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Desalination and Water Purification Research and Development Program Report No. 217

Pilot Testing Cost- and Performance-Optimized Photovoltaic-Powered Electrodialysis Reversal Desalination Systems

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14. ABSTRACT
The goal of this project is to experimentally validate cost and performance optimized architectures for community-scale, off-grid, solar-powered electrodialysis reversal (EDR) brackish water desalination systems. This project builds on the research generated from the lab-scale project ongoing with the PIs (R16AC00122: System-Level Cost and Performance Optimization for Photovoltaic-Powered Electrodialysis Reversal Desalination). The proposed research uses the analytical models created during the lab-scale project for predicting cost and performance of photovoltaic-powered (PV) EDR systems, and the methodology for co-optimizing PV and EDR subsystems. These analytical models are used to design and build optimized PV-EDR architectures, which are experimentally tested at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico. The achievements within this project include: (1) we experimentally validate our analytical models and optimization methods for creating cost- and performance-optimal PV-EDR architectures that lower the costs of potable water production by more than 40 percent compared to non-optimized PV-EDR architectures; (2) we implement and evaluate the feasibility of voltage and flow control systems for PV-EDR; and (3) we design and build pilot-scale time-variant PV-EDR prototypes and experimentally test it at BGNDRF. The experimental testing demonstrates the time-variant system's high effectiveness of using variable solar power to produce water efficiently. The improved conversion from variable solar power to freshwater can potentially enable producing same amount of water during the daytime when the sun is available, indicating a further 10 to 20 percent cost reduction associated with battery storage in the traditional static-operated systems.

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by

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Mission Statements

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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.

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Acronyms and Abbreviations

AC	Alternating Current
AEM	Anion Exchange Membrane
CEM	Cation Exchange Membrane
DC	Direct Current
ED	Electrodialysis
EDR	Electrodialysis Reversal
GEAR	Global Engineering and Research
NF	Nanofiltration
PV	Photovoltaic
RO	Reverse Osmosis
TDS	Total Dissolved Solids
WHO	World Health Organization

Measurements

m^2	square meter
m^3	cubic meter
$	dollar
kWh	kilowatt hour
°C	degree Celsius
V	volt
ppm	parts per million
TDS	total dissolved solids
mg/L	milligram per liter
L/min	liters per minute
L	liter
µS/cm	micro-Siemens per centimeter

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Executive Summary

This report summarizes the work performed under the Bureau of Reclamation Desalination and Water Purification Research and Development Program (Award No. R17AC00150). The goal of this project is to experimentally validate cost- and performance-optimized architectures for community-scale, off-grid, solar-powered electrodialysis reversal (EDR) brackish water desalination systems.

Within the investigation, we validae our analytical models and the system-level optimization framework for designing such systems based on location-specific performance parameters. These parameters include groundwater ion concentrations, solar irradiation, spectrum, seasonal changes, and available photovoltaic (PV) technology. In addition, we develop and implement a voltage and flow rate controller for the time-variant electrodialysis (ED) system, and experimentally characterize our prototype. This is among the first community-scale experiments to investigate the behavior of variable voltage- and flow-based control on ED systems.

Compared to constant voltage and flow ED systems, the preliminary experimental results demonstrate that the voltage and flow-controlled ED system is capable of fully using an arbitrarily variable power source to desalinate groundwater. Implementing variable voltage and flow enables the controller to increase the system desalination rate to maximize production during mid-day, when solar resources are abundant, and adapt the operating conditions to continue providing the best possible performance when solar resources are low or fluctuating.

Single-batch experimental tests indicate that the time-variant operation provides an extended operational window for using variable power sources. This operation allows for the use of two times more available solar power and doubling of the desalination rate compared to the static operation of the same ED stack and PV panels. The full-day experimental tests also demonstrate that the voltage- and flow-controlled PV-EDR system has more than two times the overall solar energy use than that of the co-optimized static PV-EDR pilot system in Chelluru, India.

The demonstrated performance improvement also offers the potential to create PV-EDR systems that can meet the same daily production rate as a static-control system, but within a significantly reduced operational time and without the need for energy storage. Using the voltage and flow control strategy developed and validated here, a simulated time-variant ED system can produce 31 percent more water in 17 percent less operational time compared to the static ED system built in Chelluru, given the same weather conditions. These results indicate the potential of the time-variant PV-EDR systems and lay the foundation for further integration of this operational innovation with new stack designs and system-level optimization, with the goal of developing cost- and performance-optimized PV-EDR systems.

1. Introduction

Rising population growth and industrialization are expected to significantly stress the available water resources in the United States (U.S. Geological Survey, 2013). Adding previously untapped water sources to the existing portfolio therefore becomes vital for addressing future water needs. These potential sources include the inexhaustible supply of seawater, as well as large quantities of inland brackish water available in the United States (U.S. Geological Survey, 1965). More than 50 percent of the world's groundwater is brackish, and is available at elevations below 1,000 feet across much of the contiguous United States (U.S. Geological Survey, 1965). Both of these sources, however, are unsuitable for direct use without treatment due to their salt and mineral content.

The National Research Council's report on the state of desalination technologies in the United States (National Research Council, 2008) states that both brackish water and seawater sources will need to be tapped to meet future water supply needs. To make such sources economically and environmentally viable, it is necessary to research novel desalination system configurations that can use renewable sources of primary energy such as solar, wind, and tidal power.

Prior studies have shown that PV-EDR systems have the potential to provide disruptive, economically sustainable water solutions, particularly in rural, off-grid communities with brackish groundwater (Campione, et al., 2018). These insights led to the award of the 2015 USAID Desal Prize to Prof. Winter's group for demonstration of a successful village-scale PV-EDR system. When compared to the more commonly used technology of reverse osmosis (RO), PV-EDR reduces energy consumption per unit volume of product water by half and improves recovery of input water from 40 to 95 percent. This can be a critical factor in making desalination viable for communities that lack access to reliable grid-based electricity. While the use of solar power for PV-EDR systems decreases the operational cost of water desalination, it also increases the capital cost. The decreased operational cost comes from removing all expenditures related to grid electricity. The increased capital cost comes from the panels, supporting control system, inverters, and batteries. Understanding these tradeoffs in system and cost is critical to designing an optimal system for a given market.

1.1. Brackish Water Desalination

The World Health Organization (WHO) guidelines for potable water quality suggest that in addition to reducing biological and chemical contaminants to recommended levels, salt content (total dissolved solids, or TDS) should be reduced to less than 500 ppm (World Health Organization, 2014). Brackish water sources are increasingly becoming a significant contributor to the overall water portfolio in the United States (National Research Council, 2008). An estimated 77 percent of total online desalination capacity in the country sources brackish water

(World Health Organization, 2014). More than 60 percent of the land area of India is underlain with groundwater with salt contents above the recommended level (500 mg/L), particularly in rural areas (Central Ground Water Board Ministry of Water Resources, 2010). Therefore, brackish water desalination plays a vital role in potable water production for rural communities.

Membrane-based methods are the most prevalent, accounting for 56 percent of the total capacity of desalination plants currently operating in the world (U.S. Geological Survey, 2013). Membrane-based processes include technologies such as RO, nanofiltration (NF), electrodialysis (ED), and electrodialysis reversal (EDR). RO-based technologies make up the largest market share, accounting for 53 percent of global desalination plant capacity (National Ground Water Association, 2010). The National Research Council's report on desalination (National Research Council, 2008) considers RO-based technologies to be relatively mature, effectively making them a baseline for comparing new techniques and processes.

An alternative to RO that is specifically suited to community-scale desalination of brackish groundwater is ED/EDR-based systems. We define the size of a community as approximately 3,000 people, who would require about 10,000 L/day of drinking water, per WHO standards (2 to 4.5 liters per person per day). This is a characteristic target system size; the theory that is produced under this research program aims to enable PV-EDR systems to be designed for smaller and larger applications. 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 or cathode and trap them between ion exchange membranes. For water salinities in the range of interest, approximately 1,000 to 2000 parts per million (ppm), ED requires less than half the energy per unit volume of product water when compared to RO, drastically reducing the capital cost of an off-grid power system. ED can also reach recovery ratios (product water/input water volumes) of 95 percent; in contrast, community-scale RO systems typically only recover 40 percent (Campione, et al., 2018). 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 process switches the diluate and concentrate streams and is termed as electrodialysis reversal (EDR). ED and EDR also 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 toward 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.

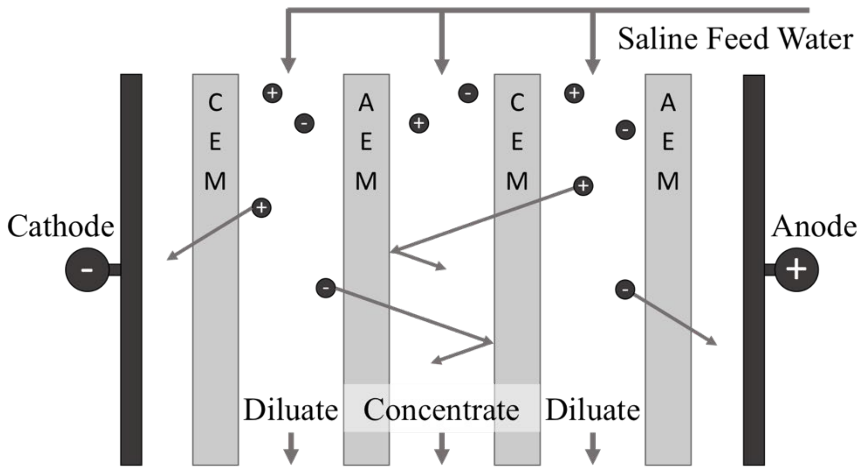

Figure 1. The ED process pulls ions out of the feed water solution through the application of an electric potential across a series of alternating anion and cation exchange membranes (AEM, CEM).

1.3. PV-EDR Brackish Water Desalination Systems

For desalination technologies to achieve pipe parity with respect to municipally delivered potable water, the targets that have been proposed by The White House Report on water technology innovation are less than $0.50 spent in total cost, 1 kWh of energy consumed, and less than 1 lb. of carbon dioxide generated, over the course of producing 1 cubic meter of water (National Research Council, 2008). Our preliminary estimates for the PV-EDR system that won the USAID Desal Prize indicated that it is likely possible to achieve 0.5 kWh of energy consumed, and 0.1 lb. of carbon dioxide generated (for an intensity of 100 g eq. CO_2/kWh (Global Water Intelligence, 2006)) per cubic meter of water produced, assuming an input TDS of 1,800 ppm. Our USAID Desal Prize prototype, which was tested at the Brackish Groundwater National Desalination Research Facility (BGNDRF) in Alamogordo, New Mexico, produced water for $2.26 per cubic meter, considering a 10-year amortization of the capital cost. The largest drivers for cost in our prototype were the capital costs due to over-sized PV and EDR subsystems purchased from third-party vendors. Our models for PV-EDR-based desalination indicate that optimizing the size of these systems and manufacturing ED stacks in OEM-owned, large-scale production facilities in India can reduce the total cost of product water to $0.68 per cubic meter. Therefore, optimizing PV and EDR subsystems presents a strong potential for improving performance of PV-EDR-based desalination with regard to pipe parity. Our initial estimates show that optimized PV-EDR architectures can potentially reduce capital and operational costs by about 50 percent when compared to non-optimized PV-EDR systems.

While the use of a PV power supply for ED and EDR systems has been well studied (Ortiz, et al., 2006), 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 tested for RO and NF processes (Adiga, et al., 1987) (Kuroda, et al., 1987), 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. Given the facts that: (1) ED/EDR requires 50 percent less energy per cubic meter of produced water when compared to RO, and (2) ED/EDR can reach a recovery ratio of 95 percent, the development of cost- and performance-optimized PV-EDR systems could disrupt current desalination technologies available for brackish water sources (Wright & Winter V, 2014).

1.4. Cost- and Performance-Optimized PV-EDR Water Desalination Systems

Our previous lab-scale research (R16AC00122: System-Level Cost and Performance Optimization for Photovoltaic-Powered Electrodialysis Reversal Desalination) addressed the knowledge gap in co-optimizing PV power systems and EDR stacks to create cost- and performance-optimized PV-EDR system architectures. This presents a significant research challenge, as modeling the multi-objective optimization framework requires quantification of system performance for PV-EDR systems, which can be characterized using multiple interrelated metrics such as recovery rate, ion removal rate, volume of product water per unit primary energy, and total operating hours. Furthermore, these metrics are also a function of location-specific environmental variables such as solar irradiance, spectrum, and weather.

Our preliminary results indicate that design parameters in PV-EDR desalination systems that significantly affect capital cost include ion exchange membrane pair area, electrode area, solar panel area, pumping power, battery backup capacity, and volume of water storage. To significantly reduce capital and operational costs of the overall PV-EDR system, we are extending state-of-the-art cost models so that they can be used in our optimization algorithms for discovering cost-optimal system-level configurations for the PV and the EDR subsystems. Given location-specific environmental variables, the optimization algorithm generates global and off-the-shelf optimal component specifications.

A fundamental, novel research insight that has emerged from our lab-scale work is that time-variant voltage and flow control of ED stacks offers a previously untapped means for further reducing the capital and operational costs of PV-EDR systems. Current community-scale PV-EDR systems (including our previous designs) apply a constant voltage across the ED stack. This voltage is determined by the limiting current density of the stack at the desired salinity of product water. Additionally, such systems do not employ any specific control strategies for flow rates of feed water or concentrate (in the case of batch operation) into the ED stack. Our analytical models for ED-based desalination show that time-variant control strategies for applied voltage and feed flow rate can result in: (1) reduction of the overall stack size and hence the capital cost for ED-based systems; and (2) reduction in operational overhead of PV-EDR systems due to the ability to match the production rates of desalinated water throughout the day with the amount of available solar irradiance. We also anticipate such systems can operate with minimal or no energy storage, leading to the reduced cost of battery backup systems.

2. Design of Co-Optimized PV-EDR Systems

In our previous work, we developed an analytical performance model for existing, commercially available EDR stacks (Wright & Winter V, 2014). This model allows us to predict the performance of an EDR system in which the feed stream and the concentrate stream operate in continuous or batch modes. Here, the performance of the EDR system can refer to multiple measurements such as recovery rate, ion removal rate, volume of product water per unit primary energy, and total operating hours, which characterize the overall efficiency of the desalination process. Our prior research project (R16AC00122: System-Level Cost and Performance Optimization for Photovoltaic-Powered Electrodialysis Reversal Desalination) extended this model by creating predictive analytical models for system-level cost and performance. These models are used to develop frameworks for co-optimizing the PV power system and EDR systems. The resulting knowledge helped us design globally optimal PV-EDR systems that use off-the-shelf parts and new configurations of ED stacks.

For the current research project, the level of flexibility available for designing the EDR system is restricted by the number of configurations afforded by the selected ED stack. We included these constraints into our co-optimization models and designed cost- and performance-optimized pumping and PV-power systems for a specific configuration of the ED stack.

This project used a Suez manufactured ED stack that has been purchased by the GEAR Lab through in-kind research funding from a complimentary project focused on optimizing power production and water storage for PV-EDR brackish water desalination. As a part of this complementary project, we designed and built a PV-EDR system for rural India to explore strategies for location-specific cost optimization of PV power systems by exploring buffering strategies using (1) energy storage systems such as batteries; and (2) variable levels of product-water storage.

2.1. The Co-Optimization of the PV and EDR Subsystems

An optimized PV-EDR system design should achieve high technical performance, low capital cost, and low lifetime cost. This optimization depends on a series of complex, interdependent trade-offs between elements, such as capital cost versus operational cost, pumping power versus ED process power, etc. Wright et al. (2018) recently published a robust model of ED that can predict desalination rate, limiting current density, and energy consumption of pumping and ion removal across membranes. The model was validated at two diverse size scales and ED stack designs without explicitly deriving empirical parameters or conducting prior system characterization, which provides a powerful tool for designing ED systems. Leveraging the robustness of the ED model, Bian et al. (2019) created a co-optimal system design theory that articulated the solar power system (PV and battery storage) and ED system behavior in a holistic model, allowing these systems to be cost- and performance-optimized at the same time. Using this theory, the co-optimal PV-EDR design achieved a 42 percent reduction from the $40,138 capital cost of a PV-EDR system designed using a conventional method of designing the desalination sub-system and the power sub-system sequentially (Bian, et al., 2019). The cost-saving strategies of the co-optimal PV-EDR system include: 1) long daily operating hours with relatively low production rates can reduce the required number of membrane pairs, which reduces the capital cost of membranes; and 2) flexible schedule of ED operation and storage of excessive water when good solar resource is available on sunny days, as water storage is cheaper than the equivalent energy storage in batteries (Bian, et al., 2019). To understand and further improve this theoretical co-optimal PV-EDR design (Bian, et al., 2019), experiments in the field are necessary to identify and evaluate the pain points and real-world factors. These insights are critical to realizing a cost-effective, off-grid water solution.

Due to the coupled nature of the PV and EDR subsystems, it is nontrivial to determine what configuration of the ED stack, pump models, and PV panel area; the capacity of batteries; and water storage tanks will lead to the lowest capital cost system, and a full-factorial study would be too time-consuming and inefficient. To deal with this issue, the conventional engineering practice finds a system design based on empirical assumptions. Alternatively, Bian et. al. (2019) proposed a PV-EDR performance model that couples the PV, batteries, water tanks, pumps, and ED stack subsystems into a holistic model, as illustrated in Figure 2. The holistic model can more efficiently determine a near-cost-optimal combination of these components and the accompanying operational specifications, because the holistic model enables the design process co-optimizing the solar power subsystem (the PV panel and the batteries) and the ED desalination subsystem (the ED stack and the water tanks) simultaneously.

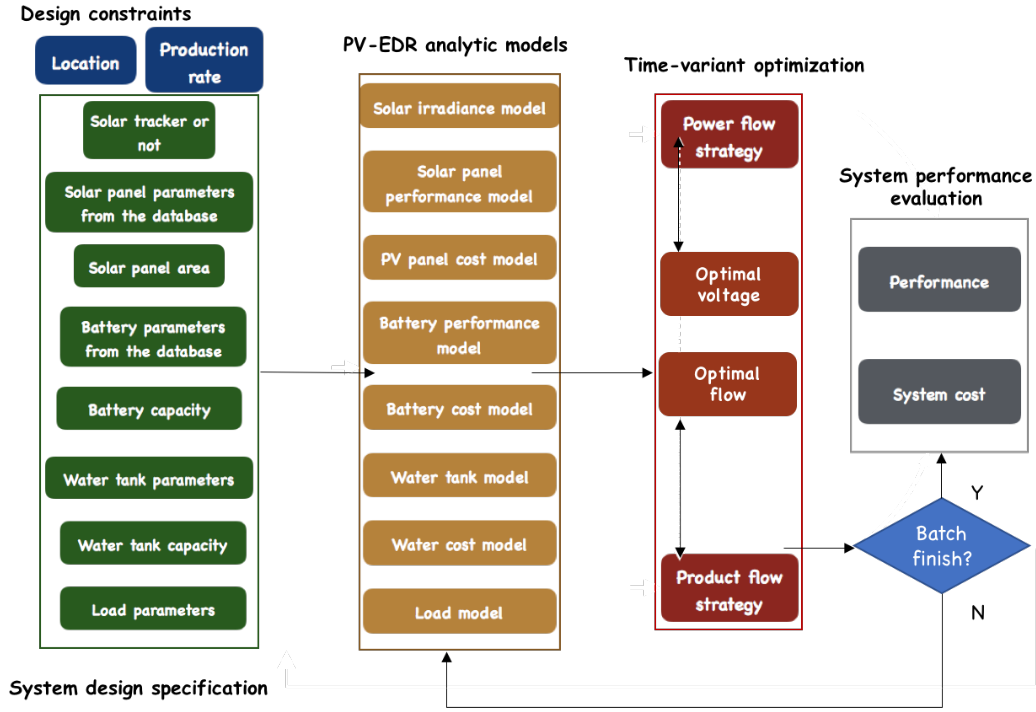

Figure 2. Simulation framework of the time-variant PV-EDR system.

A co-optimal community-scale PV-EDR system is designed given specific location-dependent weather and water demand in rural India. The system design in Chelluru (an Indian village 70 km northeast of Hyderabad with a population of more than 2,000 people and a groundwater salinity of 1,300 to 1,500 mg/L, varying with the seasons) is selected for the field test. Currently, the local drinking water needs in Chelluru are primarily met by an on-grid RO brackish water desalination plant, which has been installed, operated, and maintained by Tata Projects Ltd. for 8 years. The Chelluru village was chosen for this project to allow for convenient operation and maintenance by the current operator in the village, and because it is an RO system site within accessible distance from the Tata Projects headquarters, so that the staff can regularly monitor the system performance and collect data on the time-variant water consumption in the village.

2.2. Field Testing of the Co-Optimized PV-EDR System

The prototyped PV-EDR system is shown in Figure 3 and its specifications are listed in Table 1. Figure 4 shows the performance of the PV-EDR pilot on a typical day of operation. Figure 4a demonstrates 13 ED batches were achieved on that day and produced 5.9 m^3 of potable water. From Figure 4a, the operation time was slightly longer in the pilot than in the simulation. This is mainly due the time required to adjust the pH immediately after filling the tanks (about 15 minutes per batch), which was initiated to mitigate scaling encountered during the first few months of testing. During pH adjustment, two pumps were running to recirculate and mix both tanks, which can be seen in the measured ED power profile in Figure 4b and Figure 4a. The energy consumption due to acid dosing was very small (about 2 percent of the total ED specific energy consumption for producing water in kWh/m^3), and the temporary manual acid dosing procedure is likely to be improved. Therefore, at this stage, the pumping power and time required for pH adjustment were not considered in the simulation.

From Figure 4a, we can observe the daily battery cycle of the PV-EDR system. We take the initial energy capacity of the battery as a reference set to zero kWh. When desalination started at 7:00 a.m., the battery was discharged to power the first batch before the sun was fully up. With the increase of solar power, the energy flow of the battery started to increase until the battery was fully charged at mid-day. The battery started to discharge again at 5:30 p.m., when the PV power became insufficient. The battery bank was large enough to power the system over the entire day.

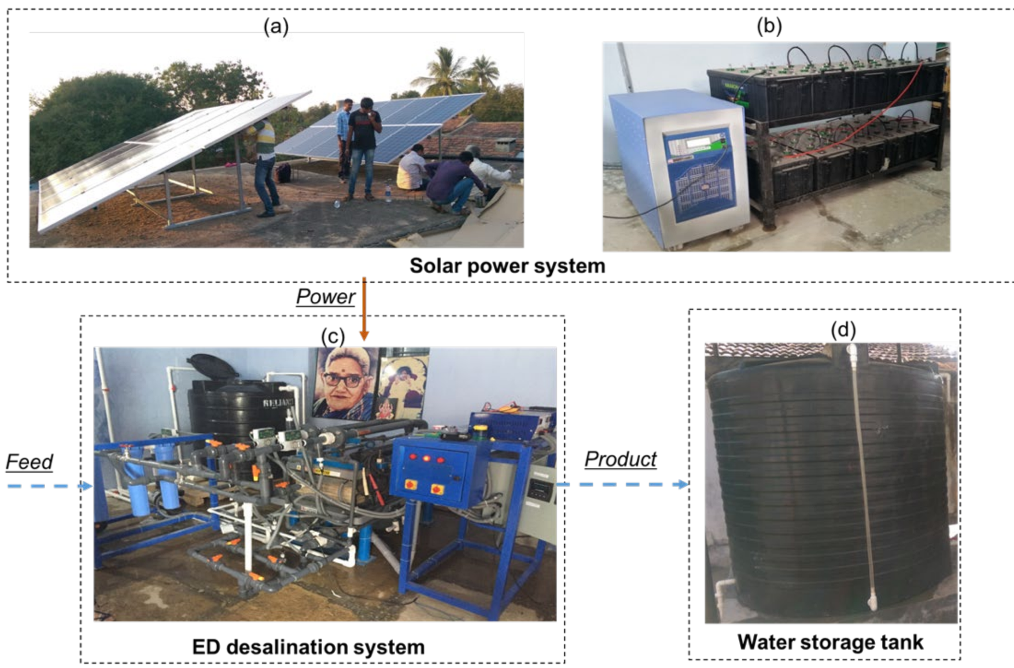

Figure 3. The system built in Chelluru India. (a) The installed rooftop solar panels. (b) The installed inverter and battery storage. (c) The installed ED system. (d) The installed water storage. The solid line indicates power flow. The dashed line indicates water flow.

Table 1. System design of the pilot-scale co-optimized PV-EDR system in Chelluru.

Design variable	Value
PV area (m^2)	40
Battery capacity (kWh)	16
Water storage volume (m^3)	10

Design variable	Value
ED cell pairs	56
Batch size (m^3)	0.45

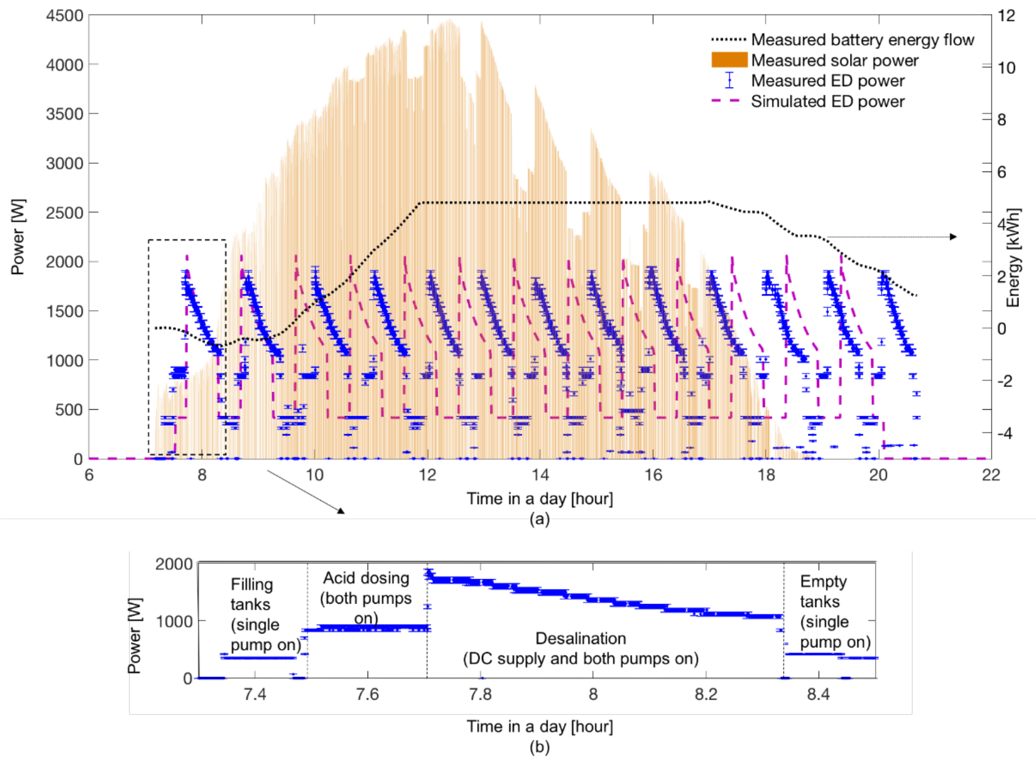

Figure 4. Experimental results of the PV-EDR in Chelluru. (a) Daily power profiles for the solar PV panels and ED system, along with the energy flow of the batteries, from field testing of the Chelluru system on May 2, 2018. (b) A power profile of a single batch on the same day, including filling tanks, acid dosing, ED desalination in batch mode, and emptying tanks.

3. Design and Implementation of Voltage and Flow Control System for ED Stack

3.1. Design of Voltage and Flow Rate Control Systems for ED Stack

A fundamental insight that has also emerged from our initial research is that time-variant voltage and flow control of ED stacks offer a previously untapped means for further reducing the capital and operational costs of PV-EDR systems. Currently, the optimized static EDR system applies a constant voltage and constant flow rates over the stack to hold the current density in the stack relatively constant over the entire desalination process. However, this limits static EDR systems to operate at a maximum voltage limited by the limiting current density of product water at the desired salinity level. The limiting current density, however, significantly varies during the desalination process; the current carrying capacity of water is proportional to the concentration of ions dissolved in it. Thus, in the beginning of the desalination process, a larger current can be safely applied through the stack without splitting water molecules. This property can be exploited using voltage-controlled ED stacks, such that the voltage applied through the stack varies with decrease in salinity of the diluate tank concentration.

For PV-EDR systems, another constraint imposed is the amount of solar irradiance available at a specific time of the day. As shown in Figure 4, power consumption by ED is relatively similar between batches irrespective of varying solar resources over a day. An alternative to this option is to design variable voltage and flow-rate-based stacks whose energy consumption profiles can follow the variation in solar irradiance through the day. Thus, such systems can increase the rate of production of desalinated water during peak sunshine hours and gradually reduce the rates during morning and evening hours. This enables the creation of PV-EDR systems with minimal or no energy storage requirements. As batteries and storage systems are a significant portion of the overall cost of the PV-EDR system, their removal can further reduce capital and operational costs of brackish water desalination.

The implementation of the time-variant PV-EDR system is illustrated in Figure 5. Connected to a control cabinet, there are two types of signals: sensing signals and control signals. Depending on the control strategies, different measured signals are required to calculate the time-dependent voltage or/and flow rate. We developed two real-time optimal control strategies: a correlation-based method and a model-based method. In the correlation-based method, first, empirical correlations are fitted by various off-line simulation results using the PV-EDR model. The correlations (namely look-up tables) are used to do real-time calculations of voltage or/and flow rates for the time-variant ED operation subject to a given variable solar power input. The performance of the off-line method is limited by the uncertainty of the solar power input; running all possible operations in advance is difficult. Alternatively, the model-based control strategy solves an online optimization problem using the developed PV-EDR model with many online measurements such as conductivity of the brine and diluate streams. One challenge of the model-based method is the computational cost that the online optimization needs to be solved fast enough to control the time-dependent ED system.

To realize the online model-based optimization to maximize water production with a given arbitrary power input, we modified the robust ED model in Wright et al. (2018) and integrated the simplified model into an optimization solution at every control time step.

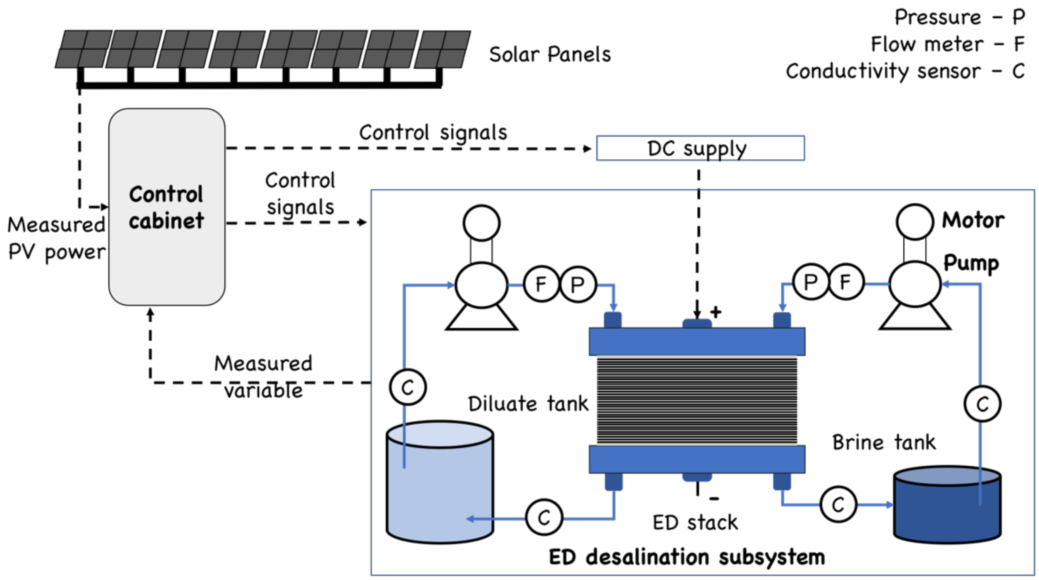

Figure 5. An illustration of the solar-driven time-variant PV-EDR system. The control cabinet receives measurements from the ED desalination sub-system, makes decisions of time-dependent voltage or/and flow rates, and sends them to the DC supply or/and variable speed drives to control the voltage on the electrodes and velocity of flow in the channels.

3.2. Building and Preliminary Testing of the Voltage-Controlled PV-EDR System

First, we tested the feasibility of the time-variant control framework at MIT using a bench-scale ED system (Figure 6). We tested the variable voltage control using Raspberry Pi programmable logic controller (PLC) modules, and Python scripting to vary and optimize the voltage during ED batch operation. We used the correlation-based control strategy by generating a diluate concentration-based look-up table of voltage, which was applied in the experimental testing to vary the DC supply's voltage output. Mimicked solar data were scaled down from real-world data of our referenced system (Figure 4) by proportionally decreasing both the length of daytime and peak power, with respect to our bench-scale system's scale. The ED operation was optimized using the mimicked time-dependent solar power input, and the generated concentration-based voltage table was used as a predefined function in the Python scripting to calculate the voltage output, depending on the measured diluate concentration. The experimental results are plotted in Figure 7, in which the voltage applied is about 80 percent of the limiting current density.

The experimental results demonstrate that the hardware for signal acquisition, communication, and control worked well. The voltage was successfully changed by an external program that optimized the voltage with online measurements. Although the control strategy used in this preliminary testing was the correlation-based method, the hardware will also work for the model-based control strategy by implementing the strategy in the Python scripting. Additionally, the variable voltage control was demonstrated to be able to accelerate the desalination rate, although the preliminary experimental results are slightly differentiated from the simulation. The simulation completed 12 batches during the daytime, while the desalination rate of the experiment was slower and only achieved 11 batches. The deviations were partially caused by manually replacing brine and diluate water with feed water once the target diluate concentration was reached. The manual operation tasks, and their associated time, were not considered in the simulation.

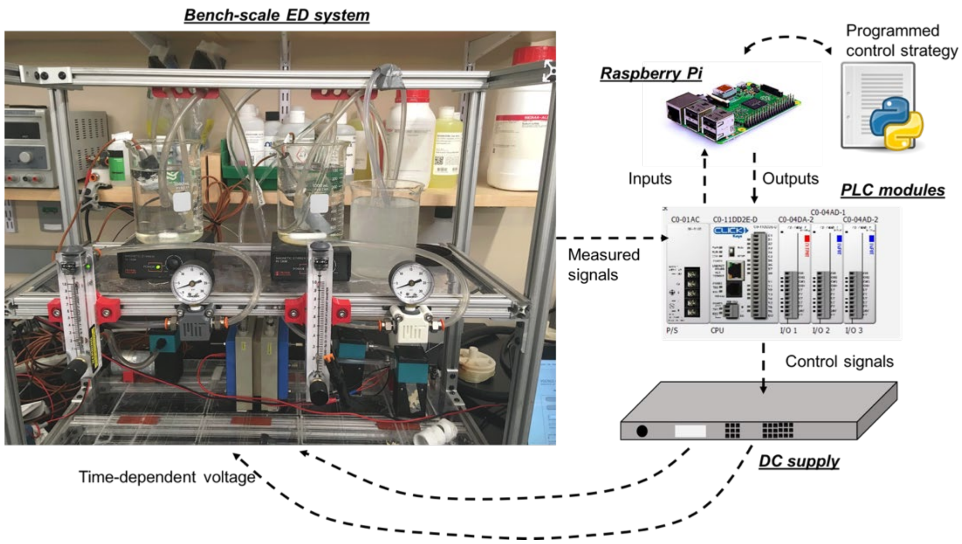

Figure 6. An illustration of variable voltage control in the bench-scale system testing. The system is actively monitored by measuring conductivity within the ED batch and sending voltage signals to DC supply for the voltage control.

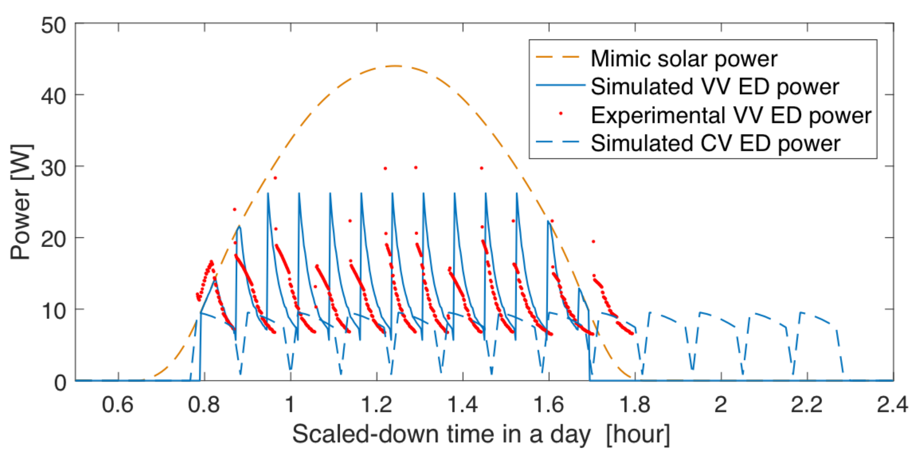

Figure 7. Simulated variable voltage (VV) ED in a mimicked solar day, which is scaled down from the referenced Chelluru system's operating conditions by proportionally reducing daytime and solar power.

4. Experimental Testing in BGNDRF and Data Collection

4.1. Formulation of the Control Problem for the New Time-variant PV-ED System

The voltage-controlled ED system in the lab, as shown above, already indicate the potential of a time-variant ED system in adaptively changing production rate under a variable power. This section further investigates the model-based control of both voltage and flow. The time-variant ED operation with the flow and voltage control provides additional flexibility for water production and energy use compared to the voltage-controlled ED, but how to control the system effectively is a new question. Compared to the static operation, when the voltage is changeable, the constraint is not violated for most of the batch, leading to additional operational domain for voltage control. As elucidated in the study of voltage-controlled bench-scale ED systems, the current density is much lower than the limiting current density for earlier times in the batch, causing the membranes to be under-used. The untapped capacity allows higher current density due to the variable voltage operation that the membranes could provide initially during the batch cycle but remains unused with constant-voltage operation.

Furthermore, when the flow rates of the diluate and the concentration are allowed to be variable within the batch operation, the operational domain for the time-variant operation becomes significantly increased for both flow and voltage control, as shown in Figure 8. In the variable flow operation, if we assume that the flow is controlled between the maximal flow (max-flow) rate and the minimal flow (min-flow) rate, the operational domain of the flow and voltage control is determined by the two operations with the limiting conditions. The upper operational boundary of the current density is controlled by the limiting current density when the flow rate is operated at the max-flow rate, and the lower operational boundary is determined by the current density of the constant voltage operation of an ED batch that is operated at the min-flow rate. Both the upper and lower boundaries of the time-variant ED operational window are dependent on the diluate concentration, as shown in Figure 8. The concentration-dependence of operational boundaries leads to the varying range of the applicable voltage and flow rates for the time-variant control. Therefore, a time-variant ED batch can be any trajectory from the feed concentration to the product concentration within the operational domain (the blue region in Figure 8), and the control problem of the time-variant ED is to optimize the trajectory to achieve a predefined objective, which is to maximize the desalination rate with given variable power inputs in this study.

In fact, the controlled time-variant ED operation is synonymous with continuous desalination using multiple hydraulic stages and electrical stages that change the flow rates and the voltage when the concentration is changing between the connected stacks. In contrast, the time-variant ED batch can alter the voltage and the flow rates without adding extra hydraulic-stage or electrical-stage membrane stacks, which reduce the system capital cost. Because measuring the diluate and concentrate conductivity is standard practice for deciding the end of the batch operation, the voltage-control uses the measured conductivity data to search for an optimal voltage. The flow control is achieved by changing the pump speed using variable speed drive.

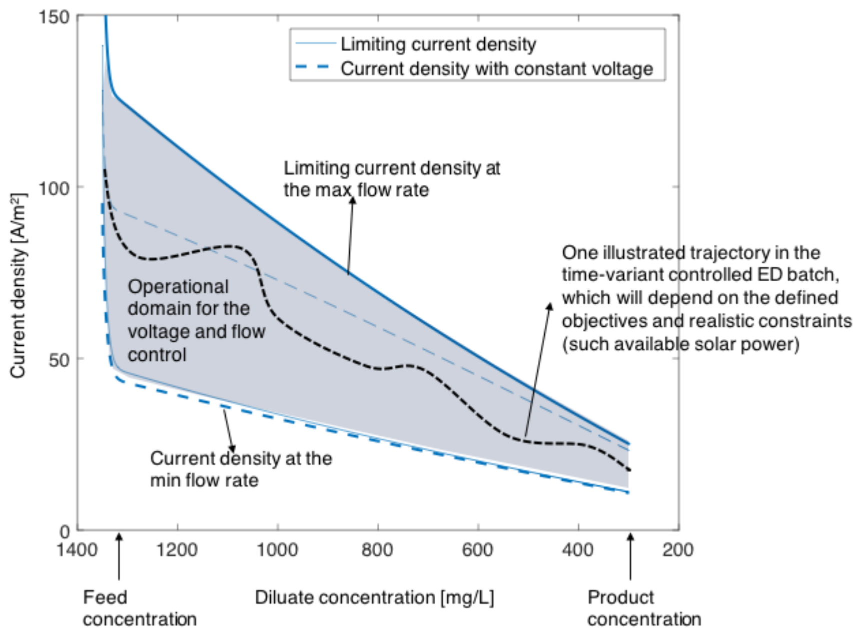

Figure 8. The operational domain of the time-variant ED operation is subject to the voltage and flow control. The operational domain for the voltage is flow control, which can be used to adopt variable power. The minimal flow rate can be as low as zero when the system operation is temporally shut down. The time-variant ED system can adaptively change its production rate to any arbitrary trajectory of an ED batch from feed to product.

4.2. The Built Time-variant PV-EDR Pilot System in BGNDRF

A time-variant ED prototype (Figure 9) is built for validating the proposed control theory. The model of the ED stack is AQ3-1-2-50-35, manufactured by Suez Water Technology. The ED system is operated in batch mode. For the sensors in the system, two Omega FP1408 flow meters are used to monitor the flow rate (±1.33 L/min) in the diluate and concentrate channels. Connectivity Instruments CDCE-90 in-line conductivity probes interfacing with CDCN-91 conductivity controllers were used to monitor the conductivity (±2 percent) at entry and exit of the ED stack. All sensors interfaced with CLICK I/O PLC Analog input and output modules C0-04AD-1, C0-04AD-2, and C0-04DA-2. Master is realized by a Python script that can be hosted on a Raspberry pi. Both communicate via Modbus. The flow rate over each electrode was held at 6 to 8 L/min using the sodium sulfate solution with a conductivity over 14 mS/cm.

Two Xylem Goulds SV-11 pumps are selected for the system to pump the diluate and concentrate flows. Two Xylem CentriPro Aquavar pump controllers control the pump speeds. The voltage is supplied by a TDK-Lambda GEN 60-25 DC supply (±1 percent). The polarity of the applied voltage is reversed between batches, and eight total valves at the entrance and exit of the stack are used to switch the diluate and concentrate channels in the stack. The reversal operation is necessary to reduce the scaling propensity in ED desalination.

The solar power is generated using the SolarRover Mojave-3 at BGNDRF. The solar truck is rated for 4.6 kW solar array. We set up the signal communication between the SolarRover and our control through an Ethernet connection by which the real-time solar power is managed to read and feed to the controller.

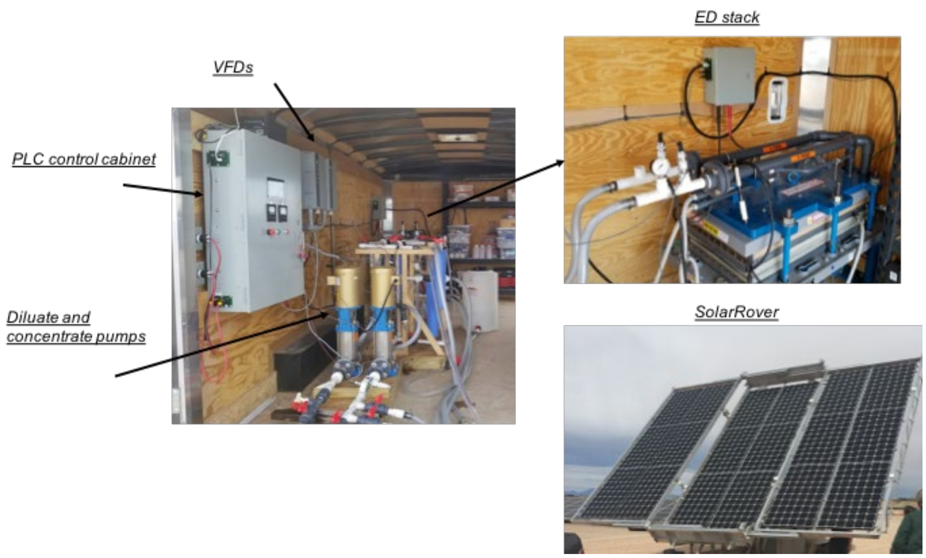

Figure 9. The time-variant PV-EDR system built in BGNDRF, Alamogordo, New Mexico. The SolarRover provides electricity from solar irradiance. VFDs are used to control the pump speeds and flow rates of pumps. The PLC control cabinet is for monitoring and controlling the system.

4.3. Preliminary Results of the PV-ED Field Testing at BGNDRF

After calibrating the built PV-ED pilot system in BGNDRF, experimental tests are developed to validate the developed dynamic ED model and the model-based controller, and to investigate the performance of the voltage- and flow-controlled ED system. The preliminary results of the single-batch ED operation are plotted in Figure 10, in which the voltage-controlled ED operations are benchmarked with the static constant voltage ED operations at two flow rates (25 L/min and 42 L/min). The measured current and power consumption of the time-variant ED operation, as shown by the blue symbols in Figure 10a and Figure 10b, respectively, demonstrate the enlarged operational window of the time-variant ED system. The power consumption of the ED at 42 L/min is about three times of that of the batch at 25 L/min, indicating the system is capable of adapting a variety of power inputs within these two power boundaries. When more power is consumed in the batch at 42 L/min, using the proposed control strategy that maximizes the desalination rate, the batch time is reduced by 48 percent (Figure 10c).

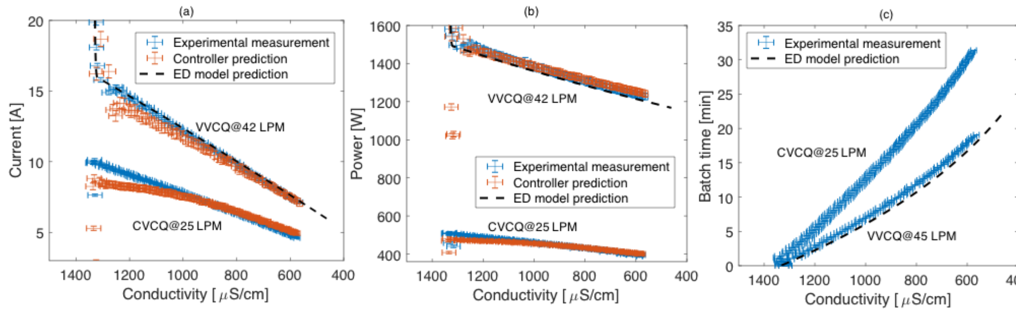

Figure 10. The preliminary results of the time-variant ED batch. VVVQ represents the variable voltage and variable flow rate operation. CVCQ represents the constant voltage and constant flow rate operation. (a) The current in the stack versus the conductivity of the diluate. (b) The total power consumption, including both the ED desalination power and the pumping power, versus the conductivity of the diluate. (c) The batch time versus the conductivity of the diluate.

The red symbols in Figure 10 represent the real-time predictions by the controller during operation. The controller prediction agrees well with the measurement in the variable voltage-controlled ED operation. This good prediction validates the controller model in simulating the system dynamics and ensures the controller performance in maximizing the desalination rate. Additionally, the dashed line in Figure 10 is the simulated system performance of the VVVQ ED operation using the developed ED model and the controller model. As shown in Figure 10, the simulated system performance closely matches the measured system performance of the voltage-controlled ED batch, which validates the modelling framework built upon the ED model and the controller model to simulate a time-variant ED system. This is a combined modelling tool that enables us and other ED designers to create time-variant ED systems in the future.

In addition to the single-batch ED tests, we also undertook daily tests of the PV-ED system. Figure 11 shows the results of one such daily test. The power profiles of the desalination power consumption versus the available solar power clearly demonstrates the pilot time-variant PV-ED prototype in matching the instantaneous solar power. The controlled ED system closely follows the solar power fluctuation in the cloudy day throughout the day. As the ED power is constrained between the maximum power and the minimal power consumption by our predefined flow rate limits (10 to 42 L/min), the ED power shows its adaptability to arbitrary power within the range.

The accumulated energy performance of the PV-ED system is shown in Figure 11. The overall fraction of solar energy directly used is about 77 percent, which is significantly higher than a conventional static ED operation (it reaches only 32 percent in the experimental daily test of the Chelluru system, as shown in Figure 4, and is expected to be about 40 percent for an identical system to the experimental BGNDRF system in static operation).

This significantly increased solar energy use leads to a significant reduction in the battery capacity required for shifting the variable solar power and the daily operation time. The experimental battery SOC data show that 0.25 kWh battery capacity is required to achieve daily production in time-variant operation (Figure 11), whereas 4.75 kWh would be needed to reach the same output in constant operation. Because the system can adaptively maximize the desalination rate subject to the instantaneous solar power, it can desalinate quicker during high-irradiance times (Figure 12). Therefore, all the daily water production occurs during daylight hours in time-variant operation, and the production rate is predicted to increase by about 50 percent compared to constant operation.

The increased energy and desalination performance of the time-variant operation leads to significant cost reduction. For this particular system design, the reduction in battery needs and daily operation time cut capital costs by 16 percent and operational costs by 22 percent (calculations using components and resources cost data in India as of 2019).

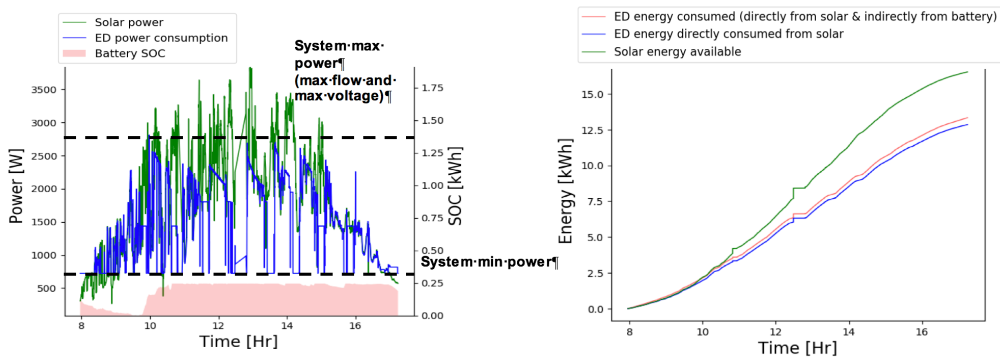

Figure 11. Energy use of the variable solar resources in the daily experimental test. (a) The ED power consumption and available solar power profiles, with corresponding battery usage for a minimal battery capacity of 0.25 kWh. (b) The cumulative available solar energy and the energy consumed by the ED system, both directly from the sun and total (from sun and batteries).

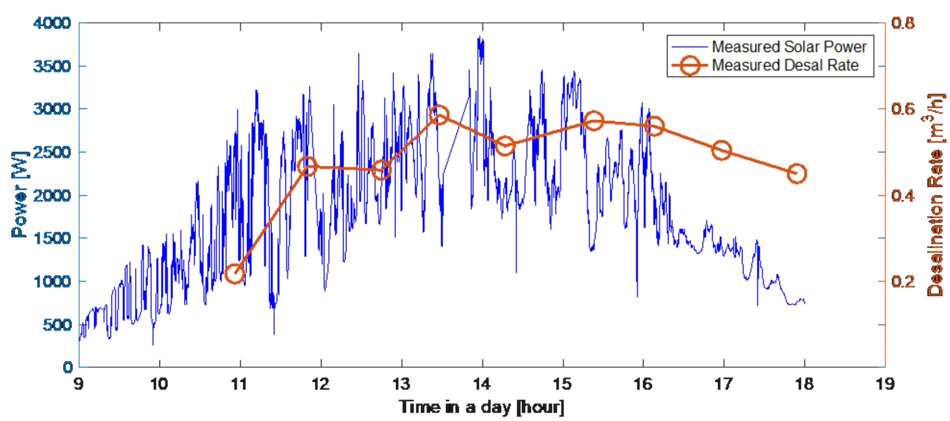

Figure 12. Time-variant desalination rate in the daily experimental test. The ED system can adapt the freshwater production rate to the instant available solar energy and desalinate faster at high irradiance times.

5. Refine Analytical Models and Develop a Roadmap for Commercial Systems

Putting the validated time-variant ED model and the controller model into the previously developed PV-ED holistic modelling framework enables optimal system design and exploration of the operational domain for lower water cost. To demonstrate potential cost savings, we use the refined analytic model to simulate a daily test of the Chelluru system, with the voltage and flow control in the same solar resources as shown in Figure 4. The results are plotted in Figure 13, in which the maximal flow rate considered in the control is 78 L/min (equivalent to a flow velocity of 20 cm/s) in the membrane channels).

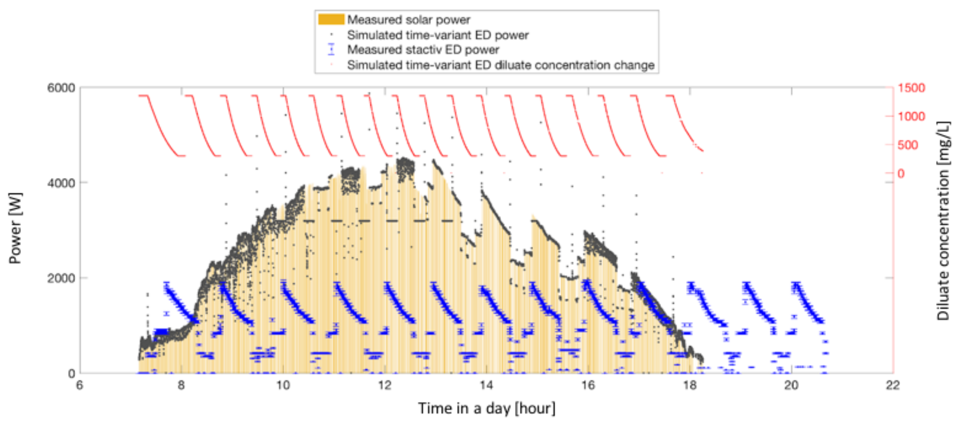

Figure 13. Simulated daily performance of the Chelluru pilot system operated in the time-variant operation mode.

Given the same solar power available on the day, the simulated time-variant ED system finishes 17 batches during the daytime. Compared to the static ED system built in Chelluru, the time variant operation can produce 31 percent more water with 17 percent less time. The increased solar energy efficiency and shortened operating time also significantly reduces the required battery capacity, which is 14 percent of the system capital cost.

This project demonstrates the capability of the time-variant operation to effectively produce water by adaptively consuming the variable power. The enhanced flexibility increases the PV-ED system robustness to fluctuating solar power, which is uncertain and difficult to forecast. To commercialize the technology, we need to further refine the system and components for the time-variant-operated ED systems. As current ED stack is designed for on-grid systems, the flow channel length is relatively long, restricting the operational domain of the time-variant ED systems. New designs of the ED stack with short membrane length will further improve the flexibility of operation and will lead to both capital cost reduction and performance improvement.

Therefore, we will leverage our longtime research partner Tata Projects, Ltd., which will contribute market insights and system-level design input to help catalyze the creation of commercially viable PV-EDR technology. We will also use our close relationship with Suez Water Technologies and Solutions, the market leader in manufacturing electrodialysis systems, which has provided guidance on our work for many years and has donated, or sold at a significant discount, ED products that will be used in this program. Finally, given our track record of running community-scale field pilots at BGNDRF, and in India and Gaza with support from USAID and UNICEF, we feel uniquely positioned to disseminate our PV-EDR technology worldwide following this pilot study.

6. Conclusions

6.1. Conclusions

During the investigation, the cost- and performance-optimal design of the PV-EDR is studied and explored by field-testing a community-scale PV-EDR pilot and creating a novel time-variant PV-ED system. Our work focuses on refining and validating our co-optimal design theory of the static PV-EDR system and designing and implementing voltage- and flow-controlled PV-EDR prototypes. We created voltage- and flow-rate-control strategies and a pilot-scale prototype that optimize ED behaviors for adapting to variable solar power in real time. The work in this project lays a foundation for achieving the overall goal of reducing the cost and environmental impact of brackish water desalination systems via efficient use of renewable solar energy.

With the developed model and built prototypes, the pilot PV-EDR system in Chelluru indicated our co-optimal design theory in cost-effectively balancing the system cost-performance trade-offs, and managed both short-term and long-term solar intermittence and variance by leveraging PV as an equivalent energy buffer, battery storage, water storage, and ED operation. Therefore, the design theory with the holistic model provides a credible tool for off-grid ED designers to minimize the water cost while maintaining system performance and accounting for local factors in India.

Furthermore, the developed time-variant PV-EDR system and control strategy demonstrate the system potential of effectively using instantaneous variable solar power. The developed ED dynamic model and the model-based controller successfully predict the system dynamics with variable voltage and flow rate operation. With both the bench-scale and pilot-scale time-variant PV-EDR prototypes and testing, the models are validated and the expected performance improvements are demonstrated. In the single-batch test, the power consumption of the voltage-controlled ED at 42 L/min is associated with a 48 percent faster desalination rate while consuming two times more power than the batch at 25 L/min, indicating the system is capable of adapting to a variety of variable power inputs to manipulate the desalination rate. In the daily test, the overall instantaneous solar energy utilization rate of the pilot-scale PV-EDR prototype is

75 percent, which is significantly higher than a conventional static ED operation with an instantaneous solar efficiency of 32 percent.

6.2. Recommended Next Steps

The goal of this project is to create a PV-EDR system with lower cost and higher reliability and resilience in a rural environment compared to existing water solutions. To further explore the potential in cost savings, future work will experimentally investigate cost- and performance-optimized architectures for time-variant, voltage- and flow-controlled, community-scale, PV-EDR brackish water desalination systems. Future work will integrate many of the techniques our team has invented to reduce the cost of PV-EDR systems, including parametrically characterizing ED stack behavior and optimizing the membrane, electrode, and flow channel dimensions for minimum energetic and capital cost. We predict these innovations, demonstrated through the proposed pilot, will lower the capital cost of community-scale (10 m^3/day) PV-EDR systems by approximately 60 percent compared to current technology and design practices.

We will leverage our close relationship with Suez Water Technologies and Solutions, the market leader in manufacturing ED systems, to explore new stack designs that are specifically optimal for community-scale desalination and time-variant EDR operation. These potentially novel designs will integrate with the time-variant operation theory and our co-optimal design theory to further lower the desalination system cost. We will also leverage our longtime research partner Tata Projects, Ltd. on our path to commercializing this new water technology.

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