Renewable and Sustainable Energy Reviews 81 (2018) 1–21

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Membrane technology in renewable-energy-driven desalination

Aamer Ali[b,*], Ramato Ashu Tufa[b], Francesca Macedonio[a,b], Efrem Curcio[b], Enrico Drioli[a,b,c,d]

[a] National Research Council - Institute on Membrane Technology (ITM–CNR), Via Pietro BUCCI, c/o The University of Calabria,cubo 17C, 87036 Rende CS, Italy

[b] University of Calabria - Department of Environmental and Chemical Engineering, cubo 44A, Via Pietro BUCCI, 87036 Rende CS, Italy

[c] Hanyang University, WCU Energy Engineering Department, Room 917 9th Floor FTC Bldg., 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea

[d] Centre of Excellence in Desalination Technology, King Abdulaziz University, Jeddah, Saudi Arabia

ARTICLE INFO

Keywords:
Desalination
Renewable energy
Membrane operations
Pressure retarded osmosis
Reverse electrodialysis
Membrane distillation

ABSTRACT

Growing requirements of freshwater and unsustainable nature of fossil fuels are driving the interest in using renewable energy for desalination applications. Due to their less energy-intensive nature and small footprint, membrane-based desalination operations are gaining significant interest in this regard. Substantial efforts have been observed in integrating traditional renewable and relatively green sources of energy (wind, solar, geothermal, tidal and nuclear) with membrane-based desalination operations, mainly reverse osmosis (RO) and electrodialysis (ED). Due to recent developments and progresses in membrane technology, interesting membrane operations including membrane distillation (MD), pressure retarded osmosis (PRO) and reverse electrodialysis (RED) have emerged. These operations are capable of generating clean and sustainable electricity from various waste streams including brine and impaired water which otherwise are considered environmental liabilities. PRO and RED require mixing of a high salinity solution (such as seawater or brine and wastewater, respectively) with a low salinity solution to generate electricity. MD has shown the potential to generate freshwater and electricity as standalone process. Integration of MD with PRO or RED enhances the performance of these processes and provides a clean and sustainable route to produce freshwater and energy. The current study reviews the recent progresses and developments in applying renewable energy sources in membrane-based desalination with special attention on emerging membrane operations with proven capability to generate energy from wastewater streams.

1. Introduction

Sources of freshwater have been the center for the growth of civilization since ancient times, evident from geographic location of old civilizations and cities [1]. Last few decades, however, have witnessed outstandingly huge increase in water consumption mainly due to improved living standards, increased population and massive industrialization. Consequently, insufficient availability of fresh water has emerged as an increasingly important challenge in many areas across the globe. Development and further growth of civilization in water-stressed areas are, therefore, strongly linked with the amount of available water. It has been predicted that two third of world population will be suffering from lack of access to clean water by 2025 (unwater.org). Even though water is one of the most abundant materials available on earth, occupying 75% of surface; yet, most part of the water reservoirs is not directly usable. Conventional resources of freshwater including rivers, lakes and groundwater contain only 0.65% of global water. On top of that, distribution of freshwater resources is not proportional to the population and water usage in various parts of the world [2]. These statistics argue loudly in favor of extracting portable water from non-conventional sources including sea, rivers and lakes available in water-stressed regions.

The salinity content of brackish water are upto 10,000 ppm and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts making these waters unsuitable for drinking and most domestic uses. Considering the indicators about drinking water quality, World Health Organization (WHO) permits a salinity of 500 parts per million (ppm) and 1000 ppm in certain cases [3]. Desalination process brings the total dissolved solids down to the permissible limit. Desalination has been mainly used for seawater (67%), followed by brackish water (19%), river water (8%) and wastewater (6%) [4]. Historically, it has been performed by using thermal energy. The basic concept of thermal desalination has been adopted well even in today's thermal desalination processes including

* Corresponding author.
E-mail address: a.aamer@itm.cnr.it (A. Ali).

http://dx.doi.org/10.1016/j.rser.2017.07.047
Received 27 September 2016; Received in revised form 7 April 2017; Accepted 10 July 2017

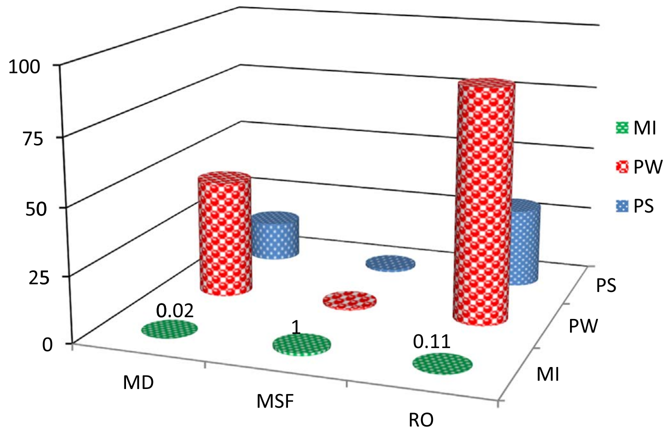

Fig. 1. PI metrics for MD, multi stage flash and RO [13].

multi-stage flash (MSF), multiple-effect distillation (MED) and thermal vapor compression (TVC). Relatively recently, membrane techniques using electrical energy have replaced thermal desalination in many parts of the world [5,6], mainly due to their less energy intensive nature. A third category based upon hybridization of thermal and membrane processes has also evolved. The examples include MD and MSF/MED integrated with RO.

In addition to energy saving, membrane processes also offer the advantages of compactness, light weightiness and high productivity which put these processes in perfect alignment with process intensification strategy [7–10]. In order to quantify these advantages, Drioli and Criscuoli [7] have applied/introduced some metrics including mass intensity (MI) (defined as the ratio of mass of raw material input to product output), productivity to weight ratio (PW) and productivity to size ratio (PS). On the basis of these metrics, a quantitative comparison of membrane processes with conventional MSF has been shown in Fig. 1. The figure is based on a plant with desalination capacity of 1250 m^3/day. The data for MSF plant has been taken from reference [11] while the flux data, module dimensions and weight for RO have been adopted from the commercial manufacturers [12]. The weight and volume of MD modules has been considered equal to that of RO. Various process intensification metrics plotted in Fig. 1 indicate that both RO and MD have lower MI than MSF due to high recovery rate. On the other hand, PW and PS for membrane processes are considerably higher indicating their superiority in terms of less weight and small footprints.

Although many milestones have been achieved in enhancing the performance of desalination processes, yet a significant margin for improvement exists. The current desalination techniques (especially thermal techniques) require substantial quantities of energy to achieve separation of salts from seawater. It has been estimated that the current global desalination capacities consume 75.2 TWh of energy per year [14]. Despite all technological improvements, RO, being the most economically viable technology at the commercial scale, still consumes between 3 and 4 kW h/m^3 that is more than double of the minimum (1.06 kW h/m^3) theoretical energy requirement (foe seawater at 35,000 ppm salt and at a typical 50% recovery) [195]. This directly affects the specific water cost that many developing countries facing the water crisis may not afford. The current scenario of desalination capacities reflects this fact [3]. For instance, desalination has been most widely adopted in Middle East (mainly in Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Oman, and Bahrain), Spain, Australia and certain parts of North America where people have high purchasing power and living standards [15]. In order to grow the desalination sector in other water stressed regions of the world at the same pace, desalination cost must be lower down [16]. The second challenge for sustainable growth of desalination sector is the use of fossil fuel that creates environmental and sustainability-related concerns. The current total installed capacity of desalination systems is more than 90 million m^3/day (idadesal.org), equivalent to 0.6% of total global freshwater supply (www.idadesal.org/desalination-101/desalination-by-the-number/). The calculations show that this capacity requires more than 850 million tons of oil each year [5]. This figure will become even higher with further expansion and development of desalination plants in various parts of the world. On the other hand, known fossil fuel resources are reported to vanish in next 50 years. In terms of carbon footprint, the current desalination plants across the globe emit 76 million tons of CO_2 annually that will approach to 218 million tons by 2040 [17]. Furthermore, any variation in price and supply of petroleum will directly influence the desalination sector. This scenario highlights the importance of introducing renewable, green and more sustainable practices in desalination sector. Comparative cost of power production from renewable energy (0.07, 0.05 and 0.05–0.09 $/kW h for geothermal, wind and solar powered, respectively) and fossil fuel (0.05–0.09 $/kW h) argue further in favor of using renewable energy instead of fossil fuel [6]. Renewable desalination has potential to address the challenges faced by conventional desalination. It is expected to become economically feasible as the costs of renewable technologies continue to decline and the prices of fossil fuels continue to increase.

Membrane operations driven with renewable energy can make desalination more sustainable and environment-friendly [18,19]. Among membrane operations, RO and ED have been mainly investigated for renewable desalination. However, with progress in membrane technology, interesting membrane processes are emerging with potentially important contribution in desalination. Relatively new processes include MD, forward osmosis (FO), RED and PRO. These processes have the potential to exploit/ generate renewable energy and can overcome the issues related with conventional desalination processes. The objective of the current study is to review the recent progress in applying renewable energy in membrane-based desalination. The study also intends to analyze the recent developments, perspectives, challenges and future research directions for relatively less-explored membrane operations capable of producing renewable energy in desalination and wastewater treatment sectors.

1.1. Types of renewable energy for desalination

Various sources of renewable energy are available in different regions across the globe. Main conventional renewable energy sources of interest for desalination include solar, geothermal, wind and tidal/ wave. Nuclear energy (discussed in detail in Section 1.1.5) is another form of emission-free energy but has not been adopted widely for desalination applications due to waste disposal issues and safety-related concerns. The progress in renewable energy based desalination is closely related with the corresponding development in renewable energy technologies. The growth of these technologies in recent years has been summarized in Fig. 2. The figure shows that the net amount of

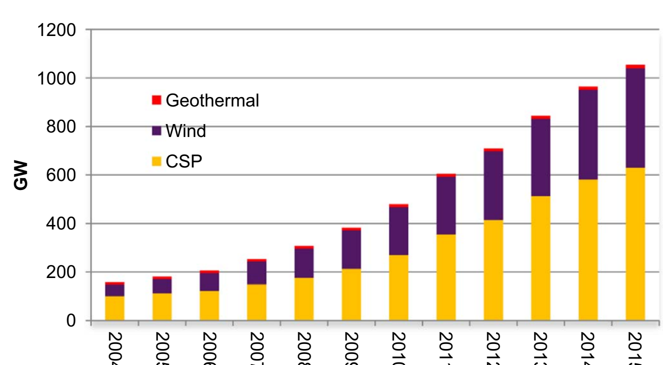

Fig. 2. Evolution of global renewable energy capacity.