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Energy efficiency breakdown of reverse osmosis and its implications on future innovation roadmap for desalination

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HIGHLIGHTS

- Energy consumption in reverse osmosis desalination is comprehensively broken down.
- Authors show that reverse osmosis energy efficiency is asymptoting.
- Role of high permeability membranes for desalination efficiency is discussed.
- Low energy membranes will not give significant desalination energy savings anymore.
- Role of high permeability membranes in future of desalination is discussed.

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ABSTRACT

In this paper, authors breakdown the specific energy consumption for seawater and brackish water desalination in an attempt to quantify the value of high permeability membranes on specific energy consumption for desalination. The trends from the analysis presented in this paper show that in both seawater and brackish desalination we are approaching thermodynamic limitations. The Gibbs free energy of mixing accounts for almost half of the specific energy consumption for seawater desalination and for brackish water desalination system losses and frictional losses account for major share of energy consumption. It is also shown that in both seawater and brackish water desalination, just high permeability membranes will not give substantial returns. Spacers, membranes, module designs and system are all areas that need to improve to make any significant enhancement in energy efficiency of reverse osmosis desalination.

1. Introduction

Rising population and urbanization are putting ever increasing demands on energy, food and water. It is projected that the world population will reach from its current 7 billion to 8 billion by 2026 and to 9 billion by 2042 [1]. The energy demand, to sustain human development at current pace with this population growth, is projected to grow from 12 billion tonne of oil equivalent in 2009 to around 18 billion tonne of oil equivalent by 2035 [2]. Demand on global agriculture is forecasted to be double that of 2005 by 2050 [3]. Water scarcity, a serious problem threatening a global water crisis, will be more prominent as water is not only needed for drinking and sustenance but also to support the energy and food industry. It is projected that by 2025 about two third of the population will be living in water stressed regions as compared to one third at present [4]. With freshwater sources depleting with increasing withdrawal and consumption of water, there is an increasing need for desalination and water treatment.

As shown in Fig. 1, water is needed for energy generation: thermoelectric power, nuclear power, hydro power, harvesting bio fuels and other renewables [5–10]. Energy is needed for water treatment, purification and distribution. Water is needed for agriculture and harvesting livestock and processing food. Also, energy is needed for agriculture, for transportation and storage of food. In addition, produced water treatment is becoming very important in exploration of fossils like oil

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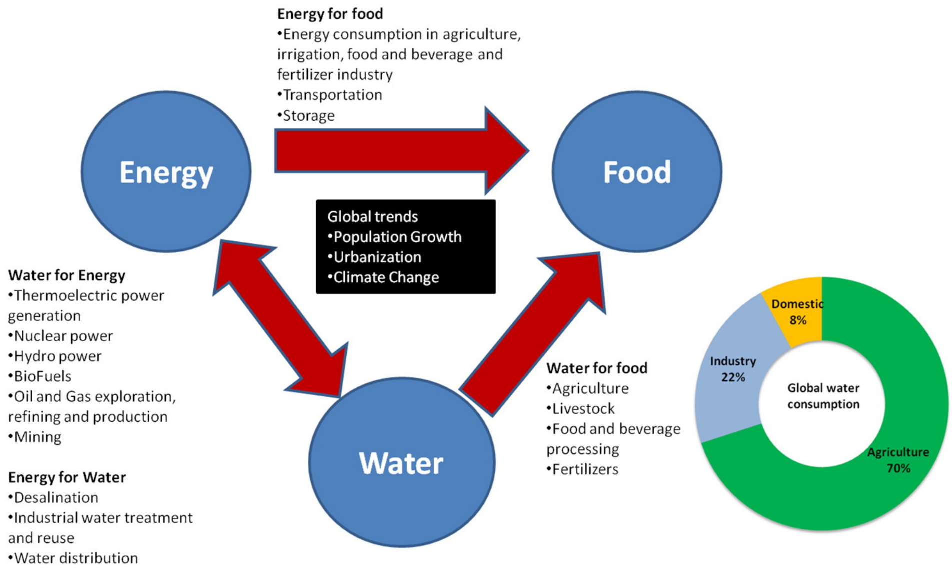

Fig. 1. Water–energy–food nexus.

and gas, shale oil and gas, and hydraulic fracking. Due to depleting freshwater resources, industrial water reuse e.g. water reuse in manufacturing of chemicals and goods is becoming of prime importance as desalinating seawater and transporting it inland is impractical due to prohibitive cost. This water–energy–food nexus, the nexus amongst the key pillars of sustainability, is becoming increasingly important. As we plan a sustainable global future, innovation has to be done keeping this nexus in mind.

Water lies right at the heart of this very evident water–energy–food nexus. In addition to seawater desalination, increasingly greater need is the industrial water needs to support the energy and the food industry, as the depletion and use of freshwater resources is constantly straining our once relatively abundant freshwater resources.

The water desalination and treatment industry classifies the two major desalination areas as seawater desalination and brackish water desalination. Inland water desalination, treatment and reuse, in general terms, can be collectively termed as brackish water desalination, whereas seawater desalination, as name suggests, refers to purifying seawater desalination mainly for drinking water and domestic usage. Middle East, Australia, Europe and Singapore have large installations of seawater desalination plants due to their proximity to the coast and minimal freshwater resource availability. As we think of water treatment, it is important to look at the total cost of treated water for these 2 major classes of water purification. This cost is largely broken down into Capital cost, Energy cost, Operational cost [11–14]. Distribution costs are not included in this cost calculations as they can vary quite widely. However, it should be noted that distribution costs further dilute the cost contribution of the factors discussed.

Innovation in water purification has to impact the cost of water overall. For seawater desalination, we can see the cost of capital and cost of energy take the lion's share of the cost of water. However for total brackish water, cost of capital, cost of energy and operating costs (maintenance, chemicals, membrane replacement), all three dominate the total cost [11–14].

With innovation in thermal and reverse osmosis desalination technologies over the last few decades, we have a reduction in total cost of water [12] and a reduction in specific energy consumption (kW h/m^3) for water purification [15]. For reverse osmosis in particular, one of the most promising desalination technologies due to its low carbon footprint, the increase in energy efficiency and reduction in cost has been due higher efficiency pumps, higher efficiency energy recovery devices, lower energy and higher salt rejection membranes, high efficiency membrane modules, membrane modules packing more and more active area, optimized feed spacers and more efficient system designs.

The questions in front of us, as we think of further innovation in the desalination and water treatment space, are:

1. How can we achieve further increase in energy efficiency of water purification?
2. What are other ways to reduce the total cost of water?

2. Desalination is now limited by thermodynamics

With rising energy costs and the increasing water–energy–food nexus, it is important that we optimize the energy efficiency of desalination. Energy's cost contribution is close to 50% in seawater desalination [11–14], and even though the cost contribution in brackish water desalination is about 10%, with rising energy process, it can play a much bigger role in the future.

In order to calculate the energy efficiency of reverse osmosis or any other desalination process and to calculate a theoretically attainable efficiency, we have to start by applying second law of thermodynamics to separations in general [16,17] which can be stated in desalination context as — for a spontaneous mixing process, any process to unmix the constituents will require more energy than was released during mixing it. In other words, practically, the energy will be greater than as calculated by Gibbs free energy of unmixing ($\Delta G_{unmixing}$) and the Gibbs free energy of unmixing will be the thermodynamically minimum energy needed for the separation. The additional energy will be accounted for by additional work that would need to be done on the system (W). This additional work will depend on the technology used for separation and the energy losses incurred while doing this work.

Hence separation energy efficiency (η_E) can be defined for any separation process [16,18], as:

$$\eta_E = \frac{\Delta G_{unmixing}}{\Delta G_{unmixing} + W} = \frac{E_{thermodynamic,min}}{E_{thermodynamic,min} + W}. \tag{1}$$

For desalination, the energy required to recover a given percent of pure water from a salt–water feed (% Recovery) is generally used as a metric to quantify energy consumption for the entire separation process. This metric is termed as specific energy and has the units of kW h/m^3. Specific energy for a given desalination process is a function of the thermodynamic properties of the feed (feed composition and concentration, temperature), the recovery and the inherent efficiency of the

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