

6.3.4. Phase 4: Percent Recovery

The next phase tested for the overall percent recovery of the ED-PV unit.

The percent recovery of product water versus concentrate and flush waste (brine) was recorded throughout an 8 to 12-hour day of testing. The unit's total percent recovery was tested at two different water qualities: 2,310 µS/cm (Well #1) and 3,250 µS/cm (70% of Well 1 and 30% of Well 3 mix). These water qualities were selected for testing the overall unit's percent recovery because they are in the average range of water quality that this specific unit is designed to treat.

Each test began with 170 liters (L) of feed water at the quality discussed. The unit operated with a constant flow of 25 mL/s and ED stack voltage of 24 V. Each amount of product, concentrate, and flush volume dumped was recorded. The initial feed water quality was reduced to below 1,000 µS/cm, and the concentrate tank was dumped when it reached a conductivity above 8,000 µS/cm. The electrode flush tank waste was dumped after 10 product batches (about 100 L).

In system batch operations, the percent recovery depends on the initial feed water quality. Testing the unit at 2,310 µS/cm resulted in 13 product batches (about 130 L) and 4 waste batches (about 40 L concentrate and flush). These volumes produced a 76% recovery in about 12 hours. The 3,250 µS/cm batch resulted in a 61% recovery with 10 product batches (about 100 L) and 5 waste batches (about 50 L concentrate and flush) in 15 hours (Table 15).

Table 15. Phase 4. Percent Recovery Results

Week 7 (August 24, 2015 – August 28, 2015):

Constant System Parameters	Values	Percent Recovery
Initial Feed Water Quality	2,310 µS/cm	75%
Stack Voltage	24 V	
Product Water Quality	<1,000 µS/cm	
Dump Water Quality	>8,000 µS/cm	

Week 8 (August 31, 2015 – September 4, 2015):

Constant System Parameters	Values	Percent Recovery
Initial Feed Water Quality	3,250 µS/cm	65%
Stack Voltage	24 V	
Product Water Quality	<1,000 µS/cm	
Dump Water Quality	>8,000 µS/cm	

The data recorded suggests that the system produces a higher amount of product volume with lower initial feed water qualities (Figure 38). As the dilute flow passes through the ED stack multiple times, the concentrate flow becomes heavily concentrated. With a high initial feed water salt concentration, the concentrate tank becomes rapidly concentrated, requiring higher waste volumes. The feed water qualities should not exceed 4,000 µS/cm in this ED-PV system.

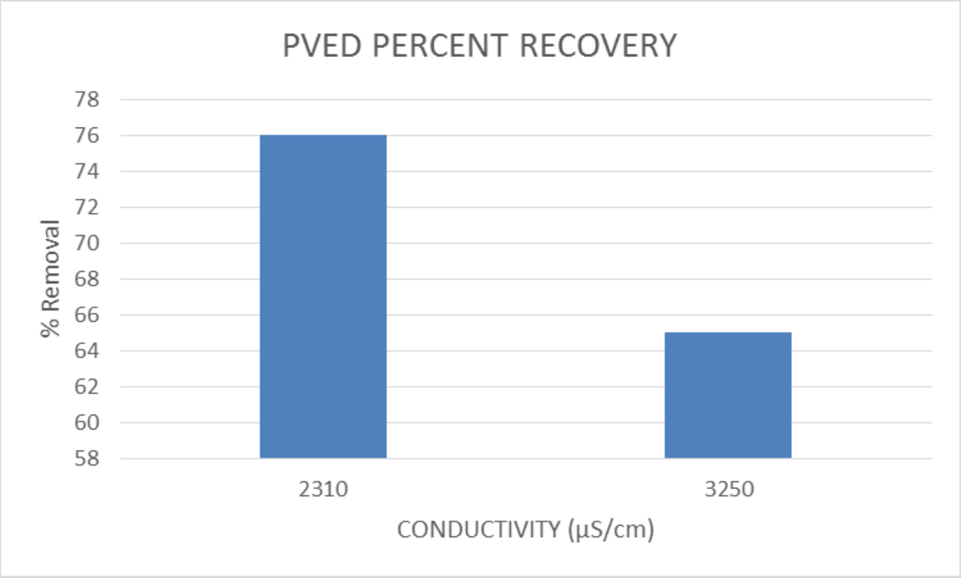


Figure 38. Percent recovery at two feed water qualities.

7. Significant Findings and Accomplishments

7.1. Project Dissemination

Thirteen Civil Engineering students have worked on this project and eleven have already graduated, spending the 2014-2015 academic year working on this project as their senior project. Many presentations have been made in different technical local and national settings. Conferences attended thus far include:

- The 22nd Annual Southern California Conference for Undergraduate Research (SCCUR)
- The 2015 Asian American Engineer of the Year (AAEOY) Event: STEM Presentation and Poster Competition
- The 3rd Annual Cal Poly Pomona Student Research Conference (*Winner of the best engineering personation award*)
- The 2015 WaterReuse California Annual Conference (*Winner of the Best Paper Award*)
- The 8th Metropolitan Water District's Annual Eco Innovators Showcase
- The 29th Annual California State University Student Research Competition
- The 2015 Environmental & Water Resources Institute (EWRI) World Environmental and Water Resources Congress (Parsons Brinkerhoff Student Competition) (*Second place in the nation*)
- The 2016 American Water Works Association (AWWA)/AMTA Membrane Technology Conference.

7.2. Patent

Throughout the process of developing the ED-PV unit, patenting opportunities of the systems is being investigated. There are similar existing patents to the unit design:

- The Department of the Interior has a patent US6042701 A. Although this unit uses an electrodialysis reversal (EDR), the solar powered system is similar to the current unit design. Their solar powered system is programmed to operate continuously for 24 hours unattended by using a circuit board control. The circuit board controls the entire system, such as reversing functions, fail safe-modes, and electrode flushing functions. This patent, though, has expired in 2004 due to failure to pay maintenance fees. Therefore, it is a possibility that the automated controller system for the design can be patented based on this patent.

- 中国海洋大学 (China Ocean University has a patent CN103193304 A, which uses PV to power an ED unit to treat brackish and seawater. Any excess energy from the PV cells are stored into a battery. The patent is not official as of August 2013 and is under a “Request of Examination as to Substance” review.

There are a number of patents for sole PV and ED technologies; however, dynamic flow control based on the availability of solar power on an ED-PV technology has not been filed by other inventors. The two patents mentioned above are perhaps the closest to what will be patented as a result of this work. A provisional patent application has been submitted and the full patent application was submitted in summer 2016. The focus of this invention is the controllers and electrical components of the system. The Cal Poly Pomona, the Office of Technology Transfer is leading this effort.

8. Future Work

Although the project is officially concluded, Cal Poly Pomona team is still working on improving the process and looking into potential options for further dissemination of the results and commercialization of the process as a marketable product. Cal Poly Pomona team will follow up with activities, including:

- Improving and modifying the system components, housing unit, flow piping system, code, and system automation

- Piloting the process in a remote rural area where long-term data collection is feasible to demonstrate the robustness of the system

- Looking for other sources of funding to further advance the process and improve methods for concentrate minimization

- Installing the decentralized ED-PV units in a disadvantaged community (DAC) in California

- Commercializing the unit and finding potential investors.

9. Updated Timeline

The development of an automated ED-PV unit is separated into a preliminary design phase, phase I, phase II, and phase III. Phase I consists of the final design, construction, and testing of a working ED unit. Phase II consists of sizing PV panels and incorporating a semi-automation system into the unit. Phase III includes calibration of the unit to a fully-automated system as well as refining the unit for maximum efficiency. Data analysis and report development was performed after completion of Phase III. The table below describes critical tasks and timeline. Each task corresponds to a task identification number that can be referred to in Table 16.

Table 16. Critical Task Deadlines

Task ID	Task Name	Duration	Start	Finish	Predecessors
1	Team Organization and Divisions	8 days	Mon 8/4/14	Wed 8/13/14	
2	Initial Research	34 days	Thu 8/14/14	Tue 9/30/14	1
3	Preliminary Design	50 days	Wed 10/1/14	Tue 12/9/14	2
4	Draft Quarterly Report 1			Thu 11/27/14	
5	Final Quarterly Report 1			Mon 12/8/14	4
6	Phase I: Final Design	15 days	Wed 12/10/14	Tue 12/30/14	3
7	Phase I: Construction	15 days	Wed 12/31/14	Tue 1/20/15	6
8	Phase I: Testing	15 days	Wed 1/21/15	Tue 2/10/15	7
9	Phase II: Semi-Automation	25 days	Fri 2/27/15	Thu 4/2/15	8
10	Phase II: Testing	10 days	Thu 4/2/15	Wed 4/15/15	9
11	Phase III: Calibration for Full-Automation	15 days	Wed 4/15/15	Tue 5/5/15	10
12	Phase III: Testing and Troubleshooting	16 days	Wed 5/6/15	Wed 5/27/15	11
13	Draft Quarterly Report 2			Wed 3/25/15	
14	Final Quarterly Report 2			Tue 3/31/15	13
15	Final Quarterly Report 3			Fri 6/5/15	12
16	Preparation for BGNDRF	20 days	Thu 5/28/15	Wed 6/24/15	12
17	Testing at BGNDRF	67 days	Mon 7/1/2015	Mon 09/7/2015	1
18	Data Analysis	77 days		Fri 10/23/15	1
19	Final Quarterly Report 4			Fri 10/30/15	1
20	Final Report to Reclamation			Sun 4/21/2016	

10. Reference List

Al Suleimani, Z. and Nair, V. R. (2000). Desalination by Solar-Powered Reverse Osmosis in a Remote Area of the Sultanate of Oman. Applied Energy, 65(1-4), 367–380. doi:10.1016/S0306-2619(99)00100-2

Al-Karaghouli, A. A., and Kazmerski, L. L. (2011). Renewable Energy Opportunities in Water Desalination. In M. Schorr (Ed.), Desalination, Trends and Technologies (p. 334). Rijeka, Croatia: Tech. http://cdn.intechopen.com/pdfs/13758/InTech-Renewable_energy_opportunities_in_water_desalination.pdf.

Al-Karaghouli, A., Renne, D., and Kazmerski, L. L. (2010). Technical and Economic Assessment of Photovoltaic-Driven Desalination Systems. Renewable Energy, 35(2), 323–328. doi:10.1016/j.renene.2009.05.018.

Ali, M. T., Fath, H. E. S., and Armstrong, P. R. (2011). A Comprehensive Techno-Economical Review of Indirect Solar Desalination. Renewable and Sustainable Energy Reviews, 15(8), 4187–4199. doi:10.1016/j.rser.2011.05.012.

AlMadani, H. M. N. (2003). Water Desalination by Solar Powered Electrodialysis Process. Renewable Energy, 28(12), 1915–1924. doi:10.1016/S0960-1481(03)00014-4.

Bilton, Amy M., Wiesman, R., Arif, A.F.M., Zubair, S.M. and Dubowsky, S., (2011). On the Feasibility of Community-Scale Photovoltaic-Powered Reverse Osmosis Desalination Systems for Remote Locations. Renewable Energy, 36, (12) 3246-3256. https://EconPapers.repec.org/RePEc:eee:renene:v:36:y:2011:i:12:p:3246-3256.

Charcosset, C. (2009). A Review of Membrane Processes and Renewable Energies for Desalination. Desalination, 245(1-3), 214–231. doi:10.1016/j.desal.2008.06.020

Clifford, D. (2011). Fundamentals of Radium and Uranium Removal from Drinking Water. Houston University. http://www.epa.gov/ogwdw/radionuclides/pdfs/webcast/presentations/rads_treatment_dennis_clifford.pdf.

EPA. Please see U.S. EPA.

García-Rodríguez, L. (2003). Renewable Energy Applications in Desalination: State of the Art. Solar Energy, 75(5), 381–393. doi:10.1016/j.solener.2003.08.005

Herold, D. and Neskakis, A. (2001). A Small PV-driven Reverse Osmosis Desalination Plant on the Island of Gran Canaria. Desalination, 137(1-3), 285–292. doi:10.1016/S0011-9164(01)00230-2

Kesner, M. (2001). Batch Process or Continuous Process ? Journal of Chemical Education, 78(1). http://stwww.weizmann.ac.il/g-chem/learnchem/Print.asp?Kind=3&ID=18_03.

Larock, B. E., Jeppson, R. W., and Watters, G. Z. (2000). Hydraulics of Pipeline Systems (page 533). Boca Raton: CRC Press.

Ma, Q. and Lu, H. (2011). Wind Energy Technologies Integrated with Desalination Systems: Review and State-of-the-art. Desalination, 277(1-3), 274–280. doi:10.1016/j.desal.2011.04.041

Macedonio F., E. Drioli, A.A. Gusev, A. Bardow, R. Semiat, and M. Kurihara (2012). Efficient Technologies for Worldwide Clean Water Supply. Chemical Engineering and Processing (51) 2-17. gwri-ic.technion.ac.il/pdf/gwri_abstracts/2012_1/77.pdf.

Namboodiri, V. and Rajagopalan, N. (2014). Comprehensive Water Quality and Purification. In Comprehensive Water Quality and Purification (2) 98–119. Elsevier. doi:10.1016/B978-0-12-382182-9.00095-5.

Ortiz, J. M., Expósito, E., Gallud, F., García-García, V., Montiel, V., and Aldaz, A. (2007). Electrodialysis of Brackish Water Powered by Photovoltaic Energy Without Batteries: Direct Connection Behaviour. Desalination, 208(1-3), 89–100. doi:10.1016/j.desal.2006.05.026

Ortiz, J., Exposito, E., Gallud, F., Garciagarcia, V., Montiel, V., and Aldaz, A. (2008). Desalination of Underground Brackish Waters Using an Electrodialysis System Powered Directly by Photovoltaic Energy. Solar Energy Materials and Solar Cells, 92(12), 1677–1688. doi:10.1016/j.solmat.2008.07.020

Sharon, H. and Reddy, K. S. (2015). A Review of Solar Energy Driven Desalination Technologies. Renewable and Sustainable Energy Reviews (41) 1080–1118. doi:10.1016/j.rser.2014.09.002

Tanaka, Y. (2010). A Computer Simulation of Feed and Bleed Ion Exchange Membrane Electrodialysis for Desalination of Saline Water. Desalination, 254(1-3), 99–107. doi:10.1016/j.desal.2009.12.008.

Tanaka, Y. (2014). Development of a Computer Simulation Program of Feed And Bleed Ion Exchange Membrane Electrodialysis for Saline Water Desalination. Desalination, 342, 126–138. doi:10.1016/j.desal.2013.08.016

Tsiakis, P. and Papageorgiou, L. G. (2005). Optimal Design of an Electrodialysis Brackish Water Desalination Plant. Desalination, 173(2), 173–186. doi:10.1016/j.desal.2004.08.031

Uche, J., Círez, F., Bayod, A.A., and Martínez, A. (2013). On-grid and Off-grid Batch-ED (Electrodialysis) Process: Simulation and Experimental Tests. Energy (57) 44–54. doi:10.1016/j.energy.2013.02.056.

U.S. Environmental Protection Agency. (2012). Guidelines for Water Reuse. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100FS7K.TXT.

U.S. Environmental Protection Agency. (n.d.). Secondary Drinking Water Regulations: Guidance for Nuisance Chemicals. Retrieved March 18, 2018, from https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals.

Valero, F., and Arbós, R. (2010). Desalination of Brackish River Water Using Electrodialysis Reversal (EDR). Desalination, 253(1-3), 170–174. doi:10.1016/j.desal.2009.11.011.

Valero, Barceló, and Arbós (2010). Electrodialysis Technology - Theory and Applications. In Michael Schorr (Eds.) Desalination Trends, & Technologies (pp. 3-20). Rijeka, Croatia: Published by InTech.

Veza, J. M., Penate, B., and Castellano, F. (2001). Electrodialysis Desalination Designed for Wind Energy (On-grid Tests). Desalination, 141, 53–61.

Veza, J. M., Penate, B., and Castellano, F. (2004). Electrodialysis Desalination Designed for Off-grid Wind Energy. Desalination, 160, 211–221.

Appendix A: Excel Calculations for Faraday’s Law

Color Code Schematic:			
		🟨	Chemical Parameters that include redundancy such as Total Alkanlity
		🟧	Redundant or uncounted normality values
		🟫	Assumptions made; This made need later double checking
		🟦	Numbers

Faraday's Law	**I = F*Qd*ΔN/cp/e**							
A) Current to Reach zero normality								
Faraday's constant, F: (amp*s/equv)	96500	**I (amps)=**	**7.12**					
Flowrate of Dilute, Qd (gal/min)	0.3							
Change of Normality,ΔN: (equv)	0.04							
Number of Cell Pairs, cp:	10							
Current efficency thru membrane, e:(%)	100							
Negative Charges from Anions (-)				Ion	Valence (e-)	MW (g/mol)	Molarity (mol/L)	Normality (equv/L)
Parameter Name	Reporting Units	Data						
Alkalinity, Bicarbonate (as CaCO3)	mg/L CaCO3	98		HCO3-	-1	61.0168	1.9595E-03	-1.9595E-03
Alkalinity, Carbonate	mg/L CaCO3	0	u	CO3-2	-2	60.0089	0	0
Alkalinity, Hydroxide	mg/L CaCO3	0	u	OH-	-1	17.0073	0	0
Total Alkalinity (as CaCO3)	color Units	98	0	(HCO3-) & (CO3-2) & (OH-)	-1			
P-Alkalinity (As CaCO3) mL of titrant	mL	0	v					
Bromide	mg/L	0	u	Br-	-1	79.9040	0	0
Chloride	mg/L	37	0	Cl-	-1	35.4530	1.0436E-03	-1.0436E-03
Cyanide	mg/L	0	u	CN-	-1	26.0174	0	0
Fluoride	mg/L	1.6	0	F-	-1	18.9980	8.4219E-05	-8.4219E-05
Nitrogen, Nitrate (as N)	mg/L	0	u	NO3-	-1	62.0049	0	0
Nitrate+Nitrite (as N)	mg/L	0	u	(NO3-) & (NO2-)	-1			0
Nitrogen, Nitrite (As N)	mg/L	0	u	NO2-	-1	46.0055	0	0
Perchlorate	mg/L	0	u	ClO4-	-1	99.4506	0	0
Phosphorus, Orthophosphate (as P)	mg/L	0	u	PO4-3	-3	94.9706	0	0
Phosphorus, Total (as P)	mg/L	0	u					
Solids, Filterable Total Dissolved Solids	mg/L	2650	X					
Sulfate	mg/L	1700	0	SO4-2	-2	96.0626	1.7697E-02	-3.5394E-02
							SUM:	**-0.0385**

Metals and Major Cations (+)								
Parameter Name	Reporting Units	Data		Ion	Valence (e-)	MW(g/mol)	Molarity (mol/L)	Normality(equv/L)
Aluminum	mg/L	0	u	Al+3	3	26.9810	0	0
Arsenic	mg/L	0	J	As+3	3	74.9210	0	0
Barium	mg/L	0.038	0	Ba+2	2	137.3270	2.7671E-07	5.5342E-07
Boron	mg/L	0.38	0	B+3	3	10.8110	3.5149E-05	1.0545E-04
Cadmium	mg/L	0	u	Cd+2	2	112.4110	0	0
Calcium	mg/L	200	0	Ca+2	2	40.0780	4.9903E-03	9.9805E-03
Chromium	mg/L	0	u	(Cr+3) & (Cr+6)	4.5	51.9961	0	0
Cobalt	mg/L	0	J	Co+2	2	58.9330	0	0
Copper	mg/L	0.018	0	Cu+2	2	63.5460	2.8326E-07	5.6652E-07
Iron (Dissolved)	mg/L	0	u	Fe+2	2	55.8450	0	0
Iron (Total)	mg/L	0.028	0	(Fe+2) & (Fe+3)	3	55.8450	5.0139E-07	1.5042E-06
Lead	mg/L	0.0026	0	Pb+2	2	207.2000	1.2548E-08	2.5097E-08
Magnesium	mg/L	48	0	Mg+2	2	24.3050	1.9749E-03	3.9498E-03
Manganese (Dissolved)	mg/L	0.052	X	Mn+2	2	54.9380	9.4652E-07	1.8930E-06
Manganese (Total)	mg/L	0.057	X	(Mn+2) & (Mn+3)	2.1	54.9380	1.0375E-06	2.1661E-06
Mercury	mg/L	0	u	Hg+2	2	200.5900	0	0
Molybdenum	mg/L	0.016	0	Mo+4	4	95.9400	1.6677E-07	6.6708E-07
Nickel	mg/L	0	J	Ni+2	2	58.6934	0	0
Potassium	mg/L	8.6	0	K+	1	39.0983	2.1996E-04	2.1996E-04
Selenium	mg/L	0.001	0	Se+6	6	78.9600	1.2665E-08	7.5988E-08
Silicon Dioxide	mg/L	24	0	SiO2	4	60.0848	3.9944E-04	1.5977E-03
Silver	mg/L	0	u	Ag+	1	107.8682	0	0
Sodium	mg/L	540	0	Na+	1	22.9890	2.3489E-02	2.3489E-02
Strontium	mg/L	6	0	Sr+2	2	87.6200	6.8478E-05	1.3696E-04
Uranium	mg/L	0.0025	0	(U+3) & (U+4)	3.5	238.0280	1.0503E-08	3.6760E-08
Zinc	mg/L	0.018	0	Zn+2	2	65.4090	2.7519E-07	5.5038E-07
							SUM:	**0.0395**

Notes from BGNDRF Well 1 Water Chemistry Data dated November 18, 2013 for Data Annotations:

u = concentration not detected at reporting limit
J = analyte detected below quantification limit
v = verified concentration
Z = Not Defined, or Zero
H = Holding times for preparation or analysis exceeded
X = Value exceeds maximum contaminant level
E = Value above quantitation range

= Nitrate sample arrived at lab past holding time. The value from Nitrate + Nitrite analysis was substitutes for Nitrate values because Nitrite was expected to be below detection.

Appendix B: Limiting Current Data

Photovoltaic Electrodialysis Desalination

Flowrate (gpm)	Current (A)	Salt % Removal	Intial Conductivity (µS/cm)	T (Cº)	Voltage (V)	Concentrate Conductivity(µS/cm)	Date	Notes
0.60	0.60	8.58	2680	n/ab	18	2690	1/30/15	Stack setup #1 + Hach (Lab)
0.60	0.80	9.33	2680	n/ab	10.74	2780	1/30/15	Stack setup #1 + Hach (Lab)
0.60	1.00	12.31	2680	n/ab	12.45	2760	1/30/15	Stack setup #1 + Hach (Lab)
0.60	1.40	13.06	2680	n/ab	17.4	2840	1/30/15	Stack setup #1 + Hach (Lab)
0.60	1.80	15.67	2680	n/ab	20	2940	1/30/15	Stack setup #1 + Hach (Lab)
0.60	2.00	17.16	2680	n/ab	21.1	2990	1/30/15	Stack setup #1 + Hach (Lab)
0.70	0.40	4.02	3480	21.1	10	3510	2/4/15	Stack setup #1 + Hach (Lab)
0.45	0.80	7.76	3480	21.1	15	3500	2/4/15	Stack setup #1 + Hach (Lab)
0.45	1.40	13.22	3480	21.1	25	3760	2/4/15	Stack setup #1 + Hach (Lab)
0.29	0.40	4.55	2860	21	9.94	3030	2/4/15	Stack setup #1 + Hach (Lab)
0.29	0.80	10.14	2860	21	16	3260	2/4/15	Stack setup #1 + Hach (Lab)
0.29	1.20	15.73	2860	21	28	3540	2/4/15	Stack setup #1 + Hach (Lab)
0.45	1.50	11.49	3480	21.1	29	3770	2/4/15	Stack setup #1 + Hach (Lab)
0.29	1.40	16.08	2860	21	25	3520	2/4/15	Stack setup #1 + Hach (Lab)
0.27	2.50	50.00	2000	n/ab	18	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.27	3.00	53.63	1900	n/ab	21	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.27	4.00	63.16	1900	n/ab	26	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.27	4.80	68.42	1900	n/ab	30	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.27	1.00	36.84	1900	n/ab	12.5	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.27	2.50	52.94	1700	n/ab	20	n/ab	2/12/15	Stack setup #2 + EcoTestr Pen
0.34	0.50	37.50	800	n/ab	19	1900	2/18/15	Omit; mixed up In & Out
0.34	0.50	22.22	1800	n/ab	12.6	1700	2/18/15	Omit; mixed up In & Out

Photovoltaic Electrodialysis Desalination

Flowrate (gpm)	Current (A)	Salt % Removal	Intial Conductivity (µS/cm)	T (Cº)	Voltage (V)	Concentrate Conductivity(µS/cm)	Date	Notes
0.34	1.00	26.32	1900	n/ab	20.8	2400	2/18/15	Omit; mixed up In & Out
0.34	1.30	27.78	1800	n/ab	28	2600	2/18/15	Omit; mixed up In & Out
0.14	0.50	9.09	2200	n/ab	11.3	1900	2/18/15	Omit; mixed up In & Out
0.14	1.00	14.29	2100	n/ab	19	2100	2/18/15	Omit; mixed up In & Out
0.14	1.30	23.81	2100	n/ab	27	2000	2/18/15	Omit; mixed up In & Out
0.34	0.60	55.56	900	n/ab	30	1900	2/18/15	Omit; mixed up In & Out
0.34	1.10	42.86	1400	n/ab	27	2200	2/18/15	Omit; mixed up In & Out
0.34	0.60	28.57	1400	n/ab	14.5	1800	2/18/15	Omit; mixed up In & Out
0.34	0.85	40.00	1500	n/ab	20	1900	2/18/15	Omit; mixed up In & Out
0.51	0.50	16.67	3000	n/ab	8.5	3000	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	1.00	26.67	3000	n/ab	16.5	3400	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	0.25	10.34	2900	n/ab	5.5	3000	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	0.50	12.00	5000	n/ab	6.6	4800	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	1.00	14.00	5000	n/ab	10.5	5200	2/19/15	Stack setup #2 + EcoTestr Pen
0.25	1.50	53.33	3000	n/ab	25.7	4000	2/19/15	Stack setup #2 + EcoTestr Pen
0.25	1.70	56.67	3000	n/ab	30	4300	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	1.50	16.00	5000	n/ab	15.2	5000	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	0.85	23.08	5200	n/ab	19.8	5700	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	2.00	23.08	5200	n/ab	19.8	5700	2/19/15	Stack setup #2 + EcoTestr Pen
0.16	2.00	45.10	5100	n/ab	28	6300	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	0.50	11.54	5200	n/ab	6.4	5200	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	1.00	21.57	5100	n/ab	11.6	5400	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	2.30	53.57	5600	n/ab	2.9	7600	2/19/15	Stack setup #2 + EcoTestr Pen

Flowrate (gpm)	Current (A)	Salt % Removal	Intial Conductivity (µS/cm)	T (Cº)	Voltage (V)	Concentrate Conductivity(µS/cm)	Date	Notes
0.25	0.50	27.59	2900	n/ab	10	3400	2/19/15	Stack setup #2 + EcoTestr Pen
0.25	1.20	66.67	3000	n/ab	30	4300	2/19/15	Stack setup #2 + EcoTestr Pen
0.25	0.90	17.24	2900	n/ab	16	3500	2/19/15	Stack setup #2 + EcoTestr Pen
0.25	0.25	13.33	3000	n/ab	5.7	2900	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	1.00	23.33	3000	n/ab	13.4	3200	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	0.25	6.67	3000	n/ab	5.3	2900	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	0.85	40.00	3000	n/ab	26.5	3700	2/19/15	Stack setup #2 + EcoTestr Pen
0.51	2.00	40.00	3000	n/ab	26.5	3700	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	1.50	21.57	5100	n/ab	17	5600	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	2.00	35.29	5100	n/ab	22	6200	2/19/15	Stack setup #2 + EcoTestr Pen
0.34	2.70	39.22	5100	n/ab	30	6300	2/19/15	Stack setup #2 + EcoTestr Pen
0.31	0.50	10.74	4470	n/ab	7	4950	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.00	11.88	4460	n/ab	11.5	4900	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.60	26.62	4470	n/ab	27	5650	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.50	24.78	4480	n/ab	16.5	5430	2/20/15	Stack setup #2 + Hach (Lab)
0.31	0.80	11.74	4430	n/ab	9.6	4930	2/20/15	Stack setup #2 + Hach (Lab)
0.31	2.00	15.73	4450	n/ab	23	5210	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.80	21.55	2970	n/ab	30	3480	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.60	44.14	2950	n/ab	21.8	4160	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.00	11.37	2990	n/ab	14	3360	2/20/15	Stack setup #2 + Hach (Lab)
0.31	0.50	10.85	2950	n/ab	8	3370	2/20/15	Stack setup #2 + Hach (Lab)
0.31	0.50	11.13	5660	n/ab	9.4	6060	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.00	7.99	5630	n/ab	16.2	6470	2/20/15	Stack setup #2 + Hach (Lab)

Flowrate (gpm)	Current (A)	Salt % Removal	Intial Conductivity (µS/cm)	T (Cº)	Voltage (V)	Concentrate Conductivity(µS/cm)	Date	Notes
0.31	1.60	15.52	5090	n/ab	30	7120	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.50	20.56	5690	n/ab	22.9	6820	2/20/15	Stack setup #2 + Hach (Lab)
0.31	0.80	5.70	5610	n/ab	13.4	5980	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.80	45.75	3270	n/ab	25	4560	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.60	36.52	3250	n/ab	20.4	3930	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.00	12.42	3220	n/ab	12.8	3660	2/20/15	Stack setup #2 + Hach (Lab)
0.31	0.50	2.79	3230	n/ab	7.7	3390	2/20/15	Stack setup #2 + Hach (Lab)
0.31	2.00	30.77	3250	n/ab	30	4440	2/20/15	Stack setup #2 + Hach (Lab)
0.31	1.30	6.75	3260	n/ab	15.8	3440	2/20/15	Stack setup #2 + Hach (Lab)
0.58	0.20	1.84	4890	21.2	4.85	4970	3/23/15	Omit; short-circuit pooling
0.58	0.50	5.53	4880	21.3	7.55	5080	3/23/15	Omit; short-circuit pooling
0.58	0.75	7.84	4850	21.3	9.5	5180	3/23/15	Omit; short-circuit pooling
0.58	1.00	10.29	4860	21.3	11.45	5280	3/23/15	Omit; short-circuit pooling
0.58	0.20	2.86	4890	21.2	4.85	4960	3/23/15	Omit; short-circuit pooling
0.58	0.50	5.75	4870	21.3	7.05	5080	3/23/15	Omit; short-circuit pooling
0.58	0.75	8.83	4870	21.3	9.72	5190	3/23/15	Omit; short-circuit pooling
0.58	1.00	11.29	4870	21.3	11.4	5300	3/23/15	Omit; short-circuit pooling
0.46	1.00	14.40	4860	21.2	11.73	5360	3/23/15	Omit; short-circuit pooling
0.46	1.50	16.98	4770	21.2	13.02	5510	3/23/15	Omit; short-circuit pooling
0.46	2.00	27.60	4710	21.2	16.38	5600	3/23/15	Omit; short-circuit pooling
0.58	0.20	2.25	4890	21.2	4.83	4980	3/23/15	Omit; short-circuit pooling
0.58	0.50	5.54	4870	21.3	7.59	5080	3/23/15	Omit; short-circuit pooling
0.58	0.75	4.73	4860	21.3	9.66	5180	3/23/15	Omit; short-circuit pooling

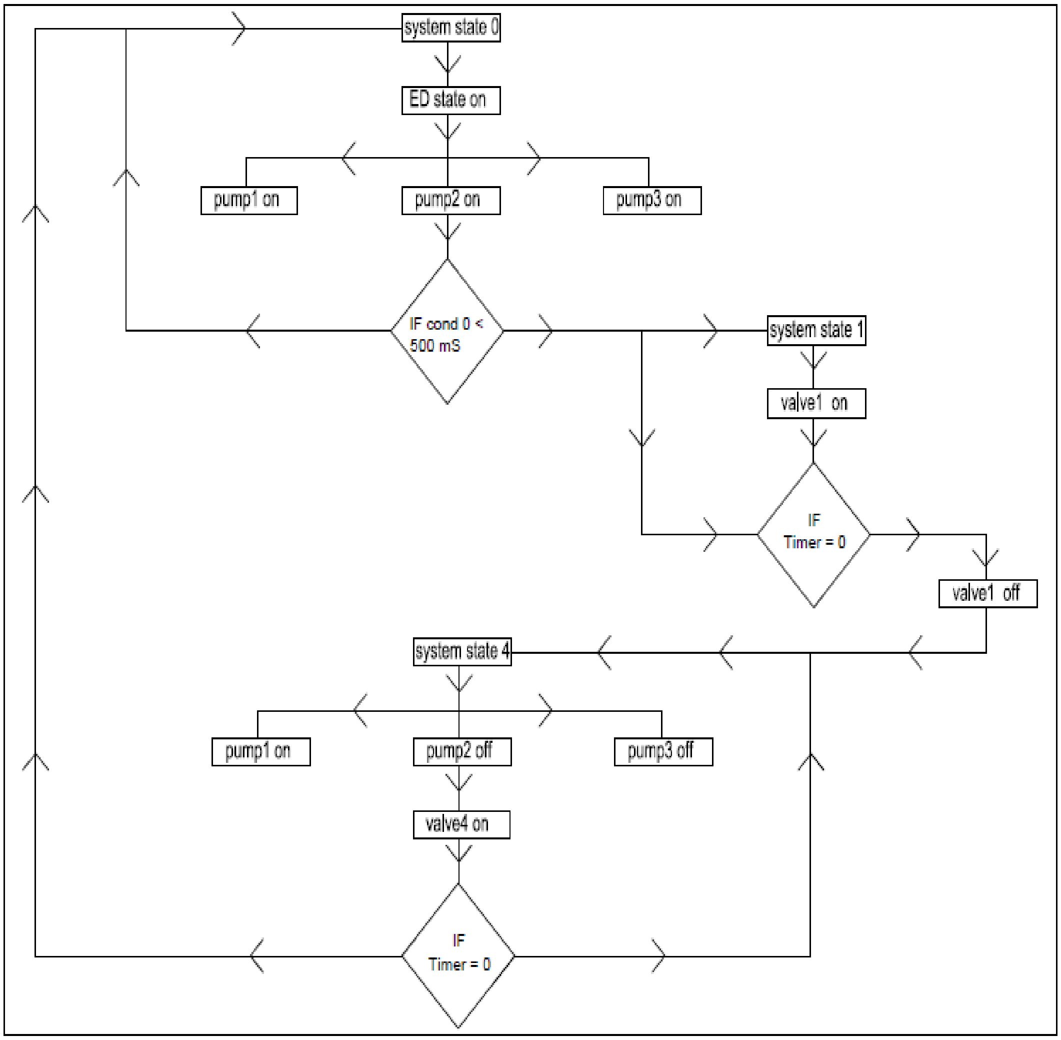
Flowrate (gpm)	Current (A)	Salt % Removal	Intial Conductivity (µS/cm)	T (Cº)	Voltage (V)	Concentrate Conductivity(µS/cm)	Date	Notes
0.58	1.00	10.91	4860	21.3	11.37	5270	3/23/15	Omit; short-circuit pooling
0.46	1.00	12.58	4850	21.2	12	5340	3/23/15	Omit; short-circuit pooling
0.46	1.50	21.09	4790	21.2	13.05	5580	3/23/15	Omit; short-circuit pooling
0.46	2.00	28.18	4790	21.2	16.4	5810	3/23/15	Omit; short-circuit pooling
0.46	1.00	14.20	4860	21.2	11.58	5390	3/23/15	Omit; short-circuit pooling
0.46	1.50	23.17	4790	21.2	13.03	5490	3/23/15	Omit; short-circuit pooling

Notes for Limiting Current Data Annotations:
n/ab = data not measured during testing

Stack setup #1 = stack assembled of 10 cell pairs with alternating 6 #1 hydraulic stages and 4 #2 hydraulic stages
Stack setup #2 = stack assembled of 20 cell pairs with alternating 12 #1 hydraulic stages and 8 #2 hydraulic stages
Stack setup #3 = stack assembled of 20 cell pairs with 12 #1 and 8 #2 hydraulic stages on opposite sides; sideways orientation (3/23/15)
Hach (Lab) = conductivity measured by Hach conductivity meter located in Cal Poly Pomona wastewater lab
Hach (new) = conductivity measured by Hach H170 pH/Conductivity meter (used for testing on 3/23/15)
EcoTestr Pen = conductivity measured by EcoTestr pocket conductivity meter

2/18/15: Mixed up In & Out = Omit data results due to switched electrode flush and concentrate inlet to wrong circulation buckets (water source) so initial water conductivity was not constant throughout testing as recorded in data
3/23/15: Short-circuit pooling = Omit data results due short circuiting of stack from saline water pooling in tie rod cavities due to stack’s sideways orientation and leakage from permeable membrane

Appendix C: System Flow Logic Diagram


system state 0
ED state on
pump1 on
pump2 on
pump3 on
IF cond 0 < 500 mS
system state 1
valve1 on
IF Timer = 0
valve1 off
system state 4
pump1 on
pump2 off
pump3 off
valve4 on
IF Timer = 0

SYSTEM ARDUINO CODE:
“MASTER CODE V3”

```
//#include <RTClib.h>
//#include <Wire.h>
#include <LiquidCrystal.h>
//#include <TimerOne.h>
//#include <TimerThree.h>
// Cond 1 = A0
// Cond 2 = A1
// Cond 3 = A2
// Temp Sense = A3
// Photo 1 = A4
// Photo 2 = A5
// Photo 3 = A6
// Photo 4 = A7
// Bat Voltage = A8
// Solar Pannel Voltage =A9
//Multiplexer input pin = A10
// Load Voltage = A13
// Solar = A14
// Load = A15
// Tank Level 1 = MX0
// Tank Level 2 = MX1
// Tank Level 3 = MX2
// Tank Level 4 = MX3
// Pump sense 1 = MX4
// Pump sense 2 = MX5
// Pump sense 3 = MX6

// *Digital Read*
//flow sensor 1 = 2
//flow sensor 2 = 3
//flow sensor 3 = 21
//flow sensor 4 = 20
//flow sensor 5 = 19
//flow sensor 6 = 18
// LCD button 1 = 22
// LCD button 1 = 23
// Pannel Button = 24

// *Digital Write*
//Stepper driection =25
// Stepper steps = 26
```

```
// Stepper enable = 49
// Pump pin 1 = 4
// Pump pin 2 = 5
// Pump pin 3 = 6
// Stack controll MOSFET = 7
// Battery Charging MOSFET = 8
// Buck Reg Battery = 9
// Buck Reg ED = 10
// Valve 1 = 27
// Valve 2 = 28
// Valve 3 = 29
// Valve 4 = 30
// Valve 5 = 31
// Valve 6 = 41
// Valve 7 = 42
// Valve 8 = 43
// LCD RS pin =32
// LCD Enable pin =33
// LCD D4 pin =34
// LCD D5 pin =35
// LCD D6 pin = 36
// LCD D7 pin = 37
// Status light R = 38
// Status Light B = 39
// Status Light G = 40
// Multiplexer A = 44
// Multiplexer B = 45
// Multiplexer C = 46
// INA =
// INB =


#define FLOWSENSORPIN1 2
#define FLOWSENSORPIN2 3
#define FLOWSENSORPIN3 21
//#define SOL_AMPS_CHAN 14 // Defining the adc channel to read solar amps
//#define SOL_VOLTS_CHAN 9 // defining the adc channel to read solar volts
#define BAT_VOLTS_CHAN 8 // defining the adc channel to read battery volts
//#define ED_AMPS_CHAN 15
//#define ED_VOLTS_CHAN 13
#define COND_0_CHAN 0
#define COND_1_CHAN 1
#define COND_2_CHAN 2
#define TEMP_CHAN 3
```

```
#define TANK1_MX0_CHAN 10
//#define TANK2_MX1_CHAN 11
//#define TANK3_MX2_CHAN 12
//#define TANK4 MX3
#define VALVE1 27 // product dump pair
#define VALVE2 28 // concentrate waste dump pair
#define VALVE3 29 // Electrode Waste dump pair
#define VALVE4 30 // Product Fill
#define VALVE5 31 // Nothing
#define VALVE6 41 // Dilute Fill
#define VALVE7 42 // Concentrate Fill
#define VALVE8 43 // Electrode Fill
#define load_pin 49
#define AVG_NUM 8 // number of iterations of the adc routine to average the adc readings
//#define SOL_AMPS_SCALE 0.0251 // the scaling value for raw adc reading to get solar amps // (5/1024)*(R1+R2)/R2
//#define SOL_VOLTS_SCALE 0.02976 // the scaling value for raw adc reading to get solar volts
#define BAT_VOLTS_SCALE 0.02976 // the scaling value for raw adc reading to get battery volts
//#define ED_AMPS_SCALE 0.0251
//#define ED_VOLTS_SCALE 0.07813
//#define PWM_PIN 9 // the output pin for the pwm (only pin 9 avaliable for timer 1 at 50kHz)
//#define PWM_ENABLE_PIN 8 // pin used to control shutoff function of the IR2104 MOSFET driver (hight the mosfet driver is on)
//#define PWM_FULL 1023 // the actual value used by the Timer1 routines for 100% pwm duty cycle
//#define PWM_MAX 100 // the value for pwm duty cyle 0-100%
//#define PWM_MIN 60 // the value for pwm duty cyle 0-100% (below this value the running in the system is = 0)
//#define PWM_START 90 // the value for pwm duty cyle 0-100%
//#define PWM_INC 1 //the value the increment to the pwm value for the ppt algorithm

//#define ED_PWM_PIN 10 // the output pin for the pwm ED(only pin 9 avaliable for timer 1 at 50kHz)
//#define ED_PWM_ENABLE_PIN 11 // pin used to control shutoff function of the IR2104 MOSFET driver (hight the mosfet driver is on)
//#define ED_PWM_FULL 1023 // the actual value used by the Timer1 routines for 100% pwm duty cycle
//#define ED_PWM_MAX 100 // the value for pwm duty cyle 0-100%
```

```
//#define ED_PWM_MIN 60 // the value for pwm duty cyle 0-100% (below this value the running in the system is = 0)
//#define ED_PWM_START 90 // the value for pwm duty cyle 0-100%
//#define ED_PWM_INC 1 //the value the increment to the pwm value for the ppt algorithm

#define TRUE 1
#define FALSE 0
#define ON TRUE
#define OFF FALSE
//#define TURN_ON_MOSFETS digitalWrite(PWM_ENABLE_PIN, HIGH) // enable MOSFET driver
//#define TURN_OFF_MOSFETS digitalWrite(PWM_ENABLE_PIN, LOW) // disable MOSFET driver
//#define TURN_ON_ED_MOSFETS digitalWrite(PWM_ENABLE_PIN, HIGH) // enable MOSFET driver
//#define TURN_OFF_ED_MOSFETS digitalWrite(PWM_ENABLE_PIN, LOW) // disable MOSFET driver
#define valve1_on digitalWrite(VALVE1, HIGH) //Dilute
#define valve1_off digitalWrite(VALVE1, LOW)
#define valve2_on digitalWrite(VALVE2, HIGH) //Concentrate
#define valve2_off digitalWrite(VALVE2, LOW)
#define valve3_on digitalWrite(VALVE3, HIGH) //Electrode
#define valve3_off digitalWrite(VALVE3, LOW)

#define valve4_on digitalWrite(VALVE4, HIGH) //Fill Valve
#define valve4_off digitalWrite(VALVE4, LOW)

#define valve6_on digitalWrite(VALVE6, HIGH) //Fill Dilute
#define valve6_off digitalWrite(VALVE6, LOW)

#define valve7_on digitalWrite(VALVE7, HIGH) //Fill Concentrate
#define valve7_off digitalWrite(VALVE7, LOW)

#define valve8_on digitalWrite(VALVE8, HIGH) //Fill Electrode
#define valve8_off digitalWrite(VALVE8, LOW)


//#define ONE_SECOND 50000 //count for number of interrupt in 1 second on interrupt period of 20us

//#define LOW_SOL_WATTS 5.00 //value of solar watts // this is 5.00 watts
//#define MIN_SOL_WATTS 1.00 //value of solar watts // this is 1.00 watts
#define MIN_BAT_VOLTS 11.00 //value of battery voltage // this is 11.00 volts
```

```
//#define MAX_BAT_VOLTS 14.10 //value of battery voltage// this is 14.10 volts
//#define HIGH_BAT_VOLTS 13.00 //value of battery voltage // this is 13.00 volts
#define LVD 11.5 //Low voltage disconnect setting for a 12V system
//#define OFF_NUM 9 // number of iterations of off charger state

//#define ED_AMPS_MAX 1.5 // max amps to the ED

#define PROUDUCT_DUMP 500.00 // Conductivity to activate the product valve pair in micro S
#define WASTE_DUMP 0.17 // Conductivity to activate the concentrate dump pair in V
#define ELECTRODE_DUMP // Conductivity to activate the electrode rinse dump pair in micro S
#define PUMP1 4
#define PUMP2 5
#define PUMP3 6

//----------------------------------------------------------------------------------------------------
//Defining led pins for indication
//#define LED_RED 38
//#define LED_GREEN 39
//#define LED_YELLOW 40
//----------------------------------------------------------------------------------------------------
// Defining load control pin
//#define LOAD_PIN 10 // pin-2 is used to control the load

//----------------------------------------------------------------------------------------------------
// Defining lcd back light pin
//#define BACK_LIGHT_PIN 5 // pin-2 is used to control the load
//----------------------------------------------------------------------------------------------------
/////////////////////////////////////////BIT MAP ARRAY//////////////////////////////////////////////////
//----------------------------------------------------------------------------------------------------
byte solar[8] = //icon for termometer
{
 0b11111,
 0b10101,
 0b11111,
 0b10101,
 0b11111,
 0b10101,
 0b11111,
 0b00000
```

```
};

byte battery[8] =
{
 0b01110,
 0b11011,
 0b10001,
 0b10001,
 0b11111,
 0b11111,
 0b11111,
 0b11111,
};

byte _PWM [8] =
{
 0b11101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10111,
};

byte _FLOW [8] =
{
 0b00000,
 0b00100,
 0b00010,
 0b11111,
 0b00010,
 0b00100,
 0b00000,
 0b00000,
};

byte MU[8] =
{
 0b10010,
 0b10010,
 0b10010,
 0b11110,
```

```
 0b10000,
 0b10000,
 0b10000,
 0b00000,
};

byte _ED [8] =
{
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
 0b10101,
};

byte _TANK [8] =
{
 0b10001,
 0b10001,
 0b10001,
 0b10001,
 0b10001,
 0b11111,
 0b11111,
 0b11111,
};

//-----------------------------------------------------------------------------------------------

// count how many pulses!
volatile uint16_t pulses = 0;
// track the state of the pulse pin
volatile uint8_t lastflowpinstate;
// you can try to keep time of how long it is between pulses
volatile uint32_t lastflowratetimer = 0;
// and use that to calculate a flow rate
volatile float flowrate;
// Interrupt is called once a millisecond, looks for any pulses from the sensor!
SIGNAL(TIMER0_COMPA_vect) {
 uint8_t x = digitalRead(FLOWSENSORPIN1);
```

```
 if (x == lastflowpinstate) {
 lastflowratetimer++;
 return; // nothing changed!
 }

 if (x == HIGH) {
 //low to high transition!
 pulses++;
 }
 lastflowpinstate = x;
 flowrate = 1000.0;
 flowrate /= lastflowratetimer; // in hertz
 lastflowratetimer = 0;
}

void useInterrupt(boolean v) {
 if (v) {
 // Timer0 is already used for millis() - we'll just interrupt somewhere
 // in the middle and call the "Compare A" function above
 OCR0A = 0xAF;
 TIMSK0 |= _BV(OCIE0A);
 }
 else {
 // do not call the interrupt function COMPA anymore
 TIMSK0 &= ~_BV(OCIE0A);
 }
}

// global variables

int count = 0;
int pwm = 0; //pwm duty cycle 0-100%
//float sol_amps; // solar amps
//float sol_volts; // solar volts
float bat_volts; // battery volts
//float sol_watts; // solar watts
//float old_sol_watts = 0; // solar watts from previous time through ppt routine
//float ED_volts;
//float ED_amps;
//float ED_watts;
//float total_watts;
//float avail_watts;
//int ED_AMPS_DESIRED = 1.0;
```

```
unsigned int seconds = 0; // seconds from timer routine
unsigned int prev_seconds = 0; // seconds value from previous pass
unsigned int interrupt_counter = 0; // counter for 20us interrrupt

//unsigned int seconds2=0;
//unsigned int prev_seconds2 = 0;
//unsigned int interrupt_counter2 = 0;
boolean led_on = TRUE;
int led_counter = 0;
//int delta = PWM_INC; // variable used to modify pwm duty cycle for the ppt
algorithm
//int delta2 = PWM1_INC;
float cond0;
float cond1;
float cond2;
float cond_0;
float cond_1;
float cond_2;
float gpm;
int Pump1_pwm = 100;
int Pump2_pwm = 100;
int Pump3_pwm = 100;
int desired_flowrate = 30; // Desired flowrate in mL/sec
int desired_flowrate1 = 30;
int desired_flowrate2 = 30;
//int ED_pwm = 80;
int temp1;
int TANK1;
int TANK2;
int TANK3;
int TANK4;
int Tsense1 = 1024;
int Tsense2 = 1024;
int Tsense3 = 1024;

int ED_status = 0;

long prevmilli = 0;
long prevmilli1 = 0;
long lcd_interval = 10000;
int timechk=0;

long tank_interval;
```

```
int tank_volume = 15141; //15141ml = 4GAL///11356ml = 3gal // in ml
int dump_flowrate = 40; //in ml/s
long valve_on_time = 0;
float product_dump = 500.00;// in micro seimen
float waste_dump = 0.10;
int system_state = 0;
int Dilutecount = 0;


//enum charger_mode {off, on, bulk, bat_float} charger_state; // enumerated
variable that holds state for charger state machine

// Set the pins on the I2C chip used for LCD connections:
// addr, en,rw,rs,d4,d5,d6,d7,bl,blpol
LiquidCrystal lcd(32, 33, 34, 35, 36, 37); // Set the LCD Pins
//int back_light_Pin = 5;
//int load_pin =6;
//int back_light_pin_State = 0;
int load_status = 0;
int flow_mod = 7;
int lcd_state = 0;

//------------------------------------------------------------------------------------------------
// This routine is automatically called at powerup/reset
//------------------------------------------------------------------------------------------------

void setup() // run once, when the sketch starts
{
 // pinMode(LED_RED, OUTPUT);
 //pinMode(LED_GREEN, OUTPUT);
 //pinMode(LED_YELLOW, OUTPUT);
 //pinMode(PWM_ENABLE_PIN, OUTPUT); // sets the digital pin as output
 //pinMode(ED_PWM_ENABLE_PIN,OUTPUT);
 //Timer1.initialize(20); // initialize timer1, and set a 20uS period
 //Timer3.initialize(10);
 //Timer1.pwm(PWM_PIN, 0); // setup pwm on pin 9, 0% duty cycle
 // Timer3.pwm(ED_PWM_PIN,0);
 //TURN_OFF_MOSFETS; //turn off MOSFET driver chip
 //Timer1.attachInterrupt(callback); // attaches callback() as a timer overflow
interrupt
 // Timer3.attachInterrupt(callback1);
 Serial.begin(9600); // open the serial port at 38400 bps:
 //pwm = PWM_START; //starting value for pwm
 //ED_pwm = ED_PWM_START;
```

```
//charger_state = off; // start with charger state as on
//pinMode(BACK_LIGHT_PIN, INPUT);
pinMode(load_pin,OUTPUT);
digitalWrite(load_pin,LOW); // default load state is OFF
// digitalWrite(BACK_LIGHT_PIN,LOW); // default LCd back light is OFF
lcd.begin(20, 4); // initialize the lcd for 16 chars 2 lines, turn on backlight
//lcd.noBacklight();
lcd.createChar(1, solar);
lcd.createChar(2, battery);
lcd.createChar(3, _PWM);
lcd.createChar(4, _FLOW);
lcd.createChar(5, MU);
//lcd.createChar(6,_COND);
lcd.createChar(7, _ED);
lcd.createChar(8, _TANK);

pinMode(FLOWSENSORPIN1, INPUT);
digitalWrite(FLOWSENSORPIN1, HIGH);
lastflowpinstate = digitalRead(FLOWSENSORPIN1);
useInterrupt(true);

pinMode(PUMP1 , OUTPUT);
pinMode(PUMP2 , OUTPUT);
pinMode(PUMP3 , OUTPUT);
pinMode(VALVE1 , OUTPUT);
pinMode(VALVE2 , OUTPUT);
pinMode(VALVE3 , OUTPUT);
pinMode(VALVE4 , OUTPUT);
pinMode(VALVE5 , OUTPUT);
pinMode(VALVE6 , OUTPUT);
pinMode(VALVE7 , OUTPUT);
pinMode(VALVE8 , OUTPUT);


pinMode(44,OUTPUT);
pinMode(45,OUTPUT);
pinMode(46,OUTPUT);
valve1_off;
valve2_off;
valve3_off;
valve4_off;
//valve5_off;
valve6_off;
valve7_off;
```

```
 valve8_off;

 digitalWrite(PUMP1,100);
 digitalWrite(PUMP2,100);
 digitalWrite(PUMP3,100);
 delay(3000);

}

//------------------------------------------------------------------------------------------------
// This is interrupt service routine for Timer1 that occurs every 20uS.
//
//------------------------------------------------------------------------------------------------
//void callback()
//{
// if (interrupt_counter++ > ONE_SECOND) { //increment interrupt_counter until
one second has passed
// interrupt_counter = 0;
// seconds++; //then increment seconds counter
// }
//}
//void callback1()
//{
// if (interrupt_counter2++ > ONE_SECOND) { //increment interrupt_counter
until one second has passed
// interrupt_counter2 = 0;
// seconds2++; //then increment seconds counter
// }
//}
//------------------------------------------------------------------------------------------------
// This routine reads and averages the analog inputs for this system, solar volts,
solar amps and
// battery volts.
//------------------------------------------------------------------------------------------------
int read_adc(int channel) {

 int sum = 0;
 int temp;
 int i;

 for (i = 0; i < AVG_NUM; i++) { // loop through reading raw adc values
AVG_NUM number of times
 temp = analogRead(channel); // read the input pin
 sum += temp; // store sum for averaging
```

```
 delayMicroseconds(50); // pauses for 50 microseconds
 }
 return (sum / AVG_NUM); // divide sum by AVG_NUM to get average and
return it
}

//---------------------------------------------------------------------------------------------
// This routine uses the Timer1.pwm function to set the pwm duty cycle.
//---------------------------------------------------------------------------------------------
//void set_pwm_duty(void) {
//
// if (pwm > PWM_MAX) {                                   // check limits of
PWM duty cyle and set to PWM_MAX
// pwm = PWM_MAX;
// }
// else if (pwm < PWM_MIN) {                              // if pwm is less than
PWM_MIN then set it to PWM_MIN
// pwm = PWM_MIN;
// }
// if (pwm < PWM_MAX) {
// Timer1.pwm(PWM_PIN, (PWM_FULL * (long)pwm / 100), 20); // use Timer1
routine to set pwm duty cycle at 20uS period
// //Timer1.pwm(PWM_PIN,(PWM_FULL * (long)pwm / 100));
// }
// else if (pwm == PWM_MAX) {                             // if pwm set to 100%
it will be on full but we have
// Timer1.pwm(PWM_PIN, (PWM_FULL - 1), 1000); // keep switching so set
duty cycle at 99.9% and slow down to 1000uS period
// //Timer1.pwm(PWM_PIN,(PWM_FULL - 1));
// }
//}
//---------------------------------------------------------------------------------------------
// This routine prints all the data out to the serial port.
//---------------------------------------------------------------------------------------------
//void print_data(void) {
//
// Serial.print(seconds, DEC);
// Serial.print(" ");
//
//// Serial.print("Charging = ");
//// if (charger_state == on) Serial.print("on ");
//// else if (charger_state == off) Serial.print("off ");
//// else if (charger_state == bulk) Serial.print("bulk ");
//// else if (charger_state == bat_float) Serial.print("float");
```

```
//// Serial.print(" ");
//
// Serial.print("pwm = ");
// Serial.print(pwm, DEC);
// Serial.print(" ");
//
//// Serial.print(" (panel) = ");
//// //print_int100_dec2(sol_amps);
//// Serial.print(sol_amps);
//// Serial.print(" ");
//
//// Serial.print("Voltage (panel) = ");
//// Serial.print(sol_volts);
//// //print_int100_dec2(sol_volts);
//// Serial.print(" ");
//
//// Serial.print("Power (panel) = ");
//// Serial.print(sol_volts);
//// // print_int100_dec2(sol_watts);
//// Serial.print(" ");
//
//// Serial.print("Battery Voltage = ");
//// Serial.print(bat_volts);
//// //print_int100_dec2(bat_volts);
//// Serial.print(" ");
//
// Serial.print("Flow Rate = ");
// Serial.print(flowrate + flow_mod);
// Serial.print(" ");
//
// Serial.print("Conductivity 0 = ");
// Serial.print(cond_0);
// Serial.print(" ");
//
// Serial.print("Conductivity 1 = ");
// Serial.print(cond_1);
// Serial.print(" ");
//
// Serial.print("Conductivity 2 = ");
// Serial.print(cond2);
// Serial.print(" ");
//
// Serial.print("Pump PWM = ");
// Serial.print(Pump1_pwm);
```

```
// Serial.print(" ");
//
// Serial.print("Temp = ");
// Serial.print(temp1);
// Serial.print(" ");
//
//
// Serial.print("\n\r");
// delay(1000);
//}

//----------------------------------------------------------------------------------------------------
// Main Loop
void loop()
{
 //run_charger();
 read_data();
 process_data();
 load_control();
 lcd_display();
 // print_data();
 flow_rate();
 ED_Control();
 valve_control();
 unsigned long currentMillis = millis();

 if (currentMillis - prevmilli > lcd_interval)
 {
 // // save the last time you blinked the LED
 // prevmilli = currentMillis;
 // if (lcd_state <= 2) {
 // lcd_state = lcd_state + 1;
 // }
 // else
 // {
 lcd_state = 2;
 //}

 }
}

//----------------------------------------------------------------------------------------------------
// This routine reads all the analog input values for the system. Then it multiplies
them by the scale
```

```
// factor to get actual value in volts or amps.
//--------------------------------------------------------------------------------------------
void read_data(void) {

 //sol_amps = (read_adc(SOL_AMPS_CHAN) * SOL_AMPS_SCALE - 13.51);
//input of solar amps
 //sol_volts = read_adc(SOL_VOLTS_CHAN) * SOL_VOLTS_SCALE; //input
of solar volts
 bat_volts = read_adc(BAT_VOLTS_CHAN) * BAT_VOLTS_SCALE; //input of
battery volts
 //ED_amps = read_adc(ED_AMPS_CHAN) * ED_AMPS_SCALE;
 //ED_volts = (read_adc(ED_VOLTS_CHAN) * ED_VOLTS_SCALE);
 cond0 = read_adc(COND_0_CHAN);
 cond1 = read_adc(COND_1_CHAN);
 cond2 = read_adc(COND_2_CHAN);

 digitalWrite(44,LOW);
 digitalWrite(45,LOW);
 digitalWrite(46,LOW);

 TANK1 = read_adc(TANK1_MX0_CHAN); //Read tank sensor1

 digitalWrite(44,LOW);
 digitalWrite(45,LOW);
 digitalWrite(46,HIGH);

 TANK2 = read_adc(TANK1_MX0_CHAN); //Read tank sensor2

 digitalWrite(44,LOW);
 digitalWrite(45,HIGH);
 digitalWrite(46,LOW);

 TANK3 = read_adc(TANK1_MX0_CHAN); //Read tank sensor3

}
void process_data(void)
{
 //sol_watts = sol_amps * sol_volts ; //calculations of solar watts
 //ED_watts = ED_amps * ED_volts;
 cond_0 = (-2004.3 * (cond0 * (5.0 / 1023.0))) + (3424.7 - 600.0); //calculation of
product condutivity
 cond_1 = cond1 * (5.0 / 1023.0);
 cond_2 = cond2;
 //system_state = 0;
```

```
 //temp1 = (4.88 * read_adc(TEMP_CHAN)-500)/10

 if (system_state == 0) //system_state0 run state
 {

 if (cond_0 < product_dump)
 {
 system_state = 1;
 timechk=1;
 }

 if (cond_1 < waste_dump)
 {
 system_state = 2;
 timechk=1;
 }

 if (cond_2 == 1023)
 {
 system_state = 3;
 timechk=1;
 }
 // if (cond_2 > ELECTRODE_DUMP)
 // {
 // system_state = 3;
 // }

// if (TANK2 > (Tsense2))
// {
// system_state=7;
// }

 // else
 // {
 // system_state = 0;
 // }
 }
}


//------------------------------------------------------------------------------------------
//
//This function displays the currnet state with the help ot the 3 LEDs
//
```

```
//-----------------------------------------------------------------------------------------------
//-----------------------------------------------------------------------------------------------
//////////////////////////////////////////////LOAD
CONTROL/////////////////////////////////////////////////////
//-----------------------------------------------------------------------------------------------

void load_control() // needs to be changed for ED stack control
{

 if (bat_volts > LVD) // check if battery is healthy
 {

 load_status = 1;
 // digitalWrite(ED_PWM_ENABLE_PIN, HIGH); // load is ON
 }
 else if (bat_volts < LVD)
 {
 load_status = 0;
 // digitalWrite(ED_PWM_ENABLE_PIN, LOW); //load is OFF
 }

 else // load will off during day
 {
 load_status = 0;
 //digitalWrite(ED_PWM_ENABLE_PIN, LOW);
 }
}
//-----------------------------------------------------------------------------------------------
//--------------------------------Led Indication------------------------------------------
//-----------------------------------------------------------------------------------------------
//-----------------------------------------------------------------------------------------------
//
// This function is used to turn all the leds off
//
//-----------------------------------------------------------------------------------------------
//void leds_off_all(void)
//{
// digitalWrite(LED_GREEN, LOW);
// digitalWrite(LED_RED, LOW);
// digitalWrite(LED_YELLOW, LOW);
//}
//-----------------------------------------------------------------------------------------------
//------------------------- LCD DISPLAY ---------------------------------------------
//-----------------------------------------------------------------------------------------------
```

```
void lcd_display()
{

 if (lcd_state == 0)
 {
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print("SOL");
 lcd.setCursor(4, 0);
 lcd.write(1);
 lcd.setCursor(0, 1);
 // lcd.print(sol_volts);
 lcd.print("V");
 lcd.setCursor(0, 2);
 // lcd.print(sol_amps);
 lcd.print("A");
 lcd.setCursor(0, 3);
 // lcd.print(sol_watts);
 lcd.print("W ");
 lcd.setCursor(8, 0);
 lcd.print("BAT");
 lcd.setCursor(12, 0);
 lcd.write(2);
 lcd.setCursor(8, 1);
 lcd.print(bat_volts);
 lcd.setCursor(8, 2);

 // if (charger_state == on)
 // lcd.print("on");
 // else if (charger_state == off)
 // lcd.print("off");
 // else if (charger_state == bulk)
 // lcd.print("bulk");
 // else if (charger_state == bat_float)
 // lcd.print("float");
 //-----------------------------------------------------------
 //--------------------Battery State Of Charge ---------------
 //-----------------------------------------------------------
 lcd.setCursor(8, 3);
 if (bat_volts >= 12.7)
 lcd.print("100%");
 else if (bat_volts >= 12.5 && bat_volts < 12.7)
 lcd.print("90%");
 else if (bat_volts >= 12.42 && bat_volts < 12.5)
```

```
lcd.print("80%");
else if (bat_volts >= 12.32 && bat_volts < 12.42)
lcd.print("70%");
else if (bat_volts >= 12.2 && bat_volts < 12.32)
lcd.print("60%");
else if (bat_volts >= 12.06 && bat_volts < 12.2)
lcd.print("50%");
else if (bat_volts >= 11.90 && bat_volts < 12.06)
lcd.print("40%");
else if (bat_volts >= 11.75 && bat_volts < 11.90)
lcd.print("30%");
else if (bat_volts >= 11.58 && bat_volts < 11.75)
lcd.print("20%");
else if (bat_volts >= 11.31 && bat_volts < 11.58)
lcd.print("10%");
else if (bat_volts < 11.3)
lcd.print("0%");

//-------------------------------------------------------------------
//------------------Duty Cycle---------------------------------------
//-------------------------------------------------------------------
lcd.setCursor(15, 0);
lcd.print("State");
lcd.setCursor(19, 0);
lcd.write(3);
lcd.setCursor(15, 1);
lcd.print(system_state);

//--------------------------------------------------------------------
//------------------------Load Status---------------------------------
//--------------------------------------------------------------------
lcd.setCursor(15, 2);
lcd.print("Load");
lcd.setCursor(15, 3);
if (load_status == 1)
{
lcd.print("On");
}
else
{
lcd.print("Off");
}

}
```

```
//-------------------------------------------------------------------
//---------------------------FLOW------------------------------------
//-------------------------------------------------------------------
if (lcd_state == 1)
{
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("FLOW");
lcd.setCursor(5, 0);
lcd.write(4);
lcd.setCursor(0, 1);
lcd.print("PROD");
lcd.setCursor(0, 2);
lcd.print(flowrate + flow_mod);
lcd.setCursor(0, 3);
lcd.print("mL/s");

lcd.setCursor(7, 0);
lcd.print("FLOW");
lcd.setCursor(12, 0);
lcd.write(4);
lcd.setCursor(7, 1);
lcd.print("CONC");
lcd.setCursor(7, 2);
//lcd.print(Pump2);
lcd.setCursor(7, 3);
lcd.print("mL/s");

lcd.setCursor(14, 0);
lcd.print("FLOW");
lcd.setCursor(19, 0);
lcd.write(4);
lcd.setCursor(14, 1);
lcd.print("ELEC");
lcd.setCursor(14, 2);
//lcd.print(Pump3);
lcd.setCursor(14, 3);
lcd.print("mL/s");
}

//-------------------------------------------------------------------
//---------------------------COND------------------------------------
//-------------------------------------------------------------------
```

```
 if (lcd_state == 2)
 {
 lcd.clear();
 lcd.setCursor(0, 0);
 lcd.print("COND");
 //lcd.setCursor(6, 0);
 // lcd.write(6);
 lcd.setCursor(0, 1);
 lcd.print("PROD");
 lcd.setCursor(0, 2);
 lcd.print(cond_0);
 lcd.setCursor(0, 3);
 lcd.write(5);
 lcd.setCursor(1, 3);
 lcd.print("S/cm");

// lcd.setCursor(7, 0);
// lcd.print("FLOW");
// lcd.setCursor(12, 0);
// lcd.write(4);
// lcd.setCursor(7, 1);
// lcd.print("PROD");
// lcd.setCursor(7, 2);
// lcd.print(flowrate + flow_mod);
// lcd.setCursor(7, 3);
// lcd.print("mL/s");

 lcd.setCursor(15, 0);
 lcd.print("State");
 lcd.setCursor(19, 0);
 lcd.write(3);
 lcd.setCursor(16, 1);
 lcd.print(system_state);

 lcd.setCursor(15, 2);
 lcd.print("Load");
 lcd.setCursor(15, 3);
 if (ED_status == 1)
 {
 lcd.print("On");
 }
 else
 {
 lcd.print("Off");
```

```
}
// lcd.clear();
// lcd.setCursor(0, 0);
// lcd.print("COND");
// //lcd.setCursor(6, 0);
// // lcd.write(6);
// lcd.setCursor(0, 1);
// lcd.print("PROD");
// lcd.setCursor(0, 2);
// lcd.print(cond_0);
// lcd.setCursor(0, 3);
// lcd.write(5);
// lcd.setCursor(1, 3);
// lcd.print("S/cm");

lcd.setCursor(7, 0);
lcd.print("COND");
lcd.setCursor(12, 0);
lcd.write(6);
lcd.setCursor(7, 1);
lcd.print("CONC");
lcd.setCursor(7, 2);
lcd.print(cond_1);
lcd.setCursor(11, 3);
lcd.write(5);
lcd.setCursor(8, 3);
lcd.print("S/cm");
//
// lcd.setCursor(14, 0);
// lcd.print("COND");
// //lcd.setCursor(20, 0);
// //lcd.write(6);
// lcd.setCursor(14, 1);
// lcd.print("ELEC");
// lcd.setCursor(14, 2);
// lcd.print(cond2);
// lcd.setCursor(14, 3);
// lcd.write(5);
// lcd.setCursor(15, 3);
// lcd.print("S/cm");


}
```

```
//----------------------------------------------------------------------
//----------------------------MISC-------------------------------------
//----------------------------------------------------------------------
if (lcd_state == 3)
{

lcd.clear();
lcd.setCursor(0, 0);
lcd.print("ED");
lcd.setCursor(4, 0);
lcd.write(7);
lcd.setCursor(0, 1);
//lcd.print(ED_VOLTS);
lcd.setCursor(5, 1);
lcd.print("V");
lcd.setCursor(0, 2);
//lcd.print(ED_AMPS);
lcd.setCursor(5, 2);
lcd.print("A");
lcd.setCursor(0, 3);
//lcd.print(ED_WATTS);
lcd.setCursor(5, 3);
lcd.print("W");

lcd.setCursor(7, 0);
lcd.print("%RMVL");
lcd.setCursor(7, 1);
//lcd.print(%_RMVL)
lcd.setCursor(13, 0);
lcd.print("TANK");
lcd.setCursor(19, 0);
lcd.write(8);
lcd.setCursor(13, 1);
lcd.print("1");
lcd.setCursor(13, 2);
lcd.print("2");
lcd.setCursor(13, 3);
lcd.print("3");
lcd.setCursor(15, 1);
//lcd.print(TANK_1,"%");
lcd.setCursor(15, 2);
//lcd.print(TANK_2,"%");
lcd.setCursor(15, 3);
//lcd.print(TANK_3,"%");
```

```
 }

}
void flow_rate(void)
{
 float liters = pulses;
 liters /= 7.5;
 liters /= 60.0;

 if (system_state == 0)
 {
 if ((desired_flowrate > (flowrate + flow_mod)) && Pump1_pwm < 254 )
 {
 Pump1_pwm = Pump1_pwm + 1;
 }
 else
 {
 if (Pump1_pwm > 40)
 {
 Pump1_pwm = Pump1_pwm - 1 ;
 }
 }
 // if ((desired_flowrate1 > (flowrate1 + flow_mod1)) && Pump2_pwm < 254 )
 // {
 // Pump2_pwm = Pump2_pwm + 1;
 // }
 // else
 // {
 // if (Pump2_pwm > 40)
 // {
 // Pump2_pwm = Pump2_pwm - 1 ;
 // }
 // }
 //
 // if ((desired_flowrate3 > (flowrate3 + flow_mod3)) && Pump3_pwm < 254 )
 // {
 // Pump3_pwm = Pump3_pwm + 1;
 // }
 // else
 // {
 // if (Pump3_pwm > 40)
 // {
```

```
 // Pump3_pwm = Pump3_pwm - 1 ;
 // }
 // }

// analogWrite(PUMP1, Pump1_pwm);
// analogWrite(PUMP2, Pump1_pwm);
// analogWrite(PUMP3, Pump1_pwm);
 }
}
void ED_Control(void)
{
 if (load_status == 1 && ED_status == 1) // both are set on
 {
 digitalWrite(load_pin, HIGH);
 }
 else
 {
 digitalWrite(load_pin, LOW);
 }
}


void valve_control(void)
{
 unsigned long currentMillis1 = millis(); //how many sec go by

 if (system_state == 0) //system_state0 run state
 {
 valve1_off;
 ED_status=1;
 load_status=1;
 analogWrite(PUMP1, 150);
 analogWrite(PUMP2, 150);
 analogWrite(PUMP3, 150);
 }

 if (system_state == 1) //Product drain
 {

 if (timechk==1)
 {
 prevmilli1=currentMillis1;
 timechk = 0;
 }
```

```
analogWrite(PUMP1,200);
analogWrite(PUMP2,75);
analogWrite(PUMP3,150);
valve_on_time = tank_volume / (flowrate+flow_mod); // in seconds
ED_status = 1;
valve1_on;
if (currentMillis1 - prevmilli1 > (valve_on_time * 1000.0)) // used for draining product
{
prevmilli1 = currentMillis1;
valve1_off;
system_state = 4;
}
}
if (system_state == 4) //dilute fill
{
valve1_off;
ED_status = 0;
load_status=0;
valve4_on; // Feed Valve
valve6_on; // Dilute fill Valve
valve7_on;
valve8_on;

analogWrite(PUMP1,254);
analogWrite(PUMP2,0);
analogWrite(PUMP3,0);

if(TANK1 > Tsense1)
{
//Dilutecount = Dilutecount + 1; //flush check
valve4_off; // Feed Valve
valve6_off; // Dilute fill Valve
valve7_off;
valve8_off;
analogWrite(PUMP1,150);
analogWrite(PUMP2,150);
analogWrite(PUMP3,150);
delay(30000);
system_state = 0;
}
}
if (system_state == 2) //concentrate dump
{
```

```
if (timechk==1)
{
prevmilli1=currentMillis1;
timechk=0;
}
analogWrite(PUMP1,150);
analogWrite(PUMP2,150);
analogWrite(PUMP3,150);
valve_on_time = tank_volume / (flowrate+flow_mod); // in seconds
ED_status = 1;
valve2_on;
if (currentMillis1 - prevmilli1 > (valve_on_time * 1000.0)) // used for draining concentrate
{
prevmilli1 = currentMillis1;
valve2_off;
system_state = 5;
}
}
if (system_state == 5) // concentrate fill
{
ED_status = 0;
valve4_on; // Feed Valve
valve8_on; // Concentrate Fill
analogWrite(PUMP1,0);
analogWrite(PUMP2,254);
analogWrite(PUMP3,0);

if(TANK2 > Tsense2)
{
valve4_off; // Feed Valve
valve8_off; // Concentrate Fill
analogWrite(PUMP1,250);
analogWrite(PUMP2,250);
analogWrite(PUMP3,250);
delay(30000);
system_state = 0;
}
}


if (system_state == 3) //electrode dump
{
```

```
 if (timechk==1)
 {
 prevmilli1=currentMillis1;
 timechk=0;
 }
 analogWrite(PUMP1,150);
 analogWrite(PUMP2,100);
 analogWrite(PUMP3,250);
 valve_on_time = tank_volume / (flowrate+flow_mod); // in seconds
 ED_status = 1;
 valve3_on; //elctrode pair
 if (currentMillis1 - prevmilli1 > (valve_on_time * 1000.0)) // used for draining
electrode
 {
 prevmilli1 = currentMillis1;
 valve3_off;
 system_state = 6;
 }
 }
 if (system_state == 6) //electrode fill
 {
 ED_status = 0;
 valve4_on;
 valve6_on;
 analogWrite(PUMP1,0);
 analogWrite(PUMP2,0);
 analogWrite(PUMP3,254);

 if(TANK3 > Tsense3)
 {
 valve4_off;
 valve6_off;
 analogWrite(PUMP1,250);
 analogWrite(PUMP2,250);
 analogWrite(PUMP3,250);
 delay(30000);
 system_state = 0;
 Dilutecount = 0;
 }
 }
 if (system_state==7) //overflow protection
 {
 if (TANK2 > (Tsense2))
 {
```

```
 valve2_on;
 delay(5000);
 valve2_off;
 system_state=0;
 }
 }

}
```