Desalination 445 (2018) 213–224

Contents lists available at ScienceDirect

Desalination

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

Energy considerations associated with increased adoption of seawater desalination in the United States

Prakash Rao[a,*], William R. Morrow III[a], Arian Aghajanzadeh[a], Paul Sheaffer[a], Caroline Dollinger[b], Sabine Brueske[b], Joe Cresko[c]

[a] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, United States
[b] Energetics, 7075 Samuel Morse Drive, Suite 100, Columbia, MD 21046, United States
[c] U.S. Department of Energy, Advanced Manufacturing Office, 1000 Independence Ave. SW, Washington, DC 20585, United States

ARTICLE INFO

Keywords:
Seawater desalination
Reverse osmosis
Water stress
Desalination energy

ABSTRACT

Due in part to increased water demand and uncertainty around the availability of existing freshwater resources, there is interest in expanding the use of seawater desalination in the U.S. In order for greater adoption to occur, existing barriers need to be mitigated. One of these barriers is the energy consumption of seawater desalination. This paper reviews the existing energy requirements for membrane and thermal-based seawater desalination systems to produce potable water. Through literature review, it identifies the commercially-available option with the lowest energy intensity and the thermodynamic minimum energy requirement for each unit operation of the system. The paper then estimates the energy requirements to expand seawater desalination capacity to meet the potable water needs of water-stressed regions in the U.S. The results show that supplying 10% of the potable water demand for these regions located within 250 miles of a coastline using the lowest energy-intensity seawater desalination system commercially available would require < 0.1% of 2018 U.S. electricity consumption. This increases to approximately 0.5% if all public water for these same regions is supplied via desalinated seawater. These estimates of the energy implications of broader adoption provide an initial comparison to current U.S. electricity consumption.

1. Introduction

Global water demand in 2050 is projected to be 155% of 2000 levels [1]. By this time, limits on human consumption of freshwater are expected to exceed the Earth's safe limit for stability [2,3]. In the U.S., state water planners are already concerned about meeting growing demand. In a survey conducted in 2013 by the U.S. Government Accountability Office, 40 of 50 state water managers expected freshwater shortages within their state in the following ten years under typical weather conditions, and 42 expected shortages in the subsequent 10–20 years [4]. The shortages are expected in the absence of impacts from climate change, which is projected to exacerbate water shortages globally [5–8]. Additionally, irreversible damages to the environment and water resources can occur from depleting our freshwater resources. For example, heavy reliance on groundwater can lead to aquifer contamination by seawater intrusion or depletion beyond the point of recharge. Land subsidence and infrastructure damage are other potential consequences of overdrawing from groundwater sources [9,10]. Developing water plans that meet projected demands and are resilient against uncertain future water availability is an emerging challenge for regional planners. The consequences of inaction are severe; the World Economic Forum recently cited water crisis as one of the most likely and impactful global risks in the near term [11].

The utilization of seawater can be part of a diverse water supply portfolio to meet projected water demands. However, in the U.S., seawater is a far less utilized water source for potable water compared to fresh ground or surface water. In 2010, < 1% of public water supply in the U.S. was sourced from saline (sea or brackish) water [12]. This is due in part to the energy intensity (defined as energy consumption/unit of product water) necessary to treat seawater for potable use. In the U.S., the estimated energy intensity of installed seawater desalination facilities (between 3.2 kWh/m^3 and 4.5 kWh/m^3) can be over 25 times larger than it is for freshwater systems (0.12 kWh/m^3 in New York state) [13–16]. For reference, the average home in the U.S. consumes 29.5 kWh in a day [17]. The energy required to produce 1 m^3 of potable water (typical per person use in the U.S. is 0.37 m^3/day) from seawater at an energy intensity of 3.2 kWh/m^3 is equivalent to the energy consumed by a typical U.S. home in 2.6 h [18]. For further context, a small

* Corresponding author.
E-mail address: PRao@lbl.gov (P. Rao).

https://doi.org/10.1016/j.desal.2018.08.014
Received 29 May 2018; Received in revised form 14 August 2018; Accepted 15 August 2018
0011-9164/

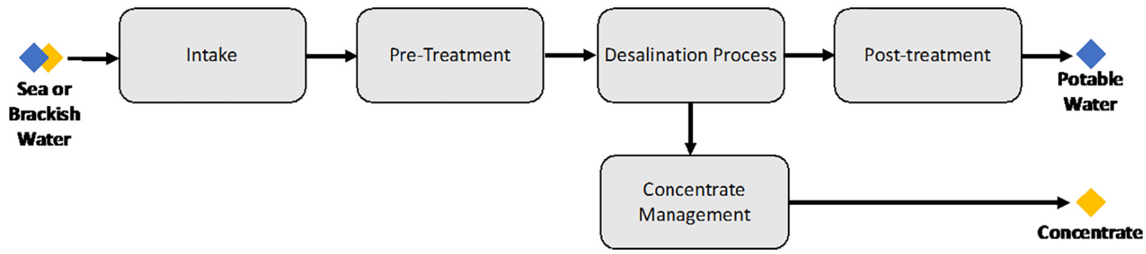

Fig. 1. Unit operations of a desalination system, as defined in this paper. Adapted from U.S. Department of Energy [23].

room air conditioner operating for 1.4 h consumes 2.5 kWh [19]. This suggests that the energy intensity of seawater desalination is high when compared to other water supply options but comparable with other energy-consuming services.

In addition to the higher energy intensity compared to existing water supply options, there are several other barriers to the adoption of seawater desalination in the U.S. One major barrier is the high initial cost of large, centralized desalination facilities (which include not only the capital costs, but also costs to acquire coastal land, permits for siting and the environmental impacts of seawater intake and concentrate discharge) and subsequent amortization. This, along with the increased energy consumption, leads to higher cost of water produced through seawater desalination relative to potable water produced from freshwater. However, seawater desalination offers several benefits. The feedwater (the oceans) are vast and generally available at no-cost. Due in part to this, seawater desalination offers a water supply option that is resilient against water stress. Further, while the cost of water produced through seawater desalination is relatively high, it can also be predictable and relatively steady. This provides water planners with more certainty when developing multi-year plans to meet projected water demands. Additionally, seawater desalination in conjunction with water storage offers the potential to facilitate the integration of intermittent renewable electricity generation (e.g., solar) into the electric grid.

As regional water planners consider seawater desalination, a question that emerges is the impact on the regional energy sources from adding seawater desalination to their water supply portfolio. Energy and water – two important resources/services for human development – cannot be fully decoupled, and there is a need to consider one when planning on the development of the other [20,21]. Further, while the energy intensity for desalination has dropped significantly over the past forty years, future research and development has the potential to lower it further [22].

In order to better understand the energy consumption of different seawater desalination systems and the energy implications associated with their increased adoption in the U.S., this paper will:

1. Define the desalination system, based on consistent set of key unit operations/components.
2. Map the various desalination technology options from a variety of water sources for a range of end-uses, based on salinity and capacity requirements.
3. Briefly summarize installed seawater desalination capacity globally and in the U.S., and relevance to water stressed regions in the U.S.
4. Review several membrane and thermal-based seawater desalination system technologies to produce potable water, and identify the state-of-the-art (SOA) and thermodynamic minimum (TM) energy intensities for each component of the desalination system.
5. Develop scenarios that estimate the energy requirements associated with broader adoption of SOA membrane-based seawater desalination systems to serve the water supply needs of water stressed regions in the U.S. These estimates are intended to provide general guidance on the energy implications of increased adoption. Reductions achievable through optimization of the water conveyance system are likely possible, but not explored in this paper.
6. Discuss other considerations and barriers when planning for increased adoption of seawater desalination.

The results are intended to assist regional and national water planners in the U.S. to better assess the full energy implications associated with increasing seawater desalination capacity for potable water production. It can also be used by policymakers who are developing research and development portfolios related to desalination to better understand the limit for energy reductions in seawater desalination systems over commercially-available ones.

2. Background

2.1. Desalination system and applications

For the purposes of this paper, the desalination system is subdivided into five unit operations: intake, pre-treatment, the desalination process, posttreatment of the product water, and disposal of the concentrate (concentrate management). These steps are illustrated in Fig. 1. Additionally, pumping energy will be required to integrate the product water with the existing water supply network.

The selection and pairing of the system components will be dependent upon many factors, including the desalination system application, where the *application* refers to the desalination of an alternate water source for a given end use. The feasibility of a system component for an application will depend at minimum on the salinity and available/required flow rates of the water source, end use, and concentrate disposal site. To help identify feasible desalination pathways, Fig. 2, originally developed by the U.S. Department of Energy and adapted for this paper, shows typical ranges of capacity (m^3/day) and salinity (% total dissolved solids) for various freshwater-alternate sources, end use requirements, concentrate disposal thresholds, and commercially-available desalination technology operating ranges [23]. As shown in the legend to Fig. 2, three sets of capacity and salinity ranges are shown for the desalination technologies. The first describes the feedwater input, while the second and third describe the concentrate and product water. By matching the output capacity and salinity of a preceding system component with those of the input requirements for the next system component, feasible desalination pathways can be identified. These pathways are not intended to show an optimized system (in terms of energy efficiency, cost, etc.), but to eliminate technically infeasible pathways for a selected application. For example, from Fig. 2 one can determine that capacitive deionization is not appropriate for seawater and multi-stage flash is not appropriate for low salinity feedwaters.

The pathways explored in this paper - seawater to municipal potable water - are one of many, with a single exemplary pathway shown in Fig. 2 with arrows. One water source (seawater) was selected for one end-use (municipal-scale potable water) and one concentrate disposal option (ocean). Many desalination technologies can be used for these specified conditions, including reverse osmosis (RO), multi-effect distillation (MED), and multi-stage flash (MSF). This paper will review RO,