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Feasibility study of an electrodialysis system for in-home water desalination in urban India

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ABSTRACT

Poor quality of drinking water delivered to homes by state utilities, and a large reliance on brackish ground water resources in parts of urban India, has resulted in the adoption of in-home water treatment solutions. The only existing in-home water treatment solution capable of desalination is reverse osmosis (RO). However, existing RO products can recover only 25–50% of the feed water supplied as usable product water. In this study, an alternative solution that relies on electrodialysis (ED) was designed and experimentally shown to achieve a recovery of 80%, producing 12 L/h of water at the desired salinity of 350 ppm from a feed salinity of 3000 ppm. The cost and size of the proposed system were also found to be comparable to existing in-home RO systems. In-home ED water treatment systems could compete with existing RO products while providing the advantage of improved water-conservation in water-stressed India.

1. Introduction

The Indian government has expressed an aim to provide clean drinking water to all of its citizens (Government of India, 2002), but this target has yet to be achieved. While the percentage of people with improved access to drinking water sources has increased from 69–92% nationally from 1990 to 2010, an estimated 97 million people still rely on surface water, unprotected dug wells and springs, or water delivered by carts (WHO/UNICEF, 2012). Even among those with improved access, the 2011 census found that piped water is supplied to only 71% and 35% of urban and rural households, respectively (Census of India, 2011). Furthermore, no major city has developed the capability to provide a 24 h water supply, with most supplying only 4–5 h of water each day (Mckenzie and Ray, 2005). Quality of the available water in urban environments is also a concern since only 62% of the tap water supply is treated before delivery (Census of India, 2011). A survey conducted by the Society for Clean Environment (2003) found the proportion of tested water samples that were unfit for drinking to be as high as 70% in certain municipal wards of Mumbai (Sridhar, 2003).

Compounding the problem of poor access and quality is the salinity of available water. There is a high reliance on groundwater resources to meet the population needs across much of the country. According to a study performed by the Central Ground Water Board, 60% of this groundwater was classified as brackish (Board, 2010). Water from these sources was characterized as having high salt content with total dissolved solids (TDS) ranging from 500 ppm (ppm) to 3000 ppm. This salinity exceeds the 500 ppm TDS standard recommended by the Bureau of Indian Standards (BIS) for drinking water (Bureau of Indian Standards, 2012), and is indicative of poor palatability. The consumption of high salinity water may also pose adverse health effects including gastro-intestinal irritation (Bureau of Indian Standards, 2012) and the development of kidney stones (Bellizzi et al., 1999). It has been therefore hypothesized that water treatment methods that reduce levels of TDS, improving taste in the process, will experience high rates of adoption (Wright and Winter V, 2014).

Since the current public infrastructure is unable to reliably deliver safe, desalinated, and uncontaminated water to homes, consumers have turned to in-home water purification. However, methods which include straining water though a cloth, boiling, or ultraviolet (UV) treatment do not address the high levels of TDS present in the water. The only commercially available in-home water treatment method currently used in urban India that can remove TDS is reverse osmosis

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Nomenclature

Acronyms

AEM	Anion Exchange Membrane
BIS	Bureau of Indian Standards
CEM	Cation Exchange Membrane
CCRO	Closed Circuit Reverse Osmosis
ED	Electrodialysis
EDR	Electrodialysis Reversal
ID	Internal Diameter
INR	Indian Rupee
L	Liter
L/h	Liters per Hour
M	Molarity
PPM	Parts per Million
RO	Reverse Osmosis
RR	Recovery Ratio
TDS	Total Dissolved Solids

Symbols

A	Membrane area (m2)
B0	Falkenhagen equation constant
B1	Falkenhagen equation constant
B2	Falkenhagen equation constant
D	Diffusion coefficient (m2/s)
F	Faraday constant (C/mol)
i	Current density (A/m2)
I	Current (A)
l	Thickness of membranes (mm)
L	Gap between membranes (mm)
MW	Molecular weight (g/mol)
N	Number of cell pairs
p	Pressure (MPa)
P	Power (W)
V^t	Tank volume (L)
Q	Internal stack flow rate (L/h)
r	Resistance (Ω-cm2)
R	Gas constant (J/mol-K)
S	Salinity (ppm)
t	Time (s)
t+	Transport number of cation
t-	Transport number of anion
T	Temperature (K)
v	Flow velocity (cm/s)
Vol	Volume
z	Charge number

Subscripts

a	Anion exchange membrane
c	Cation exchange membrane
ch	Channel
con	Concentrate
dil	Diluate
f	Feed (input water)
p	Product (output water)

Greek

ϕ	Current efficiency
Π	Osmotic pressure

(RO). However, in-home RO systems operate at low water recoveries (25–50% (KENT RO Systems Ltd; Hindustan Unilever Ltd, 2014)), thereby further stressing the limited resources.

Conversations with Tata Chemicals Ltd (Shah, 2014)., a provider of in-home RO systems in India, informed us that there is an unmet need among consumers for an in-home desalination product that can recover more water than current in-home RO systems. To meet this need, we considered alternatives to RO such as electrodialysis (ED) (Strathmann, 2010), capacitive deionization (Oren, 2008), thermal desalination technologies and a higher recovery version of RO called closed circuit reverse osmosis (CCRO) (Efraty et al., 2011). Our evaluation informed us that ED was the technology alternative that was most ready for deployment in India. Key highlights of this evaluation are discussed in Appendix A.

ED is an alternative method for desalination that can provide higher recovery and lower energy consumption compared to RO for the groundwater salinity range present in India (Wright and Winter V., 2014). This technology has been widely implemented at a larger scale for applications that include waste-water treatment, production of potable water, and salt production (Strathmann, 2010). Pilat (2001, 2003) had reported the use of ED for in-home water treatment applications along with a summary of the features of a few systems that were commercially deployed in Russia. One system was for the desalinating 3000 ppm water to produce 50 L/h of drinking water at 300 ppm. However, the cost of the systems was not mentioned. Important technical information such as membrane area, water flow rate within the stack, and membrane specifications were also not reported which made estimating cost difficult. Since the publication of Pilat's work, significant advances in RO membranes have made in-home RO systems less expensive. With the reported information, it was not possible to effectively characterize the technical design and the economic feasibility of in-home ED in urban India, where the required flow rates are lower and systems needed to be more compact than the systems reported by Pilat (Pilat, 2001). Recent progress made in the process modeling of ED (Ortiz et al., 2005) also enable optimizing and characterizing in-home ED systems in a way that has not been possible before.

1.1. Objective

In combination with necessary additional pre and post-treatment, ED demonstrates the potential to satisfy an unmet consumer need: a cost-competitive, high recovery in-home desalination and water treatment system. In this work, we assess the design requirements for an in-home water desalination system for use in urban Indian households, and evaluate the technical design and economic feasibility of implementing the simplest configuration of ED to serve this application. The design requirements for an in-home desalination system are first presented. An ED system architecture appropriate for in-home desalination was selected. An analytical process model for ED was used to optimize an experimental ED stack design that could achieve the design requirements. Results from our technical feasibility tests highlighting an optimal ED stack design, a conceptualization of the complete in-home ED water treatment product and an estimate of the cost of the final product are presented. Limitations of our study and recommendations for future work are also discussed.

2. Design requirements

2.1. Requirements drawn from existing products

There are different types of water purifiers currently available in the

Indian market. Table 1 presents the technology options available to consumers, alongside the concept investigated in this paper.

Reverse osmosis (RO) is currently the only commercially offered technology that provides desalination for the in-home water purification market. Table 2 summarizes the features found in current in-home RO units that influenced the requirements defined for this project.

2.2. Summary of design requirements

The design requirements listed in Table 3 were developed based on a review of existing consumer desalination products and discussions with the project partner, Tata Chemicals Ltd. These specifications informed the selection of an appropriate desalination technology, the design of the process architecture, and the development of a concept product.

3. Electrodialysis system

3.1. Stack components

An ED stack consists of two electrodes, a cathode and an anode, along with a series of anion (AEM) and cation exchange membranes (CEM) separated by spacers that provide two isolated flow paths. Each set of anion and cation exchange membranes constitutes a cell pair (Fig. 1). All of these components are packaged in a housing that has inlets and outlets for the feed water, desalinated (diluate) water, reject (concentrate) water, and rinse solution for the electrodes.

Current ED stacks contain titanium electrodes that are coated with platinum. The use of these electrodes in a small-scale in-home system requires additional consideration. When a voltage potential is applied across the electrodes, water molecules dissociate at the cathode to produce hydroxide (OH-) ion and hydrogen gas (H_2). At the anode, hydrogen ions (H+), oxygen (O_2), and chlorine gas (Cl_2) are produced. Gas formation at the electrodes increases the electrical resistance of the stack and the acidic nature of the anode stream, which can produce scaling on that electrode. To prevent this occurrence and the formation of Cl_2, a Na_2SO_4 solution is rinsed over the electrodes. The use of Na_2SO_4 necessitates physical separation from the other flow paths in the stack, which requires the use of an additional tank, pump, and associated plumbing.

3.2. System architecture

ED can be implemented in two distinct architectures: batch and continuous. The batch process involves recirculation of both the diluate and concentrate streams through the stack until the salt concentration in the diluate tank decreases to the desired level. A schematic for this process is provided in Fig. 2.

In the continuous process, stack parameters such as voltage and flow rate would be modulated to produce the desired salinity in the diluate stream within a single pass, based upon the feed water salinity available in the user's house. In order to prevent saturation in the concentrate stream, a small fraction of the diluate is added to it at the stack outlet (Fig. 3).

Table 4 provides a side-by-side comparison of the two architectures. Although a continuous architecture would allow for instant water desalination and simpler plumbing, the batch architecture is better suited to our application. Variations in the input salinity for different households would require modulation of the voltage and/or flow rate in the continuous architecture. The batch control system, on the other hand, is less complex in this respect because it relies on recirculation through the stack at a constant voltage until the target salinity level is achieved and a constant voltage can be applied. Recirculation can also allow a smaller stack to be used than for a comparable continuous process, thereby reducing the capital cost and size of the treatment system.

3.3. Model

The performance of the batch ED process, with respect to stream concentrations, time to desalinate, and power consumption was simulated using a detailed analytical model originally developed by Ortiz et al., 2005 and further improved by (Wright and Winter V, 2014). Validation has been conducted by both Ortiz and Wright, with Ortiz having reported deviations between model predictions and experimental data of less than 7% for power consumption, time to desalinate, and stream concentrations. This model treats the ED stack as a collection of identical functional units known as cell pairs. The voltage across each cell pair is:

$$V_{cp}=\frac{V_t - V_{el}}{N} \tag{1}$$

where V_t is the total applied voltage, V_{el} is the voltage drop across the electrodes, and N is the number of cell pairs in the stack. The cell pair voltage can further be expressed as a function of the current density (i) in the stack and the resistance (R) and voltage (E_{mem}) across the membranes, which are themselves a function of the salt concentration in the diluate (C_{dil}) and concentrate (C_{con}) channels:

$$V_{cp}=iR(C_{dil}, C_{con})-E_{mem}(C_{dil}, C_{con}) \tag{2}$$

This relationship is depicted using a circuit diagram (Fig. 4).

The rate of change of diluate concentration is related to the current by

$$NVol_{ch}\left(\frac{dC_{dil}}{dt}\right)=Q_{dil}(C_{dil,in}-C_{dil})-\frac{N\phi I}{zF}+\frac{NAD_a(C_{con,a,w}-C_{dil,a,w})}{l_a}+\frac{NAD_c(C_{con,c,w}-C_{dil,c,w})}{l_a} \tag{3}$$

where Vol_{ch} is the volume of each channel, $C_{dil,\ in}$ is the concentration of diluate entering the channel, Q_{dil} is the diluate recirculation volumetric flow rate, < mmEquation id="eqn1" / > is current efficiency, I is current in Ampere, z is the charge number of the ion, l is the membrane thickness, F is Faraday's constant, D is the diffusion coefficient of the exchange membrane, A is membrane area, and ($C_{conc,\ a,w}$ - $C_{dil,\ a,w}$) and ($C_{conc,c,w}$ - $C_{dil,c,w}$) are the concentration differences of ions across the AEM and CEM respectively.

Experimental stack conditions such as stack voltage, number of cell pairs, initial diluate and concentrate salinity were given as inputs to the model. Values for the constants used in the model are provided in Table 5.

3.4. Design and optimization

The model described above was used to optimize the ED stack parameters for minimizing the time required to desalinate a stream with an influent salinity of 3000 ppm, which was identified to be at the upper end of the groundwater salinity range in India (Wright and Winter V, 2014), to the target salinity of 350 ppm at a rate that exceeds

Table 1
Available product categories comparison.

Technology	Gravity Driven	Reverse Osmosis	Electrodialysis concept
Example	Tata Swach Silver Boost	Pureit Marvella	N/A
Desalination	No	Yes	Yes
Sediment Filtration	Yes	Yes	Yes
Carbon Filtration	Yes	Yes	Yes
Ultraviolet Treatment	No	Yes	Yes
Recovery Ratio	100%	25 – 50%	Up to 95%

Table 2
RO product comparison.

Manufacturer	KENT	Pureit	Tata
Model	Supreme RO (KENT RO Systems Ltd)	Marvella RO (Hindustan Unilever Ltd, 2014)	Swach Ultima Silver RO (Tata Chemicals Ltd, 2014)
Price (INR)	17,000	15,290	16,999
Dimensions (mm)	L 430 W 270 H 630	L 265 W 360 H 480	L 168 W 420 H 537
Weight (kg)	10.9	7.8	11.05
Production Rate (L/h)	15[a]	9–12[b]	15
Storage Capacity (L)	9	10	7
Power Consumption (W)	60	36	55
Recovery (%)	50[a]	25[b]	Unknown

[a] Reported for a feed salinity of 750 ppm and is expected to decrease for higher salinities. Output salinity is not reported
[b] Input and output salinities are not reported.

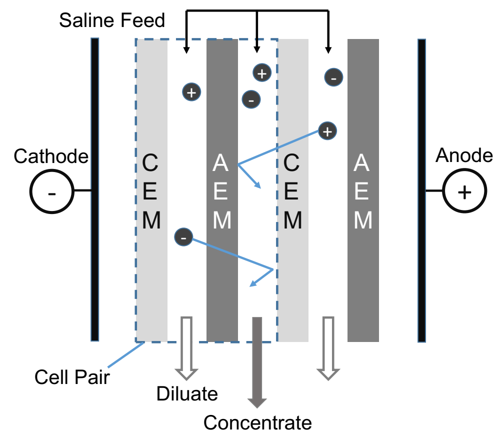

Fig. 1. A voltage potential is applied across a series of alternating cathode exchange membranes (CEM) and anion exchange membranes (AEM) in an Electrodialysis (ED) stack to separate the feed solution to concentrate and diluate streams.

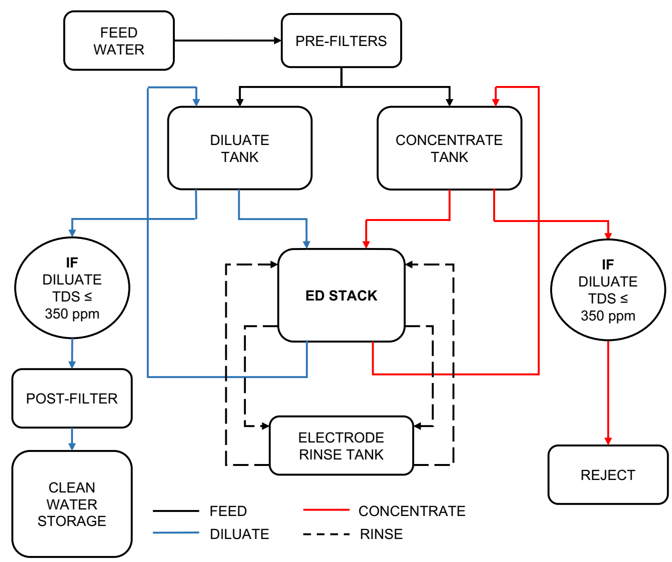

Fig. 2. Flow diagram for batch ED process.

the minimum target of 12 L/h. The ranges considered for model input variables in this optimization are provided in Table 6.

From Eqs. (2) and (3), the rate of change of concentration in the diluate or concentrate channels is proportional to the stack current, membrane area, and recirculation rate. In order to reduce the desalination time, the sensitivity of each of these terms to the rate of concentration change was investigated.

First, the voltage of the cell pair was optimized with the number of modeled cell pairs (N) initially set to 25. The time required for desalination decreased with increasing cell pair voltage (Fig. 5). The manufacturer recommended that the voltage across each cell pair not exceed 2 V to avoid membrane degradation (Personal Communication, 2014). Thus, with an appropriate factor of safety accounting for voltage fluctuations, an optimal cell pair voltage (V_{cp}) of 1.6 V was selected.

The effective area for each individual membrane was fixed to 8 cmx8 cm, given the geometry of the PCCell ED 640002 stack (PCA GmbH) (GmbH, 2014) that was available for testing. Therefore, the membrane area in the ED stack was increased by increasing the total number of cell pairs. The recirculation rate was also proportionately increased in order to maintain a constant flow velocity of 2.78 cm/s in the channels. This was observed to be the maximum velocity that the experimental stack could maintain without producing large fluctuations in the outlet pressure. Fig. 6 indicates how desalination time reduces with increasing number of cell pairs. The resulting total voltage is also shown. The manufacturer recommended that the total voltage drop across the stack be limited to 33 V, accounting for a 3 V drop across the electrodes (Personal Communication, 2014). Constrained to a maximum of 18 cell pairs by this voltage limit, the peak lab stack performance was limited to just under a 5 min duration for desalinating a 1 L solution. This design point, graphically depicted at the intersection of the dashed lines in Fig. 6, met the performance specifications of the target system. It was therefore selected for validation through experimentation.

For a commercial in-home ED stack, the number of cell pairs could be increased beyond 18 to further reduce desalination time. The

Table 3
Design requirements.

Requirement	**Description**
Water Recovery	The product should recover at least 80% of the feed as product water. A higher water recovery product is less wasteful and more desirable.
Water Treatment Rate (Time to Desalinate)	The minimum acceptable treatment rate is 12 L/h. Additionally, the product should treat 1 L in at most 5 min. Higher treatment rate is desirable.
Storage Capacity	Capacity of 10 L of treated water is required to provide a safety stock of water for times when water and electricity is otherwise unavailable.
Unit Cost / Sales Price	The unit should be priced to compete with existing household desalination products offered in the Indian market. Hence, the manufacturing cost should support a sales price target of less than $270 (18,000 INR).
Input and Output Water Salinities	Treatment of input water with salinity up to 3000 ppm TDS is required. The product should produce output water with salinity no greater than 500 ppm TDS. An output water salinity of 350 ppm should be targeted to provide margin from the 500 ppm limit.
Electrically Powered	The product should be capable of operating from standard Indian outlet power (220 VAC, 50 Hz). The power consumption should be less than 200 W, which is approximately that of a typical Indian home refrigerator.

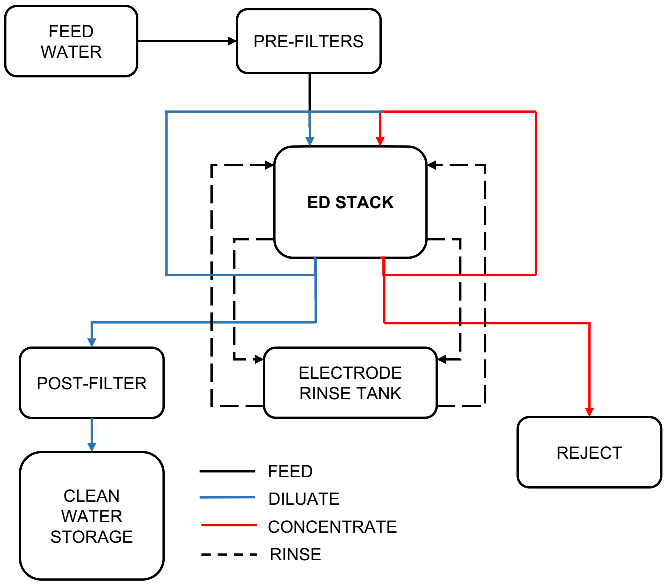

Fig. 3. Flow diagram for continuous ED process.

Table 4
ED architecture comparison.

Design Considerations	Batch	Continuous
Diluate Flow	Recirculation	Single pass
Concentrate Flow	Recirculation	Recirculation
Process Tanks	2	1
Transfer Pumps	2	2
Voltage Applied	Can remain fixed for varying feed salinity	Variable for varying feed salinity
Flow Control	Simple	Complex
Treatment Capacity	Flexible	Fixed

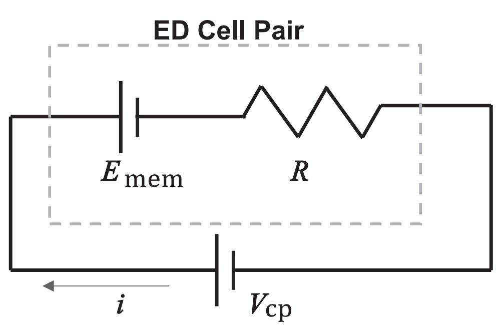

Fig. 4. Simplified depiction of an ED cell pair using an electrical circuit analogue.

predicted peak power consumption, given a cell pair voltage of 1.6 V, was 40 W for 18 cell pairs. Increasing the number of cell pairs to 40 would be expected to increase the stack power consumption to 90 W with an additional 118 W to operate the pumps. The corresponding annual cost of electricity for meeting the drinking requirements for a household (approximately 3 L per person daily (Gleick, 1996)) is expected to be less than $12, assuming a tariff of $0.057 per kWh (Maharashtra State Electricity Distribution Company Ltd, 2014). Therefore, the operating power consumption was not a constraining factor in this design. Instead, the final capital costs and required operating margins would determine the maximum number of cell pairs within a commercial unit.

Table 5
Value of constants used in model described by Ortiz et al. and Wright.

Constants	Value	Units	Ref.
A	64	cm^2	
B_0	0.3277		(Kortüm, 1965)
B_1	0.2271		(Kortüm, 1965)
B_2	54.164		(Kortüm, 1965)
D_a (in AEM)	3.28×10^{-11}	m^2/s	(Nwal Amang et al., 2003)
D_c (in CEM)	3.28×10^{-11}	m^2/s	
F	96,485	C/mol	
l_a	0.2	mm	(GmbH, 2014)
l_c	0.2	mm	(GmbH, 2014)
L	0.5	mm	
ϕ	0.92		(Wright, 2014)
r_a	29	Ωcm^2	(Wright and Winter V, 2014)
r_c	24	Ωcm^2	(Wright and Winter V, 2014)
R	8.31	J/mol-K	
t_+	0.4		(Dobos, 1975)
t_-	0.6		(Dobos, 1975)
T	293	K	
V	2.78	cm/s	(Wright and Winter V, 2014)
V_{el}	0.9, 3	V	(Wright and Winter V, 2014; Personal Communication, 2014)

Table 6
Ranges evaluated for varied input parameters.

Parameters varied	Value	Units
V_{cp}	1–2	V
N	0–40	
V_{dil}^{t}	2.2–2.7	L
V_{con}^{t}	0.6–1.1	L
Q	20–72	L/h

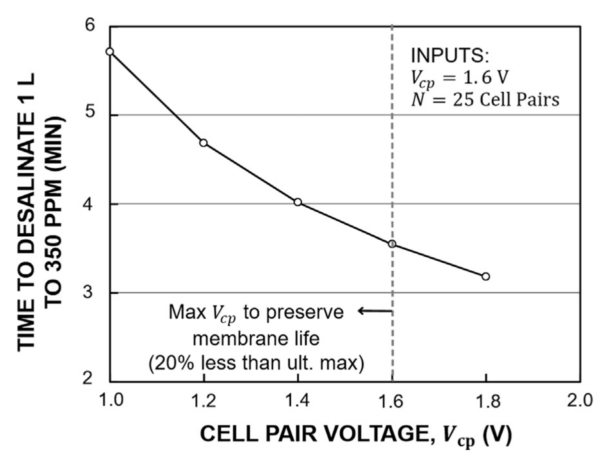

Fig. 5. Model results showing time to desalinate 1 L of diluate from 3000 ppm to 350 ppm for varying cell pair voltages across 25 cell pairs.

4. Validation

4.1. Experimental setup

The predicted performance of the ED system was validated using an experimental test configuration which consisted of one PCCell ED 64002 lab-scale test unit outfitted with 18 anion and cation exchange membrane pairs (PCA-Polymerchemie Altmeier, 2014) effectively measuring 8 cm x 8 cm each, associated spacers, and titanium electrodes with platinum-iridium alloy coating (Fig. 7). In the following section, it is shown that the form factor of this stack allows it to be incorporated into a package that is similar to RO products currently

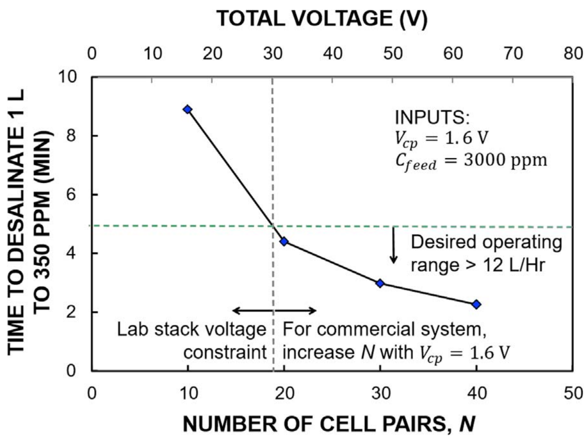

Fig. 6. Model results showing time to desalinate 1 L of diluate from 3000 ppm to 350 ppm for increasing number of cell pairs, each producing a voltage drop of 1.6 V. The horizontal and vertical dashed lines indicate the desired operating range and test stack constraints respectively.

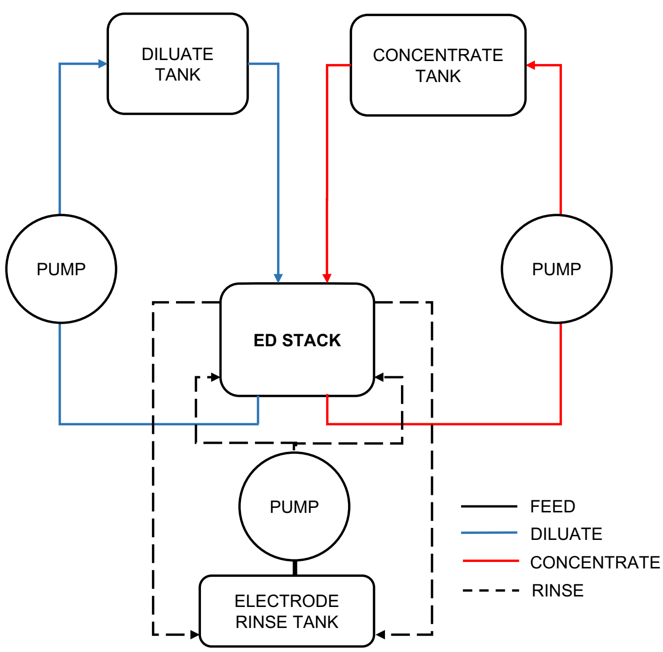

Fig. 7. Flow diagram of experimental setup.

available on the market.

In all the tests, deionized water was mixed with lab-grade sodium chloride (Sigma-Aldrich, 2014) to formulate the 3000 ppm test solution which was to be desalinated to the target salinity of 350 ppm. The test solution was divided into two 1 L beakers, one for each of the diluate and concentrate streams. During the experiment, magnetic stirring plates were used within the beakers to mix the diluate and concentrate solutions, and a Model 3250 m (Jenco Instruments) (Jenco) was used to monitor conductivity and salinity levels. Two NF300 KPDC diaphragm pumps (KNF Flodos) (Flodos, 2014) were used to circulate the diluate and concentrate streams between the ED stack and the respective beakers through ¼-in ID tubing. The flow rate through the stack was varied using 7430 Series glass tube flowmeters with valves (King Instrument) (King Instrument Company, 2014), and manual-read pressure gauges were installed to monitor pressure upstream and downstream of the stack in the diluate and concentrate streams.

A separate solution of deionized water and sodium sulfate (0.2 M) (Sigma-Aldrich, 2014) was formulated for the electrode rinse stream. It was circulated during each test by an MD-20RZ centrifugal pump

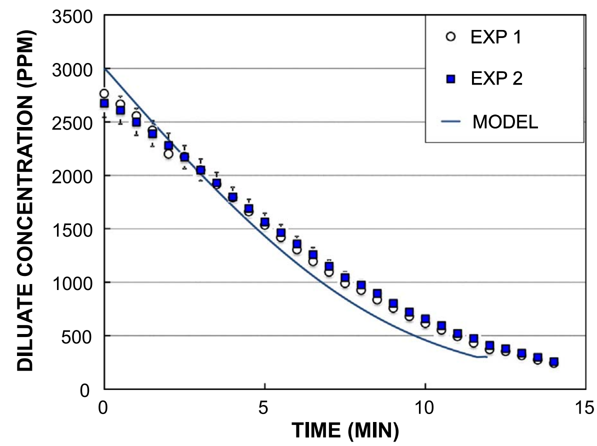

Fig. 8. Diluate concentration plotted against time for two identical tests (EXP 1 and EXP 2) using 18 cell pairs, 1.6 V/cell pair, and at a circulation rate of 72 L/h. Error bars represent Type B uncertainty of 6–8% in concentration measurements.

(Iwaki) (Iwaki America Inc, 2014) at approximately 2.5 LPM.

4.2. Results

A total of 2.96 L with a salinity of 3000 ppm was created. In order to produce a recovery ratio of 80%, 2.41 L of this total volume was treated as the diluate with the remaining 0.55 L as concentrate. The solutions were circulated at a volumetric flow rate of 72 L/h. Two tests were performed in succession, with a period of stack flushing with fresh 3000 ppm salinity solution lasting approximately 5 min between each test. The peak power consumed in the tests was 88 W: 53 W for the three pumps and 35 W for the ED stack.

The target salinity of 350 ppm was achieved within 13 min, which was within 13% of the duration predicted by the model (Fig. 8). The error bars reflect a maximum uncertainty of 8%. Therefore, the experiment indicated that electrodialysis could successfully desalinate the feed water to the desired salinity level at 80% recovery, yielding 12 L/h of potable water as predicted by the model.

4.3. Sources of error

Fluctuations in the probe readings, gradients in the beakers, and measurement variation over the 10–15 s duration when each reading was taken contributed to a total uncertainty of 6–8% in the concentration measurements. Uncertainties related to solution preparation, as well as voltage and current measurements, were negligibly small in comparison (< 0.1%).

4.4. Relevance of performance results to other water compositions

In this work, we studied the technical feasibility of using ED for in-home water desalination. The water composition that our model and experiments were based on was sodium chloride. Practically, the water used in homes in India has ions other than sodium chloride. Depending on the source of water and the geography, there may be calcium, sulfates, nitrates, fluoride etc. However, to a first order, the physics of separation of charged ions in the ED process is approximated well by a model solution of aqueous sodium chloride. While the stack may have to be re-designed marginally to account for minor differences in transport properties between ions, we expect the ED concept highlighted here to be feasible for all water compositions at the salinity level of 3000 ppm.

5. Product conceptualization

ED only removes charged particles and does not disinfect the water if biological contaminants are present. Therefore, it is important to retain the pre- and post-filtration components from existing in-home RO water purifiers. These components include a sediment filter and carbon filter for pre-filtration, as well as a carbon filter and UV filter for post filtration. Since ED membranes are less sensitive to sediments in the feed supply than RO membranes (Pilat, 2001), less pre-filtration is likely required. However, given the primary focus on desalination, this filtration requirement was not analyzed in this study. Fig. 9 is a schematic of the complete in-home electrodialysis system and the water flow paths.

An important aspect of demonstrating the feasibility of an in-home ED system is ensuring that all the components can be packaged within a form factor acceptable to the consumer. Since users are already accustomed to the size and functionality of in-home RO units, the design concept for this ED system inherited a similar form factor (Fig. 10).

An exploded view of the proposed ED water treatment system is visually illustrated in Fig. 11. Although it does not include smaller components such as valves and tubing, it serves to demonstrate the general concept. The model incorporates the PCCell test unit as the ED stack, but an alternative stack may be implemented in the commercial version. The use of different pumps or alterations to the length to width ratio of the stack (preserving the area) may provide a superior packaging or performance solution as well. Given the conceptual nature of this work, these modifications were not investigated during this study.

5.1. Cost

One of the objectives of this study was to assess the cost-competitiveness of an electrodialysis in-home water treatment system against existing RO desalination products in the Indian market. The complete system is estimated to cost $206, as detailed in Table 7. Assuming a 30% margin on cost, the system sale price of approximately $270 is competitive with the prices listed in Table 2 for existing RO systems. Therefore, an initial cost estimate also indicates that the proposed in-home ED system could be commercially viable in the India's water-purification market.

Overall, the ED stack accounted for approximately 46% of the manufactured system cost. The most significant cost of the ED stack is associated with the platinum-coated titanium electrodes for which the coating accounts for more than 90% of the component cost. This cost was estimated directly from supplier quotations (General Electric Company, 2014; Ltd, 2014; X.S.S.T. Corporation, 2014; Ltd, 2014). General Electric (General Electric Company, 2014), Membranes International (Inc, 2014), PCA GmbH (PCA-Polymerchemie Altmeier, 2014), and IonTech (Hangzhou, 2014) were capable of supplying ion exchange membranes to the specifications provided, but often at sizes larger than required for the smaller household system. Consequently, the estimate provided assumes linear scaling of cost with membrane area.

The remaining 54% of the total system cost was largely attributed to pumps, filtration systems, and the UV treatment module. Here, the replacement costs for comparable components from existing RO systems, primarily the Kent RO device (House, 2014), were used to estimate prices. It is anticipated that manufacturing or purchasing these components at scale will result in cost reductions.

Note that maintenance and replacement costs were not considered in this feasibility study. In order to provide these estimates, further work aimed at characterizing the membrane life under the anticipated operating conditions is required.

6. Limitations and recommendations for future work

Experiments were conducted using sodium-chloride solutions. While this approach was appropriate for evaluating the desalination performance of the system in this feasibility study, further testing with other components found in Indian groundwater (including nitrate, fluoride, and arsenic) is recommended. In addition, the susceptibility of the system to scaling was not investigated in this study. Scaling may decrease the lifetime of components and subsequently affect the cost of ownership; therefore, it should also be addressed in future work.

We intended for our work to be a first-order feasibility of the simplest configuration of the ED technology. Thus, certain developments and ED variants were not studied in this work. A development that was not analyzed in this paper was the use of new carbon electrodes developed General Electric (GE Power and Water, 2013) instead of platinum-coated titanium electrodes. Carbon electrodes present a promising avenue for decreasing the cost of the system by reducing electrode costs (Barber et al., 2013). In addition to providing a less expensive alternative to titanium electrodes, they do not require degasifiers, thereby potentially eliminating the need for an electrode rinse solution and a rinse pump. Future development work should study this alternative design which could significantly lower costs. Future development work should also consider the feasibility of Electrodialysis Reversal (EDR), the variant of ED where the stack polarity is periodically reversed to reduce fouling occurring on the membranes.

7. Conclusion

This study indicated that it is feasible to design a small-scale electrodialysis system that can process groundwater in the salinity range of 500–3000 ppm typically found in India while providing a higher water recovery than existing RO products. The electrodialysis system conceptualized in this study provided an 80% recovery, producing desalinated water at a rate of 12 L/h. Furthermore, it was shown that such a product could be priced and packaged in a manner that is familiar to consumers. At $270, the cost of the proposed system was estimated to be within the price range of existing in-home RO products, with potential reductions that could be realized with economies of scale

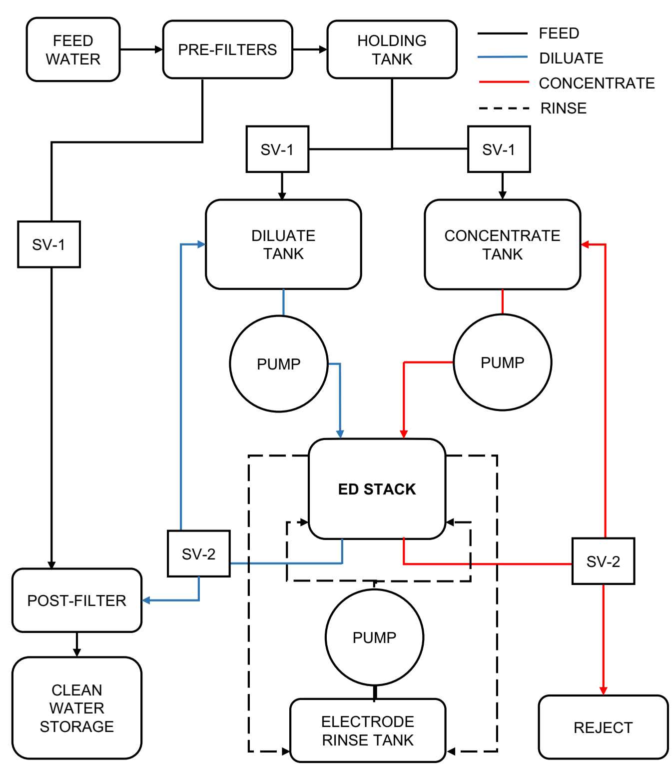

Fig. 9. Flow path of an in-home ED water treatment system including pre- and post-filtration components.

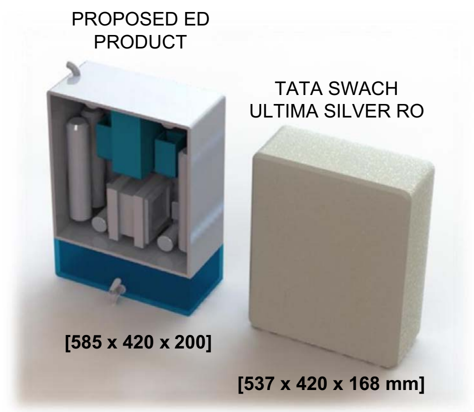

Fig. 10. Comparison of product dimensions between the ED concept and the Tata Swach Ultima Silver RO unit (Tata Chemicals Ltd, 2014).

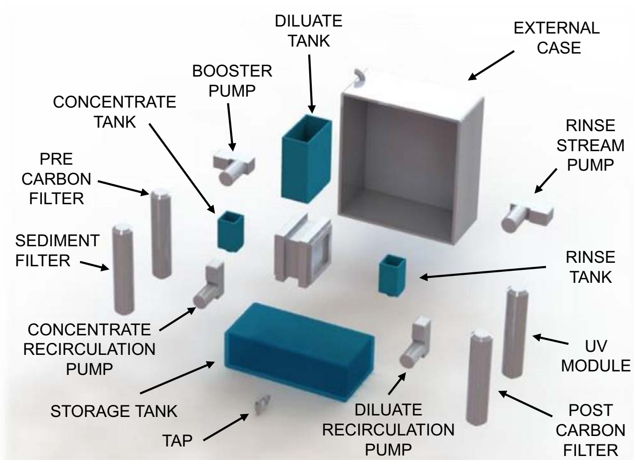

Fig. 11. Exploded view of product concept.

Table 7
Cost estimate of proposed ED system.

ED Stack Components	Unit Cost (USD)	Cost Estimate (USD)
Cation Exchange Membranes	$\$25/m^2$	\$11.50
Anion Exchange Membranes	$\$25/m^2$	\$11.50
Spacers	$\$4/m^2$	\$3.50
Platinum-Coated Titanium Electrodes	$\$5\ 000/m^2$	\$64.00
Stack Frame	\$5.00	\$5.00
Sub-Total		\$95.50
Additional System Components		
Pumps (Diluate, Concentrate, Rinse)	\$14	\$42.00
Sediment Filter	\$13	\$13.00
Carbon Filter x 2	\$3	\$6.00
UV System	\$13	\$13.00
Tanks x 4	\$2.50	\$10.00
Housing	\$5.00	\$5.00
Float Switches x 3	\$2	\$6.00
Tubing	\$1 /m	\$2.00
Flow Restrictor	\$2.50	\$2.50
Conductivity Sensor	\$11.00	\$11.00
Sub-Total		\$110.50
Total Manufacturing Cost		**\$206.00 (13 760 INR)**
30% Margin on Manufacturing Cost		\$61.80
Total Cost to Consumer		**\$271.80 (18 160 INR)**

in purchasing and manufacturing pumps and filtration components.

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APPENDIX A. Choice of electrodialysis for in-home desalination

Several high water recovery technologies were considered for in-home desalination including electrodialysis (ED), closed circuit reverse osmosis (CCRO) (Efraty et al., 2011; Warsinger et al., 2016), capacitive deionization (Oren, 2008), and thermal technologies ranging from simple boiling to multi-effect distillation (MED).

Thermal technologies were disqualified as a viable alternative due to their intensive energy requirements. MED, the most energy efficient thermal desalination technology re-uses the heat of condensation around 15 times to produce water (Al-Shammiri and Safar, 1999). The power requirement for an MED system is given by:

$$P_{\mathrm{MED}} \approx \frac{Q_{\mathrm{p,reqd}}}{\rho_{\mathrm{w}}} \times \frac{h_{\mathrm{fg}}}{15} \approx 500W \tag{4}$$

where, $Q_{\mathrm{p,reqd}}$ is the required design treated water flow rate of 12 L/h from Table 1, ρ_{w} is the density of pure water with a value of 997 kg/m^3, h_{fg} is the latent heat of vaporization of water with an approximate value of 2260 kJ/kg. The calculated power requirement was 500 W well more than the design requirement of 200 W outlined in Table 1.

Capacitive deionization was not selected due to our concerns around whether the technology was ready for commercial deployment in urban India. Subramani (Subramani et al., 2011) had previously reported that appropriate electrodes were not widely commercially available and that there was difficulty in obtaining a high water recovery due to ion buildup over time.

CCRO and ED emerged as the leading candidates for in-home desalination. CCRO, compared to conventional RO used in the commercially available products previously described, is a novel technology that operates as a semi-batch process where the operating pressure is increased during the process as higher recoveries are achieved. For any RO or CCRO system, the maximum operating pressure ($p_{\mathrm{max,RO/CCRO}}$) is given by:

$$p_{\mathrm{max,RO/CCRO}} = \Delta\Pi_{\mathrm{max,RO/CCRO}} + \Delta p_{\mathrm{pinch}} \tag{4}$$

where, ($\Delta\Pi_{\mathrm{max,RO/CCRO}}$) is the highest osmotic pressure seen in the system, corresponding to the highest salinity seen in the system, and $\Delta p_{pinch}$is a minimum pinch pressure maintained. For our calculation, we assumed Δp_{pinch} to be 0.2 MPa based on available data for in-home RO systems. $\Delta\Pi_{\mathrm{max,RO/CCRO}}$ is related to the highest salinity seen in the system through the van 't Hoff relationship (Robinson and Stokes, 2012) as:

$$\Delta\Pi_{\mathrm{max,RO/CCRO}} = i\mathrm{RT}\frac{1}{MW_{\mathrm{NaCl}}} \times \frac{S_{\mathrm{f}}}{1 - RR} \tag{4}$$

where i is the van 't Hoff factor taken to be 1.83 based on literature data (Nayar et al., Lienhard V), R is the universal gas constant, T is temperature of the water being treated in Kelvin, .$\frac{S_{\mathrm{f}}}{1-RR}$ corresponds to the salinity of brine leaving an RO/CCRO system, S_{f} is the salinity of the feed water being treated, which is 3000 ppm here, RR is the recovery ratio given by the ratio of flow rate of treated product water to the feed water and MW_{NaCl} is the molecular weight of sodium chloride, 58 g/mol. For an *RR* of 0.8, corresponding to a recovery of 80%, $\Delta\Pi_{max,RO/CCRO}$ was 1.2 MPa leading to $p_{max,RO/CCRO}$ being 1.4 MPa. By comparison, current in-home RO systems operating at a *RR* of 0.3–0.4, would have a $p_{max,RO/CCRO}$ of 0.5 MPa. To achieve 80% recovery using CCRO, operating pressures have to be 3 times higher than that of current in-home RO systems. We estimated that the higher pressure requirements and the need for pumps that can vary pressure dynamically would keep the price of in-home CCRO well above that of in-home RO systems. For this reason, we eliminated CCRO.

ED showed the most promise for cost-effective deployment and was the most ready technology. ED had been used for several applications for fifty years (Strathmann, 2010) with our literature review also showing that ED had been previously considered for in-home water desalination (Pilat, 2001, 2003) with at least 200 compact ED water treatment systems commercially deployed (Pilat, 2001). An in-home ED system had several advantages over an in-home RO system: two to three times longer membrane life than RO leading to less frequent membrane replacement (Wright and Winter V., 2014; Pilat, 2001), higher water recoveries, ability to operate at higher salinities, lower energy requirements (Wright and Winter V., 2014; Pilat, 2001) and potentially lower costs (Pilat, 2001). Given these features, ED was selected to be the most suitable technology for in-home desalination in urban India.

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