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Desalination and Water Purification Research
and Development Program Report No. 210

System-Level Cost and Performance Optimization for Photovoltaic-Powered Electrodialysis Reversal Desalination

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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14. ABSTRACT
This work investigated and subsequently modelled cost-optimal system architectures for solar powered electrodialysis reversal (EDR) water desalination systems. The highly coupled nature of power, energy, operation time, and cost of photovoltaic (PV) and EDR subsystems presents challenges for cost-optimal systems. We modelled these relationships and developed an optimization framework to discover cost- and performance-optimal system architectures. Results from sensitivity analysis on the cost-structure for this design model revealed that the total cost of the PV-EDR system is highly correlated to the area of ED membranes and the number of electrode pairs. With the developed model and optimization framework, the benchmarked village-scale PV-EDR system analysis indicated that the optimum PV-EDR system had a 44% capital cost reduction from to the rule-of-thumb system design. We investigated the value of cost optimization for a community-scale, off-grid PV-EDR desalination system based on real-world data available from a village in India. We also created updated EDR behavior models and tested a laboratory-scale prototype that used carbon electrodes. Our aim is to use this work as a foundation for achieving the overall goal of reducing the cost and environmental impact of brackish water desalination systems via efficient utilization of renewable energy sources such as solar power.

15. SUBJECT TERMS
electrodydialysis reversal, photovoltaic, brackish water desalination, cost-and performance- optimization

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Prepared for the Bureau of Reclamation Under Agreement No. R16AC00122

by

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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

Acknowledgments

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Acronyms and Abbreviations

AC	alternative current
AEM	anion exchange membrane
CEM	cation exchange membrane
DC	direct current
DWPR	Desalination and Water Purification Program
ED	electrodialysis
EDR	electrodialysis reversal
GEAR	Global Engineering and Research
GHI	Global Horizontal Irradiance
NF	nanofiltration
PSM	pump selection metric
PSO	particle swarm optimization
PV	photovoltaic
Reclamation	Bureau of Reclamation
RO	reverse osmosis
TDS	total dissolved solids
WHO	World Health Organization
USAID	United States Agency for International Development

Measurements

°C	degree Celsius
$	dollar
kWh	kilowatt hour
L	liter
LPH	liters per hour
m^2	square meter
m^3	cubic meter
mg/L	milligrams per liter
ppm	parts per million
V	volt
W	watt

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Executive Summary

This project investigated and subsequently modelled cost-optimal system architectures for solar powered electrodialysis reversal (EDR) water desalination systems under the Bureau of Reclamation's (Reclamation) Desalination and Water Purification Program (DWPR). Cost-optimal system architectures present a significant research challenge because of the highly coupled nature of power, energy, operation time, and cost of photovoltaic (PV) and EDR subsystems. The project was divided into three tasks, described below.

Task 1: Develop an integrated cost and performance model for the PV-EDR system

- *Developed a bottom-up cost model for calculating the capital cost of PV and EDR subsystems.* Our model includes capital costs for ED membranes (in dollars per cell pair [$/cell pair]) and electrodes, pumps, solar panels (in dollars per square meter [$/m^2]), batteries (in dollars per kilowatt hour [$/kWh]) and water tanks (in dollars per cubic meter [$/m^3]). The project's additional work has built on these insights to develop design methods for cost-optimal PV-EDR architectures. Results from sensitivity analysis on the cost-structure for this design model revealed that the total cost of the PV-EDR system is highly correlated to the area of electrodialysis (ED) membranes and the number of electrode pairs. These two components account for 55% of the total cost in the optimized PV-EDR system.

- *Created an energy yield model* that can predict location-specific power output of a given area of photovoltaic panels for use in PV-EDR systems.

- *Formulated an analytical model for optimizing PV-EDR system costs* while maintaining 100% operational availability and producing the specified volume of desalinated water.

Task 2: Optimize the developed PV-EDR model at a system level

- *Benchmarked the cost-optimized PV-EDR system for a specific real-world scenario against a PV-EDR system designed using heuristic guidelines.* The optimized system was found to have a 44% lower capital cost than the system designed using heuristics. This result validates our cost-optimization approach for off-grid PV-EDR brackish water desalination.

- *Created an optimization framework for discovering cost-optimal PV-EDR architectures* for community-scale, off-grid PV-EDR desalination systems. The optimization framework uses heuristic optimization methods to optimize both system performance and cost. The framework can find the optimum system configuration of solar panel area, battery capacity,

water tank, EDR pairs, and batch size, taking advantages of co-optimizing both solar power system and EDR unit.

- *Conducted a multi-objective optimization of a benchmark PV-EDR system.* The Pareto-optimal profiles of total system capital cost and output reliability for the benchmark system was obtained. Results of this optimization are currently being tested in a community-scale experiment in Chelluru, India.

Task 3: Experiment to characterize carbon electrode EDR stacks

- *Built lab-scale carbon electrodes.* Unfortunately, the electrodes were too fragile and eroded too easily to use in testing.

- *Designed, built, and tested a lab-scale EDR system.* Experimental testing of the prototyped lab-scale EDR stack were carried out. The experimental results were used to verify the mathematical models.

1. Introduction

The rising trend of population growth and industrialization is expected to add significant stresses to the available sources of water in the country (National Research Council 2008). Therefore, it is imperative to consider previously untapped sources to add to the existing water portfolio. The virtually inexhaustible availability of sea water and the large quantities of inland brackish water available in the United States (Feth et al. 1965) make these untapped sources vital for addressing future water needs.

Recent advances in desalting technologies (i.e., better membranes and fouling control) and reductions in cost have contributed to the rise of desalination as a viable alternative for meeting present and future needs for potable water. As energy and capital costs are significant contributors to the overall cost of desalination technologies, research on optimal use of primary energy sources (especially means for using renewable energy) is required to sustain this growth trend.

1.1. Brackish Water Desalination

Brackish water is generally defined as saline water with total dissolved solids (TDS) in the range of 500-15,000 parts per million (ppm). Usually, brackish water is not suitable for direct consumption. The World Health Organization (WHO) guidelines for potable water quality suggests that salt content (i.e., TDS) should be reduced to less than 500 parts per million (ppm), along with reducing biological and chemical contaminants to recommended levels (WHO 2004). Brackish water sources are increasingly becoming a significant contributor to the overall water portfolio in the United States (National Ground Water Association 2010). An estimated 77% of the total online desalination plants in the country treat brackish water (Global Water Intelligence 2006). In-depth studies on the quantity and quality of brackish water aquifers in the Unites States have not been conducted. Feth et al. 1965 did conduct a preliminary map of shallow groundwater in the United States, and noted some site-specific data from El Paso, Texas; Indian Wells Valley Water District, California; Sarasota County, Florida; and Colorado River near Andrade, Colorado with TDS concentrations ranging between 1,000 - 3,200 milligrams per liter (mg/L) (see also National Research Council 2008). However, these values may not represent the overall variations in water quality across the country.

The predominant technologies for desalting brackish water can be classified into membrane, thermal, and ion-exchange based processes. Among these methods, membrane-based methods are the most prevalent. Membrane-based processes include technologies such as reverse osmosis (RO), nanofiltration (NF), electrodialysis (ED), and electrodialysis reversal (EDR). RO-based technologies make up the largest market share, accounting for 53% of global desalination plant capacity (Al-Karaghouli and Kazmerski 2011). The National Council of Research’s report on desalination (2008) considers RO-based technologies to be relatively mature, effectively making them a baseline for comparing new techniques and processes.

ED/EDR based systems are an alternative to RO and are specifically suited to community-scale desalination of brackish groundwater. Whereas RO uses mechanical pressure to force water through a semi-permeable membrane, ED/EDR uses an electric potential to attract salt ions to an anode/cathode and trap the ions between ion exchange membranes. ED requires less than half the energy per unit volume of product water than RO for water salinities of approximately 1,000 - 2,000 parts per million (ppm)—drastically reducing the capital cost of an off-grid power system. ED can also reach recovery ratios (product water/input water volumes) of 95% compared to community-scale RO systems that typically only recover 40% (Wright and Winter 2014). Furthermore, if the potential applied to the ED stack is reversed at set time intervals, the membranes have a longer life compared to those in RO. This EDR process effectively switches the diluate and concentrate streams (hence the name “electrodialysis reversal”). ED and EDR have lower vulnerability to feed water changes and less sensitivity to chlorine.

1.2. Electrodialysis Water Desalination

In the ED process, saline water is pumped through a stack of ion exchange membranes (Figure 1). By applying an electric potential across the stack (at the anode and cathode), anions are pulled toward the anode and cations toward the cathode. The ED stack consists of alternating pairs of ion exchange membranes. Anion exchange membranes (AEM) only allow anions to pass through, while cation exchange membranes (CEM) only pass cations. As anions move towards the anode due to the electric potential, they are blocked by the CEM and remain in the concentrate stream. Similarly, cations moving toward the cathode are blocked when they reach the first AEM. In a commercial ED stack, there are multiple alternating CEM and AEM pairs, resulting in alternating compartments of diluted and concentrated saline flow.

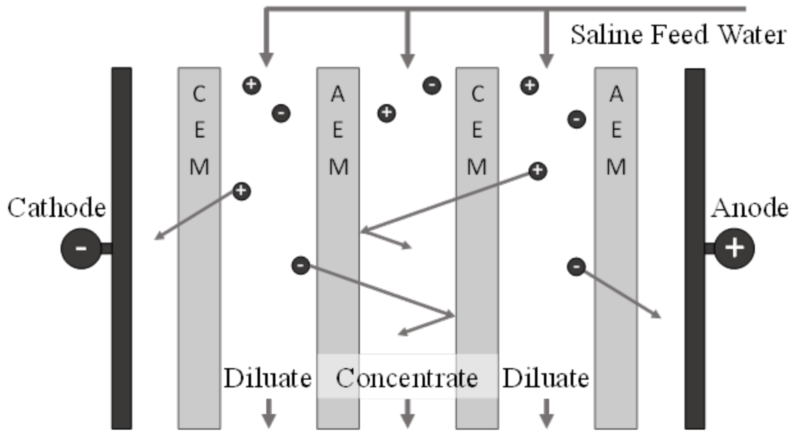

Figure 1.— Schematic representation of the electrodialysis (ED) process. ED pulls ions out of the feed water solution by applying an electric potential across a series of alternating anion and cation exchange membranes.

1.3. V-EDR Water Desalination System

In most current commercial ED/EDR systems, electric power is supplied by connecting the system to the electric grid. Although this setup reduces capital costs by obviating the need for auxiliary power equipment (such as batteries), they are limited by:

(1) **Operational costs for such systems that are heavily correlated to the costs of primary energy production.** Such costs are expected to rise in the near future and consequently, ED/EDR systems that are directly connected to the grid may become economically unattractive.

(2) **The environmental impact associated with operating on-grid ED/EDR systems is significantly correlated to the grid mix.** Close to 80% of the electricity mix in the country consists of 3 fossil fuel sources—petroleum, natural gas, and coal (Energy Information Administration 2015.). Therefore, an increase in demand for on-grid desalination technologies might have a significantly negative impact on climate change.

(3) **Energy conversion losses.** On-grid EDR systems accrue energy conversion losses of about 5 - 10% due to the need to convert alternating current (AC) to direct current (DC) for powering the EDR stacks. On the other hand, PV-EDR systems can directly supply DC power and can be specifically optimized to match the coupled behavior of the PV and ED/EDR subsystems.

For desalination technologies to achieve pipe parity with respect to delivered potable water, to produce one cubic meter (m^3) of water, the desalination process would need to cost less than 50 cents, use less than on kilowatt hour (kWh) of energy and generate less than one pound of carbon dioxide (The White House, 2015). PV-EDR water desalination systems have the potential to meet these targets for pipe parity. To do so, critical research gaps need to be filled with regards to system-level cost and performance optimization of PV-EDR systems.

Using a PV power supply for ED and EDR systems has been well studied (Charcosset 2009). However, most community-scale PV-ED/EDR systems rely on batteries for buffering input power. Additionally, these systems are not optimized to match the coupled behavior of the PV and ED/EDR subsystems. While battery-less PV systems have been field tested for desalination technologies such as reverse osmosis and nanofiltration (Thomson and Infield 2003 and Richards et al. 2005), to the best of our knowledge, no such systems for ED and EDR exist. Furthermore, we could not find any published literature on system-level cost and performance optimization of PV-EDR systems. This knowledge gap is significant, as lowering capital costs for PV-based ED and EDR-based systems can significantly reduce the cost of desalting brackish water. Developing cost and performance optimized PV-EDR systems could disrupt current desalting technologies available for water sources with a TDS up to 2,000 ppm because |(1) ED/EDR requires 50% less energy per cubic meter of produced water when compared to RO and (2) ED/EDR can reach a recovery ratio of 95%.

Wright et al. (2015) designed a PV-EDR system, which won the 2015 USAID Desal Prize (Figure 2), a United States Agency for International Development (USAID)-sponsored competition to create small-scale, low-cost, off-grid desalination systems. Variants of this system were in India and Gaza in 2016. However, this system includes oversized PV and EDR subsystems made from off-the-shelf components and that are not cost-optimized for site-specific environmental parameters. **This research project is critical to create optimized, low-cost PV-EDR systems that couple a minimum power and capital cost PV array with an appropriately sized EDR stack.**

Figure 2.— PV-EDR system designed by Wright et al. (2015) that won the 2015 USAID Desal Prize.

1.4. Project Objectives and Tasks

This project investigated and subsequently modelled cost-optimal system architectures for solar powered EDR water desalination systems. This objective presents a significant research challenge because of the highly coupled nature of power, energy, operation time, and cost of PV and EDR subsystems. Our work is focusing on three tasks which are described in detail in subsequent chapters.

- Task 1: Develop an integrated cost and performance model for PV-EDR
- Task 2: Optimize the developed PV-EDR model at a system level
- Task 3: Experiment to characterize carbon electrode EDR stacks

2. Develop an Integrated Cost and Performance Model for the PV-EDR System

The bottom-up cost and performance model for the PV-EDR is described in this chapter. It includes EDR system model, PV model, PV-EDR coupling model, power system model, pump selection model, and cost model.

2.1. Generalized EDR System Performance Model

The model used for predicting the performance and behavior of batch electrodialysis systems in this work has been described and validated in our previous work (Wright and Winter 2014). A few major concepts are summarized below to highlight their relevance to the overall optimization of a PV-EDR system.

A greater voltage applied across the ED stack induces a larger current. Throughout the batch desalination process, the current moves ions from the diluate stream into the concentrate stream. The variation of concentration in each stream as the batch progresses is shown in Figure 3.

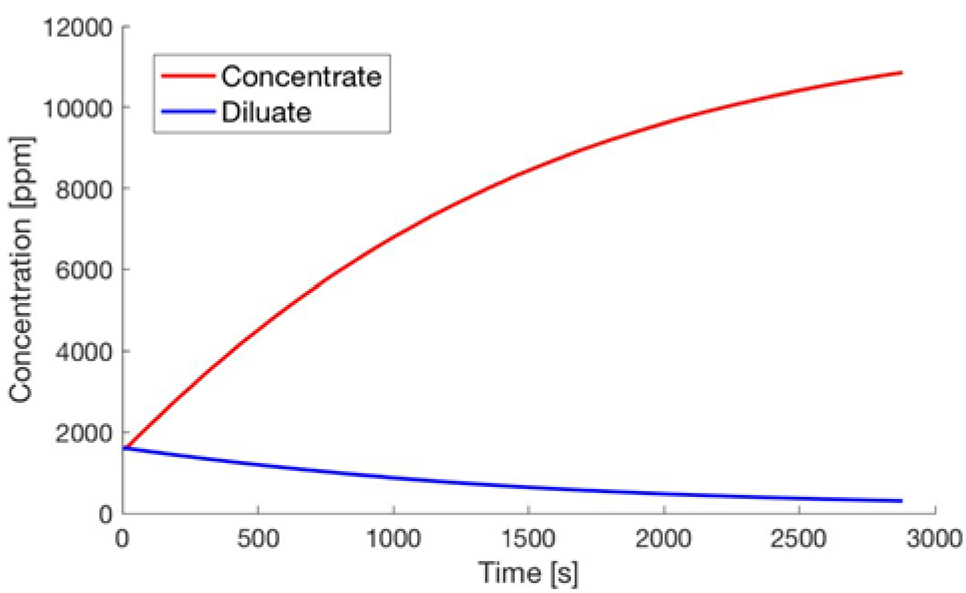

Figure 3.— Concentration of the diluate and concentrate streams as a function of time.

Over the course of a batch process at constant voltage, the current decreases over time, meaning that the desalination process of removing ions from the diluate stream becomes slower and slower. This also results in decreasing power over the course of a batch, as shown in Figure 4.

The overall rate of desalination can be varied using the:

- Voltage applied across the ED stack,
- Number of cell pairs, and
- Varying linear flow velocity through the stack.

Therefore, these are considered as input design parameters. The energy and power profiles are also affected by the desalination rate, as adding more cell pairs and raising the applied voltage requires more power but only produces small differences in terms of the energy per volume of clean drinking water. We considered the limitations of the variables we could change. The applied voltage must be high enough to produce water with the desired TDS level at a specified rate of water production. On the other hand, the applied voltage must not be so high that limiting current density is reached during the desalination process, as this can result in electrolysis (i.e., splitting water into H^+ and OH^- ions).

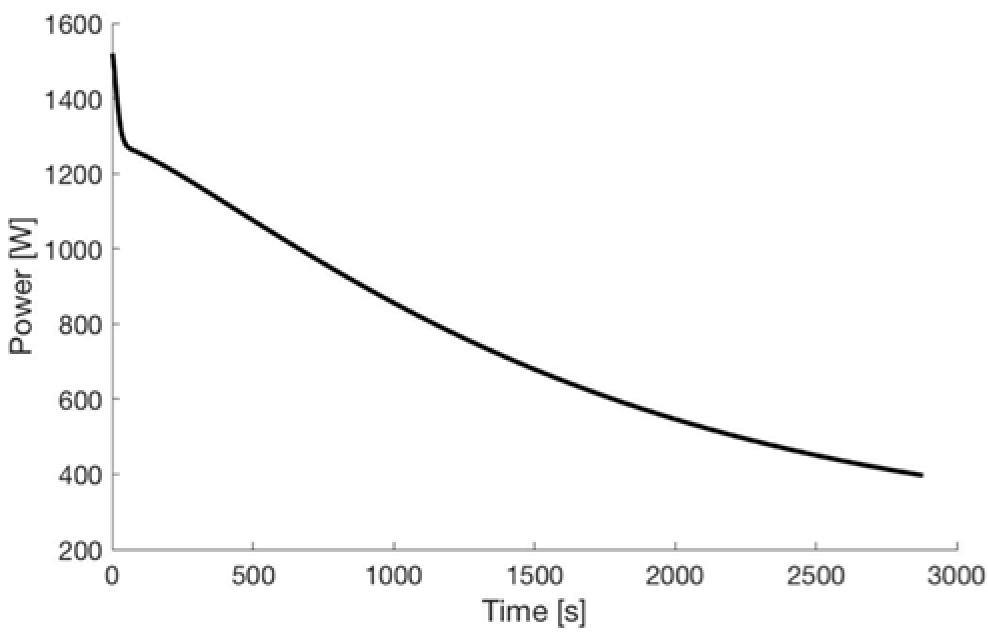

Figure 4.— Sample power profile of a single EDR batch.

2.2. PV System Performance Model

The minimum area of required PV cells ($A_{PV,\min}$) is found by taking the total energy required to desalinate a year's worth of water and dividing by the energy producible by one square meter of PV panels in a characteristic year. In this analysis, a nominal 15% PV energy efficiency, η_{PV} , was adjusted for temperature according to Equation 1:

$$\eta_{PV}(t) = \eta_{PV,norm}[1 + \alpha_p(T_{amb}(t) + k \cdot GHI(t) - T_{std})] \quad (1)$$

Where:
$\eta_{PV,norm}$ is the nominal PV efficiency
α_p is the temperature degradation coefficient
$T_{amb}(t)$ is the ambient temperature
k is the Ross coefficient, which relates irradiance to module temperature
$GHI(t)$ is the global horizontal irradiance
T_{std} is the standard testing temperature

2.3. PV-EDR Coupled Behavior and Simulation Model

We developed a PV-EDR model using the theory described above to design cost-minimized PV-EDR systems for any location. This model is composed of four modules: the EDR module, the pump selection module, the power system module, and the cost module. It was designed to take location-specific parameters and specified values of design variables as inputs and produce a system capital cost and output reliability for the specific design. This process flow is depicted in Figure 5.

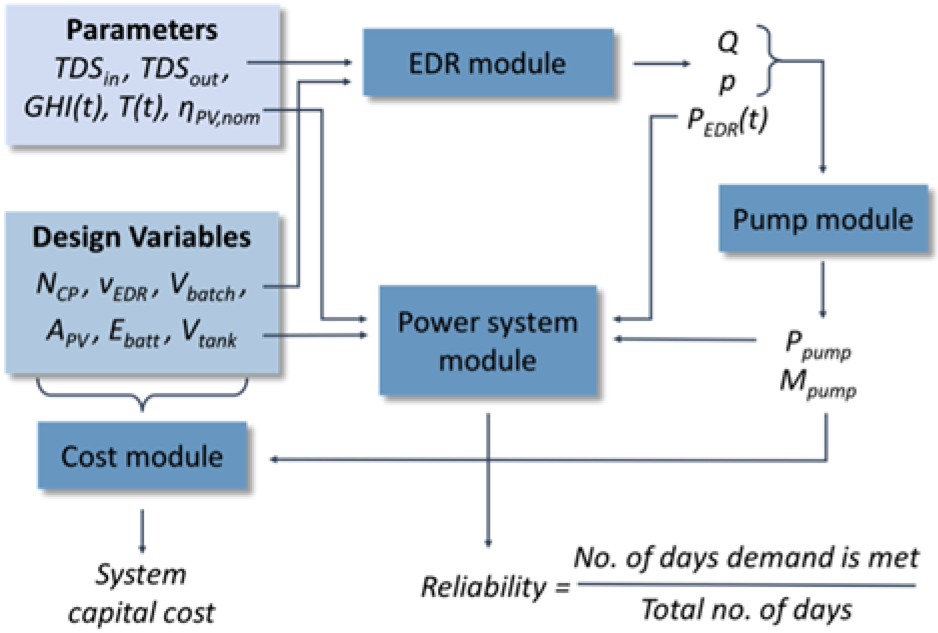

Figure 5.— Flowchart of the PV-EDR coupled behavior simulation model.

Where:

TDS_{in} is the input salinity

TDS_{out} is the output salinity

GHI is the global horizontal irradiance

T is temperature

$\eta_{PV,norm}$ is the nominal PV efficiency

N_{CP} is the number of cell pairs

v_{EDR} is the stack voltage

V_{batch} is the batch volume

A_{PV} is the area of the PV array

E_{batt} is the battery capacity

$V_{tan\,k}$ is the water storage tank volume

Q is the flow rate

p is the pressure

P_{EDR} is the power required for EDR over a batch

P_{pump} is the pumping power

M_{pump} is the pump model

2.4. Pump Selection Module

Based on the EDR system's flow and pressure requirements, an optimal pump must be chosen that minimizes cost, power consumption, and difference between the actual and the desired flow and pressure. Due to a poor correlation between pump performance metrics and cost, a database was created to select specific pump models from.

The pump selection module takes the system curve as well as the desired pressure and flow rate of the EDR system as inputs. These are compared to the pressure-flow curves of the pumps in the database. The intersection points represent the expected actual operating point of the pump. A pump selection metric (PSM) (Equation 2), was created to evaluate the quality of choice of the pump based on pump cost, power consumption, and the difference between the flow rate at the intersection to the desired flow rate.

$$PSM = C_{pump} + 3P_{pump} + 750\left|Q_{desired} - Q_{actual}\right| \tag{2}$$

Minimizing the cost of the pump directly translates to capital cost reductions. Minimizing the nominal power of the pump translates to operating cost reductions due to lower power system requirements. Minimizing the difference between the actual and desired flow rate will decrease the likelihood of the desalination process becoming affected due to a greatly different flow rate. The cost coefficient is 1 because it has a direct correlation to the overall system capital cost. It is estimated here that the power consumption of the pump would add approximately $3 per watt (W) of cost to the PV power system. The flow rate difference coefficient of 750 was determined through numerical comparison demonstrating that it was high enough that the flow differential would be unlikely to exceed 0.1 m^3/hour, and thus would be unlikely to significantly change the predicted pumping pressure required or the desalination process. The pump in the database with the lowest PSM value for the desired flow rate and pressure is chosen for the design.

2.5. Power System Module

Solar is an intermittent power source that varies on daily and seasonal scales. A PV-powered system must have the energy storage capacity to provide the required power to the load despite fluctuations on the daily scale (such as clouds and night-time operation) and variations on the yearly scale, such as lower solar irradiance during the winter season. A combination of PV panels and batteries can meet the power supply profile of a prolonged electrical load. The optimal sizing of the PV array and battery pack depends on location-specific weather data such as irradiance and ambient temperature, the power profile of the load, and the relative cost of PV and batteries.

The power system module uses time-resolved solar irradiance $GHI(t)$, time resolved temperature data $T(t)$, and nominal PV efficiency $\eta_{PV,norm}$ as parameter inputs to calculate the estimated PV efficiency $\eta_{PV}(t)$. Design-specific values of PV array area A_{PV}, battery capacity E_{batt}, and water storage tank volume V_{tank}, as well as the power profiles of the EDR unit $P_{EDR}(t)$ and pump $P_{pump}(t)$ are fed into the module. The energy flow into and out of the batteries and the water flow into and out of the water storage tanks are simulated over the reference year period, and an output reliability corresponding to the percentage of days over the year for which water supply meets demand was calculated. The simulation decides when to run a batch, simulate the charging and discharging of the batteries, and simulate the water withdrawal over the course of a day, according to the logic tree depicted in Figure 6. Within the simulation, the battery maximum discharge depth allowed in the models is 50%, a value selected to prolong battery lifetime.

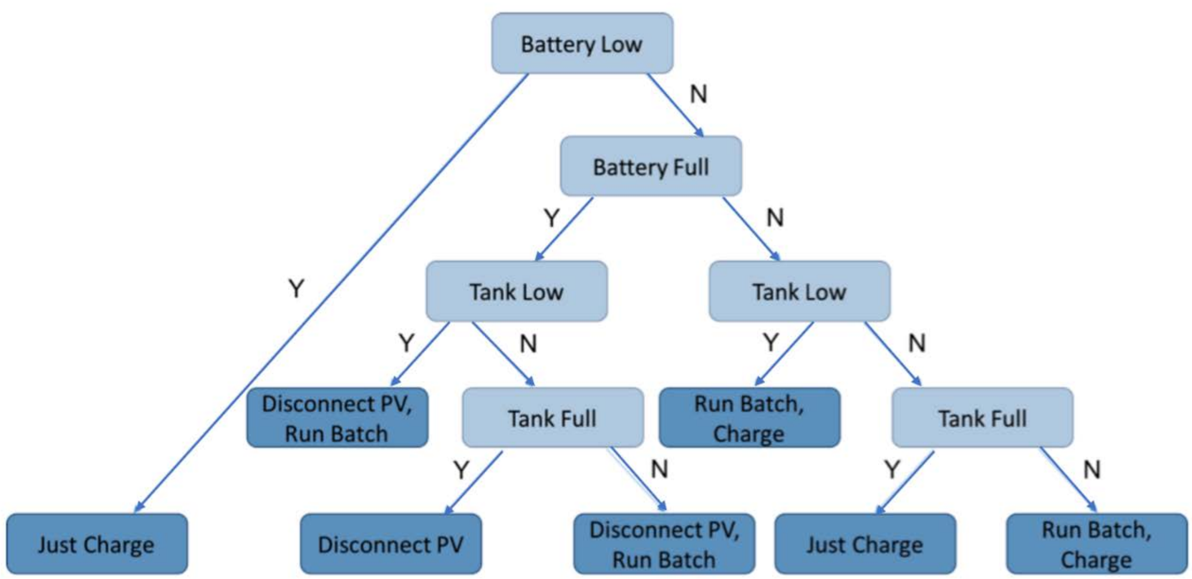

Figure 6.— Power system logic tree for the power system module, detailing the conditions for charging the batteries and running an EDR batch.

2.6. Cost Module

The cost module calculates the cost of the PV-EDR system based on the design variables and the selected pump according to Equation 3:

$$C_{sys} = C_{PV} A_{PV} + C_{batt} E_{batt} + C_{\text{tank}} V_{\text{tank}} + C_{CP} N_{CP} + 2C_{elec} + 2C_{pump} \tag{3}$$

Where:

C_{sys} is the system capital cost

C_{PV} is the PV array cost

C_{batt} is the battery bank cost

$C_{\tan k}$ is the water storage tank cost

C_{CP} is the membrane cell pair cost

C_{elec} is the electrode cost

C_{pump} is the pump cost

A_{PV} is the area of the PV array [square meter, m^2]

E_{batt} is the battery capacity [kilowatt hour, kWh]

$V_{\tan k}$ is the water storage tank volume [cubic meter, m^3]

N_{CP} is the number of membrane cell pairs.

The cost of PV, batteries, and water storage were all determined based on local or commonly used component costs. The cost of ED cell pairs and electrodes are based on estimates from supplier quotations for the GE Model Number AQ3-1-2-50/35 ED stack.

3. Optimize the Developed PV-EDR Model at a System Level

Using the cost and performance model for PV-EDR system, we optimized at a system-level as described in this chapter. Both single-objective and multi-objective optimization are utilized in the system-level optimization and analysis of a benchmarked community-scale PV-EDR system.

3.1. Single-objective Optimization of Cost and Performance

The methodology adopted for cost-optimization is shown in Figure 7. We used a particle swarm optimization (PSO) approach to iteratively perturb initial design variables and obtain the cost-optimal design that met performance specifications.

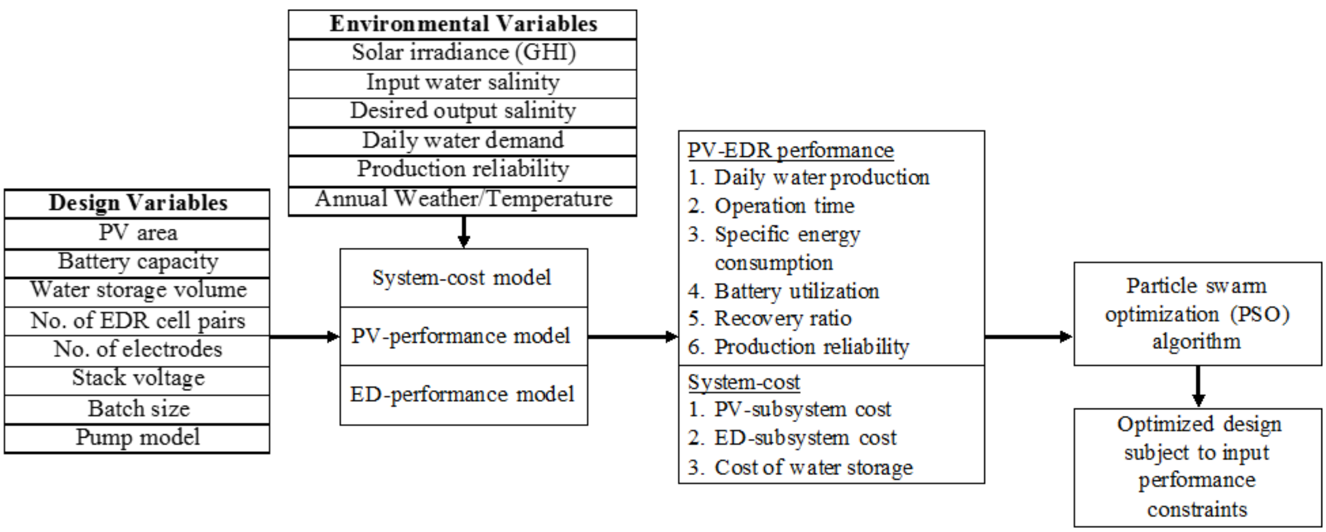

Figure 7.—Power system logic tree for the power system module, detailing the conditions for charging the batteries and running an EDR batch.

Using the optimization framework discussed above, we benchmarked a cost-optimal PV-EDR system architecture with respect to a heuristics-based architecture. Heuristics-based approaches are commonly used in the industry to design PV-EDR systems. To benchmark the systems in a real-world setting, we worked with our corporate partner (TATA Projects, Ltd.) and obtained environmental parameters for Chelluru, a village in India. (Table 1) summarizes the data.

Table 1.— Environmental Variables for Chelluru, India

Parameter	Value
Input TDS	1,600 ppm
Output TDS	300 ppm
Daily water production	10 m^3
Water production reliability	100%
Solar irradiance	2014 GHI data for Chelluru

We estimated the unit costs for PV-EDR system components based on market data from commercial vendors (Table 2).

Table 2.— Unit Component Costs for PV-EDR System

Design Variable	Symbol	Cost
PV area	A_{PV}	\$98/m^2
Battery capacity	E_{batt}	\$150/kWh
Water storage volume	V_{tank}	\$110/m^3
No. of EDR cell pairs	N_{CP}	\$150/cell pair
No. of electrodes	N_{elec}	\$2,000/electrode
Pump model	-	Varies based on pump

The heuristics-based design given in Table 3, created with input from TATA Projects, represents a system that would be designed using common industry practices.

Table 3.— Heuristics-based Design for Chelluru, India

Design Variable	Symbol	Quantity
PV area	A_{PV}	11.6 m^2
Battery capacity	E_{batt}	62.6 kWh
Water storage volume	V_{tank}	5 m^3
No. of EDR cell pairs	N_{CP}	136
No. of electrodes	N_{elec}	2
Stack voltage	V_{EDR}	98 V
Batch size	V_{batch}	1 m^3
Pump model	-	CNP CHL 2-30 (x2)

Based on the input water quality and desired output water quality (Table 1), an EDR stack with a production rate of 1,250 liters per hour (LPH) and 1 m^3 batch size with 136 cell pairs, and a single electrical stage was selected to produce 10 m^3 per day. This flow rate was chosen because it leads to 8 hours of daily operation, which is consistent with an 8-hour daily operation schedule similar to that of an existing on-grid RO system at Chelluru. This ED stack design was the lowest cost found (when considered independently from the PV system) that produced 10 m^3 per day at a 1,250 LPH production rate. A suitable pump that is locally available was suggested by TATA Projects, Ltd. based on their knowledge of the local market. An EDR system with these characteristics has a daily energy requirement, $E_{EDR,d}$, of 10.4 kWh per day. The total system cost for this design was calculated using the cost model described in the previous section.

The system cost for the heuristics-based design of the PV-EDR system was $36,176.

The optimization approach described in the previous section was used to determine the optimal system architecture for a PV-EDR system that meets the requirements of Chelluru. The design variables of the resulting optimized design are shown below.

Table 4.— Cost-optimized PV-EDR System Design

Design Variables	Symbol	Quantity
PV area	A_{PV}	40 m^2
Battery capacity	E_{batt}	15.5 kWh
Water storage volume	V_{tank}	10 m^3
No. of EDR cell pairs	N_{CP}	56
No. of electrodes	N_{elec}	2
Stack voltage	V_{EDR}	40 V
Batch size	V_{batch}	0.5 m^3
Pump model	-	Kirloskar Wonder III (x2)

The total system cost based on these optimized system design variables was found to be $19,833. A breakdown of costs for the two designs in shown in Figure 8.

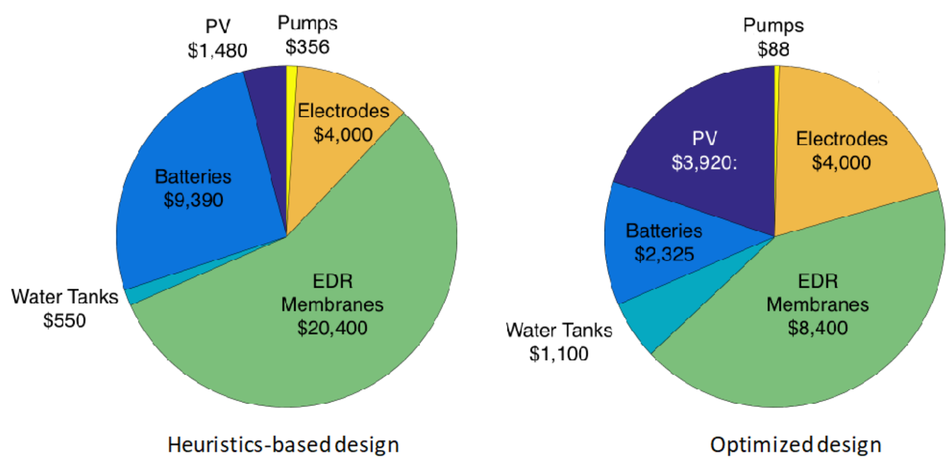

Figure 8.—Cost breakdown for the two PV-EDR system designs. The total cost of the heuristics-based design is $36,176. The optimized design cost is $19,833.

In summary, we investigated the value of cost optimization for a community-scale, off-grid PV-EDR desalination system based on real-world data available from Chelluru, India. We compared a PV-EDR system in which the PV and EDR subsystems were designed independently using (1) commonly used heuristics and (2) cost-optimal architecture. Both systems were designed to desalinate 1,600 ppm water to produce 10 m^3 of 300 ppm product water per day. The optimized system cost was $19,833, compared to $36,176 for the system designed according to heuristics. The optimized system had fewer cell pairs due to their high relative cost, resulting in a slower production rate and longer total operating time to meet water demand. Because of this, energy storage was needed to allow for operation during non-daylight hours. The design also suggests that it is preferable to overproduce energy from more PV than to store more energy in batteries. The optimal design maximized water storage allowed by the site, reflecting the cost effectiveness of storing energy as desalinated water compared to storage in batteries. The significant cost reductions and insights about design tradeoffs gained from this analysis highlight the benefits of optimization for the design of low-cost PV-EDR systems. Future work will examine the optimization sensitivity to changing component costs and different locations in other regions of the world which need a means for off-grid brackish water desalination.

3.2. Multi-objective Optimization of PV-EDR Model

The simulation model of the PV-EDR coupled system, including EDR module, the pump selection module, the power system module, and the cost module, uses location-dependent environmental variables and cost variations as the input variables to calculate the pre-defined objectives for a specific location. This multi-objective optimization and analysis takes into account location-specific environmental and demand parameters, including solar irradiance variations and local water salinity levels. We considered both a performance objective (output reliability) and a system cost objective (system total capital cost) in the multi-objective optimization.

Based on the reliability and cost objectives, the multi-objective optimizer first formulates and converts the multi-objective optimization problem into a series of constrained single-objective optimization problems. The method optimizes one objective by constraining it to satisfactory values before running an optimization algorithm, which requires the prior knowledge of the searching area of the objective. In this case, we set the output reliability as several values from 80% to 100% and used the PSO approach to minimize the system capital cost. The PSO optimization loop keeps searching and exploring the spaces of the design variables for the optimized design in each constrained optimization problem. Therefore, by running all the formulated constrained optimization problems, the Pareto-optimal designs are obtained.

We further used the case study community-scale PV-EDR system to test with the multi-objective optimization theory. The Pareto-optimal profiles of total system capital cost and output reliability for the case study system in Chelluru are shown in Figure 9. As the production reliability constraint is eased, the capital cost drops sharply, suggesting that just a few more days of sunshine are responsible for a significantly lowered the system cost. Specifically, a 2% reduction in production reliability (8 more days of sunshine per year) reduces capital cost by 5.7%, while a 10% reduction in production reliability (37 more days of sunshine per year) reduces capital cost by 10.3%.

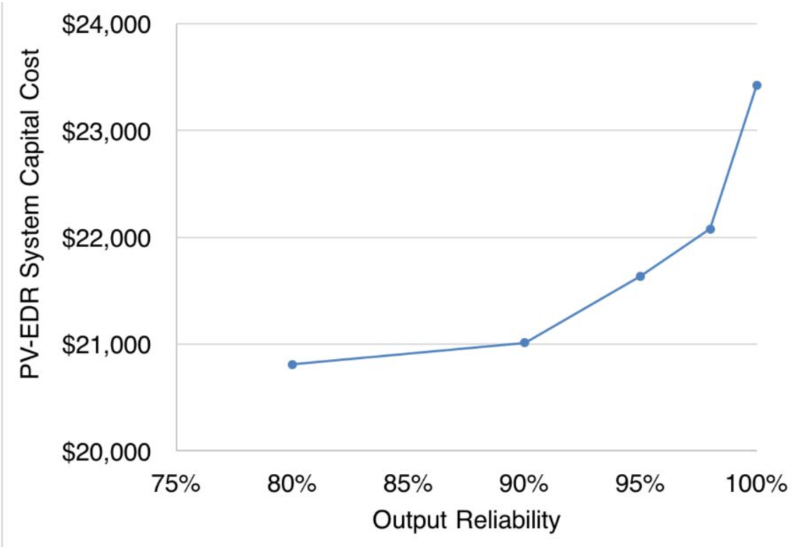

Figure 9.**— Pareto-optimal design of the PV-EDR system with respect to the production reliability and the system capital cost.**

The PV-EDR model was designed so that days with a failed water production volume could be penalized by a cost value. If the cost of a failed day of water production is known (e.g., the cost to truck in water for that day), that cost can be implemented into the model to find a lower cost solution. For the village system, we aimed to provide 100% production reliability relative to the reference year. However, the additional flexibility of multiple water sources could be used to design an adequate PV-EDR solution at lower cost in future work. Furthermore, inputting actual seasonal water demand into the simulation would illuminate whether the days of lower water production (cloudy, rainy days) coincide with days of lower water demand, potentially reducing the number of failed days. In this analysis, the water demand was assumed constant at 10 m^3 per day year-round due to the lack of water demand data.

3.3. Sensitivity Analysis of PV-EDR System Capital Cost to Individual Component Cost

The parameters of the case study system designed for Chelluru were used to conduct a sensitivity analysis on cost and explore avenues for cost reductions. We investigated the sensitivity of the PV-EDR system capital cost to individual component costs of the PV panel, battery, EDR membranes, and electrodes. Figure 10 shows the impact on system cost by changing the cost of each component. From this analysis, it is evident that the total system capital cost is more sensitive to the cost of the membranes than to the cost of batteries or PV panels.

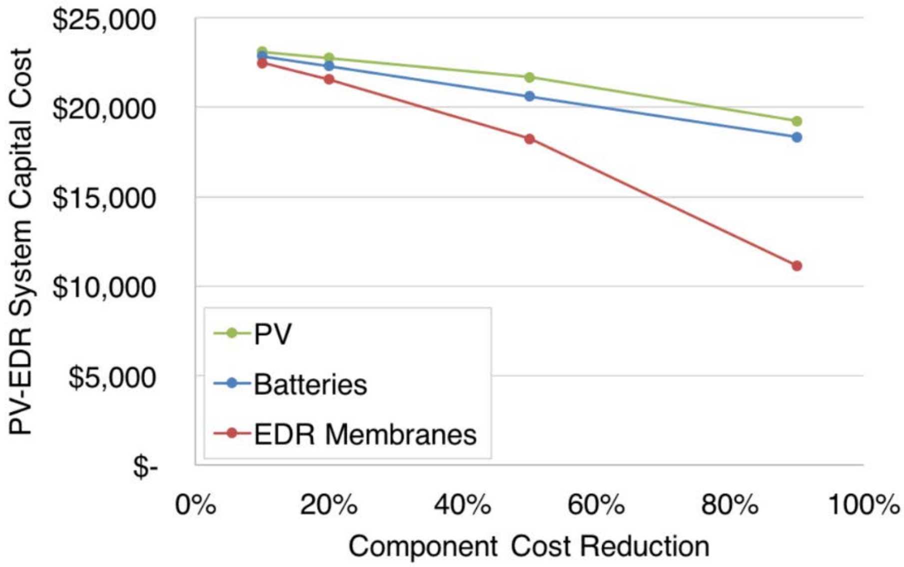

Figure 10.— Sensitivity of PV-EDR capital cost to individual component cost.

Currently, the optimal design is heavily influenced by the high current capital cost of EDR membranes (~$100/m^2). However, it is not unreasonable to assume that ED membrane costs will drop significantly from the current cost of the membranes used in the ED stack specified for the case study system for Chelluru, which is made by GE. Hangzhou Iontech, a company producing and selling ED systems, quoted their membranes cost at $40/m^2. The potential market for PV-EDR systems throughout the world is enormous, indicating that the cost of membranes will be driven down in the future with greater economies of scale. We are currently in discussions with GE water to offer lower cost membranes and demonstrate the large potential market for their products. Using carbon electrodes will also lower the capital costs of ED stacks in the future.

4. Experiment to Characterize Carbon Electrode EDR Stacks

In Task 3, we explored the carbon electrode EDR stacks in the lab-scale EDR system. As our goal was to first characterize the stack behavior, it was prudent and efficient to use a DC power supply. The miniature EDR system was not powered by PV power in our lab for the early stage testing. We can simulate PV-power using a programmable power supply in the future.

4.1. Design and Fabrication of Carbon Electrodes

We designed and fabricated a pair of lab-scale carbon electrodes (Figure 11), made from graphite. These prototypes were not usable because 1) a slow rate of material removal was required during machining to prevent fracture and 2) once integrated into an ED stack, the prototypes eroded—resulting in graphite particles in the electrode rinse stream. Our future work will include further testing of carbon electrode prototypes. This may be possible by casting the electrodes from graphite particles and a binder using a mold, depositing a graphite-binder mixture on a flexible polymer sheet, and using carbon electrodes made commercially (by GE Water).

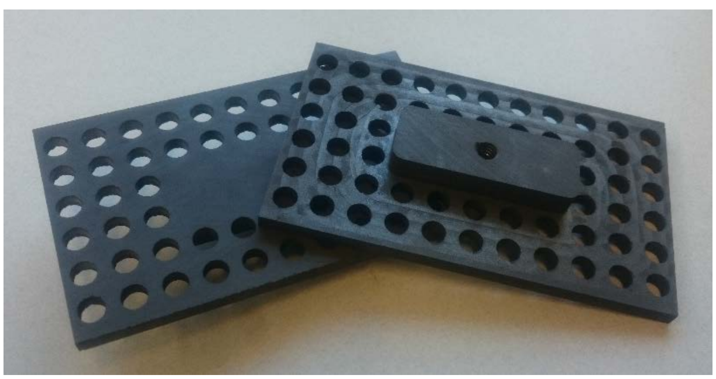

Figure 11.— Pair of lab-scale carbon electrodes.

4.2. Design and Fabrication of a Lab-scale EDR Stack

We have designed and built two prototype lab-scale EDR stacks (Figure 12). The reason for designing and constructing two prototypes was that the first encountered severe corrosion concerns. Collaborating with another one of our corporate sponsors in India, Eureka Forbes, we successfully demonstrated that the small stacks could desalinate brackish groundwater and behaved as predicted by our parametric design theory.

Figure 12.— Photos of the designed and fabricated lab-scale EDR stacks.

One of the major insights gained during this project was that ED stacks can be operated with variable voltage in a batch desalination process. At the beginning of a constant voltage batch process, the diluate stream can carry more current than is conventionally applied, as the voltage is set to reach limiting current density in the dilate stream at the end of the batch (when the stream has the least amount of ions). As a result, a much higher voltage (and thus current and ion removal rate) can be achieved in the beginning of the batch. The voltage is then reduced throughout the batch as the salinity of the diluate stream decreases. Thus, ED stacks for such systems can be made smaller compared to the stacks for static voltage systems when designing for a specific rate of product water output. As the cost of ED stack is roughly proportional to the surface area of the stack and is dominated by membrane and electrode costs, reducing the size of the stack can reduce the capital cost of EDR systems significantly.

The Phase II of this project, which has been awarded by Reclamation, will explore variable voltage ED systems as a means of cost reduction. This project will include a field test of a time-variant system that modulates its power consumption in proportion to solar irradiance.

4.3. Experimental Results of the Lab-scale EDR Stack

We carried out experimental tests of the lab-scale EDR stack prototypes at Global Engineering and Research (GEAR) Lab. At the early stage, the lab-scale EDR stack was operating at invariant conditions, which are constant voltage and constant flow rate. We tested feed water salinity between 1,000-2,000 ppm, which is the range covering most brackish water. Parameters used for the tests are listed in Table 5. Some of the experimental results are plotted in Figure 13, including both diluate conductivity and current with respect to operating time during the test.

Table 5.— Cost-optimized PV-EDR System Design

Variables	Quantity
Flow rates	108 LPH
Diluate volume	1.8 L
Brine volume	0.3 L
Recovery	0.86
Feed salinity	1,000 ppm
Diluate salinity	100 ppm
Stack voltage	20 V

L = liter

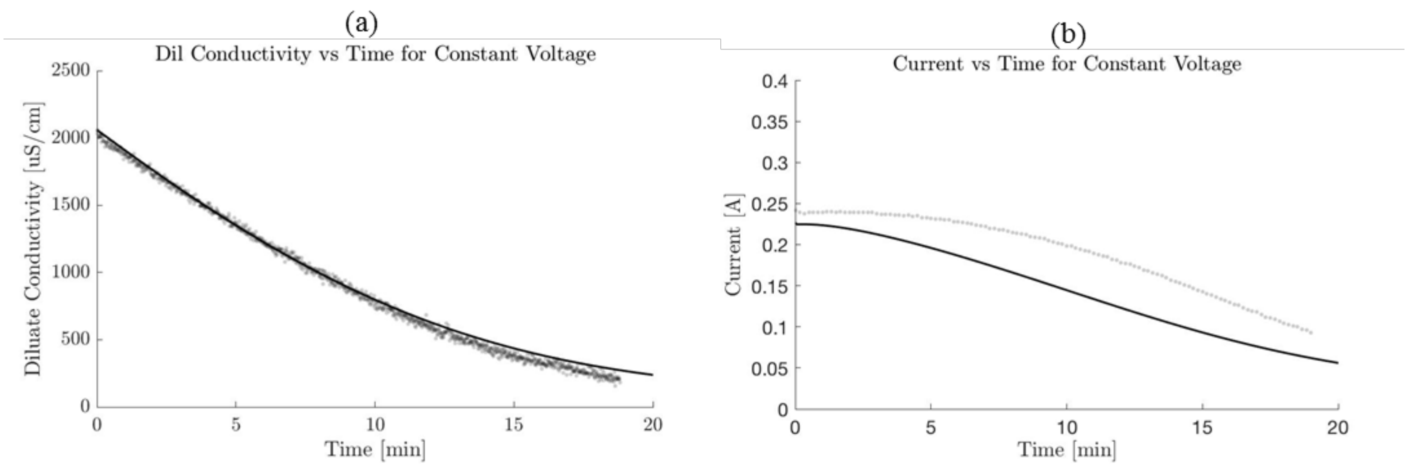

Figure 13.— Experimental results of the lab-scale EDR stack. Conductivity of diluate flow and current are shown in (a) and (b), respectively. Solid lines are theoretical predictions; dots are experimental data.

According to the results in Figure 13(a), experimental results of diluate conductivity (which represents diluate salinity) are very close to the modeling results, indicating high accuracy of mass transfer model of ion across membranes in EDR unit. In addition, the current profile plotted in Figure 13(b) also showed reasonable agreement between experimental and modeling results. Therefore, the mathematical model of lab-scale EDR stack will be used as the basis for exploring time-variant EDR operation for Phase II of this project.

5. Conclusion

During the investigation, an integrated cost and performance model for the PV-EDR system was developed by resolving the highly coupled nature of power, energy, operation time, and cost of PV and EDR subsystems. Our work focused on modeling these relationships and developing an optimization framework to discover cost- and performance-optimal system architectures. We also created updated EDR behavior models and a laboratory-scale prototype that utilized carbon electrodes. The work in this project is a foundation for achieving the overall goal of reducing the cost and environmental impact of brackish water desalination systems via efficient utilization of renewable energy sources such as solar power.

With the developed model, the total cost of the PV-EDR system is highly correlated to the area of ED membranes and the number of electrode pairs play a significant role on the cost-structure for this design model. Then, the case study of the benchmarked the cost-optimized PV-EDR system for a specific real-world scenario against a PV-EDR system designed using heuristic guidelines indicated that the optimized system was found to have a 44% lower capital cost than the system designed using heuristics.

Furthermore, we designed, built, and tested lab-scale EDR system. Experimental testing of the prototyped lab-scale EDR stack showed the EDR behaviors and validated the developed EDR model. We also built and tested lab-scale carbon electrodes. Unfortunately, the electrodes were too fragile, and eroded too easily, to use in testing.

Major conclusions include:

- The optimized system had fewer cell pairs due to their high relative cost, resulting in a slower production rate and longer total operating time to meet water demand. Because of this, energy storage was needed to allow for operation during non-daylight hours.

- It is preferable to overproduce energy from more PV than to store more energy in batteries

- A few days of more sunshine are responsible for a significantly lower system cost.

- The total system capital cost is more sensitive to the cost of the membranes than to the cost of batteries or PV panels.

- ED stacks can be operated with variable voltage in a batch desalination process.

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