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Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India

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HIGHLIGHTS

- Sixty percent of the land area of India is underlain with brackish groundwater.
- System design requirements are determined using technical and ethnographic factors.
- Electrodialysis can obtain a high recovery ratio with low specific energy and cost.
- In off-grid areas, ED has the potential to be more cost effective than RO.
- Direct-drive PV-ED could disrupt the village water purification market.

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ABSTRACT

This paper justifies photovoltaic (PV)-powered electrodialysis (ED) as an energy and cost-effective means of desalinating groundwater in rural India and presents the design requirements for a village-level system. Saline groundwater, which underlies 60% of India, can negatively impact health as well as cause a water source to be discarded because of its taste. A quarter of India's population live in villages of 2000–5000 people, many of which do not have reliable access to electricity. Most village-scale, on-grid desalination plants use reverse osmosis (RO), which is economically unviable in off-grid locations. Technical and ethnographic factors are used to develop an argument for PV-ED for rural locations, including: system capacity, biological and chemical contaminant removal; water aesthetics; recovery ratio; energy source; economics of water provision; maintenance; and the energetic and cost considerations of available technologies. Within the salinity range of groundwater in India, ED requires less specific energy than RO (75% less at 1000 mg/L and 30% less at 3000 mg/L). At 2000 mg/L, this energetic scaling translates to a 50% lower PV power system cost for ED versus RO. PV-ED has the potential to greatly expand the reach of desalination units for rural India.

1. Introduction

India has nearly 600,000 villages that collectively house 800 million people [1], 11% of whom 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 rainwater, 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 still be contaminated [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 can contain higher levels of chemical contamination. Water with salinity levels above the taste threshold (>500 mg/L) underlies 60% of the land in India [4]. Along with the health effects associated with high sodium intake, saline water is undesirable to users because of its poor taste [5]. 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, non-governmental organizations (NGOs) have begun to install reverse osmosis (RO) systems. While some of these systems have been successfully operating for up to 5 years, many have failed due to lack of proper maintenance or the inability to keep up with operational costs. Electricity costs account for ≈54% of the operational expense of current village-scale RO systems [6].

In this paper we present the process of defining target design requirements for any off-grid water purification system in rural India. A review of the desalination technologies suitable for small-scale applications is included. Our results indicate that a community-scale photovoltaic

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(PV) powered electrodialysis 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, stronger membrane components resulting in longer membrane lifetime, and less required pretreatment.

2. System design requirements for a village-scale water plant

The following system design requirements were elucidated through a combination of technical literature review and engagement with end users, NGOs, manufacturers, government officials, and industry leaders working directly in the Indian market. Justification for each requirement is explained in the following subsections.

1. Daily water output: 6–15 m^3/day
2. Contaminant removal: Biological and chemical contaminants reduced to levels recommended by the WHO; salts (TDS) reduced to less than 500 mg/L
3. Recovery ratio: Maximized
4. Energy source: Solar
5. Capital and operational cost: Desalination system plus solar power system less than ₹755,000 INR (≈$12,100 USD)[1]
6. Maintenance: System able to be maintained in the field by a village operator with limited technical training

2.1. Daily water output

The water quantity required for consumption by a specific population group depends on the physical activity level of the individuals and the climate of the region. For example, manual laborers and pregnant or lactating women require more daily water than the average person. The World Health Organization (WHO) concludes that a minimum of 2 l per person is required for an average adult in average conditions, while 4.5 l is required for manual laborers working in an average temperature of 32 °C [7]. The needs of the average person in an Indian village is likely to fall between these values given the warm climate conditions and physical activity of the inhabitants. A separate study completed by Gleick suggests a value of 3 l per capita per day for adults in developing countries [8]. In our analysis, we use an average of 3 l per capita per day in order to determine plant capacity.

The required daily water output of a village plant is determined by both the water quantity required per individual and the population of the village. Data from the 2001 Indian Census was used to construct the histogram in Fig. 1, which shows that the median villager lives in a village of 2000–4999 people [1]. For this population size and based on 3 l per capita per day, our target plant capacity is 6–15 m^3 per day.

2.2. Contaminant removal

There are three primary categories of water quality: biological, chemical, and physical (Table 1). Proper selection of a water purification technology depends on the contaminants present in the feed water source.

2.2.1. Biological quality

Biological water quality refers to all pathogenic microorganisms. These pathogens cause infectious diseases, the most common health risk associated with drinking-water [9]. A 2012 study by Walker et al. estimates that 33.4% of deaths of children in India under 5 years of age were due to diarrhea in 2008 [10]. Diarrheal diseases are the third ranking cause of premature death in India, accounting for 6.8% of the total number of years of life lost, a quantifier of premature mortality that puts greater weight on younger deaths than older deaths [11]. The removal of pathogenic microorganisms to the levels required by the WHO and the Indian Standard for Drinking Water (ISO 10500) should be a requirement for any water purification system [9,12].

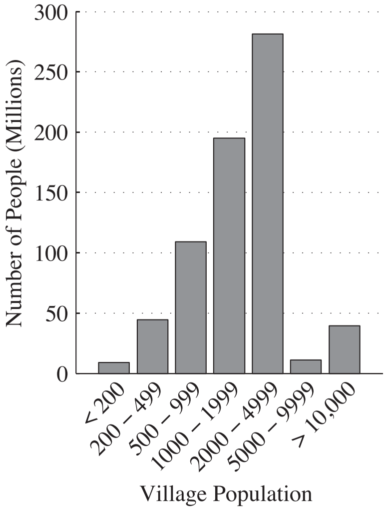

Fig. 1. Number of people living in villages of different populations. The median Indian villager lives in a village of 2000–4999 people.

2.2.2. Chemical quality

The primary chemical contaminants in Indian groundwater are arsenic, fluoride, iron, nitrates and brackishness (salinity). The Central Groundwater Board of India has compiled maps of the prevalence of each of these contaminants throughout the country [4]. The importance and prevalence of brackish ground water specifically will be covered in this section. We conclude that a village-scale desalination (in addition to purification) system would more than double the area of India in which groundwater used as a drinking water source would be acceptable.

Salinity is a measure of chemical water quality that negatively contributes to the safety and aesthetics of a water source if above a certain threshold. Water resources can be divided into two categories according to the number of total dissolved solids (TDS)[2] they contain: 1) freshwater and 2) saline water. As a reference point, the salinity of seawater averages 35,000 mg/L and human blood is approximately 9000 mg/L. When a human drinks seawater, osmosis forces water from the blood stream in an attempt to equalize the salt concentrations, causing dehydration.

Table 2 provides an estimation of the major water resources on Earth by category [13]. Note that freshwater accounts for only 2.5% of world's water and that the majority of that water is not accessible because it is held in the form of glaciers and permanent snow cover. Rapid global population growth and industrialization place considerable pressure on the little fresh water resource that is available.

Groundwater is typically of higher microbiological quality than surface water and has more uniform characteristics year round [14]. Fresh groundwater is water that is found subsurface and has low levels of TDS (less than 500 mg/L). Brackish groundwater has higher levels of TDS (between 500 and 10,000 mg/L). Table 2 shows that there is more available brackish groundwater than fresh groundwater. The available global groundwater resource is doubled if brackish groundwater is considered as a potential source.

Brackish groundwater lies below approximately 60% of the land area of India (Fig. 2) [4]. The green area represents groundwater that has a salinity of 480–960 mg/L and accounts for 37.5% of the total land area. The yellow area represents groundwater that has a salinity of 960–1920 mg/L and accounts for 10.6% of the total land area. The red area represents groundwater that has a salinity greater than 1920 mg/L

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[1] Throughout this article, ₹ refers to the Indian Rupee (INR); $ refers to the United States Dollar (USD).

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

Table 1
Categories of water quality.

Biological	Bacteria
	Viruses
	Protozoa
	Coliform bacteria
	Helminths
	Fungi, algae
Chemical	pH
	Anions and cations
	Alkalinity
	Hardness
	Dissolved gases
	Organic and inorganic pollutants
Physical	Total solids
	Turbidity
	Color, taste, odor
	Temperature

and accounts for 11.9% of the total land area. A village-scale purification system that can desalinate and remove biological and chemical contaminants would more than double the area of India in which groundwater used as a drinking water source would be acceptable.

2.2.3. Physical quality

Physical quality refers to water aesthetics. Although poor aesthetic quality of water does not directly affect the user's health, it can cause the user to reject the source altogether. Users expect water to be clear, odorless, sweet, cool, and fresh if it is of high quality [5].

In January 2013, the authors conducted nine interviews with residents in five different villages in Maharashtra State. In one village, five families where interviewed individually. In the remaining four villages, the interviews were held with a group of adults, averaging between 15 and 30 people. In all cases, the residents interviewed were recommended by the NGO working in the community as people knowledgeable about the water situation in their community and who had access to the village's improved water source. The goal of the interviews were exploratory in nature; users were asked about the source of their drinking water, water purification habits, and knowledge of household water purification devices sold in India. In seven of the nine interviews, the high salinity of their water source was mentioned. The context in which salinity was brought up by the users fell into the following categories: 1) the water source "tastes salty," 2) the salinity in the bore well made "coughing increase and it harder to digest," 3) salts harden on clay filters making them unusable, 4) off-the-shelf household water treatment options were undesirable since they didn't remove the salty taste, 5) salts in the water "ruin cookware." The number of times that salinity was mentioned as an issue by these end users without prompt surprised the authors, leading to further investigation of the importance of desalination in water purification for rural villages in India.

The interview findings were substantiated through literature review. In a user study of water treatment and storage products completed in India by PATH Safe Water Project, the most common reason for selecting a water source was the source's perceived water quality, which is given by color, smell, taste, and temperature [16]. This means that purifiers that do not improve the aesthetics of the output water are judged as not improving the quality of the water, even if harmful biological and chemical contaminants are being removed. If the quality of the water is perceived as poor, the water will not be used. The effect of aesthetic factors is not limited to developing regions; 39% of bottled water users in the United States choose bottled water because it tastes better than tap water according to a nationwide survey of 1754 consumers [17].

Table 2
Global distribution of water [13].

Water resource	Percent of total water
Saline water	97.5
Oceans and seas	96.54
Saline groundwater	0.93
Saltwater lakes	0.006
Freshwater	2.5
Glaciers and snow cover	1.74
Fresh groundwater	0.76
Fresh lakes	0.007
Wetlands	0.001
Rivers	0.0001

Providing access to a safe water source does not guarantee that the target user will actually adopt the provided solution. Because changing water collection and purification habits require behavior change, implementing new water treatment plants can be difficult, particularly if users are asked to pay for them [18]. Echenique and Seshagiri surveyed 400 households in Hyderabad, India, asking each to choose between five different options of water supply. Each option included a different mixture of features (quality of water, quantity of water, duration of supply, and flow rate) at different costs. The study found that users greatly prioritize improvements in water quality over other features and thus are more willing to pay for such improvements [19].

TDS plays an important role in aesthetic quality. The taste quality of water in regards to salt content was first described by W.H. Bruvold in 1969 (Table 3) where water with TDS less than 200 mg/L is rated as excellent [15]. In addition to causing poor taste, a study by Singh et al. showed that users in India find saline water ineffective in quenching thirst and unsuitable for cooking [5]. It is because of both the potential health effects and acceptability concerns that the Indian Standard for Drinking Water sets two limits in regards to salinity: the acceptable limit for total dissolved solids is 500 mg/L because palatability decreases and gastrointestinal irritation may occur in higher concentrations, the permissible limit if no other source is available is 2000 mg/L [12].

A system that targets water aesthetics (particularly salt removal) as well as biological and chemical performance will create reassurance about the improved water quality and encourage the behavior change necessary for people to use it.

2.3. Recovery ratio

The recovery ratio of a desalination system is defined as the volume flow rate of product to the volume flow rate of input feed water. The importance of the recovery ratio depends on the application. In the regions of India that require desalination, groundwater supply is also limited, and a high recovery ratio means more efficient use of that limited water resource. In contrast, if the water treatment system has unlimited feed water (as is the case for coastal seawater desalination plants), the recovery ratio may not be as important.

Having 15% of the world's population but only 6% of the world's water resources, India is designated as a water-stressed country [14]. Fig. 3 shows areas of physical and economic water scarcity in India [20]. Dark orange regions represent areas that have already exceeded the sustainable limit of water withdrawal for the region and are considered to have physical water scarcity. Light orange regions are approaching physical water scarcity. Purple regions represent areas in which human, institutional, and financial capital limit access to water, rather than a physical shortage. Comparing Figs. 2 to 3, the areas with highest groundwater salinity are also the areas of physical water scarcity.

The recovery ratio of a system also defines the volume and concentration of the brine or wastewater stream. Treatment and organized disposal of brine did not occur at any of the village scale RO plants visited by the authors; the brine stream is routed out of the treatment plant and discharged on the ground a short distance away. Increasing the recovery ratio of a desalination plant leads to a smaller, more concentrated, volume of brine. With a lower volume, basic brine management methods such as evaporation ponds could be implemented at a lower cost than that required for a higher volume. Having a high recovery

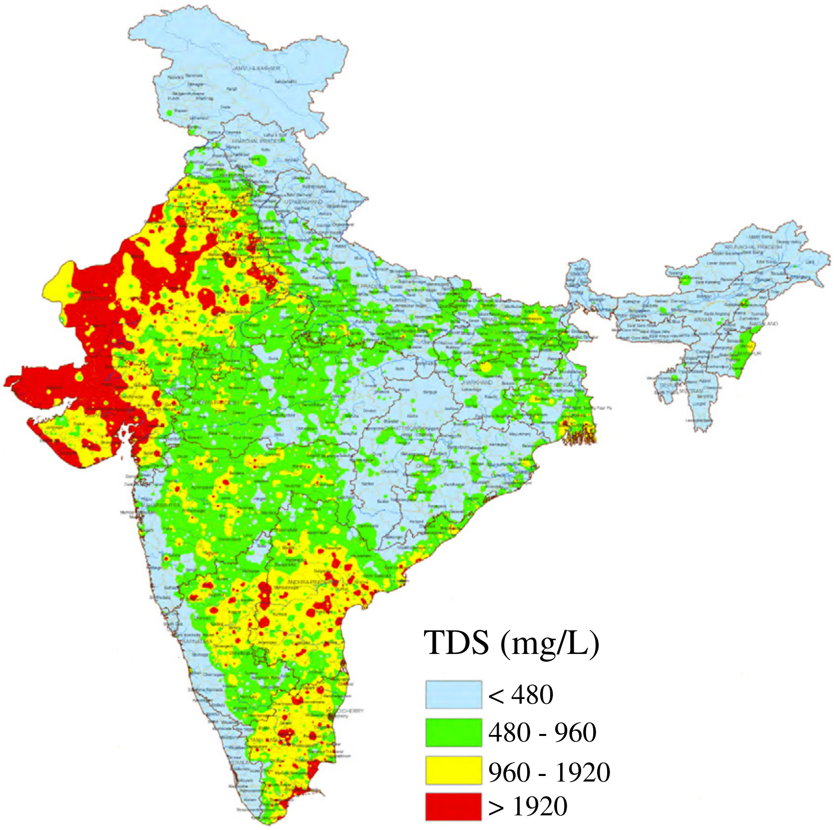

Fig. 2. Map of salinity levels in Indian groundwater [4]. Groundwater with a salinity level greater than 480 mg/L underlies 60% of the land area in India. At this level, the aesthetic quality of the water source is compromised.

ratio is important for any inland desalination plant where brine management will be practiced and especially in areas where physical water scarcity is of concern. This leads to the requirement of maximizing the recovery ratio for any desalination plant installed in these areas.

2.4. 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 that use electricity, kerosene, or other sources for lighting. In 2011, only 55.3% of rural households used electricity for lighting [21]. In addition to the problem of access to a 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 [6,22]. For example, if a village needs a total of 6000 l per day and power is available for 6 h, then a 1000 l per hour (LPH) plant is acceptable. However, if that same village only has access to power for 2 h, then a 3000 l 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 be less expensive to supplement grid power with additional energy generation in the form of diesel generators or solar than to oversize the system as a whole.

Table 3
Taste quality as a function of TDS [15].

Potability	Excellent	Good	Fair	Poor	Unacceptable
TDS value (mg/L)	<200	201–600	601–1000	1001–1300	>1300

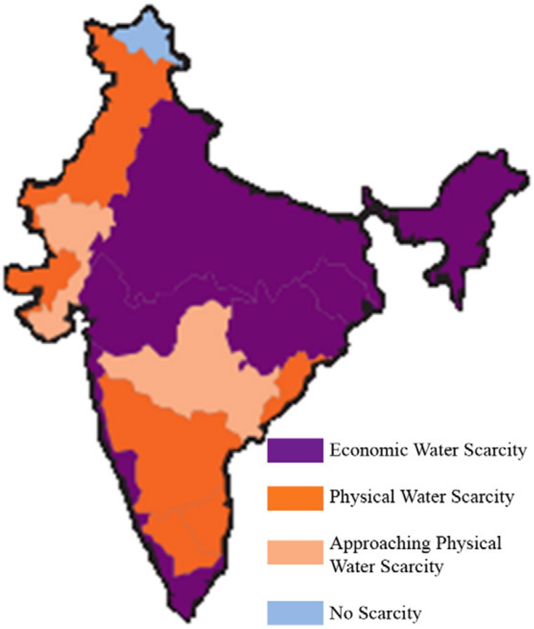

Fig. 3. Map of India highlighting areas of physical and economic water scarcity [20]. Maximizing the recovery ratio of a desalination system is important for areas having or approaching physical water scarcity.

Solar power is the best solution to supplement energy in a village-size system. A study completed by Abraham and Luthra in 2011 showed that there is an economic benefit to using solar over diesel for desalination systems requiring less than 3 kWh/m^3 and having a daily plant capacity of less than 70 m^3/day [23]. Similarly, Bilton 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 when powered by solar than diesel [24].

The average annual solar irradiance received in India is 4–6 kWh/m^2/day [25]. Fig. 4 shows the regional variation in solar irradiance [26]. Comparing Figs. 4 and 2, the areas with high solar potential correspond to the areas with high groundwater salinity. As a result, solar power is the best power source for desalination in locations with intermittent or no grid access and high salinity groundwater.

2.5. Capital and operational cost

While solar power decreases the operational cost of a desalination system compared to on-grid systems, it increases the capital cost. The decreased operational cost comes from removing all expenditure on electricity (normally the highest component of operational expense for an on-grid RO system) [27]. The increased capital cost comes from the panels, supporting control system, inverters, and batteries.

In order for a new design to be economically viable, the cost of the system must be equal to or less than the cost of current on-grid rural desalination systems. Tata Projects Limited offers RO systems that cater to different water types, and in capacities ranging from 250 to 5000 LPH. The company had installed 577 on-grid plants in India at the time of our conversation in January 2014 [6]. Their 1000 LPH plant accounts for over half of their sales. 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 ₹3 per 20 l can.

The capital cost of the entire 1000 LPH system including the shelter, storage tanks, power connections and wiring, bore well, excavation work, and installation charges is ₹688,000 (≈$11,000). Of this total, ₹355,000 (≈$5700) is for the 1000 LPH plant itself. The system has an operational cost (including energy, operator salary, chemicals, prefilter and membrane replacement) of ₹0.047/L (≈$0.75/$m^3$). The payback 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 appear economically sustainable.

Electricity costs are the largest component of the operational expense of current village-scale RO systems, accounting for 54% of the recurring expenditures [6]. This is below that that occurred in a seawater RO plant, in which electricity accounts for ≈63% of the operations cost [27].

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 h of grid connection per day. Pilot installations of the 1000 LPH plant running off of PV power and tested by Tata Projects cost an additional ₹400,000 (≈$6400). This added cost is more than the cost of the RO plant itself. Indian financial institutions which are willing to work with the 2–3-year payback period for the on-grid RO systems are not willing to do the same for the extended payback period that comes with the off-grid systems. This makes PV-RO systems not economically viable at this time [6]. Because of this, off-grid locations remain underserved as the capital costs of PV-powered

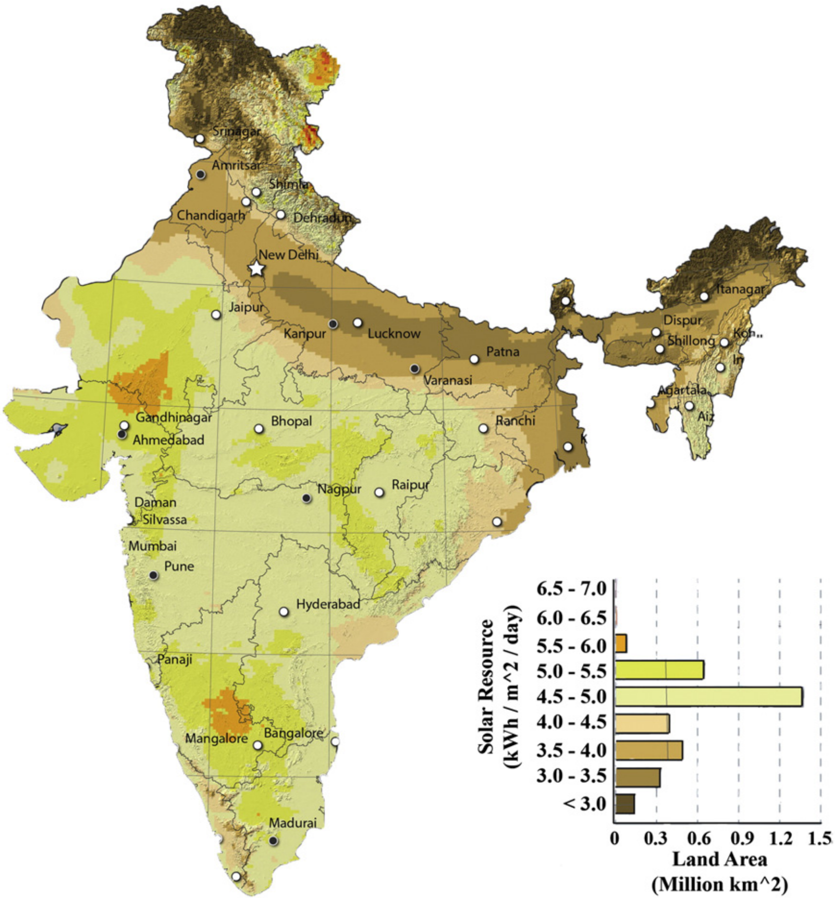

Fig. 4. Map of solar irradiation in India [26]. High annual solar irradiance in India makes the country a prime candidate for PV-powered systems in off-grid locations. Areas with high solar potential often overlie areas of high groundwater salinity and physical water scarcity (see Figs. 2 and 3).

systems inhibit installation in these areas. In order to make a solar powered system viable, the energy requirements of the desalination technology need to be lowered below those required for RO, and attempts to drive the system without battery storage are economically favorable.

2.6. Maintenance

The type and frequency of required maintenance as well as the skill level required to perform that maintenance is another important feature of a water purification plant for rural villages. Many rural plants have failed due to a lack of properly trained operators or insufficient supply chains for replacement filters and membranes. In order to understand how successful community-scale village level systems are maintained, the authors visited plants installed by NGOs and industry leaders (Safe Water Network, Drinkwell Systems, Gram Vikas, Naandi Foundation, and Tata Projects) in four states (Maharashtra, Andhra Pradesh, Odisha, and Punjab). Successful operation and maintenance resulted from two primary factors: 1) a well-trained and paid local operator, and 2) availability of technical support should the local operator not be able to fix a problem.

An example of successful operation and maintenance schemes is employed by Safe Water Network, which trains a local operator to perform daily tasks such as backflushing the system, recording TDS and pressure values, adding chemicals, changing pre-filter cartridges and collecting money from users. The operator calls for technical support from the NGO for more complicated maintenance. The described level of maintenance has shown to be sustainable both technically and economically and thus can be used as a benchmark for future designs at the village scale. A village-scale desalination system must be maintained in the field by an operator with limited training.

3. Desalination technologies: description and energetics

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 are distillation using a solar still, as well as more complicated systems such as multi-stage 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 3000 m^3/day and for higher salinities than those present in Indian groundwater [28].

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.

3.1. 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

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

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. Eq. (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 3000 people requiring 9 m^3/day of drinking water, a unit efficiency of 0.5 [29] and an average daily incident solar energy of 18,000 kJ/m^{2}day [29], the land area required would be 2260 m^2. With the capital cost of solar stills in India at approximately \$38.3/m^2 [29], the capital cost of a system for this village size would be \$86,558, nearly eight times that of Tata Projects 1000 LPH RO plant.

In addition to the large land area and capital cost 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 can cover the glass, reducing the efficiency. 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 required for health. Because solar stills require extended daily maintenance, large land areas, and are not cost competitive compared to the current rural desalination systems, they should not be considered for community scale water purification.

3.2. 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 diluate stream with low salt concentration, and one concentrated brine stream (Fig. 5 right). The applied pressure forces water to move in the opposite direction of the natural flow that occurs in osmosis (Fig. 5 left).

The power required to complete the reverse osmosis process is

$$P_{RO} = \frac{p_{hp} Q_{feed}}{\eta_{pm}}, \tag{2}$$

where Q_{feed} is the flow rate of the feed water stream, p_{hp} is the applied membrane pressure from the high pressure pump, and η_{pm} is the combined efficiency of the high pressure pump and motor. In order to

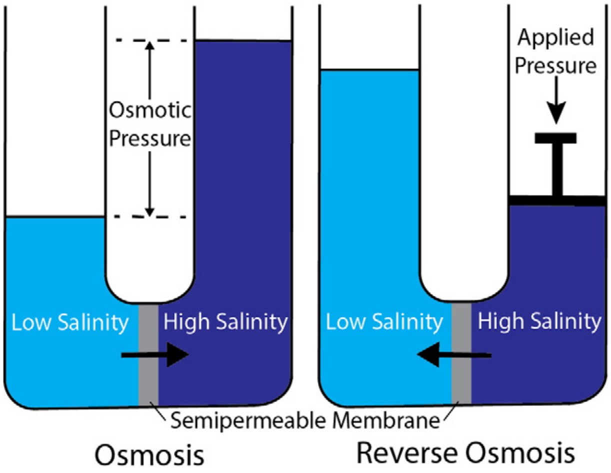

Fig. 5. Reverse osmosis process. RO (right) is completed when a pressure greater than the osmotic pressure of a solution is used to move water through a semi-permeable membrane.

determine the specific energy requirement, P_{RO} is divided by Q_{prod}, the flow rate of the product water stream.

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

The applied pressure must be greater than the osmotic pressure of the feed stream in order to complete RO. For the village-scale RO plants the authors visited, the applied pressure was 500–1300 kPa above the osmotic pressure of the brine stream in order to achieve optimal flow rates through the selected membrane stacks. Because osmotic pressure increases with salinity, high salinity RO requires more energy per unit of water produced than brackish water RO.

The brine stream leaves the membrane at a pressure over the osmotic pressure. In seawater RO, the energy from this high pressure 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 [6].

3.3. Electrodialysis

In the electrodialysis (ED) process, saline water is pumped through an electrodialysis stack (Fig. 6). When an electric potential difference is applied across the stack at the anode and cathode, anions move toward the anode and cations toward 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 toward 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 toward 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 compartments 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 the product of the current through the stack and the voltage applied at the electrodes. The relationship between current and the total applied voltage is

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

where N is the number of cell pairs in the stack, i is the current density (A/m^2), and R_{dil}, R_{conc}, R_{AEM}, R_{CEM} are the area resistances of the diluate stream, concentrate stream, AEM and CEM, respectively (Ω m^2). V_{elec} and $V_{potential}$ are the electrode potential and concentration potential, respectively.

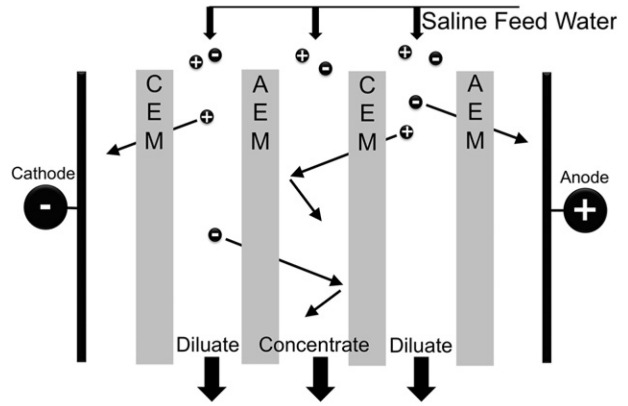

Fig. 6. Electrodialysis process. ED is the process of pulling ions out of solution through the application of an electric potential across a series of alternating anion and cation exchange membranes (AEM, CEM).

The instantaneous current density can be calculated if the applied voltage, number of cell pairs, and resistances are known (Eq. (4)). 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 relationship for the specific aqueous solution. For aqueous NaCl, the Falkenhagen equation is used [30]. 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:

$$E_{spec,ED} = \frac{\int_{t=0}^{t=t_{final}} iAV_{total}\, \mathrm{d}t}{\forall_{prod}}, \tag{5}$$

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

$$A_{total} = \frac{Q_{dil}\left(C_{feed}^{in} - C_{dil}^{out}\right) zF}{N\phi i}, \tag{6}$$

where C_{feed}^{in} and C_{dil}^{out} are the concentrations of the feed stream at the inlet and the diluate stream at the 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 (the efficiency with which ions are transferred in the system). Eq. (6) shows a linear relationship between membrane area and the feed water salt concentration. This equation also shows an inverse relationship between membrane area and the current density; achieving a higher current allows for higher ion transport and is the result of a lower stack resistance.

Eqs. (4) and (6) assume that the concentrate and diluate compartments have the same flow conditions and geometries and that 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 [31,32].

3.4. 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 [33]. Eq. (7) describes the least specific energy of separation. It represents the limit of a completely reversible desalination operation (entropy generation is zero) and thus is the thermodynamic limit for any desalination technology. It is included here for the purposes of comparison to the already described specific energies of RO and ED technologies.

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

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 feed water salinity.

4. Selection of most appropriate

4.1. Desalination technology

The following sections compare RO and ED technologies in the areas of energy per unit of water produced, cost per unit of water produced relative to distillation, functionality and maintainability. Through these comparisons, we find that ED better suits the socioeconomic and technical requirements for village-scale desalination in rural India.

4.2. Energetic comparison

For both RO and ED, the energy consumption of the system depends on the salinity of the feed water. Unlike membrane based methods of desalination, the energy input to a solar still is independent of feed salt concentration.

In order to compare the energy requirements of each of the described technologies, Eqs. (3), (5), and (7) are used to produce Fig. 7. Note that in each case the full system was modeled using equations provided by Ortiz [31] for ED and Bilton [24] for RO. The applied pressure for RO was selected to be 900 kPa 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 mg/L, ED requires 75% less specific energy than RO. The benefit linearly decreases as feed water salinity increases.

4.3. Economic comparison

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. 8 [34]. 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 pretreatment equipment. The operating cost is determined by the energy consumption, membrane and pre filter replacement, pretreatment chemicals, and general maintenance. Fig. 8 represents the relative total process cost of distillation, RO, and ED 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.

Fig. 8 shows that ED costs increase faster with salt concentration than RO, resulting in a point around 5000 mg/L 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 (Eqs. (5) and (6)). In an RO system it is primarily the operational cost that depends on feed water salinity (Eq. (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. 7), 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 2000 mg/L, the capital cost of the power system to run a Tata Projects 1000 LPH plant is reduced by 50%, from ₹400,000 (≈$6400) to ₹200,000 (≈$3200), using ED instead of RO.

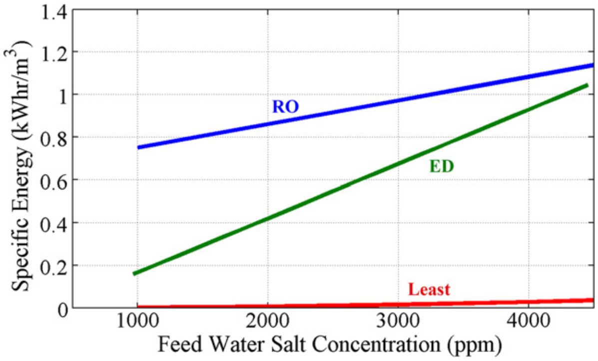

Fig. 7. Dependence of specific energy on feed water salinity. The salinity range presented represents that commonly found in Indian groundwater. The energy required for RO and ED is compared to the thermodynamic least energy needed to separate the given salt concentration from water.

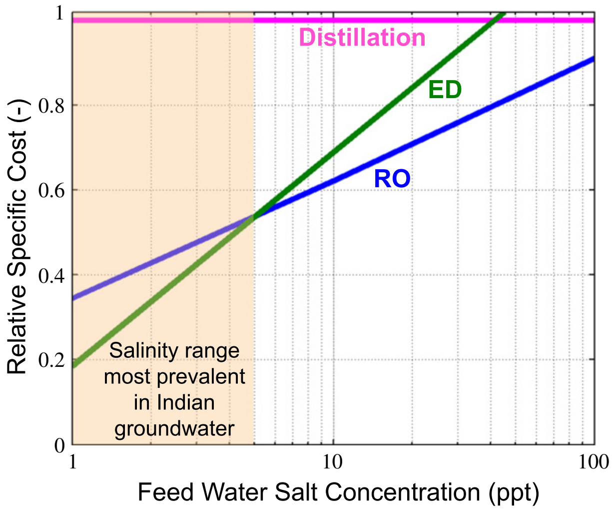

Fig. 8. The dependence of specific cost on feed water salinity. Relative specific cost ($/unit of water produced) of reverse osmosis and electrodialysis technologies in comparison to the specific cost of distillation, which is independent of feed water concentration.

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. 8), and 2) if moving off-grid, the capital cost of the power system is reduced as well.

4.4. Functionality and maintenance comparison

The mechanism by which RO and ED complete desalination is different, resulting in different contaminant removal. RO membranes act as a physical barrier and are thus able to remove contaminants other than salts, including heavy metals, most pesticides, and biological contamination. ED pulls charged particles out of water without the use of a physical barrier and thus the ED system alone removes ions only. The primary chemical contaminants in India are arsenic, fluoride, iron, nitrates, and dissolved salts, all of which are charged ions and thus removable by ED.

Neither ED nor RO systems are installed without pre- and post-treatment. In both cases, pretreatment is used to remove suspended particles and pathogens greater than 5 μm. The pretreatment process protects the membranes and prevents clogging and increased pressure drop. This process is important for RO membranes, which are more sensitive to feed water quality than ED membranes. While RO membranes can remove the pathogenic organisms, the majority are actually removed in this pretreatment step. Pretreatment in ED is done for similar reasons, but ED membranes are stronger and the flow paths are less easy to clog. Post-treatment in the form of UV disinfection is used in all village RO plants we visited. This disinfection step occurs between the treated water storage tank and the spout where users collect water. The function of this post-treatment is to ensure biological water quality at the point the water enters the user's receptacle. Although pre-treatment and UV disinfection is required in an ED system to ensure the removal of biological contamination, the treatments would not be any more extensive than that already present in village RO systems.

RO membranes are more sensitive to feed water quality and chlorine levels than ED membranes, requiring greater pretreatment. ED's relative insensitivity to chlorine levels is a benefit in villages that already have an elevated storage tank of water treated with chlorine by the local government. This water is sometimes not treated for chemical or physical quality parameters, like salt, and thus is rejected by consumers. Because of the chlorine levels in the supply, it 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 4 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 and to minimize the cost associated with brine treatment and management. Additionally, the life of ED membranes averages 10 years, which is 2–3 times longer than that of RO membranes. Although ED membranes tend to be more expensive than RO membranes, their recurring costs are lower because of their longer life. Since the energy requirement of desalination using ED is lower than that using RO for low salinities, operational cost is also lower. The combination of longer membrane life and lower operational cost makes ED less expensive for desalination in the salinity range found in Indian groundwater (Fig. 8).

5. Discussion

The need for desalination in Indian villages was discovered during user interviews, and then further justified using literature that suggests that users judge the quality of their water source based on its aesthetic quality (taste, odor, and temperature). By targeting water aesthetics through desalination as well as biological and chemical performance, one can design a system that encourages the behavior change necessary for people to use it. The prevalence of saline groundwater under 60% of the land area of India further strengthens the need for desalination. As a result of this work, it is suggested that biological and chemical contaminants should be reduced to the levels recommended by the WHO, and salts (TDS) should be reduced to less than 500 mg/L. An appropriate system should be able to achieve this water quality at a rate of 6–15 m^3/day, which is the drinking water requirement for a village of 2000–5000 people.

Three maps of India are presented (Figs. 2, 3, and 4) which show that areas of high groundwater salinity and high solar irradiation are suffering from water scarcity. From these maps we recognize the need for a maximized recovery ratio as well as the benefit of a solar powered system if grid power is not available. RO plants designed and implemented by Tata Projects were studied due to their history of economic sustainability. From these data, it is recommended that a new solar-powered system should cost less than ₹755,000 (≈\$12,100), the current cost of Tata Project's PV-powered 1000 LPH RO plant.

These requirements are used to evaluate appropriate desalination technologies for rural areas of India. The capital cost of a village-scale solar still is found to be eight times that of the current Tata Projects RO plant and is therefore not recommended for this application. ED is found to have a lower specific cost than RO at the salinity levels commonly found in inland locations. ED requires less energy per unit of water produced than RO, the most common technology currently installed in rural locations. 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. Our analysis indicates that PV-ED can better meet the socio-economic and technical challenges associated with purifying groundwater in off-grid, inland Indian communities than RO systems.

Table 4
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

6. Conclusion

This paper defines critical design requirements for village-scale water purification systems for rural India. By engaging with end users, NGOs, manufacturers, government officials, and industry leaders working directly in the Indian market, in addition to reviewing literature, it was determined that the development of a PV-ED system has the potential to greatly expand the reach of desalination systems in rural locations. The benefits of ED over RO include lower energy consumption per unit of water produced leading to lower capital cost, greater recovery ratio, and lower sensitivity to chlorine and feed water changes.

ED also has the potential to be run directly off of a PV array. Because the ED stack takes a direct voltage at the anode and cathode, DC/AC inversion and batteries are not required, further reducing the capital cost of the power system. Future work will analyze the ability of a PV-ED system to respond to the stochastic nature of both solar and drinking water habits.

Notation

A_{land}	required land area (m^2)
$\forall_{prod}$	volume of product water (m^3)
ρ	density of water (kg/m^3)
h_{fg}	latent heat of vaporization (kJ/kg)
η	efficiency of distillation unit (—)
q	incident solar energy per area per day (kJ/m^2day)
P_{RO}	power (W)
Q_{feed}	flow rate of feed water stream (m^3/s)
p_{hp}	applied membrane pressure from high pressure pump (Pa)
η_{pm}	combined efficiency of pump and motor (—)
Q_{prod}	flow rate of product water stream (m^3/s)
E_{spec}	specific energy (kWh/m^3
V_{total}	total applied voltage (V)
N	number of cell pairs (—)
i	current density (A/m^2)
R_{dil}	area resistance of diluate stream ($\Omega\ m^2$)
R_{conc}	area resistance of concentrate stream ($\Omega\ m^2$)
R_{AEM}	area resistance of AEM ($\Omega\ m^2$)
R_{CEM}	area resistance of CEM ($\Omega\ m^2$)
V_{elec}	electrode potential (V)
$V_{potential}$	concentration potential (V)
A	individual membrane area (m^2)
A_{total}	total membrane area (m^2)
Q_{dil}	flow rate of diluate water stream (m^3/s)
z	ion charge (—)
F	Faraday constant (C/mol)
C_{feed}^{in}	concentration of the feed stream at the inlet of the stack (mol/m^3)
C_{dil}^{out}	concentration of the diluate stream at the outlet of the stack (mol/m^3)
ϕ	current efficiency (—)
g_{dil}	specific Gibbs free energy of the diluate stream (J/kg)
g_{conc}	specific Gibbs free energy of the concentrate stream (J/kg)
g_{feed}	specific Gibbs free energy of the feed stream (J/kg)

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