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ENERGETIC AND SOCIOECONOMIC JUSTIFICATION FOR SOLAR-POWERED DESALINATION TECHNOLOGY FOR RURAL INDIAN VILLAGES

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ABSTRACT

This paper provides justification for solar-powered electro-dialysis desalination systems for rural Indian villages. It is estimated that 11% of India's 800 million people living in rural areas do not have access to an improved water source. If the source's quality in regards to biological, chemical, or physical contaminants is also considered, this percentage is even higher. User interviews conducted by the authors and in literature reveal that users judge the quality of their water source based on its aesthetic quality (taste, odor, and temperature). Seventy-three percent of Indian villages rely on groundwater as their primary drinking supply. However, saline groundwater underlies approximately 60% of the land area in India. Desalination is necessary in order to improve the aesthetics of this water (by reducing salinity below the taste threshold) and remove contaminants that cause health risks.

Both technical and socioeconomic factors were considered to identify the critical design requirements for inland water desalination in India. An off-grid power system is among those requirements due to the lack of grid access or intermittent supply, problems faced by half of Indian villages. The same regions in India that have high groundwater salinity also have the advantage of high solar potential, making solar a primary candidate. Within the salinity range of groundwater found in inland India, electro-dialysis would substantially reduce the energy consumption to desalinate compared to reverse osmosis, which is the

standard technology used for village-level systems. This energy savings leads to a smaller solar array required for electro-dialysis systems, translating to reduced capital costs.

INTRODUCTION

India has nearly 600,000 villages that collectively house 800 million people [1]. Of those 800 million people, 11% do not have access to an improved water source [2]. The WHO UNICEF Joint Programme for Water Supply and Sanitation (JMP) defines an improved water source as a household connection, public standpipe, borehole, protected dug well, protected spring or rain-water, where as an unimproved source would include an unprotected spring, unprotected dug well, tanker-truck, surface water, or bottled water. Even if a source is listed as "improved" it may have problems with water quality and safety [2].

Approximately 73% of Indian villages use groundwater as their primary source of drinking water [3]. Although ground water is usually of higher biological quality than surface water sources, it contains higher levels of chemical contamination. Water with salinity levels above the taste threshold underlies 60% of the land in India. Along with the health effects associated with high sodium intake, saline water is undesirable to users because of its poor taste [4]. Water that does not meet the aesthetic quality a user expects may cause it to be discarded as a viable source.

Due to the prevalence of chemical contamination in Indian groundwater sources, the government, companies, and non-

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governmental organizations (NGOs) have begun to install reverse osmosis (RO) systems. While some of these systems have been successfully operating for up to five years, others have failed due to lack of proper maintenance or the inability to keep up with operational costs. The largest component of the operational expense of current village-scale RO systems is energy. In off-grid locations where PV-powered RO has been proposed, capital cost of the solar power system is more than the capital cost of the purification and desalination unit itself, greatly increasing the pay-back period of the unit [5].

A review of the desalination technologies suitable for small-scale application is included. Our results indicate that a community-scale photovoltaic powered electro dialysis desalination system would meet the demands of rural Indian villages due to its viability as a technology at small scale, the reduced energy required versus reverse osmosis systems, and the more robust membrane components, resulting in longer membrane lifetime and less required pretreatment.

SYSTEM DESIGN REQUIREMENTS FOR VILLAGE-SCALE WATER PLANT

Representatives from all stakeholder groups including end users, NGOs, industry leaders, and manufacturers as well as literature were used to develop system design requirements in the following areas: system capacity, contaminant removal and aesthetics, recovery ratio, energy source, capital and operational cost and maintenance. The full justification of these requirements is found in previous work by the authors [6] and is summarized here.

Capacity, Contaminants, and Recovery Ratio

The water quantity required by a specific population group depends on the physical activity level of the individuals and the climate of the region. In this study a value of 3 liters per capita per day is used to determine plant capacity, which is based upon recommendation by the World Health Organization (WHO) [7] and a study completed by Gleick which focused on the water consumption needs of adults in developing countries [8]. Of the 800 million people living in villages in India, the median villager lives in a village size of 2000-5000 people. Based on 3 liters per capita per day, the target plant capacity is 6-15 m³ per day.

All biological and chemical contaminants need to be removed to the levels required by the Indian Standard for Drinking Water (ISO 10500) and the WHO [9, 10]. Biological water qual-

ity refers to all pathogenic microorganisms. These pathogens cause infectious diseases, the most common health risk associated with drinking-water [9]. It is estimated that 535,000 deaths in India were due to diarrhea in 2004 alone [11]. Additionally, chemical contamination in the form of arsenic, fluoride, iron and nitrates is prevalent in many regions of India [12].

In this work, there is particular attention paid to the issue of salt contamination. 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.

Of the available groundwater resources on Earth, 56% is considered brackish (having higher than 500ppm of total dissolved solids (TDS)¹) [13]. Similarly, brackish water underlies approximately 60% of the land area in India. A map of the salinity levels in groundwater in India is shown in Figure 1 [12]. Rapid global population growth and industrialization place considerable pressure on the little fresh water resource that is available. The available groundwater resource both globally and within India is more than doubled if brackish groundwater is considered as a potential source.

If the quality of the water is perceived as poor, the water will not be used. Users expect water to be clear, odorless, sweet, cool, and fresh if it is of high quality [4]. The taste quality of water in regards to mineral content was first described by W.H. Bruvold in 1969 (Table 1) where water with TDS less than 200 ppm is rated as excellent [14]. In addition to causing poor taste, a study by Singh et. al. showed that users find saline water ineffective in quenching thirst and unsuitable for cooking [4]. By targeting water aesthetics (by reducing salinity in brackish water sources), as well as biological and chemical performance, we can design a system that creates reassurance about the improved water quality and encourages the behavior change necessary for people to use it.

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. Having 15% of the world's population but only 6% of the world's water resources, India is designated as a water-stressed country [15]. Having a high recovery ratio is important for any inland desalination plant, especially where physical water scarcity is of concern. In India, the regions that require desalination due to groundwater salinity levels, also have physical

¹In this article TDS refers only to the combined content of all dissolved salts in the water sample.

TABLE 1: TASTE QUALITY AS A FUNCTION OF WATER TDS.

Potability	Excellent	Good	Fair	Poor	Unacceptable
TDS Value (ppm)	less than 200	201-600	601-1000	1001-1300	greater than 1300

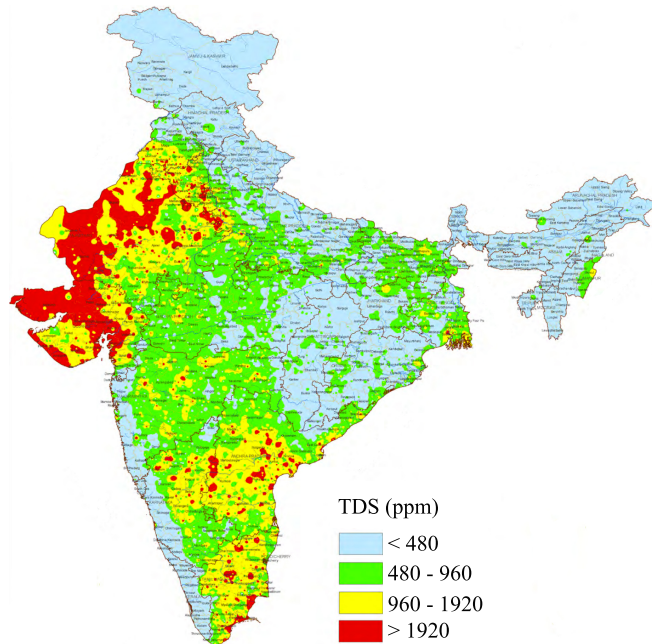


FIGURE 1: MAP OF SALINITY LEVELS IN INDIAN GROUNDWATER [12]. Groundwater with a salinity level greater than 480ppm underlies 60% of the land area in India. At this level, the aesthetic quality of the water source is compromised.

water scarcity. By maximizing the recovery ratio, there is more efficient use of limited water resources.

Sustainable Energy Source

Solar-powered desalination is a viable option for village water purification. Desalination is an energy intensive process. The method by which energy will be supplied to a new water purification and desalination plant must be explored. The first option is to use electricity from an existing grid. However, in many villages in India, this connection is not readily available. One way in which the Indian Census aims to evaluate access to electricity is by evaluating the percentage of households who use electricity, kerosene, or other sources for lighting. In 2011, only 55.3% of rural households used electricity for lighting [16], implying lack of grid connection as an issue for many villages. In addition to the problem of grid connection, the supply is frequently intermittent and available for only a few hours a day.

During interviews with NGOs that have installed rural water purification plants, it was discovered that the capacity of the system has historically been sized off of the number of hours of available power each day. For example, if a village needs a total of 6,000 liters per day and power is available for 6 hours, then a 1000 liter per hour plant is acceptable. However, if that same vil-

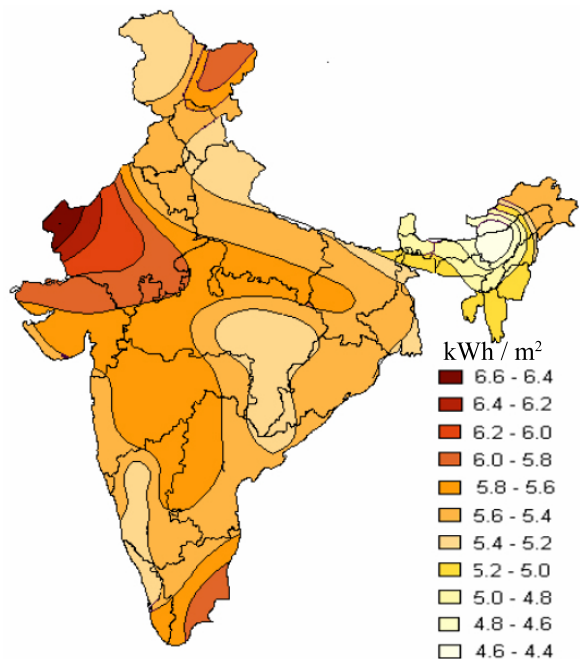


FIGURE 2: MAP OF SOLAR IRRADIATION IN INDIA [19]. High annual solar irradiance in India makes the country a prime candidate for PV-powered systems in off-grid locations. Areas with high solar potential often overlie areas of high groundwater salinity and physical water scarcity (Fig. 1).

lage only has access to power for 2 hours, then a 3,000 liter per hour system is needed, greatly increasing the capital cost of installation. The longer a desalination system can be running each day, the smaller the system needs to be to produce a given daily water requirement. Even for a village that has a grid connection for a few hours per day, it may make more sense to supplement with additional energy generation in the form of diesel generators or solar than to oversize the system as a whole.

Solar power is the best solution to supply or supplement a village-scale desalination system. To determine feasibility of solar power, the alternative use of diesel generators is considered. A study completed by Abraham and Luthra showed that there is an economic benefit to using solar over diesel for desalination systems requiring less than 3 kWh/m³ and having a daily plant capacity of less than 70m³/day [17]. Similarly Bilton et. al. completed site specific analyses for four brackish water locations and found that in each case the cost per cubic meter of water produced from a reverse osmosis system is less using solar versus diesel [18].

The average annual solar irradiance received in India is 4-6 kWh/m²/day [20]. Figure 2 shows the regional variation in solar irradiance [19]. Comparing Fig. 2 to Fig. 1, the areas of high solar potential are also the areas of high groundwater salinity.

Solar-powered desalination is the best option for locations with intermittent or no grid access and high salinity groundwater.

Capital and Operational Cost

Both the capital and operational cost of any desalination system to be installed in a village is important. While solar power decreases the operational cost of the system, it increases the capital expenditure. The capital cost comes from the panels, but also the supporting control system, inverters, and batteries.

Tata Projects Limited offers on-grid RO systems that cater to different water types, and in capacities ranging from 250 to 5,000 liters per hour (LPH). The company had installed 577 plants in India at the time of our conversation in January 2014 [5]. Accounting for over half of their sales is the 1000 LPH plant. The installed systems have been able to recover capital as well as operation and maintenance cost through the levy of user charges, at a rate of Rs 3 per 20 Liter can. The capital cost of the entire system including the shelter, storage tanks, power connections and wiring, bore well, excavation work, and installation charges is Rs 688,000 (\approx \$11,000). Of this total, Rs 355,000 (\approx \$5,700) is for the 1000 LPH plant itself. The system has an operational cost (including energy, operator salary, chemicals, pre-filter and membrane replacement) of Rs 0.047/L (\approx \$0.75/m³). The pay-back period of the described plant is 2-3 years depending on percentage of village families purchasing water on a daily basis. Tata Projects' on-grid village RO plants are economically sustainable.

Tata Projects and the NGOs leading the installation of RO plants, are currently limited to villages that are on-grid. The economics described above, for example, depend on 12 hours of grid connection per day. Pilot installations of the 1000 LPH plant running off of PV power cost an additional Rs 400,000 (\approx \$6,400). This added cost is more than the cost of the RO plant itself and makes PV-RO systems not economically viable at this time. Financial institutions are unwilling to work with the extended pay-back period [5]. In order to make a solar powered system viable, the energy requirements of the desalination technology need to be lowered, and attempts to drive the system without battery storage is encouraged.

Village-scale desalination systems have been proven to be economically sustainable by Tata Projects and their partner organizations in on-grid locations. However, off-grid locations remain underserved as the capital costs of PV-powered systems inhibit installation in these areas.

SELECTION OF DESALINATION TECHNOLOGY

Desalination technologies can be divided into two categories based upon their separation mechanism: thermal processes and membrane processes. Thermal processes use evaporation followed by condensation to produce pure water. Included in this

category is distillation using a solar still, as well as more complicated systems such as multistage flash (MSF), multiple-effect evaporation (MEE), and mechanical vapor compression (MVC). While solar stills have been implemented on a small scale in some developing regions, MSF, MEE, and MVC are only cost effective at capacities above 3,000 m³/day and for higher salinities than those present in Indian groundwater [21] and are therefore not considered in this study.

Membrane processes include reverse osmosis (RO) and electrodialysis (ED). The specific cost of water for both RO and ED scales inversely with system size, however both are modular in design, allowing them to be implemented cost effectively at smaller scales as well. Because distillation by solar still, RO, and ED are the most viable solutions for small scale desalination, they are described further in the following sections.

Technology Description and Energetic Comparison

Distillation by Solar Still. In a basic solar still, feed water is contained in a sealed basin where it is evaporated by sunlight transmitted through a plastic or glass cover. The water vapor is then condensed on the underside of the cover and runs down the slope of the cover to a collection trough. The required land area to be covered in solar still (the footprint of the system) in order to distill a given quantity of water per day is

$$A_{land} = \frac{\forall_{prod} \rho h_{fg}}{\eta q}, \quad (1)$$

where \forall_{prod} is the volume of product water required, ρ is the density of water, h_{fg} is the latent heat of vaporization, η is the efficiency of the distillation unit, and q is the incident solar energy per area per day.

The capital cost of a solar still is determined by the footprint of the system, since for any given still design the cost of the basin, glass covering, trough, etc. all scale linearly with area it needs to cover. Eqn. 1 reveals that the capital cost of the system scales linearly with the volume of water that needs to be produced. Both the capital cost of the system and the energy input are independent of feed water salinity, unlike membrane based systems. Assuming a village of 3,000 people requiring 9 m³/day of drinking water, a unit efficiency of 0.5 [22] and an average daily incident solar energy of 18,000 kJ/m²day [22], the land area required would be 2,260 m². With the capital cost of solar stills in India at approximately \$38.3/m² [22], the capital cost of a system for this village size would be \$86,558, nearly eight times that of Tata Projects 1,000 LPH RO plant.

In addition to the large land area required for such a system, solar stills have high maintenance requirements in rural settings. For example, standing water can lead to algae growth, glass covers can get broken and blowing sand covers the glass, reducing efficiencies. Pumps may be required to move the brine

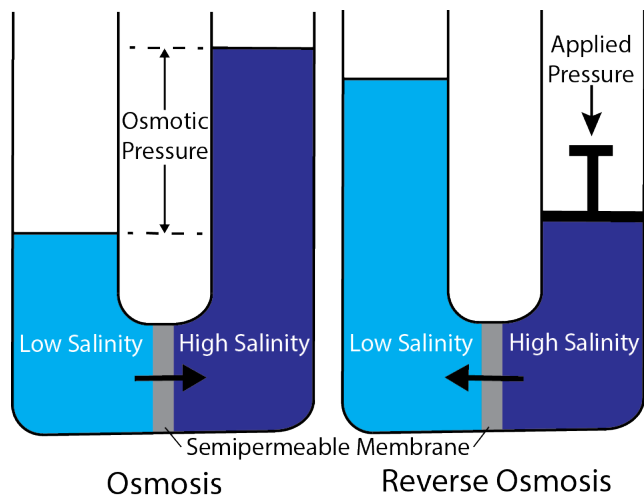


FIGURE 3: REVERSE OSMOSIS PROCESS

and product streams. In addition, distilled water is pure and thus lacks adequate levels of salts and minerals. Product water would need to be mixed with feed water to avoid this. Because the units require extended daily maintenance and large land areas, and are not cost competitive to the current rural desalination systems, they should not be considered for community scale water purification.

Reverse Osmosis. Reverse osmosis is a technology that uses an applied pressure greater than the osmotic pressure of the feed stream to move water through a semi-permeable membrane. This results in one dilute stream with low salt concentration, and one concentrated brine stream (Fig. 3 right). The applied pressure forces water to move in the opposite direction of the natural flow that occurs in osmosis (Fig. 3 left). The feasibility of photovoltaic powered community-scale rural RO systems was shown by Bilton et. al. [18].

The power required to complete the reverse osmosis process is determined by

$$P_{RO} = \frac{PHPQ_{feed}}{\eta_{HP}} \quad (2)$$

where Q_{feed} is the flow rate of the feed water stream, PHP is the applied membrane pressure from the high pressure pump, and η_{HP} is the combined efficiency of the high pressure pump and motor. In order to determine the specific energy requirement, P_{RO} is divided by Q_{prod} , the flow rate of the product water stream.

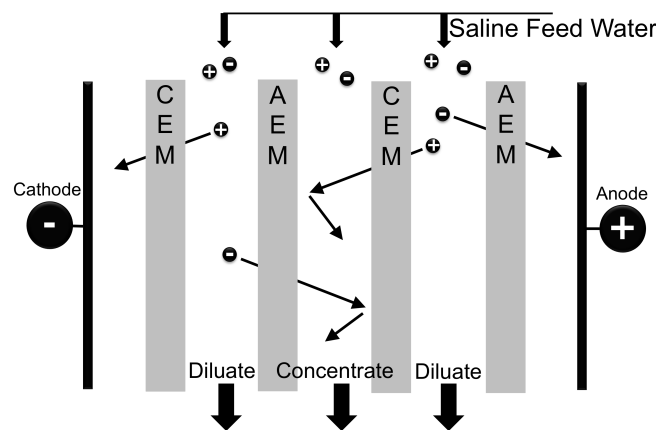


FIGURE 4: ELECTRODIALYSIS PROCESS

$$E_{spec,RO} = \frac{p_{hp}Q_{feed}}{\eta_{pm}Q_{prod}} \quad (3)$$

The applied pressure must be greater than the osmotic pressure of the feed stream in order to complete RO. Because osmotic pressure increases with increasing salinity, high salinity RO requires more energy than brackish water RO.

The brine stream leaves the membrane at a pressure just over the osmotic pressure. In seawater RO, this energy is usually recaptured using an energy recovery device (ERD) which reduces the overall power consumption of the RO process. However, in brackish water desalination at the village-scale in India, the pressures are much lower and the power savings do not make up for the capital investment of an ERD [5].

Electrodialysis Reversal. The electrodialysis (ED) process is illustrated in Figure 4. In this process, saline water is pumped through an electrodialysis stack. When an electric potential difference is applied across the stack at the anode and cathode, anions move towards the anode. However 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. Thus although an anion is moved towards the anode due to the potential difference at the electrodes, when it reaches a CEM it is blocked and therefore remains in the that stream. 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.

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 current through the stack times the voltage applied at the electrodes. The relationship between the current and voltage is given by

$$V_{total} = V_{elec} + NV_{potential} + Ni(R_{dil} + R_{conc} + R_{AEM} + R_{CEM}), \quad (4)$$

where N is the number of cell pairs in the stack, i is the current density (A/m^2), R_{dil} , R_{conc} , R_{AEM} , 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.

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 [23]. The specific energy required to desalinate water of a certain salinity is found by integrating the instantaneous power and dividing by the flow rate of product water:

$$E_{spec,ED} = \frac{\int_{t=0}^{t=final} iAV_{total} dt}{\dot{V}_{prod}}, \quad (5)$$

where A is the area of an individual membrane in the stack. The design of an ED system revolves around a tradeoff between specific energy and capital cost. The capital cost of an ED stack increases with required membrane area. The total required membrane area is

The total required membrane area is given in Equation 6, where C_{dil}^{in} and C_{dil}^{out} are the concentrations of the diluate stream at the inlet and outlet of the stack, respectively (mol/m^3), z is the ion charge, F is the Faraday constant (C/mol), and ϕ is the current efficiency.

$$A_{total} = \frac{Q_{dil}(C_{dil}^{in} - C_{dil}^{out})zF}{N\phi i} \quad (6)$$

Equations 4 and 6 assume 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 continuous versus batch process operation are found in [24, 25].

Least Energy for Desalination. The least work of separation required to extract a unit of water from a feed stream of a given salinity for any black-box separator is derived by Mistry et. al. [26]. Equation 7 describes the least specific energy of separation. It is included here for the purposes of comparison to the already described specific energies of RO and ED technologies.

$$E_{spec,least} = g_{dil} + \left(\frac{1}{r} - 1\right)g_{conc} - \frac{1}{r}g_{feed} \quad (7)$$

Here r is the recovery ratio of the system and g is the specific Gibbs free energy of each stream, which is dependent on the temperature and salinity of each stream. The least specific energy increases with increasing feed water salinity.

SELECTION OF MOST APPROPRIATE DESALINATION TECHNOLOGY

Energetic and Economic Comparison

In order to compare the energy requirements of each of the described technologies, Eqns. 3, 5, and 7 are used to produce Fig. 5. Note that in each case the full system was modeled using equations provided by Ortiz [24] for ED and Bilton [18] for RO. The applied pressure for RO was selected to be 9 bar above the osmotic pressure of the brine stream, since this was the median pressure difference observed in current village-scale RO plants visited by the authors. Only the salinity range of interest for Indian groundwater is displayed. Throughout this range, ED requires less specific energy than RO. At 1000 ppm, ED requires 75% less specific energy than RO. The benefit linearly decreases as feed water salinity increases.

Included in cost is both operational and capital expenses. The dependence of specific cost ($\$/m^3$) on feed water salinity for distillation, RO, and ED plants is summarized by Strathmann and shown graphically in Fig. 6 [27]. The highlighted portion of the graph shows the salinity range of interest for inland groundwater in India. ED has a lower specific cost than RO and distillation in this range. Strathmann calculates total process cost (a combination of capital and operating costs) as a function of feed water salinity. The capital cost is determined by the required membrane area (RO module or ED stack), pump requirements, piping, valves, storage tanks, electrical instrumentation and control equipment, energy recovery devices, and water pre-treatment equipment. The operating cost is determined by the energy consumption, membrane and pre filter replacement, pre-treatment chemicals, and general maintenance. Figure 6 represents the relative total process cost of distillation, RO, and ED

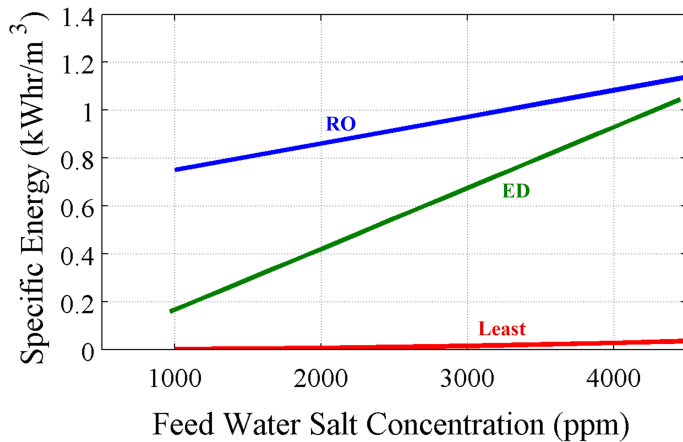


FIGURE 5: Dependence of specific energy on feed water salinity. The salinity range presented represents that commonly found in Indian groundwater. The energy required for RO and ED are compared to the thermodynamic least energy needed to separate the given salt concentration from water.

technologies. It is important to note that the total process cost of any of these systems depends on the feed water composition, membrane design, plant capacity and plant location.

Figure 6 shows that ED costs increase faster with salt concentration than RO, resulting in a point around 5,000 ppm in which RO becomes more cost effective than ED. In an ED system, both the capital cost and the operational cost depend strongly on the feed water salinity (Eqns. 5 and 6). In an RO system it is primarily the operational cost that depends on feed water salinity (Eqn. 3), as p_{hp} increases with salinity. As a result, ED costs increase faster with salt concentration than RO costs, resulting in the cross-over point.

Because ED requires less energy at the salinities present in Indian groundwater (Fig. 5), a solar-driven ED system would require a smaller solar panel array than an RO system. Using a first order estimate that the cost of the power system scales with power output of the system and assuming a groundwater salinity of 2,000 ppm, the capital cost of the power system to run a Tata Projects 1,000 LPH plant is reduced by 50%, from Rs. 400,000 (\approx \$6,400) to Rs. 200,000 (\approx \$3,200), using ED instead of RO.

The cost benefit of installing an ED plant instead of an RO plant for brackish feed water can thus be summarized in the following two ways: 1) the overall process costs for ED are lower, regardless to whether the plant is on-grid or off-grid (Fig. 6), and 2) if moving off-grid, the capital cost of the power system is reduced as well.

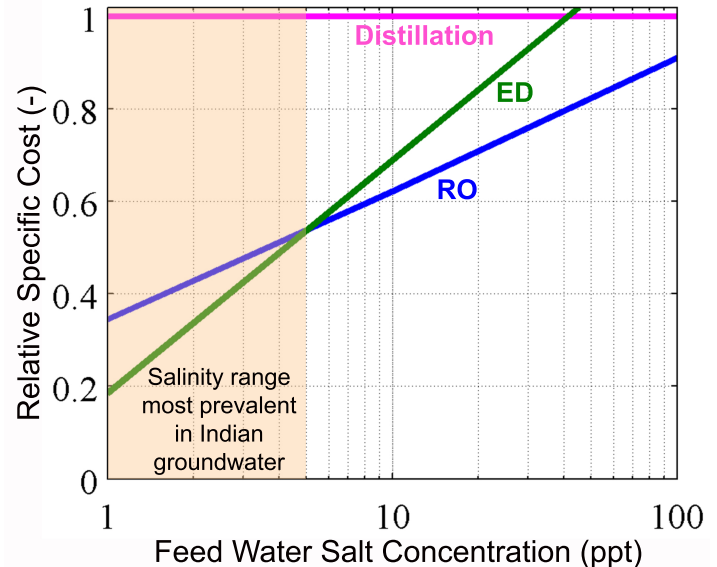


FIGURE 6: The dependence of specific cost on feed water salinity. Relative specific cost per unit of water produced) of reverse osmosis and electro dialysis technologies in comparison to the specific cost of distillation, which is independent of feed water concentration.

Functionality and Maintenance Comparison

ED and RO better meet the user requirements introduced at the beginning of this paper than distillation. In addition to the large land area required (2260 m² for a 9 m³/day system), solar stills have high maintenance requirements in rural settings. For example, standing water can lead to algae growth, glass covers can get broken and blowing sand covers the glass, reducing efficiencies. Pumps may be required to move the brine and product streams. In addition, distilled water is pure and thus lacks adequate levels of salts and minerals. Product water would need to be mixed with feed water to avoid this concern. Because the units require extended daily maintenance and large land areas, and are not cost competitive to the current rural desalination systems, they should not be considered for community scale water purification.

The sustainable operation and maintenance of village RO systems has been proven by Tata Projects [5]. RO has the added benefit of removing contaminants other than salts including most pesticides, heavy metals, and any biological contamination that remains following the pretreatment stages. RO membranes however are more sensitive to feed water quality than ED membranes, requiring greater pretreatment and having higher sensitivity to chlorine levels. ED's relative insensitivity to chlorine levels is a benefit in villages that already have an elevated storage tank of water treated with chlorine at the municipal level. This wa-

ter is currently not a potential feed water source for installed RO plants, but could potentially be a feed water source for an ED system. Table 2 further compares aspects of maintenance and functionality for RO and ED systems. The recovery ratio in ED can nearly double that achieved by current village RO installations. Maximizing the recovery ratio is important for water scarce regions in order to ensure the most efficient use of available water resources. Additionally, the life of ED membranes averages 10 years which is 2-3 times longer than that of RO membranes.

TABLE 2: MAINTENANCE AND FUNCTIONALITY COMPARISON FOR RO AND ED.

Factor	RO	ED
Recovery Ratio	30-60%	85-95%
Membrane Life	3-5 years	10 years
Vulnerability to Feed Water Changes	Higher	Lower
Contaminant Removal	Most	Salts only
Membrane Sensitivity to Chlorine	High	Low
Capital Cost of Membranes	Low	High

CONCLUSION

This paper provides justification for solar-powered electro-dialysis systems for off-grid villages in India. The need for desalination is apparent based on the prevalence of brackish groundwater in globally and within India. This is further justified by the importance that users place on a water source's aesthetic quality (taste, odor, and temperature). For villages where grid power is unavailable or intermittent, solar power is the stronger candidate to provide power to the desalination system. Two maps of India are presented which show that areas of high groundwater salinity also have the benefit of high solar irradiation. Comparing the three technologies most suitable to small-scale desalination (distillation, RO, and ED) it is found that ED requires substantially less energy per unit of water produced than the alternatives. This energy savings results in a smaller required solar array, reducing the capital cost of off-grid systems. Additionally, ED can achieve a higher recover ratio, is less sensitive to variations in feed water quality, and requires less frequent membrane replacement. Electro-dialysis better suits the socio-economic and technical challenges associated with purifying groundwater in off-grid Indian communities. The development of a direct-drive PV-ED system has the potential to greatly expand the reach of desalination units in rural locations.

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