Desalination 352 (2014) 82–91

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

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

Natasha C. Wright *, Amos G. Winter V.

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

HIGHLIGHTS

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

ARTICLE INFO

Article history:
Received 10 April 2014
Received in revised form 23 July 2014
Accepted 25 July 2014
Available online 30 August 2014

Keywords:
Electrodialysis
Brackish groundwater
Photovoltaic energy
Small-scale
Rural

ABSTRACT

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

1. Introduction

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

Approximately 73% of Indian villages use groundwater as their primary source of drinking water [3]. Although ground water is usually of higher biological quality than surface water sources, it can contain higher levels of chemical contamination. Water with salinity levels above the taste threshold (>500 mg/L) underlies 60% of the land in India [4]. Along with the health effects associated with high sodium intake, saline water is undesirable to users because of its poor taste [5]. Water that does not meet the aesthetic quality a user expects may cause it to be discarded as a viable source.

Due to the prevalence of chemical contamination in Indian groundwater sources, non-governmental organizations (NGOs) have begun to install reverse osmosis (RO) systems. While some of these systems have been successfully operating for up to 5 years, many have failed due to lack of proper maintenance or the inability to keep up with operational costs. Electricity costs account for ≈54% of the operational expense of current village-scale RO systems [6].

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

* Corresponding author.
E-mail address: ncwright@mit.edu (N.C. Wright).

http://dx.doi.org/10.1016/j.desal.2014.07.035
0011-9164/

(PV) powered electrodialysis desalination system would meet the demands of rural Indian villages due to its viability as a technology at small scale, the reduced energy required versus reverse osmosis systems, stronger membrane components resulting in longer membrane lifetime, and less required pretreatment.

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

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

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

2.1. Daily water output

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

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

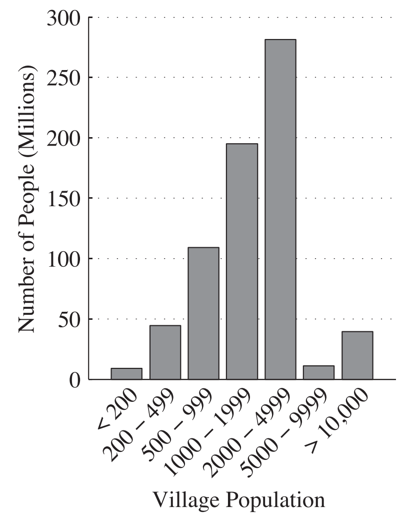

Fig. 1. Number of people living in villages of different populations. The median Indian villager lives in a village of 2000–4999 people.

2.2. Contaminant removal

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

2.2.1. Biological quality

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

2.2.2. Chemical quality

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

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

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

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

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

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

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