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JUSTIFICATION, DESIGN, AND ANALYSIS OF A VILLAGE-SCALE PHOTOVOLTAIC-POWERED ELECTRODIALYSIS REVERSAL SYSTEM FOR RURAL INDIA

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ABSTRACT

This paper presents the merits of village-scale photovoltaic (PV) powered electrodialysis reversal (EDR) systems for rural India and the design and analysis of such a system built by the authors with planned testing to be completed in March 2015 in Alamogordo, New Mexico. The requirements for the system include daily water output of 6-15 m^3/day (enough potable water for the average village size of 2,000-5,000 people), removal of dissolved salts in addition to biological contaminants, photovoltaic power source, recovery ratio of greater than 85% and appropriate maintenance and service scheme. At present, most village-scale desalination systems use reverse osmosis (RO), however the managing NGOs have found the systems to be cost prohibitive in off-grid locations. EDR has the potential to be more cost effective than currently installed village-scale RO systems in off-grid locations due to the lower specific energy consumption of EDR versus RO at high recovery ratios. This leads to lower power system cost and overall capital expense.

The system developed in this study is designed to validate whether the system requirements can be met in terms of recovery ratio, product water quality, specific energy consumption, and expected capital cost. The system is designed to desalinate 3600 ppm brackish groundwater to 350 ppm at a rate of 1.6 $m^3/hour$ and a recovery of 92%. This paper reviews the scope of the market for village scale desalination, existing groundwater salinity levels, and presents the design methodology and resulting system parameters for a village-scale PV-EDR field trial.

INTRODUCTION

With 73% of Indian villages using groundwater as their primary drinking water source [1] and 60% of the land in Indian underlain with brackish groundwater (Fig. 1), there is a large potential market for village-scale desalination in India. In this work, there is particular attention paid to the issue of groundwater salt contamination versus other potential contaminants. There are two primary reasons for this concern: 1) The prevalence of high salinity groundwater both globally and in India, and 2) Salinity causes aesthetically poor water, causing even those sources treated appropriated for other biological and chemical concerns to be rejected. Over half of the rural population in India also lives with intermittent or no access to on-grid power. This paired with the high solar potential in India (Fig. 2) suggests that solar-powered desalination may be a viable option for village water purification.

Previous work by the authors defined a series of critical design requirements for village-scale water desalination systems for rural India through a combination of literature review and engagement with end users, manufacturers, NGOs, government of-

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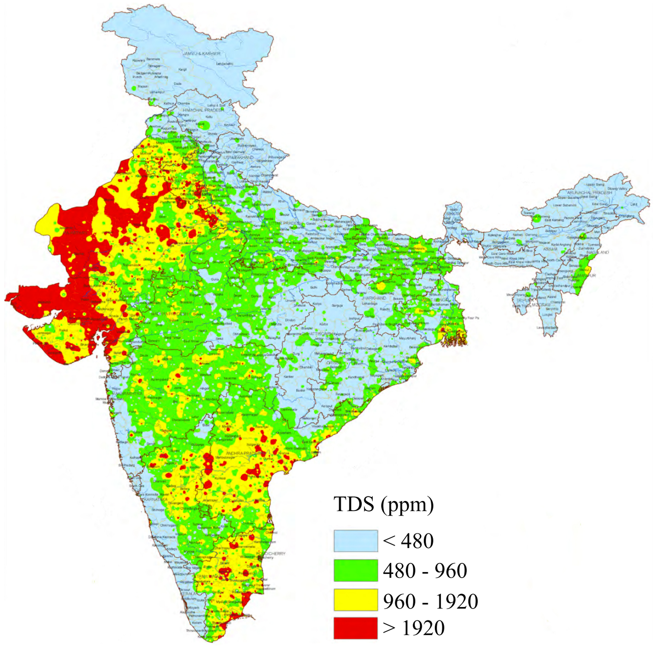

FIGURE 1: MAP OF SALINITY LEVELS IN INDIAN GROUNDWATER [2]. GROUNDWATER WITH A SALINITY LEVEL GREATER THAN 480 mg/L UNDERLIES 60% OF THE LAND AREA IN INDIA. AT THIS LEVEL, THE AESTHETIC QUALITY OF THE WATER SOURCE IS COMPROMISED.

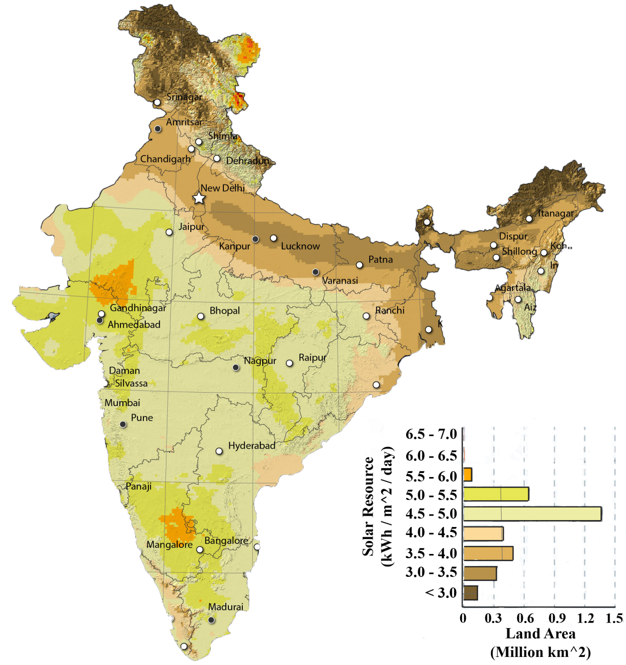

FIGURE 2: MAP OF SOLAR IRRADIATION IN INDIA [3]. HIGH ANNUAL SOLAR IRRADIANCE IN INDIA MAKES THE COUNTRY A PRIME CANDIDATE FOR PV-POWERED SYSTEMS IN OFF-GRID LOCATIONS. AREAS WITH HIGH SOLAR POTENTIAL OFTEN OVERLIE AREAS OF HIGH GROUNDWATER SALINITY AND PHYSICAL WATER SCARCITY.

ficials, and industry leaders in India [4]. At present, most village-scale desalination systems use reverse osmosis (RO), however the managing NGOs have found the systems to be cost prohibitive in off-grid locations [5]. The work concluded that several benefits of electrodialysis reversal (EDR) over RO make it a strong candidate for rural water desalination. These benefits include: lower specific energy consumption leading to lower capital cost for the PV power system, greater recovery ratio, and lower sensitivity to chlorine and feed water changes.

In the electrodialysis (ED) process, saline water is pumped through an ED stack (Fig. 3). When an electric potential difference is applied across the stack at the anode and cathode, anions move towards the anode and cations towards the cathode. The ED stack contains a series of ion exchange membranes. Anion exchange membranes (AEM) only pass anions, while cation exchange membranes (CEM) only pass cations. As an anion is moved towards the anode due to the potential difference at the electrodes, it is blocked when it reaches a CEM and remains in the concentrate compartment. Similarly, cations moving towards the cathode are blocked when they reach the first AEM. In a commercial ED stack, there are many alternating CEM and AEM pairs, resulting in alternating streams of diluted and concentrated saline flow.

Electrodialysis reversal (EDR) has the same stack setup as ED but also reverses the polarity of the stack at a certain time intervals, usually every 20-30 minutes. Reversing the polarity results in the concentrate and diluate streams switching and helps to minimize fouling of the membranes.

This article describes a prototype PV-EDR system, designed to desalinate 3600 ppm feed water at a rate of 1.6 m^3/hour and recovery of 92%. To the authors' knowledge, no published literature exists on the field-testing of village-scale PV-EDR systems. While work has been completed on the use of ED in remote areas [6, 7] and on pairing ED with PV power [8], this work has thus far remained at the laboratory scale only. Adiga et. al. completed a pilot PV-ED project with a production rate of 0.12m^3/hr in the Thar Desert (1987) [9]. With improvements in solar panel performance and cost as well as the introduction of EDR since that study, investigation into the use of PV-EDR systems at the village-scale is warranted.

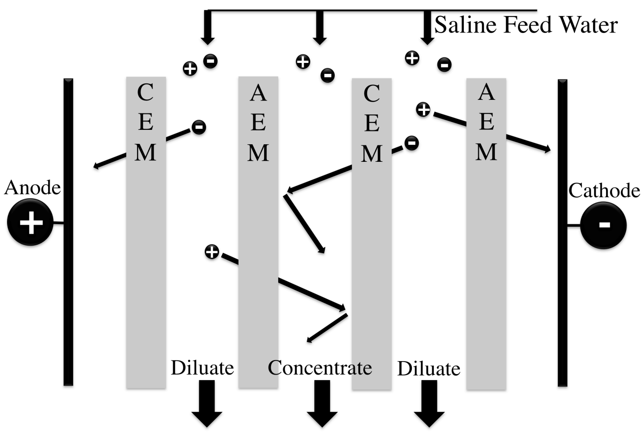

FIGURE 3: ELECTRODIALYSIS PROCESS. ED IS THE PROCESS OF PULLING IONS OUT OF SOLUTION THROUGH THE APPLICATION OF AN ELECTRIC POTENTIAL ACROSS A SERIES OF ALTERNATING ANION AND CATION EXCHANGE MEMBRANES (AEM, CEM).

PROTOTYPE STACK REQUIREMENTS AND SELECTION

Based on village size of 2000-5000 people requiring 3 liters per capita per day [10, 11], the target plant capacity is 6-15 m^3 per day. Assuming the system can be run off solar power seven hours of the day, this results in a target flow rate of 0.86 - 2.14 m^3/hour. The present system will first be tested using Well 3 at the Brackish Groundwater National Desalination Research Facility (BGNDRF); the expected feed water concentration in this well is 3600 ppm for the month of March [12]. The product water should have TDS less than 500 ppm to be acceptable for potable use [13]. Based on the above desalination rates, the authors investigated potential commercially available EDR stacks.

An individual EDR stack may contain multiple hydraulic and electrical stages. The number of hydraulic stages refers to the number of the passes the water makes along the membranes within a single stack. A single hydraulic stage typically provides 50-67% salt removal [14]. Thus for a feed concentration of 3600 ppm with a desired product water quality of less than 500 ppm, a first order analysis would suggest that three hydraulic stages would be required (Stage 1: 3600 $\rightarrow$ 1800 ppm, Stage 2: 1800 $\rightarrow$ 900 ppm, Stage 3: 900 $\rightarrow$ 450 ppm). The number of electrical stages refers to the number of electrodes in the stack. Including more than one electrical stage in a stack allows for independent control of the current at each stage, increasing the efficiency of salt removal.

Figure 4 shows the basic flow path for the smallest multiple stage industrial stack available from GE Water. The stack contains two electric stages, each with two hydraulic stages, making four total hydraulic stages. The first and third hydraulic stages contain 50 cell pairs while the second and fourth hydraulic stages contain 35 cell pairs. The reduction in cell pairs for the second hydraulic stage in each electric stage is used to increase the linear flow velocity and thus the limiting current density (LCD) of the already partially desalinated water (see description of LCD in the following section). Because the prototype system described in this paper is meant to define the performance of a full-scale system using commercially available components, this stack (Model Number AQ3-1-2-50/35) was selected for the design, even though it has one additional hydraulic stage than required.

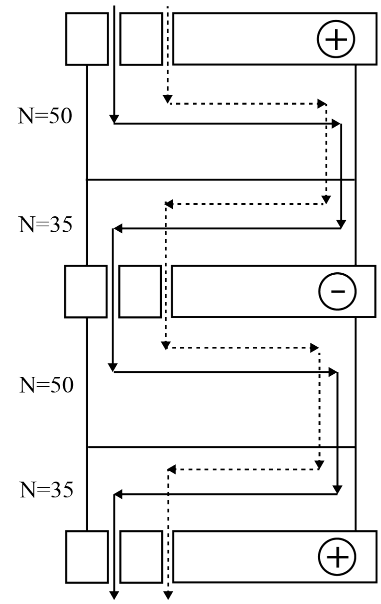

FIGURE 4: SCHEMATIC OF THE EDR STACK USED IN FULL-SCALE PROTOTYPE. THE STACK CONTAINS TWO ELECTRICAL STAGES, EACH WITH TWO HYDRAULIC STAGES OF 50 AND 35 CELL PAIRS.

GOVERNING EQUATIONS OF ELECTRODIALYSIS

Equations 1, 2, and 3 are the basis of a Matlab model developed by the authors to model the existing commercially available EDR stacks and their performance. The resulting stack performance for the AQ3-1-2-50/35 stack is shown in Table 1. Equation 1 describes the relationship between the size of the EDR stack (membrane area and number of cell pairs), the diluate stream inlet and outlet concentrations, and the applied current. It is derived from the fundamental continuity equation and the Nernst-Planck equation [9], which is used to describe the motion of ions under the influence of both an ionic concentration gradient (resulting in diffusion) and an electric field (resulting in migration). Because the design is for a system operating with the feed stream in continuous mode (the feed stream makes only one pass through the stack), steady state conditions apply, and $dC_{dil}^{out}/dt = 0$. On the right hand side of Eqn. 1, the first term represents the moles of ions entering and exiting the compartments at the inlet and outlet, the second term represents the migration of ions from diluate to concentrate compartment due to the electrical potential gradient, and the third and fourth terms represent the back-diffusion of ions due to the concentration gradient across each membrane. A parallel equation can be derived for the concentrate stream. The concentrate stream is recirculated through the stack, increasing in salinity with each pass, thus $dC_{conc}^{out}/dt > 0$.

$$\frac{dC_{dil}^{out}}{dt} = \frac{1}{NV_{cell}}[Q_{dil}(C_{dil}^{in} - C_{dil}^{out}) - \frac{N\phi I}{zF} + \frac{NAD_a(C_{conc}^{AEM} - C_{dil}^{AEM})}{l_a} + \frac{NAD_c(C_{conc}^{CEM} - C_{dil}^{CEM})}{l_c}] \quad (1)$$

Here C_{dil}^{in} and C_{dil}^{out} are the concentrations of the diluate stream at the inlet and outlet of the stack (mol/m^3), N is the number of cell pairs, V_{cell} is the volume of an individual diluate or concentrate compartment, Q_{dil} is the flow rate of the diluate stream (m^3/s), ϕ is the current efficiency, i is the current density (A/m^2), z is the ion charge, F is Faraday's constant (C/mol), l_a and l_c are the thicknesses of the anion and cation exchange membranes (m), D_a and D_c are the diffusion coefficients of the given solution in the anion and cation exchange membranes (m^2/s), and C_{dil}^{AEM}, C_{conc}^{AEM}, C_{dil}^{CEM}, C_{conc}^{CEM} are the concentrations of the diluate and concentrate streams at the interface with the anion or cation exchange membranes (AEM, CEM)(mol/m^3).

The current density in Eqn. 1 cannot exceed 70% of the limiting current density (LCD), the current density in which dissociation of water molecules would begin to occur in the boundary layer. The equation for the theoretical LCD and the empirically determined LCD are given in Eqn. 2 where a and b in the empirical equation are constants determined by measuring LCD at different linear flow velocities, u [10].

$$i_{lim} = \frac{zFC_{dil}^{out}}{\delta(t_m - t_s)} = aC_{dil}^{out}u^b \quad (2)$$

Here δ is the boundary layer thickness (m), t_m and t_s are the transport numbers of the ions in the membrane and in the solution. The final concentration in the diluate stream for any given stack and flow rate is obtained by introducing in the empirical solution for the limiting current density (Eqn. 2) into Eqn. 1.

TABLE 1: PREDICTED PERFORMANCE OF THE SELECTED EDR STACK.

Hydraulic Stage Number	**1**	**2**	**3**	**4**
Number of Cell Pairs	50	35	50	35
Concentration of Diluate Entering Stage (mol/m^3)	60.8	35.4	17.7	10.8
Concentration of Diluate Exiting Stage (mol/m^3)	35.4	17.7	10.8	6.0
Current Density Applied (A/m^2)	75.7	75.7	25.6	25.6
Total Stage Resistance (Ωm^2)	0.191	0.198	0.400	0.447
Voltage Drop Across Stage (V)	14.5	15.0	10.3	11.5
Power (W)	508.6	528.0	122.2	136.5

Alternatively, the required membrane area for any desired feed and product water concentration could also be obtained from the same equation.

In order to calculate the power required to desalinate a given quantity of water using electrodialysis, the system is analyzed as an electrical circuit, where power is equal to the product of the current through the stack and the voltage applied at the electrodes. The relationship between the current and voltage is given by Eqn. 3, where R_{dil}, R_{conc}, R_{AEM}, and R_{CEM} are the area resistances of the diluate stream, concentrate stream, AEM and CEM, respectively (Ωm^2). V_{elec} and $V_{potential}$ are the electrode potential and concentration potential, respectively. V_{total} is the total applied voltage.

$$V_{total} = V_{elec} + NV_{potential} + Ni(R_{dil} + R_{conc} + R_{AEM} + R_{CEM}) \quad (3)$$

Thus the instantaneous power consumption of an ED stack can be calculated if the applied voltage, number of cell pairs, and resistances are known. Membrane resistances and number of cell pairs are found in the electrodialysis stack manufacturer data. The resistance of the diluate and concentrate streams can be calculated by using an empirical equation for the specific aqueous solution. For NaCl, the Falkenhagen equation is used [15].

The equations in this section have a number of assumptions including that the concentrate and diluate compartments have the same flow conditions and geometries and that the back-diffusion of ions through the membranes is ignored. Full derivations of these equations and sample calculations describing their use for

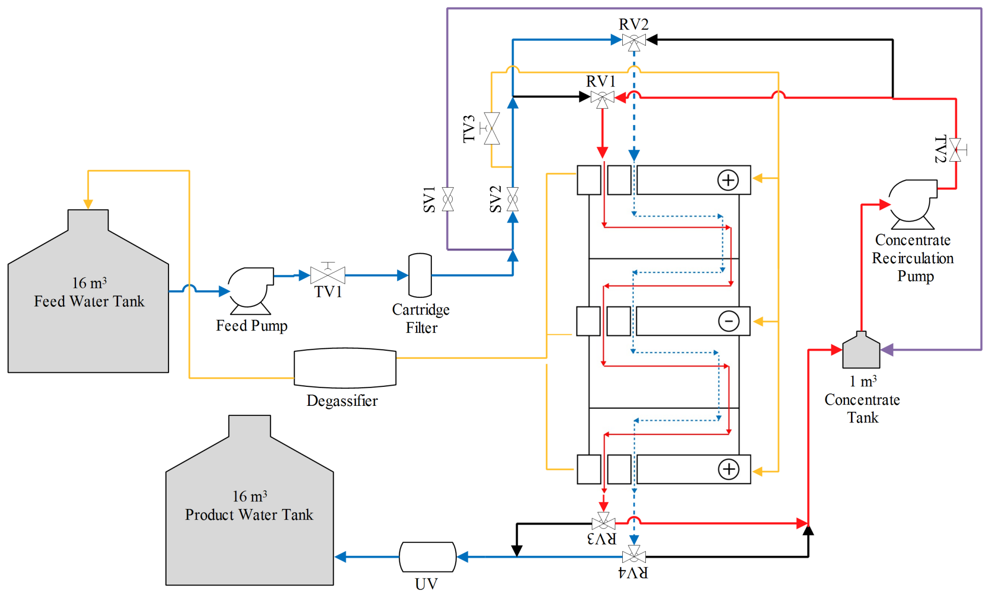

FIGURE 5: FLOW DIAGRAM OF THE EDR SYSTEM (TV=THROTTLING VALVE, SV=ONE-WAY SOLENOID VALVE, RV=3-PORT REVERSAL VALVE, UV=ULTRAVIOLET DISINFECTION).

continuous versus batch process operation are found in the bibliography [16, 17].

FLOW DIAGRAM AND SETUP OF FULL EDR SYSTEM

In addition to the EDR stack, the desalination system includes two pumps (one each for the feed stream and concentrate stream), a 10-micron cartridge filter, a UV post-treatment module, a degassifier, three throttling valves, and a series of one-way solenoid valves (Fig. 5). Because EDR alone removes only charged particles, the UV module is included to ensure that the product water meets the biological contaminant removal levels required by the Indian Standard for Drinking Water (ISO 10500) and the WHO [18, 19]. A Sterilight SC-320 Ultraviolet Sterilizer was chosen for this module and provides a UV dose of 40mJ/cm^2 at the given product water flow rate. The 10-micron cartridge filter is added as pretreatment to ensure that the turbidity level entering the stack is less than the suggested value of 2 NTU [14]. Two vertical in-line centrifugal pumps (Grundfos CRN1-5 (η_{pump}=45.6%) and CRN1-3 (η_{pump}=51.2%)) of 316SS construction were selected to pump the feed and concentrate streams, respectively. Figure 6 shows the prototype EDR system in the laboratory.

The recovery ratio of this prototype system is set to 92%. The recovery ratio of a desalination system is defined as the volume flow rate of product water to the volume flow rate of input feed water. In this system design, high recovery is achieved by first pumping 8% of the total feed water into the concentrate tank via the purple flow line (Fig. 5). Once complete, the concentrate recirculation pump and power to the stack are also turned on. The diluate stream (blue) passes through the stack only once, while the brine stream (red) recirculates through the stack and back into its tank throughout the day. This means that the concentration of this stream increases as time goes on. Every 30 minutes, polarity reversal on the stack occurs simultaneously with the switching of the four 3-port ball valves. The control and automation of the system is performed by a programmable logic controller (PLC).

The PV-power system was designed and built by Jain Irriga-

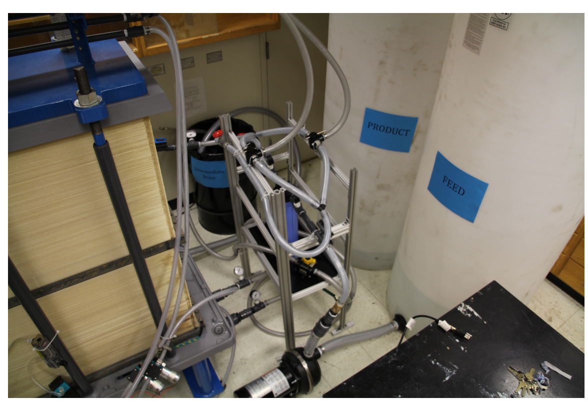

FIGURE 6: PROTOTYPE EDR SYSTEM.

TABLE 2: POWER REQUIREMENT OF EDR SYSTEM COMPONENTS.

Component	Power (W)
EDR Stack	1295.3
Feed Pump	370
Concentrate Recirculation Pump	250
Solenoid Valves and PLC	200
UV	42
Degassifier	24
Total	2181.3

tion Systems, Ltd., our company partner based in Jalgaon India, to meet the total power requirement described in Table 2. Since the current prototype should only run when full system power is available (such that pump flow rate and current applied to the EDR stack do not vary), battery buffering is used. The power system is designed to allow the entire unit to be run for seven hours. At a product water flow rate of 1.6m^3/hour, the daily capacity of the plant is expected to reach 11.2 m^3 when tested at the BGNDRF facility in March 2015.

CONCLUSION

This paper presents the justification for, and design of, a PV-EDR system for village-scale desalination for potable water production in India. The goal of the pilot plant is to validate the system model created by the authors. The system is designed to desalinate 3600 ppm brackish groundwater to 350 ppm at a rate of 1.6 m^3/hour and a recovery of 92%.

The pilot plant will be tested at the Brackish Groundwater National Desalination Research Facility in New Mexico in April and June of 2015. The goal of these trials is to validate our theoretical understanding of the system and to learn quickly in an environment similar to what we find in India in terms of solar irradiance, temperature, dust, and water quality. After a design review, the pilot will be tested in Jalgaon, India at Jain Irrigation's headquarters. The trial in Jalgaon will allow us to test even closer to end conditions and observe interaction between potential end operators and the system. Pending the results of these trials, we will be ready to move the pilot into a village for continued in-field testing.

Demonstrating that the specific energy consumption, recovery ratio, and product water quality of the trial plant aligns with that theoretically calculated would demonstrate that the further development, optimization, and deployment of PV-EDR systems is worth pursuing as a means of providing off-grid desalination in rural villages. The analysis and design presented in this work enable a system to be created that meets the water requirements for a typical Indian village.

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