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Energy use for membrane seawater desalination – current status and trends

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ABSTRACT

Technological advances of membrane seawater desalination have propelled its worldwide use. Despite the two-fold reduction of its power demand over the past 20 years, seawater desalination remains the most energy intensive alternative for production of fresh drinking water at present. This article provides an overview of the current status of energy use for seawater desalination, discusses the minimum energy demand for production of fresh water and presents key factors that influence the desalination plant energy demand for the site specific conditions of a given desalination project. The article describes key benefits and challenges associated with the implementation of energy-saving technologies and equipment such as: collocation of desalination and power plants; alternative RO system configurations proven to yield significant energy savings such as; low-recovery plant design; use of split permeate two-pass RO system configuration; three-center RO system design; and use of high productivity/low energy membrane elements, hybrid RO membrane vessel configurations, large-size high efficiency pumps and pressure-exchanger based energy recovery systems. The article also discusses emerging desalination technologies with high-energy reduction potential and provides a forecast of the potential impact of future technologies on energy use for membrane desalination.

1. Introduction

Most of the water supplies of the coastal communities worldwide have traditionally come from inland or near-shore fresh water sources – groundwater aquifers, rivers and lakes. However, changing climate patterns combined with population growth pressures and limited availability of new and inexpensive fresh water supplies are shifting water industry's attention to an emerging trend – increasing number of coastal municipalities and utilities are reaching to the ocean for fresh water.

Until recently, seawater desalination has been limited to the desert-climate dominated regions of the World. Dramatic improvements in membrane technology and energy recovery equipment over the past 20 years have allowed two-fold reduction of power needed to desalinate seawater [1–4]. Such advancements have rendered desalination more affordable and attractive alternative for sustainable water supply. The use of desalination for production of fresh drinking and industrial water has gained a significant momentum over the past two decades. The number and size of desalination projects worldwide have been growing at a rate of 5 to 6% per year since 2010, which corresponds to an addition of 3.0 to 4.0 million m^3/day of new installed desalination plant fresh water production capacity every year.

For example, between June 2015 and July 2016, the new desalination plant production capacity contracted and installed globally was 3.7 million m^3/day and the total number of new plants added during this period was 512 [5]. A total of 266 (52%) of these new plants are of large and medium size. As of July of 2016, 2.14 million m^3/day of the total last-year plant capacity (3.70 million m^3/day), is already installed and 1.56 million m^3/day is contracted and under construction. As of June 30, 2016 the total number of desalination plants worldwide was 18,983 and these plants have cumulative fresh water production capacity of 95.6 million m^3/day [5].

Salt separation from seawater requires a significant amount of energy to overcome the naturally occurring osmotic pressure exerted on the reverse osmosis membranes. Seawater reverse osmosis (SWRO) desalination uses several times more energy intensive than conventional treatment of fresh water resources. Table 1 presents the energy use associated with various water supply alternatives.

Analysis of this table indicates that the energy needed for seawater desalination is approximately eight to ten times higher than that for production of fresh water from conventional sources such as rivers, lakes, and fresh water aquifers. It should be pointed out however, that such resources are limited to less than 2.5% of the water available on the planet, and that in large urbanized centers of most developed countries worldwide traditional fresh water resources are near depletion, while new sources are not readily available to sustain long-term population growth, industrial development and quality of life.

As indicated in Table 1, energy use for water reclamation is several times lower than that for seawater desalination. However, compared to desalination water reclamation does not create new fresh drinking

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Table 1
Energy use of various water supply alternatives.

Water supply alternative	Energy use (kWh/m^3)
Conventional treatment of surface water	0.2 to 0.4
Water reclamation	0.5–1.0
Indirect potable reuse	1.5–2.0
Brackish water desalination	1.0–1.5
Desalination of Pacific Ocean water	2.5–4.0

Table 2
Typical cost and energy use for medium and large size SWRO systems.

Classification	Cost of water (US$/m^3)	SWRO system energy use (kWh/m^3)
Low-end bracket	0.5–0.8	2.5–2.8
Medium range	0.9–1.5	2.9–3.2
High-end bracket	1.6–3.0	3.3–4.0
Average	1.1	3.1

water - it merely provides a more efficient use of the already available fresh water resources. Therefore, in most coastal urban areas worldwide both seawater desalination and water reclamation are implemented in parallel and are viewed as integral parts of well-balanced and environmentally sustainable long-term water supply portfolio.

2. Energy use for seawater desalination – current status

Table 2 provides typical ranges for cost of fresh water production and energy use of reverse osmosis membrane systems of medium and large seawater desalination plants (i.e., plants with fresh water production capacity of 40,000 m^3/day, or more). This table is based on actual data from over 20 SWRO plants constructed between 2005 and 2010. As seen from Table 2, SWRO systems of best-in-class seawater desalination plants use between 2.5 and 2.8 kWh of electricity to produce 1 cubic meter of fresh water, while the industry average energy use is approximately 3.1 kWh/m^3. The industry-wide cost for production of fresh drinking water from seawater at present is approximately US$1.1/m^3. Energy expenditure typically contributes 25 to 40% of this cost depending on the unit power rate and the SWRO plant design, and equipment efficiency.

It should be pointed out that the energy use presented in Table 2 only encompasses SWRO system operations, rather than that of the energy consumption of the entire seawater desalination plant. Usually, SWRO systems contribute between 65% and 80% of total desalination plant energy demand.

Fig. 1 presents a breakdown of energy consumption within a typical seawater desalination plant using Pacific Ocean water of total dissolved solids (TDS) concentration of 33,500 mg/L as source seawater. In this illustrative example, the total plant energy use is 3.57 kWh/m^3 and the SWRO system's energy demand is 2.54 m^3/day (71% of the total plant energy use).

Usually the desalination plant's source seawater pretreatment system is the second largest user of energy. However, for some plants, where the point of desalinated water delivery is located at a long distance and/or high elevation, the energy for product water conveyance could be higher than that for seawater pretreatment.

3. Minimum energy demand for SWRO desalination

The lowest theoretical energy consumption for desalination of seawater of 33,500 mg/L and temperature of 25 °C (i.e., typical Pacific Ocean water) is 0.7 kWh/m^3. This energy use corresponds to condition of complete conversion of seawater into fresh water (100% recovery), which cannot be achieved in practical terms. For a more realistic 50% recovery, this minimum theoretical energy use would be 1.1 kWh/m^3. However, this energy consumption assessment assumes that all desalination plant equipment has 100% energy efficiency and all energy contained in the desalination plant concentrate is reused in the desalination process. Therefore, this energy threshold is the ideal theoretical minimum for seawater desalination.

Based on the systematic long-term testing of full-scale state-of-the-art desalination system by the Affordable Desalination Collaboration (ADC) in the United States (US), the lowest energy use that could be achieved with actual state-of-the art highly efficient commercially available desalination equipment and RO membranes at the time of testing (years 2006–2007) was determined to be 1.58 kWh/m^3 [6]. Such energy use was measured at RO system recovery of 42% and average SWRO membrane flux of 10.2 l/m^2·hr (lmh).

The ADC testing was completed using Pacific Ocean seawater collected by an open ocean intake and pretreated by granular media pressure filters. The ADC study concluded however, that SWRO system operation at such low recovery and flux does not yield the lowest overall cost of water production at unit cost of energy of US$0.10/kWh used for life-cycle cost assessment.

Based on a detailed cost-benefit analysis, ADC researchers have determined that the “Most Affordable Point” of SWRO system design is at plant recovery of 48% and flux of 15.3 lmh. At this operational condition the minimum SWRO system energy use was determined to be 2.0 kWh/m^3. It should be pointed out that the “Most Affordable Point” design would vary with unit cost of energy and the project-and-location specific construction and engineering costs.

4. Desalination energy use factors and trends

Energy use for seawater reverse osmosis desalination varies in a wide range and depends upon a number of factors (see Table 3).

Over the past decade, the desalination industry has successfully adopted a number of cost management approaches and technological innovations to control construction and energy costs [7]. They include evolutionary improvements of the SWRO membrane permeability and salt rejection; refinements of the isobaric-chamber and turbocharger type energy recovery equipment and systems; SWRO system configuration modifications aimed at reducing energy losses within the feed water distribution piping and vessels; and implementation of fewer, larger-size desalination trains and pumps [8,9].

One of the key issues associated with optimizing SWRO system energy use and operation costs is the quality of pretreated water fed to this system. Over the past 10 years, industry understanding of key mechanisms seawater pretreatment for membrane desalination has evolved significantly [10–18] (Choi et al., 2009). Gradually, the desalination industry is adopting the use of seawater membrane pretreatment which is believed to allow producing higher quality seawater which in turns can facilitate more cost-effective RO system design and operations [19–22].

5. Collocation of desalination and power plants

Desalination of warmer source seawater usually requires less energy for membrane separation than using seawater of ambient temperature. This potential energy reduction benefit could be applied by using warm water discharges from coastal power plants as source water for desalination. Coastal power generation plants often use seawater of ambient temperature for cooling of their electricity generation units. The cooling water discharged from a typical power generation station is usually 5 to 15 °C warmer than the ambient ocean water. Taking under consideration that energy needed for salt separation is reduced with 5 to 8% for every 10 °C of elevated seawater temperature in the temperature range of 12 to 40°C, using warmer seawater can result in measurable energy reduction [1].

Under a desalination plant – power station collocation