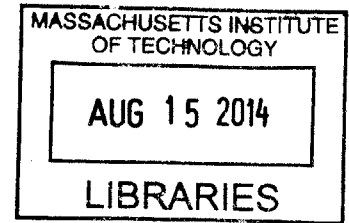


Justification of Village Scale Photovoltaic Powered Electrodialysis Desalination Systems for Rural

India

by

Natasha C. Wright



Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

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Master of Science in Mechanical Engineering

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Abstract

This thesis 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 lives in villages of 2000-5000 people, many of whom 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 1,000 ppm and 30% less at 3,000 ppm). At 2,000 ppm, 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. Additionally, a theoretical model for an electrodialysis system is presented and validated through experimental trials.

Thesis Supervisor: Amos G. Winter, V
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Chapter 1

Introduction

Day after day, day after day,
We stuck, nor breath nor motion;
As idle as a painted ship
Upon a painted ocean.

Water, water, every where,
And all the boards did shrink;
Water, water, every where,
Nor any drop to drink.

- Samuel Taylor Coleridge,
excerpt from *The Rime of the Ancient Mariner*, 1798

1.1 The Problem

In 2010 the WHO UNICEF Joint Programme for Water Supply and Sanitation (JMP) reported that 783 million people globally (11% of the total population) do not have access to an improved water source. The 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. Additionally, even if a source is listed as “improved” it may still be contaminated [1]. A study by Onda et. al. estimates that an additional 1.2 billion people use water from an improved source that has significant sanitary risk [2].

India has nearly 600,000 villages that collectively house 800 million people [3]. This rural population accounts for approximately 75% of India’s total population. India follows the global trend with the JMP reporting 15% of the rural population without access to an improved water source [1].

There are three primary categories of water quality: biological, chemical, and physical (Table 1.1). Proper selection of a water purification technology depends on the contaminants present in the feed water source.

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

Table 1.1: Categories of water quality.

Biological water quality refers to all pathogenic microorganisms. These pathogens cause infectious diseases, the most common health risk associated with drinking-water [4]. It is estimated that 535,000 deaths in India were due to diarrhea in 2004

alone [5]. 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 [6]. The removal of pathogenic microorganisms is the primary concern of any water treatment device.

Boiling, UV disinfection, chlorination, coagulation with settling, and filtration are all technologies used across the developed and developing world to improve the biological quality of drinking water. The World Health Organization has thoroughly evaluated each of these technologies for their microbial efficacy, cost, technical difficulty, and practicality for the developing world [7]. In the case of filtration, the microbial efficacy is highly dependent on the pore size of the filter medium. Figure 1-1 shows the relative size of various microbial and chemical contaminants as well as the associated type of filtration required [7].

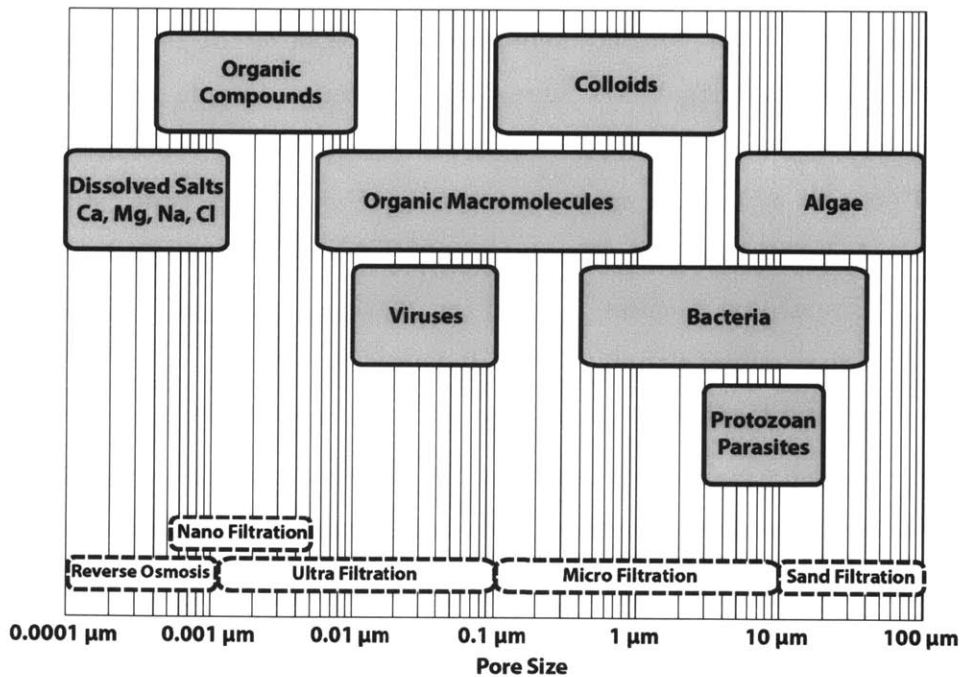


Figure 1-1: Relative size of contaminants and associated filtration technologies [7].

As you move from the right to the left in Figure 1-1 both the contaminant size

and required filter pore size decrease. Removing smaller contaminants leads to more technically advanced and expensive filter mediums as well as an increase in the energy consumption of the technology as a greater pressure is required to move water through smaller pore sizes. In the 1970s the Indian Government saw this problem and realized that using groundwater, which is usually of higher biological quality than surface water sources, could greatly reduce or even eliminate the need to treat rural water supplies. In order to provide biologically safe drinking water without the associated cost of treatment, the government began to install wells [8].

Groundwater wells were considered the least expensive and easiest to replicate method of providing rural water supplies, while avoiding the most important biological quality concerns. The National Drinking Water Supply Programme and the Accelerated Rural Water Supply Programme (ARWSP) were launched in 1969 and 1971, respectively. Both programs led to rapid expansion of water supply in rural areas. Over the course of the next two decades, 1.2 million bore wells were dug and 17,000 piped water supply schemes were provided [9]. During the 1980s, India joined the International Drinking Water Supply and Sanitation Decade with the goal of providing safe drinking water to all villages [8]. Figure 1-2 shows the distribution of the rural population in India by source of drinking water. The figure includes two studies, the National Family Health Survey which is conducted by the International Institute for Population Sciences [10] and the 2001 Indian Census Data [11]. Both studies show that approximately 70% of Indian villages use some form of well to access groundwater for their primary source of drinking water [11].

While the rapid expansion of wells in Indian villages brought about safer drinking water sources in terms of biological quality, it was completed without adequate water quality monitoring infrastructure. Water quality testing received little attention until the 1990s when issues of chemical contamination including arsenic, fluoride, nitrates, and brackishness (salinity) started to appear around the country [8].

While groundwater usually contains fewer biological contaminations, it can contain higher levels of chemical contamination. As will be further discussed in Section 2.2.1 water with salinity levels above the taste threshold (> 500 ppm) underlies 60%

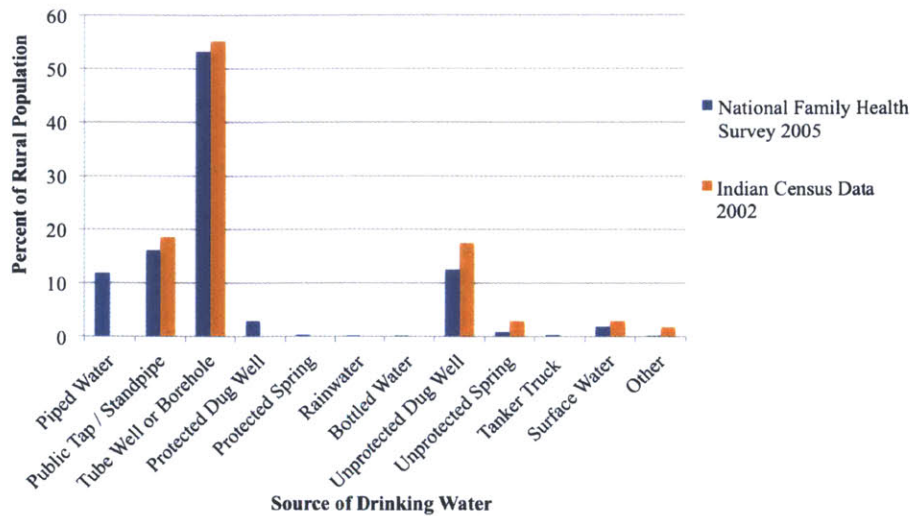


Figure 1-2: Distribution of rural population by source of drinking water for two studies.

of the land in India [12]. Along with the health effects associated with high sodium intake, saline water is undesirable to users because of its poor taste [13]. Water that does not meet the aesthetic quality a user expects may cause it to be discarded as a viable source. The next section will examine current treatment systems used by the rural population in India and will serve as a baseline for examining what a better system might contain.

1.2 Existing Purification Technologies in Rural India

The primary concern of any water treatment device is to ensure the biological quality of the product water. Throughout history, people have developed the means to improve their drinking water quality, most notably through boiling or filtration using a local material. Figure 1-3 shows the distribution of the Indian rural population by currently used water treatment method. Nearly 73% of people living in rural areas do not treat their water [10]. Of those that do, straining through a cloth and boiling

are the most popular options. The cloth frequently used to filter water is a piece of old sari cloth. While successful at removing large suspended particles and making the water appear more clean, the mesh size of this cloth is around 100-150 μm , too large to be an effective filter for biological contaminants. An important study by Colwell et. al. [14] in Bangladesh that contained 133,000 individual participants showed that by folding the sari cloth four times, the pore size is reduced to about 20 μm and a 48% reduction in cholera cases was achieved in comparison to the control. Figure 1-1 however shows that 20 μm is still not small enough to remove the majority of biological contaminants. Boiling is effective in destroying all biological contaminants and can be applied even when the water has high turbidity [7]. However fuel has limited availability and high cost in many regions of India [14].

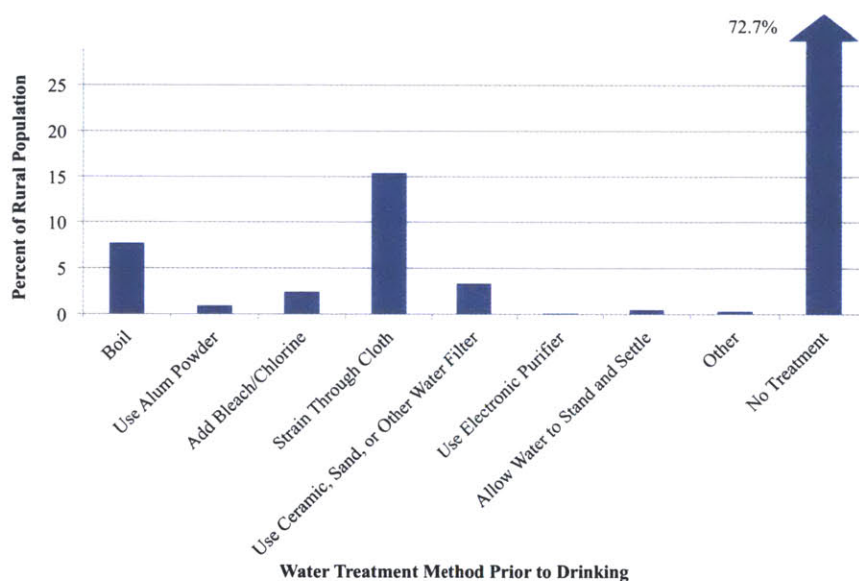


Figure 1-3: Distribution of rural population by water treatment method [10].

Due to the cost of boiling and ineffectiveness of traditional cloth filtering, many household treatment devices have been developed with the goal of providing clean water to the rural population. Table 1.2 compares seven different products in the areas of treatment mechanism, upfront product price, and the cost per cubic meter

of water produced over the product's lifetime.¹

Each of the products have different positive attributes. Aquatabs, for example, can be purchased for a small upfront cost and thus are popular among a population that has low disposable income. Rama India's stainless steel filter has a long lifetime and fits well within the kitchens of rural families which contain dishes, pots, and pans of the same material. Clay filters such as those produced by Pure Home Water can be locally manufactured and keep the water cool in summer. The Tata Swach is seen as an aspirational product, made of plastic and sold in urban areas. Even with all of these options, more than 90% of the rural population uses neither chlorine nor a filter of any type (Fig. 1-3).

Bottled water and tankers (fifth and sixth rows of Table 1.2) are included to show what some people are paying when water shortage becomes an issue. Water tankers drive to villages and fill storage tanks. This water is not considered an improved water source as the tankers can collect water from a variety of unsafe locations.

Lastly, the table contains information on the Tata Projects' community scale reverse osmosis treatment systems. Further discussion of these systems in particular is presented in Section 2.5. The system is included here as a means to compare the cost per cubic meter of treated water. Note that the cost of this community scale system is less than or comparable to the listed household water treatment devices. In addition, while the household treatment devices remove only biological contaminants, Tata Projects' system removes all chemical and physical contaminants as well.

¹In all cases a conversion of 60 INR to 1 USD is used.

Product	Treatment Mechanism	Product Price	Lifetime	Cost / m^3 of Treated Water	Source(s)
Aquatabs Water Purification Tablets	Chlorine Disinfection	\$0.25 / 30 tablets (33mg each)	Single Use	\$0.83 - \$1.67 depending on source water quality	[15]
Rama India Stainless Steel Gravity Candle Filter	Filtration	\$25 upfront and \$1.25 for new candle filters every 6,000L (every two years)	10 years for stainless steel vessel	\$1.04	[15]
Pure Home Water Clay Filter	Filtration	\$25	5 years	\$2.78	[16]
Tata Swachh Smart	Filtration, Absorption, Disinfection	\$20 upfront and \$8 for a new filter cartridge every 1,500L (twice per year)	5 years	\$6.13	[17]
Bottled Water	Varies	\$0.17-\$1.83 / liter	Single Use	\$170 - \$1,830	[18]
Private Water Tankers	Varies / Usually unknown	\$5-\$26 depending on location and size of tank	Single Use	\$1.50 - \$3.00	[19-21]
Tata Projects 1000LPH RO Plant	Prefiltration, Reverse Osmosis, UV disinfection	Capital: \$5,900 Operational: \$0.78/ m^3	20 years	\$1.55	[22]

Table 1.2: Costs of various water technologies available in the developing world.

1.3 Community Scale versus Household Water Treatment Systems

Both household water treatment and storage (HWTS) and community scale systems are currently being used to provide safe water in rural areas. It is estimated that there were 18.8 million users worldwide of HWTS systems in 2007 [23]. WaterHealth International (WHI) is one of many NGOs installing community scale systems. WHI using UV treatment at the community scale and has provided 5 million people with safe water to date [24]. Determining which method of treatment (community or household level) is most appropriate will be the focus of this section and requires looking at a variety of factors including effectiveness in preventing disease, affordability, acceptability, sustainability, and scalability.

Studies completed by Esrey [25], Clasen [26], and Fewtrell [27] have attempted to evaluate the effectiveness of water and/or sanitation interventions in the developing world. Esrey's 1991 review includes a meta-analysis of 144 studies analyzing the impact of improved water supply, sanitation, and/or hygiene facilities on the reduction of various diseases. The study did not analyze household interventions, only improvements in water quality at the source. The study showed that a 15%-17% reduction in diarrheal disease morbidity should be expected from improvements in water quality at the source [25]. Clasen's 1997 review included 33 studies from 21 countries where each study was either a randomized or quasirandomized trial of interventions to improve the microbial quality of drinking water. Both interventions at the source and at the household level were analyzed. The results showed that interventions were effective in all age groups, with household interventions being more effective than those at the source. However, "significant heterogeneity among the trials suggests that the level of effectiveness may depend on a variety of conditions that research to date cannot fully explain" [26]. Finally the meta-analysis of 64 papers completed by Fewtrell showed that providing source treatment only results in an 11% reduction in disease while household treatment results in a 30-40% reduction in disease [27].

The above studies have been used to show the value of HWTS over improvements

at the source, however they do not provide any information about the effectiveness of community scale treatment systems in today's sense. Interventions at the source include protected wells, bore holes, or distribution to public tap stands. Household interventions include improved water storage or various household treatment mechanisms. The studies thus analyze the effect of only providing a protected well, not the effect of a protected well (or other safe water source) in addition to safe storage containers. Safe storage is critical as there are many possible sources of recontamination including unclean water containers, unhygienic domestic water handling practices, and natural contamination from the ambient domestic environment as a result of uncovered containers. [27]. Frequent and substantial faecal contamination of drinking water during collection, transportation, and storage is reported by both Clasen [28] and Wright [29]. Because of this, present community based water treatment plants give each household in the village a safe storage container to ensure that water collected at the source maintains its water quality. A safe storage container is used to store treated water and is usually plastic, ceramic, or metal. The key characteristic of the container is a small opening with a cover. This opening allows water to be poured while serving as a physical barrier to users placing contaminated items such as hands or ladles into the water (Figure 1-4). While no available meta-analyses examines the effectiveness of community level treatment with safe storage, it is reasonable to assume that such a system achieves at minimum the effectiveness of a HWTS system.

Community scale and household based systems each have their own benefits and challenges when examining affordability. A community scale system has the benefit of economy of scale. For example, the Tata Projects RO Plant described in Table 1.2 serves a village of 300 families assuming 6 hours of on-grid electricity per day, for a capital investment of \$5,900. Common household filters such as the Rama India candle filter or Pure Home Water's clay filter can be purchased for \$25. In order for an organization to provide each household in the same 300 family village with one of these HWTS systems it would cost \$7,500. It is because of economy of scale that a community scale desalination plant can be provided for the around the same price as individual point of use systems with inferior treatment capabilities (Table 1.2).



Figure 1-4: Example of a safe storage container provided by Safe Water Network to each family in the village.

While for an individual family it appears that point of use treatment systems are “low-cost,” ensuring that every household in an entire village has a treatment unit results in a capital expense on the same order of a community based system using superior technology.

While HWTS systems have proven efficacy and are constantly gaining more market traction in urban areas, levels of adoption by rural users remains low [30]. Less than 5% of the rural Indian population uses a household treatment device of any type (Figure 1-3). One reason for low adoption rates of HWTS systems is that continuous use of these systems require people to change their household water management behavior. The filter has to be used consistently throughout the day and throughout the year [31]. Proper cleaning has to occur as per the filter’s directions. On the other hand, in a community based system, treatment and maintenance of the system occurs at one central location. Little behavior change is required in such a system as long as the distance to the community system is the same (or shorter) than to the previous water source.

Lastly, it is easier for organizations to monitor both water quality and long term usage of a source using a community based system. For example, at Safe Water Network’s RO plants, treated water is tested in an accredited laboratory once per month. Collecting samples from every household using a HWTS device is much

more difficult and costly. At Safe Water Network, long term usage trends for a particular family and for the community are monitored with thorough sales records. It is thus easier to report an accurate number of people using the clean water source and the data can be used to target educational campaigns to certain neighborhoods or economic levels within the village, for example. With only one system to maintain per village, organizations can sustainably scale at a faster rate than with HWTS systems

A community scale system with safe storage can provide safe drinking water to communities. In a community based system, source water can be treated for chemicals and aesthetic contaminants beyond biological contamination for a comparable price as HWTS systems that target only biological contamination. Lastly community based systems provide one single point of water treatment, allowing for easy monitoring of water quality and long term usage of safe water in the community.

1.4 Our Partner: Jain Irrigation Systems, Ltd.

In 2012, the Global Engineering and Research (GEAR) Lab at the Massachusetts Institute of Technology (MIT) and Jain Irrigation Systems, Ltd. (JISL) initiated a collaboration to develop an appropriate water purification system for rural villages in India. JISL is the second largest micro-irrigation system company in the world. JISL is involved in food processing, biotechnology and produces irrigation, piping, and solar systems. They have long standing relationships with small-scale rural farmers and have developed business models, technologies, and other services to help these farmers increase their agricultural productivity, income, and quality of life. JISL has 22 manufacturing facilities in India and 12 outside of India [32]. Due to their capabilities as a large scale manufacturer and experience in marketing, distribution, and servicing in rural areas, they serve as an appropriate and valuable partner for the development of village-scale water purification systems in India.

1.5 Outline of thesis

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 five years, many have failed due to lack of proper maintenance or the inability to keep up with operational costs.

This thesis presents 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. The results justify photovoltaic (PV)-powered electro dialysis (ED) as an energy and cost-effective means of desalinating groundwater in rural India. An outline of the thesis is as follows:

- **Chapter 2: System Design Requirements**

Technical and ethnographic factors are used to determine critical system design requirements for a village-scale water plant. These requirements include: system capacity, biological and chemical contaminant removal, water aesthetics, recovery ratio, energy source, economics of water provision, and maintenance.

- **Chapter 3: Desalination Technologies Description and Energetics**

Potential desalination technologies including distillation, reverse osmosis, and electro dialysis are compared in terms of energy consumption, system cost, functionality, and maintainability.

- **Chapter 4: Electro dialysis Modeling and Experimental Setup**

A model of electro dialysis is presented which allows for the simulation of any electro dialysis system running in batch mode. An experimental setup used to validate the model is also described. Finally, a preliminary investigation of the integration of a PV power system with electro dialysis is presented.

- **Chapter 5: Conclusion**

The results of the thesis are summarized and connected, and suggestions for future work are outlined.

Chapter 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 sections.

1. Daily Water Output: 6-15 m³/day
2. Contaminant Removal: Biological and chemical contaminants reduced to levels recommended by the WHO; salts (TDS) reduced to less than 500 ppm
3. Recovery Ratio: Maximized
4. Energy Source: Solar
5. Capital and Operational Cost: Desalination system plus solar power system less than Rs 755,000 (\approx \$12,600)
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 liters per person is required for an average adult in average conditions, while 4.5 liters is required for manual laborers working in an average temperature of 32°C [33]. 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 liters per capita per day for adults in developing countries [34]. In this analysis, an average of 3 liters per capita per day is used in order to determine plant capacity.

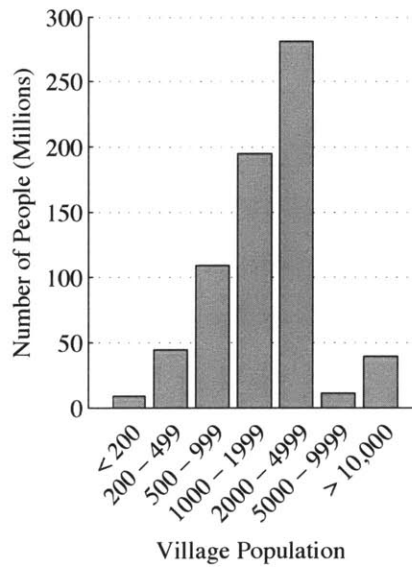


Figure 2-1: Number of people living in villages of different populations. The median Indian villager lives in a village of 2000-4999 people.

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. 2-1, which shows that the median villager lives in a village of 2,000-4,999 people [3]. For this population size and based on 3 liters per capita per day, I define a target plant capacity of 6-15 m³ per day.

2.2 Contaminant Removal

There are three categories of water quality as described in the Introduction: biological, chemical, and physical. The removal of pathogenic microorganisms (biological contaminants) 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 [4, 35]. The following sections discuss the importance of chemical and physical water quality.

2.2.1 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 [12]. The importance and prevalence of brackish ground water specifically will be covered in this section. It is concluded 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)¹ they contain: 1) freshwater and 2) saline water. As a reference point, the salinity of seawater averages 35 g/L (35,000 ppm) and human blood is approximately 9 g/L (9,000 ppm). When a human drinks seawater, osmosis forces water from the blood stream in an attempt to equalize the salt concentrations, causing dehydration.

Table 2.1 provides an estimation of the major water resources on Earth by category [36]. 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

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

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

Table 2.1: Global distribution of water [36].

has more uniform characteristics year round [37]. Fresh groundwater is water that is found subsurface and has low levels of TDS (less than 500 ppm). Brackish groundwater has higher levels of TDS (between 500 and 10,000 ppm). Table 2.1 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. 2-2) [12]. The green area represents groundwater that has a salinity of 480-960 ppm and accounts for 37.5% of the total land area. The yellow area represents groundwater that has a salinity of 960-1920 ppm and accounts for 10.6% of the total land area. The red area represents groundwater that has a salinity greater than 1920 ppm 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.

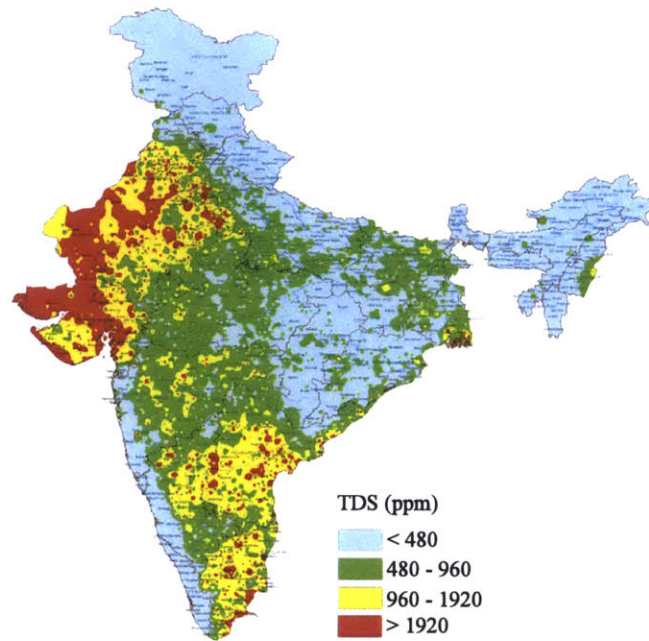


Figure 2-2: Map of salinity levels in Indian groundwater [12]. Groundwater with a salinity level greater than 480 ppm underlies 60% of the land area in India. At this level, the aesthetic quality of the water source is compromised.

2.2.2 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 [13].

In January 2013, I conducted nine interviews with residents in five different villages in Maharashtra State. In one village, five families were 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 was surprising, and lead 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 [38]. 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 nation-wide survey of 1,754 consumers [39].

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 [23]. Echenique and Seshagiri [40] 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.

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 2.2) where water with TDS less than 200 ppm is rated as excellent [41]. In addition to causing poor taste, a study by Singh et. al. [13] showed that users in India find saline water ineffective in quenching thirst and unsuitable for cooking. 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 500ppm because palatability decreases and gastrointestinal irritation may occur in higher concentrations, the permissible limit if no other source is available is 2000ppm [35].

Potability	Excellent	Good	Fair	Poor	Unacceptable
TDS Value (ppm)	< 200	201-600	601-1000	1001-1300	> 1300

Table 2.2: Taste quality as a function of TDS [41].

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 [37]. Figure 2-3 shows areas of physical and economic water scarcity in India [42]. 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.

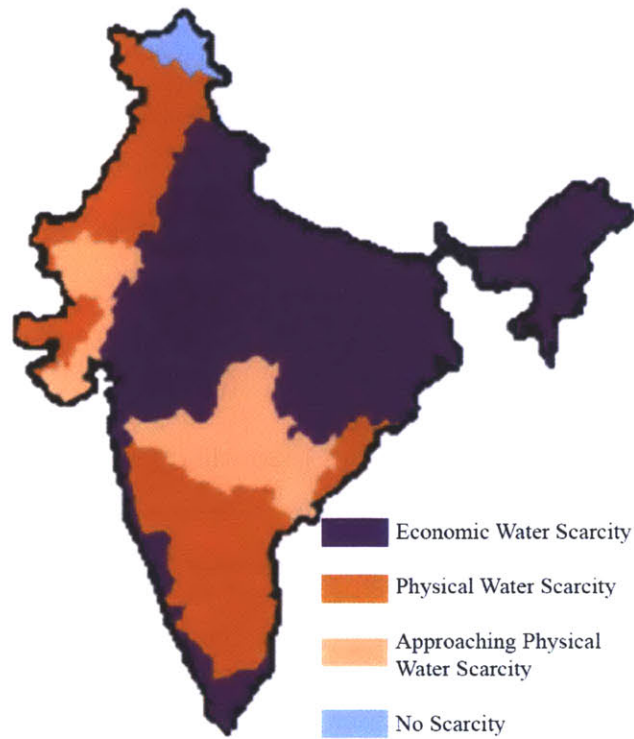


Figure 2-3: Map of India highlighting areas of physical and economic water scarcity [42]. Maximizing the recovery ratio of a desalination system is important for areas having or approaching physical water scarcity.

Comparing Fig. 2-2 to Fig. 2-3, the areas with highest groundwater salinity are also the areas of physical water scarcity. Having a high recovery ratio is important for any inland desalination plant, especially 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 [43]. 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 [22, 44]. For example, if a village needs a total of 6,000 liters per day and power is available for 6 hours, then a 1,000 liter per hour (LPH) plant is acceptable. However, if that same village 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 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.

Solar power is the best solution to supplement energy in a village-size system. A study completed by Abraham and Luthra [45] 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 70 m³/day. Similarly, Bilton [46] 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.

The average annual solar irradiance received in India is 4-6 kWh/m²/day [47].

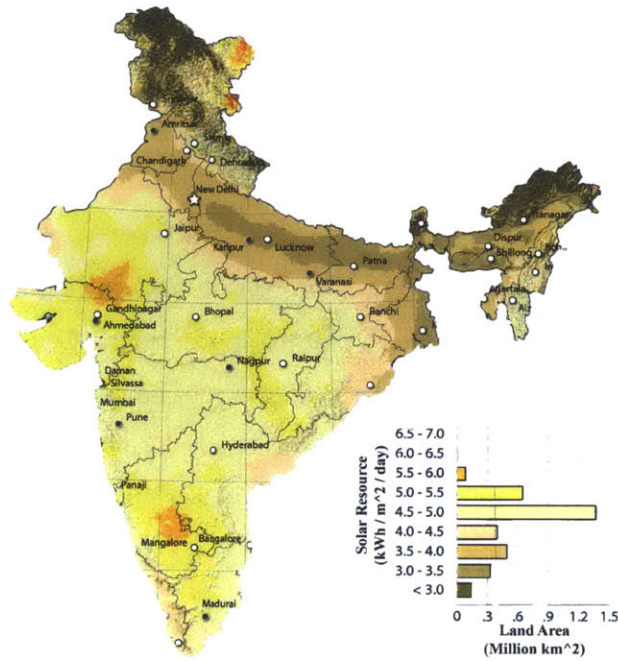


Figure 2-4: Map of solar resources in India [48]. High annual solar irradiance in India makes the country a prime candidate for PV-powered systems in off-grid locations. Areas with high solar potential often overlies areas of high groundwater salinity and physical water scarcity (see Figs. 2-2 and 2-3).

Figure 2-4 shows the regional variation in solar irradiance [48]. Comparing Fig. 2-4 to Fig. 2-2, 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) [49]. 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 5,000 LPH. The company had installed 577 on-grid plants in India at the time of our conversation in January 2014 [22]. Their 1,000 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 Rs 3 per 20 liter can.

The capital cost of the entire 1,000 LPH system including the shelter, storage tanks, power connections and wiring, bore well, excavation work, and installation charges is Rs 688,000 (\approx \$11,500).² Of this total, Rs 355,000 (\approx \$5,900) is for the 1,000 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 \$0.78/m³). 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 [22]. This is below that occurred in a seawater RO plant, in which electricity accounts for \approx 63% of the operations cost [49].

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 1,000 LPH plant running off of PV power and tested by Tata Projects cost an additional Rs 400,000 (\approx \$6,700). This added cost is more than the cost of the RO plant itself (Table 2.3).

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 [22]. Because of this, off-grid locations remain

²In all cases a conversion of 60 INR to 1 USD is used.

Component	Cost (INR)	Cost (USD)	% of Total Capital Cost of PV-Powered System
1,000 LPH RO Plant (skid mounted)	Rs 355,000	\$5,900	32.5%
Shelter, storage tanks, power connections, wiring, bore well, excavation, installation	Rs 333,000	\$5,550	30.6%
PV Power System	Rs 400,000	\$6,700	36.9%

Table 2.3: Relative cost of system components for 1,000 LPH PV-powered Tata Projects RO plant.

underserved as the capital costs of PV-powered 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, I 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 back-

flushing 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.

2.7 Conclusions

This chapter defines the critical design requirements for village-scale water purification systems for rural India. Each requirement was found by engaging with end users, NGOs, manufacturers, government officials, and industry leaders working directly in the Indian market, in addition to reviewing literature. 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 ppm. An appropriate system should be able to achieve this water quality at a rate of 6-15 m³/day, which is the drinking water requirement for a village of 2,000-5,000 people.

Three maps of India are presented (Figs. 2-2, 2-3, and 2-4) which show that areas of high groundwater salinity and high solar irradiation are suffering from water scarcity. These maps elude to 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 Rs 755,000 (\approx \$12,600), the current cost of Tata Project's PV-powered 1,000 LPH RO plant.

Chapter 3

Desalination Technologies: Description and Energetics

Desalination technologies can be divided into two categories based upon their separation mechanism: thermal processes and membrane processes (Figure 3.1). 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 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 [50].

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.

Membrane Processes	Thermal Processes
Nanofiltration (NF)	Distillation
Reverse Osmosis (RO)	Multieffect Distillation (MED)
Capacitive Deionization (CDI)	Multi Stage Flash (MSF)
Electrodialysis (ED/EDR)	Freezing
	Vapor Compression (VC)
	Humidification Dehumidification

Table 3.1: Desalination technologies divided by separation mechanism (membrane and thermal).

3.1 Description of Desalination Technologies

3.1.1 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 (Figure 3-1).

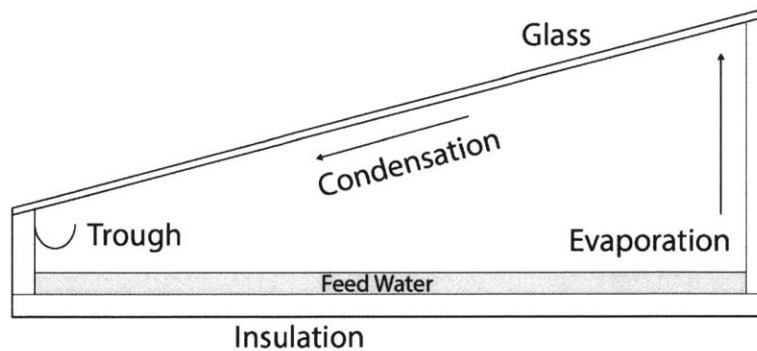


Figure 3-1: Water is first evaporated and then condensed on the underside of a glass cover in a basic solar still.

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

$$A_{land} = \frac{V_{prod} \rho h_{fg}}{\eta q}, \quad (3.1)$$

where V_{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. 3.1 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 [51] and an average daily incident solar energy of 18,000 kJ/m²day [51], the land area required would be 2,260 m². With the capital cost of solar stills in India at approximately \$38.3/m² [51], 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 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.

3.1.2 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 dilute stream with low salt concentration, and one concentrated brine stream (Fig. 3-2 right). The applied pressure forces water to move in the opposite direction of the natural flow that occurs in osmosis (Fig. 3-2 left).

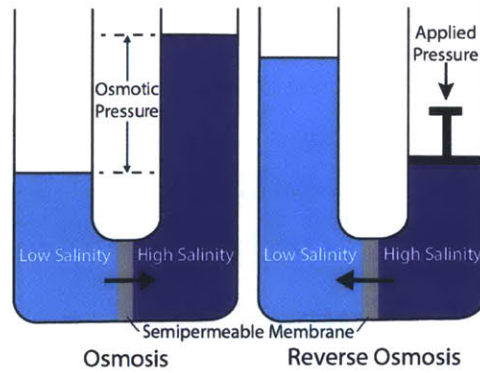


Figure 3-2: Reverse osmosis process. RO (right) is completed when a pressure greater than the osmotic pressure of a solution is used to move water through a semi-permeable membrane.

The applied pressure must be greater than the osmotic pressure of the feed stream at all points along the membrane. The osmotic pressure (π) is given by

$$\pi = \Phi RT \rho_s \sum_i m_i, \quad (3.2)$$

where Φ is the osmotic coefficient, ρ_s is the density of the pure solvent, m_i is the molality of the solute, R is the gas constant, and T is absolute temperature. As the concentration of the feed stream increases, required system pressure also increases in a nearly linear fashion (Figure 3-3). The power required to complete the reverse osmosis process (Eqn. 3.3) thus increases with increasing feed water salinity.

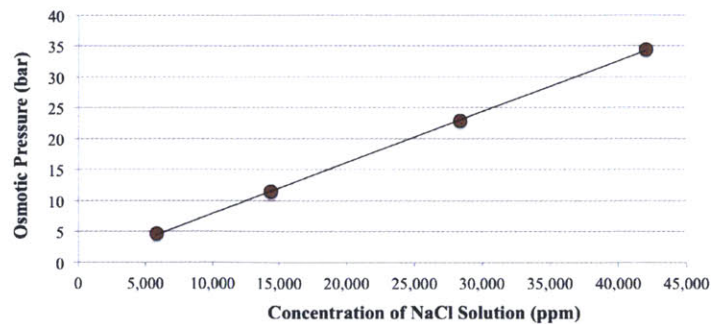


Figure 3-3: Osmotic pressure increases in a nearly linear fashion with feed water salinity, resulting in higher system pressures and more required power.

$$P_{RO} = \frac{p_{hp} Q_{feed}}{\eta_{pm}} \quad (3.3)$$

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

$$E_{spec,RO} = \frac{p_{hp} Q_{feed}}{\eta_{pm} Q_{prod}} \quad (3.4)$$

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 I visited, the applied pressure was 5-13 bar 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 and flow rates are much lower and the power savings do not make up for the capital investment of an ERD [22].

3.1.3 Electrodialysis

In the electrodialysis (ED) process, saline water is pumped through an electrodialysis stack (Fig. 3-4). When an electric potential difference is applied across the stack at the anode and cathode, anions move towards the anode and cations towards the cathode. The ED stack contains a series of ion exchange membranes. Anion exchange membranes (AEM) only pass anions, while cation exchange membranes (CEM) only pass cations. As an anion is moved towards the anode due to the potential difference at the electrodes, it is blocked when it reaches a CEM and remains in the concentrate

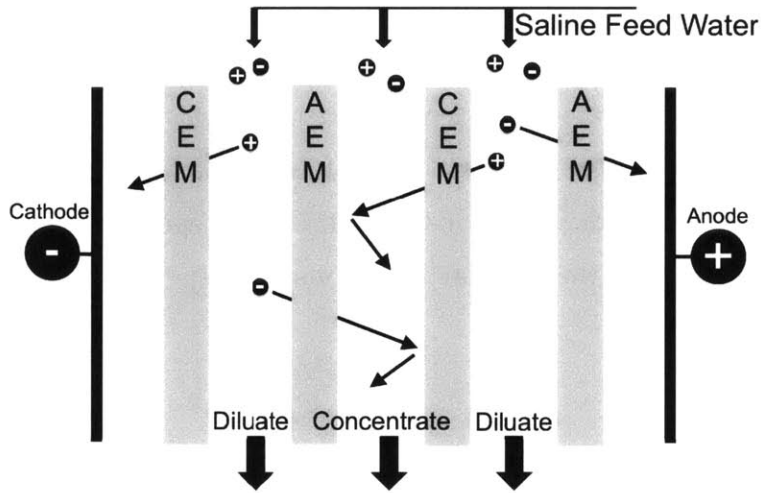


Figure 3-4: Electrodialysis process. ED is the process of pulling ions out of solution through the application of an electric potential across a series of alternating anion and cation exchange membranes (AEM, CEM).

compartment. Similarly, cations moving towards the cathode are blocked when they reach the first AEM. In a commercial ED stack, there are many alternating CEM and AEM pairs, resulting in alternating compartments of diluted and concentrated saline flow.

In order to calculate the power required to desalinate a given quantity of water using electrodesis, 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

$$\begin{aligned}
 V_{total} = & V_{elec} + NV_{potential} \\
 & +Ni(R_{dil} + R_{conc} + R_{AEM} + R_{CEM}),
 \end{aligned}
 \tag{3.5}$$

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 (Ωm^2). V_{elec} and $V_{potential}$ are the electrode potential and concentration potential, respectively.

The instantaneous current density can be calculated if the applied voltage, number of cell pairs, and resistances are known (Eqn. 3.5). 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 [52]. 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:

$$E_{spec,ED} = \frac{\int_{t=0}^{t=t_{final}} iAV_{total} dt}{V_{prod}}, \quad (3.6)$$

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

$$A_{total} = \frac{Q_{dil}(C_{feed}^{in} - C_{dil}^{out})zF}{N\phi i}, \quad (3.7)$$

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). Eqn. 3.7 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.

Equations 3.5 and 3.7 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 [53,54].

3.1.4 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 [55]. Equation 3.8 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.

$$E_{spec,least} = g_{dil} + \left(\frac{1}{r} - 1\right)g_{conc} - \frac{1}{r}g_{feed} \quad (3.8)$$

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.

3.2 Selection of Most Appropriate 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.

3.2.1 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,

Eqns. 3.4, 3.6, and 3.8 are used to produce Fig. 3-5. Note that in each case the full system was modeled using equations provided by Ortiz [53] for ED and Bilton [46] 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.

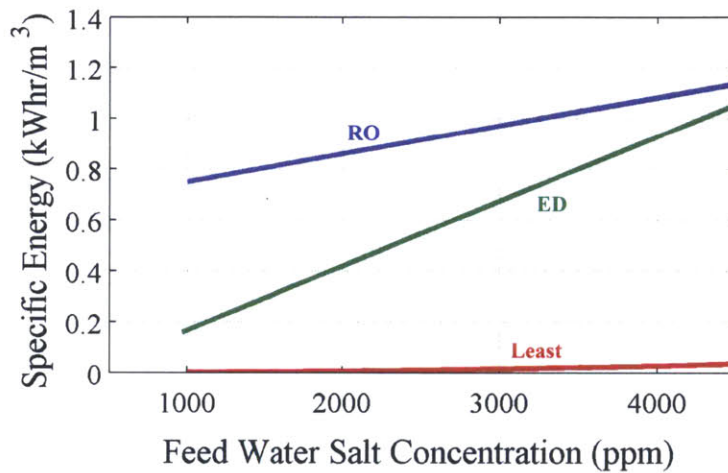


Figure 3-5: Dependence of specific energy on feed water salinity. The salinity range presented represents that commonly found in Indian groundwater. The energy required for RO and ED are compared to the thermodynamic least energy needed to separate the given salt concentration from water.

3.2.2 Economic Comparison

Included in cost is both operational and capital expenses. The dependence of specific cost ($\$/\text{m}^3$) on feed water salinity for distillation, RO, and ED plants is summarized by Strathmann and shown graphically in Fig. 3-6 [56]. 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

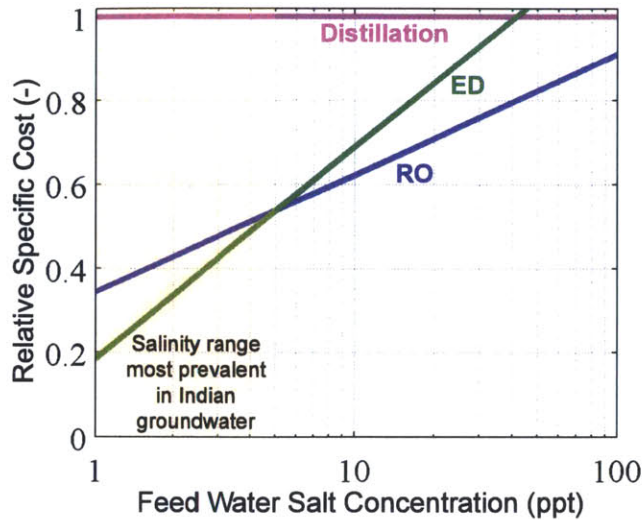


Figure 3-6: The dependance of specific cost on feed water salinity. Relative specific cost per unit of water produced) of reverse osmosis and electro dialysis technologies in comparison to the specific cost of distillation, which is independent of feed water concentration.

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. Figure 3-6 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.

Figure 3-6 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. 3.6 and 3.7). In an RO system it is primarily the operational cost that depends on feed water salinity (Eqn. 3.4), 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. 3-5), 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 \$6,700) to Rs. 200,000 (\approx \$3,350), 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. 3-6), and 2) if moving off-grid, the capital cost of the power system is reduced as well.

3.2.3 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

Table 3.2: 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

both cases, pretreatment is used to remove suspended particles and pathogens greater than 5 microns. 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. In addition, ED can be operated using a method called electro dialysis reversal (EDR) which switches the polarity of the stack at certain time intervals. EDR minimizes fouling of the membranes.

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 3.2 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. 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. 3-6).

3.3 Conclusion

This chapter uses the design requirements described in Chapter 2 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.

Chapter 4

Electrodialysis: Modeling and Experimental Setup

4.1 Electrodialysis: System Modeling

In the electrodialysis (ED) process, saline water is pumped through an electrodialysis stack (Fig. 3-4) and an electric potential applied across the stack at the anode and cathode results in alternating compartments of diluted and concentrated saline flow. A diagram of an ED system arranged for batch desalination is shown in Fig. 4-1. The system contains the ED stack, one diluate tank, and one concentrate tank. In order to determine the concentration at any given time in the stack compartments and within the tanks, the mass balance for the system must be obtained. The dashed black lines and gray boxes in Fig. 4-1 illustrate the control boundaries that will be used to determine the mass balance for the system.

The rate of change of the concentration in the diluate and concentrate tanks can be fully defined by the number of moles of ions that enter and exit the tank within a certain time frame (Eqns. 4.1 and 4.2).

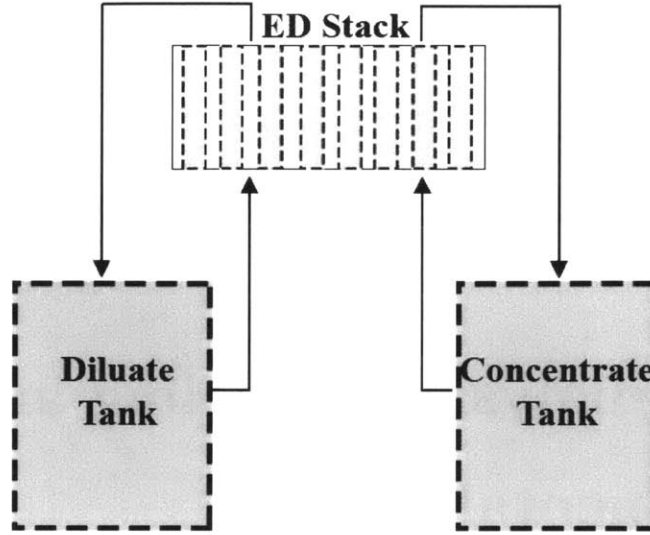


Figure 4-1: Diagram of an ED system set up for batch desalination. Dashed black lines illustrate control boundaries used in mass balance Eqns. 4.1-4.4.

Mass balance for Diluate Tank:

$$\frac{dC_{dil}^{in}}{dt} = \frac{1}{V_{dil}^{tank}} [Q_{dil} C_{dil}^{out} - Q_{dil} C_{dil}^{in}] \quad (4.1)$$

Mass balance for Concentrate Tank:

$$\frac{dC_{conc}^{in}}{dt} = \frac{1}{V_{conc}^{tank}} [Q_{conc} C_{conc}^{out} - Q_{conc} C_{conc}^{in}] \quad (4.2)$$

where C_{dil}^{in} , C_{conc}^{in} , C_{dil}^{out} , C_{conc}^{out} , are the concentrations of the diluate and concentrate streams at the inlet and outlet of the ED stack, respectively, and the V_{dil}^{tank} and V_{conc}^{tank} is the volume of water in the dilute and concentration tank.

In order to determine the mass balance within the ED stack, both the diffusion and migration of ions must be considered in addition to the moles of ions that enter and exit the stacks from the storage tanks. There are thus three modes of mass transport occurring within each diluate and concentrate compartment. Eqns. 4.3 and 4.4 are derived from the fundamental continuity equation and the Nernst-Planck equation which is used to describe the motion of ions under the influence of both an

ionic concentration gradient (resulting in diffusion) and an electric field (resulting in migration). The derivation from fundamental equations can be found in [57], and the final form given here can be found in [53]. On the right hand side of Eqns. 4.3 and 4.4, the first term represents the moles of ions entering and exiting the compartments at the inlet and outlet, the second term represents the migration of ions from diluate to concentrate compartment due to the electrical potential gradient, and the third and fourth terms represent the back-diffusion of ions due to the concentration gradient across each membrane.

Mass balance for diluate cells:

$$\frac{dC_{dil}^{out}}{dt} = \frac{1}{N\mathcal{V}_{cell}} \left[Q_{dil}(C_{dil}^{in} - C_{dil}^{out}) - \frac{N\phi I}{zF} + \frac{NAD_a(C_{conc}^{AEM} - C_{dil}^{AEM})}{l_a} + \frac{NAD_c(C_{conc}^{CEM} - C_{dil}^{CEM})}{l_c} \right] \quad (4.3)$$

Mass balance for concentrate cells:

$$\frac{dC_{conc}^{out}}{dt} = \frac{1}{N\mathcal{V}_{cell}} \left[Q_{conc}(C_{conc}^{in} - C_{conc}^{out}) + \frac{N\phi I}{zF} - \frac{NAD_a(C_{conc}^{AEM} - C_{dil}^{AEM})}{l_a} - \frac{NAD_c(C_{conc}^{CEM} - C_{dil}^{CEM})}{l_c} \right] \quad (4.4)$$

where N is the number of cell pairs, Q_{dil} and Q_{conc} are the flow rates of the diluate and concentrate streams, ϕ is the current efficiency, I is the current, z is the ion charge, F is Faraday's constant, l_a and l_c are the thicknesses of the anion and cation exchange membranes, D_a and D_c are the diffusion coefficients of the given solution in the anion and cation exchange membranes, and C_{conc}^{AEM} , C_{dil}^{AEM} , C_{conc}^{CEM} , and C_{dil}^{CEM} are the concentrations of the diluate and concentrate streams at the interface with the anion or cation exchange membranes (AEM, CEM).

Together with Eqn. 3.5 from Chapter 2, Eqns. 4.1-4.4 can be used to model the concentration in the tanks and the current, voltage, and power consumption of the stack over time. This data can then be used to predict the specific energy and time required to desalinate saline water of a given quantity and concentration. A model to simulate the theoretical behavior of an ED system with a constant applied voltage

was created in Matlab (Table 4.1).

Step	Action	Equation Used
1	Input variables are defined, including: stack parameters (membrane area (A), thickness (l), spacing (L), and resistance (R_{CEM} , R_{AEM})), applied voltage (V_{total}), flow rate (Q_{dil} , Q_{conc}), initial concentration in feed and concentrate tanks (C_{dil}^{in} and C_{conc}^{in}), desired product water concentration ($C_{dil}^{desired}$)	
2	Instantaneous concentration in dilute and concentrate tanks (C_{dil}^{in} and C_{conc}^{in}) are used to calculate the area resistances of the diluate and concentrate streams (R_{dil} and R_{conc})	Falkenhagen Eqn. [52]
3	Updated R_{dil} and R_{conc} are used to calculate new current density (i)	Eqn. 3.5
4	Updated current density (i) is used to solve for change in concentration for each stream (C_{dil}^{in} and C_{conc}^{in})	Eqns. 4.1-4.4
5	Instantaneous values are recorded in array as needed (current density, power, resistances, concentrations)	
6	Check to see if $C_{dil}^{in} < C_{dil}^{desired}$, if true go to Step 6, if false go back to Step 2	
7	Calculate the required specific energy ($E_{spec,ED}$), graph concentration concentration, power, and/or current density over time	Eqn. 3.6

Table 4.1: Table illustrating the calculation procedure to model behavior of ED system.

Simulations completed using this model are dependent on input parameters for the specific ED system, these include: ED stack parameters, applied voltage, initial concentration of feed stream, and flow rates through the the stack. The method described in Table 4.1 calculates all variables at each time step over the course of a given time duration. Alternatively, the system can also be modeled using the *ode45* solver to simultaneously solve the system of four differential equations presented in Eqns 4.1-4.4. In Fig. 4-2 the expected values of specific energy and time to desalinate for the experimental electro dialysis system in the GEAR Lab is predicted

theoretically. The details of the experimental setup itself are described in the following section.

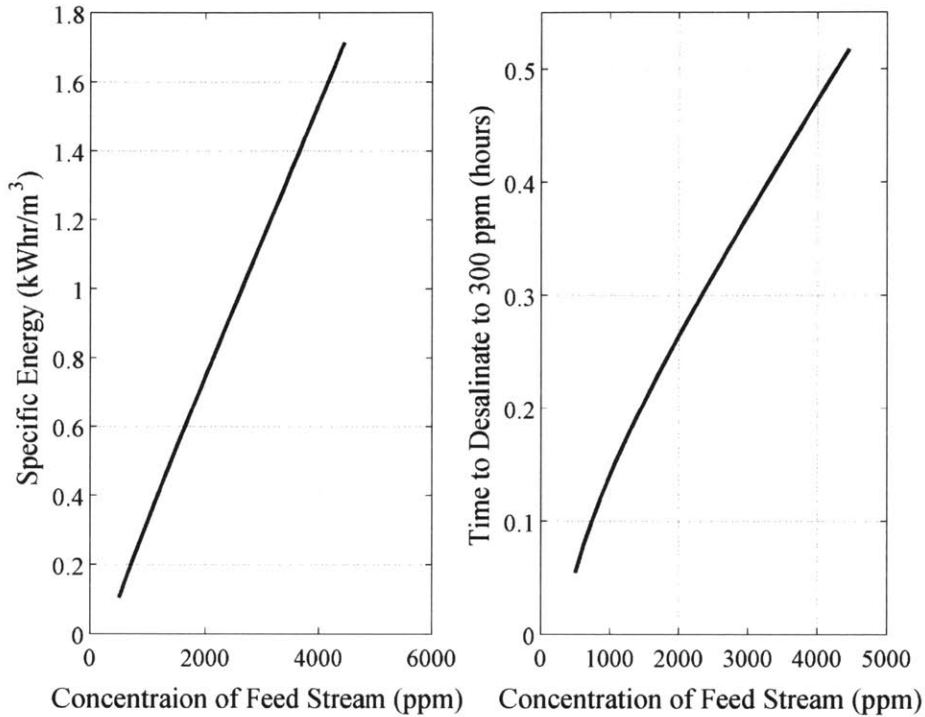


Figure 4-2: Matlab simulation sample results where the system being modeled is that located in the GEAR Lab.

4.2 Electrodialysis: Experimental Setup and Model Verification

An experimental setup (Fig. 4-3) was built in the GEAR Lab to verify the theoretical model presented in Section 4.1. The setup consists of one PC-Cell electrodialysis stack (ED 64002-101) having 10 cell pairs and 64 cm² of active membrane area. Three Iwaki pumps (WMD-20RZ-115) are used to pump the diluate, concentrate, and rinse streams. The flow diagram for the system running in both standard ED and EDR is shown in Fig. 4-4. In EDR, valves are added between the tanks and the stack. The

polarity of the stack and the valves are flipped at the same time to allow the diluate tank to continue decreasing in concentration and vice versa for the concentrate tank. A complete bill of materials for the setup can be found in Appendix A.

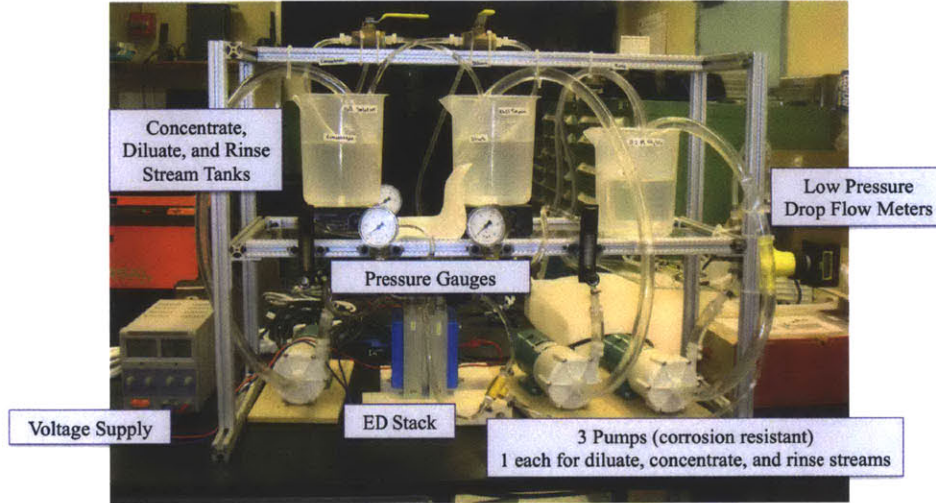


Figure 4-3: Photo of the experimental setup for electro dialysis in the GEAR Lab.

The following parameters specific to the experimental setup were used in the model to predict the behavior of the system when a starting concentration of 2000 ppm is used in both the diluate and concentrate tanks. A constant voltage of 12V was applied using a standard power supply. Both the simulation and the experiment terminated when the diluate stream reached a concentration of 350ppm.

$$\begin{array}{ll}
 V_{total} = 12V & R_{AEM} = 20\Omega cm^2 \\
 A = 0.0064m^2 & R_{CEM} = 15\Omega cm^2 \\
 l_a = l_c = 0.0002m & \forall_{conc}^{tank} = \forall_{dil}^{tank} = 0.002m^3 \\
 L = 0.0005m & Q_{dil} = Q_{conc} = 1.58 \times 10^{-5} \\
 N = 10 & t_{step} = 1s
 \end{array}$$

Good agreement was achieved between the model and experimental setup (Fig. 4-5), validating the model for future simulations of larger, village-scale systems.

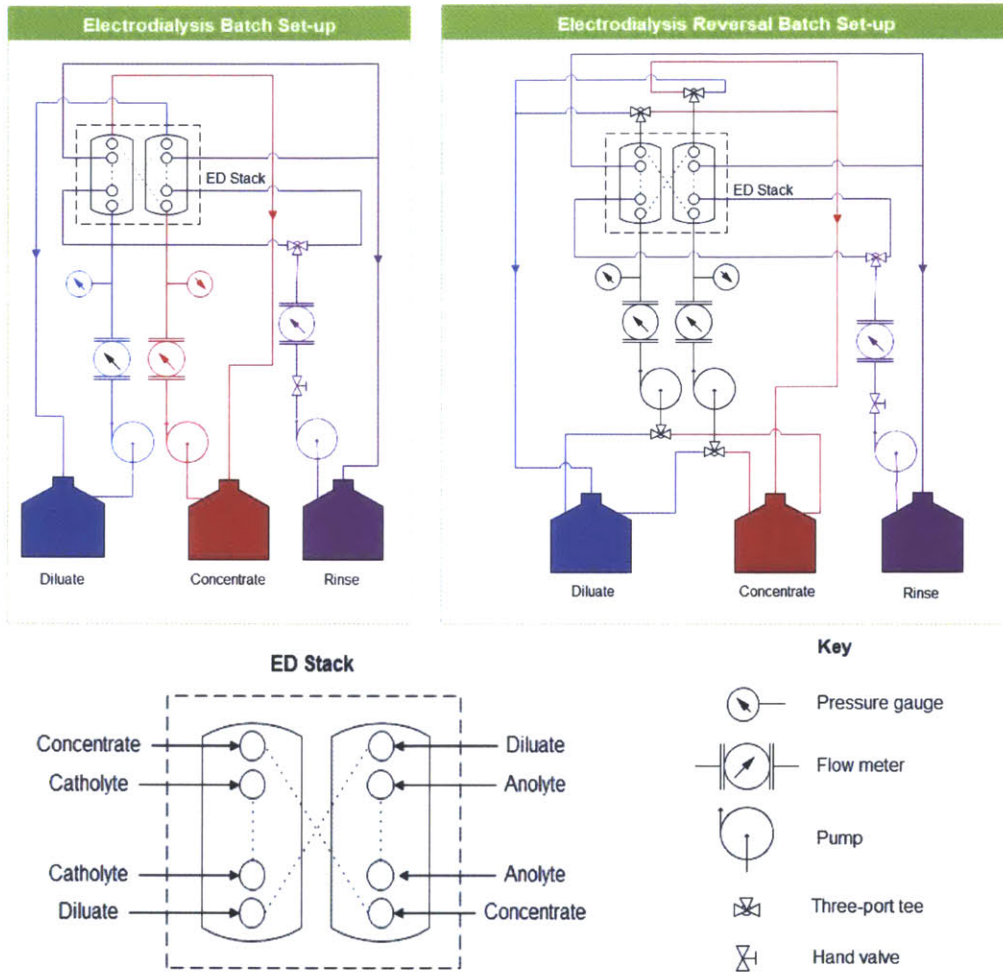


Figure 4-4: Flow diagram of experimental setup for electro dialysis and electro dialysis reversal batch system in the GEAR Lab.

4.3 Electro dialysis: The Potential for a PV-Powered System

Based on the system requirements discussed in Chapter 2, the village-scale desalination system should have the ability to be run off of solar power. ED 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. Two primary concerns about the ability

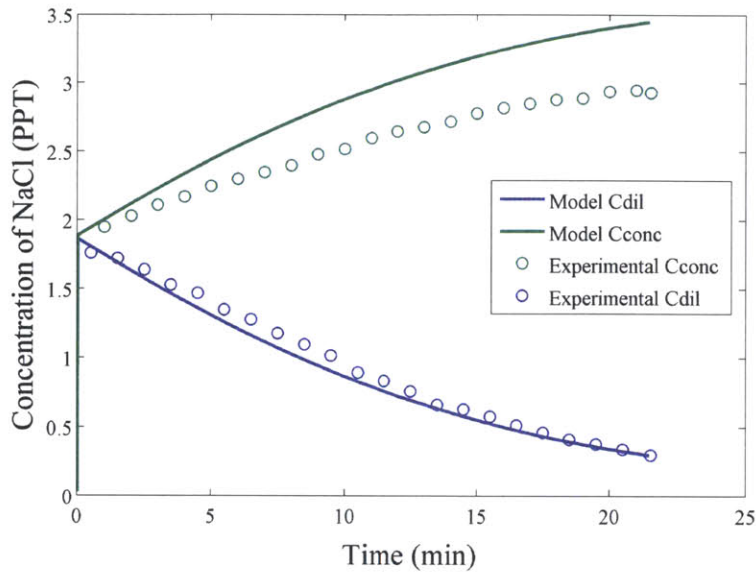


Figure 4-5: Verification of system model using experimental setup in the GEAR Lab. Good agreement is achieved between the model and the experimental data.

of any desalination technology to be paired with photovoltaic power are 1) the yearly variation in solar irradiance resulting in a variation in quantity of produced water, and 2) the technology's response to the stochastic nature of irradiance throughout a single day.

4.3.1 Yearly Variation in Solar Irradiance

Installed rural PV-RO plants ensure that the plant can produce the required daily water output every day of the year by sizing the solar panel array for the day of the year with the least irradiance [22]. This means that the solar array is oversized for the majority of days (e.g. when the irradiance is higher) and assumes that the system needs to produce the same amount of water every day of the year, determined to be 3 L / person / day in this paper. In reality, there is a seasonal variation in water consumption. For example, a nationwide study in Korea showed that the average consumption of direct tap water increased by up to 19.7% in the summer versus the

spring [58]. Similarly a study conducted in England showed that 50% of users drink more bottled water in the summer than the winter [59]. Finally, a study by Wong that analyzed 11 years of urban water consumption in Hong Kong explained yearly variation in water consumption with five factors: trend, seasonality, day-of-the-week effect, holiday effect, and climatic regression. Of these factors, seasonality had the largest effect on consumption, accounting for 28% of the variance [60]. Figure 4-6 shows the resulting mean seasonal cycle of water consumption in Hong Kong.

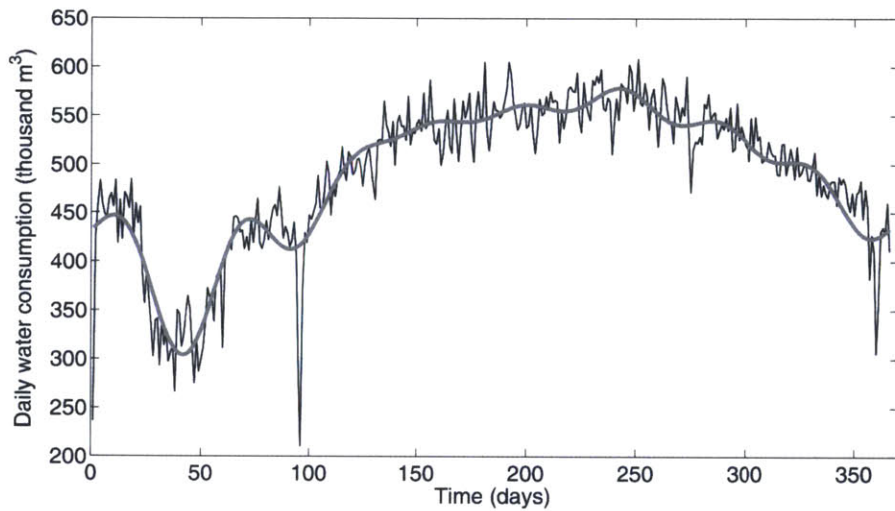


Figure 4-6: Mean seasonal cycle of urban water consumption in Hong Kong. The thin black line shows the actual water consumption; the thicker gray line is the model created by Wong [60].

These studies show that the same amount of water is not required each day of the year, and thus the desalination and solar-power system could be designed to match these fluctuating demands. Intuitively it makes sense that humans consume more water on hot days, which tend to also be days with higher solar irradiance. In order to demonstrate this principle, Fig. 4-7 shows the average global solar irradiance in Hong Kong compared to the same seasonal cycle of water consumption shown in Fig. 4-6. While trends in both water consumption and irradiance will have to be further explored for potential system installation locations, Fig. 4-7 dictates a compelling argument that variation in yearly solar irradiance may match that of

water consumption, and thus that systems do not have to be oversized to provide some steady maximum water output throughout the year.

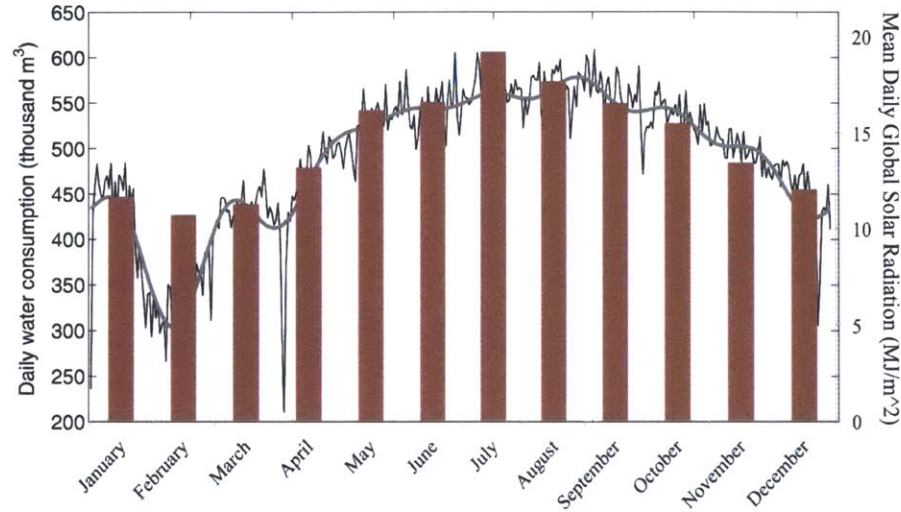


Figure 4-7: Monthly mean daily global solar radiation (red bars) recorded at King’s Park, Hong Kong, between 1961 and 1990 [61] compared to mean seasonal cycle of urban water consumption in Hong Kong (black line) [60].

4.3.2 Daily Variation Solar Irradiance

PV-powered electrodialysis with the use of batteries has been analyzed in previous literature [45, 62–64]. Due to the high cost and maintenance of batteries and ED’s innate suitability to direct current (DC power), Ortiz provides an analytical model and initial laboratory testing of a direct driven system without batteries [65, 66]. In such a system the the rate of water production depends on and varies with the solar irradiation. The study demonstrates the feasibility of an ED system powered directly by a PV array. The experimental results however are used only to verify the simulation of a three hour trial. No attempts are made to simulate the system over the course of a day, or over an entire year. Thus, the ability to both optimize and predict the performance of a direct-driven system is left to future work.

4.4 Conclusion

In this chapter, the modeling and experimental setup of an ED system is examined. A method of simulating the performance of an ED system is shown and validated through the use of an experimental setup. Further work will need to be completed to optimize the voltage and current trajectories for the experimental system. Additionally, this chapter begins discussion of the potential for a PV-ED system and hypothesizes that both yearly and daily variation in solar irradiance can be managed in a direct-driven system. In the case that solar irradiance varies with water consumption habits of the target population, the variation of water production with irradiance may be used to the designers advantage.

Chapter 5

Conclusions and Future Work

This thesis 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 and looking at the energetics of different desalination technologies, 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 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 ppm. An appropriate system should be able to achieve this water quality at a rate of 6-15 m³/day, which is the drinking water requirement for a village of 2,000-5,000 people.

Three maps of India are presented (Figs. 2-2, 2-3, and 2-4) 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 Rs 755,000 (\approx \$12,600), the current cost of Tata Project's PV-powered 1,000 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. This 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.

A disruptive opportunity to reduce the energy required for, and the cost of, off-grid rural desalination through the use of electrodialysis has been identified. However, off-grid ED systems are projected to be more expensive than on-grid RO systems. Future work on this project will aim to create off-grid desalination systems that are the same cost or lower than the on-grid RO systems currently produced by Tata Projects. Completing this aim will make off-grid desalination economically viable and enable Indian organizations to extend their desalination business into thousands of off-grid villages throughout India.

While a mathematical model of an ED system working in batch mode is presented in this work and validated through experimental testing, the first step in future work will be to extend both the model and experimental system to include a photovoltaic power source. ED 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. The updated model will allow for the analysis of an ED system's response to the stochastic nature of both solar and drinking water habits.

By fully characterizing a direct-drive PV-ED system, it will be possible to identify the components that have the greatest sensitivity to cost and performance. Improving or removing these components will lead to a lower-cost, higher performance desalination system. Potential areas for this improvement are listed below:

- *Methods of optimizing direct-drive versus battery storage:*

Comparison of battery assisted system with direct-driven system; optimization of overall system design including ED stack size, ED power system (PV panels and/or batteries), pump power system (PV panels and/or batteries), and pre filtration

- *Methods of reducing stack resistance:*

For example, utilization of Capacitive Deionization (CDI), a technology that uses just the anode and cathode without the alternating membranes, instead of Electrodialysis (ED)

- *Methods of staging technologies to achieve best energy efficiency at all salinity ranges:*

For example, in the same way that RO is more efficient at high salinities than ED, ion exchange is more energy efficient than ED at very low salinities (below 400 ppm). Staging ED and ion exchange may be an opportunity to reduce energy consumption and overall cost.

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Appendix A

Bill of Materials for Electrodialysis Experimental Setup

The following bill of materials includes the ED stack, pumps, flow and pressure meters, and tubing connection components used in the ED/EDR setup in GEAR Lab. Note that all components must be chemical resistant in order to handle high salinity levels. Iwaki chemical resistant pumps were chosen for this reason. Because the current system does not have a filter immediately before the stack, any rust build up in the system causes an increased pressure drop across the stack. All fittings and meters are thus chemical resistant as well. In addition to the specific items listed, the following quantities of tubing are also required:

- 25 feet of 1/4" ID flexible plastic tubing
- 25 feet of 5/8" ID flexible plastic tubing
- 10 feet of 5/16" ID flexible plastic tubing

ED Stack		
Item	Part Number	Quantity
PC-Cell ED Stack, 10 Cell Pair	ED 64002-101 configured for EDR	1
Concentrate and Diluate Streams		
Item	Part Number	Quantity
Bronze Barbed Hose Fitting, Adapter for 5/8" Hose ID x 1/2" NPT Male Pipe	McMaster 9431K12	6
Diverting 3-Port Bronze Ball Valve, 1/2" NPT Female	McMaster 4373K53	2
Chemical-Resistant Polypropylene Barbed Fitting, Reducing Straight for 5/8" x 1/4" Tube ID	McMaster 53415K127	2
Chemical-Resistant Polypropylene Barbed Fitting, Straight for 1/4" Tube ID x 1/4 Male Pipe Size	McMaster 53415K202	14
Sanitary White PVDF Barbed Tube Fitting, Reducing Straight for 5/16" x 1/4" Tube ID	McMaster 53055K132	4
Low-Pressure Gauge, Steel Case, 2-1/2" Dial, 1/4 Bottom, 0-10 PSI	McMaster 4026K3	2
Diverting 3-Port Bronze Ball Valve, 1/4" NPT Female	McMaster 4093T21	2
Flow meter, 7430 Series Rotameter, Tantalum Float	King Instrument 74C-234G041-5-3-3-3-4-0	2
Iwaki Pump, barbed fittings, 115V motor	Iwaki Pumps WMD-20RZ-115	2
Rinse Stream		
Item	Part Number	Quantity
Chemical-Resistant Polypropylene Barbed Fitting, Reducing Straight for 5/8" x 1/4" Tube ID	McMaster 53415K127	1
Chemical-Resistant Polypropylene Barbed Fitting, Straight for 1/4" Tube ID x 1/4 Male Pipe Size	McMaster 53415K202	7
Low-Pressure Gauge, Steel Case, 2-1/2" Dial, 1/4 Bottom, 0-10 PSI	McMaster 4026K3	1
Sanitary White PVDF Barbed Tube Fitting, Reducing Straight for 5/16" x 1/4" Tube ID	McMaster 53055K132	2
Low Pressure Drop Flow Meter	Cole Parmer EW-32556-32	1
Iwaki Pump, barbed fittings, 115V motor	Iwaki Pumps WMD-20RZ-115	1