Chapter 1

Sustainable Water Technology and Water-energy Nexus

Amira Abdelrasoul, Huu Doan and Ali Lohi

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.71716

Abstract

As water scarcity continues expanding in regions around the globe, there is an ever-increasing need to augment municipal, industrial, and agricultural water supplies through the purification of unconventional water sources, such as seawater, industrial and municipal wastewater. Due to the inextricable linkage between water and energy consumption, often called the water-energy nexus, the augmentation of water supplies must not come with a high cost energy consumption. As such, the high energy efficiency and often superior efficacy of membrane-based technologies have gained widespread implementation in various water treatment processes. Membranes allow passage of water, but largely reject salt and most other solutes, play a critical role in the majority of these processes. These types of membranes lie at the heart of traditional reverse osmosis (RO) processes.

Keywords: water, desalination, energy, reverse osmosis, membrane modules

1. Introduction

Biomimetic and bioinspired membranes are those membranes that are fabricated with natural or natural-like (inorganic, organic or hybrid) materials via biomimetic and bioinspired approaches (biomineralization, bioadhesion, self-assembly, etc.) to tailor specific properties (sophisticated structures, hierarchical organizations, controlled selectivity, antifouling or self-cleaning properties).

The accountability for today's water supplies is one of the essential concerns since clean and reliable water resources are not readily or permanently available to the global population and the industrial sectors. The world's water supply is of the uttermost importance to future development and prosperity. Even in contemporary global research, a substantial effort is being directed toward searching for water solutions. As water scarcity emerges as a concern in regions around the globe, there are exponentially growing needs to increase the potential for municipal, agricultural, and industrial water supplies with the aid of purification processes and unconventional water resources. Such unconventional resources include seawater, industrial residue water, and municipal wastewater. Because of the implicit connection between water and energy consumption, or the water-energy nexus concerns, the expansion of water supplies must not be accompanied by a high cost of energy consumption. The higher energy efficiency potential and superior efficacy of membrane-based technologies have received widespread implementation in a variety of water treatment processes and water solution projects. Desalination of seawater is a common technique used to counter the increasing shortage of freshwater in many remote global areas. In particular, desalination membranes allow for the passage of water, however, tend to reject salt and other solutes that play a critical role in the majority of these processes. These types of filtration membranes are at the core of traditional reverse osmosis (RO) processes. During desalination, the saltwater is forced through a reverse osmosis (RO) membrane at high pressures of 600–1000 psi. Due to these high pressure requirements, the energy use related to this desalination process is extensive. The continually rising energy costs and the expected limitations in conventional energy resources undermine the use of such filtration technology and instead call for the development of efficient desalination technologies as the alternative viable direction.

2. Recent and projected future needs for clean water resources

The global demand for fresh, clean water has increased by a factor of six during the period from 1900 to 1995. This increase is more than double when comparing it to the concurrent increase in population [1, 2]. This trend has further accelerated after 1995 due to increase in water use in emerging and growing global economies. On the other hand, the freshwater supply availability is being constantly reduced by growing pollution around the globe and the accumulative effects of climate change. The facts dictate that even though the amount of planet's freshwater remained fairly constant over time due to the continuous recycling process in the atmosphere, the population and its demands have dramatically exploded. This implies that with every year, the competition for a clean, copious supply of water for drinking, cooking, bathing, and sustaining life intensifies. The growing lack of access to potable water and sanitation is a major cause of disease and an obstacle to sustainable growth for a large portion of the global population [3, 4]. Many developing countries are undergoing rapid industrialization without incorporating appropriate long-term wastewater management systems, and are now facing increasing water pollution issues while still struggling with poor water supply and sanitation concerns [5]. The World Health Organization (WHO) reports that there are more than 2.5 billion people, or around 40% of the world's population currently lack access to proper sewer sanitation systems [6]. A report from the National Intelligence Council further highlights that the global water demands will drastically exceed sustainable supplies by 40% by as early as 2030 [7]. The United Nations reports on the correlation between water access and living conditions indicate that almost 4000 children die each day as a result of the various diseases instigated by unsanitary water ingestion and an absence of viable clean water resources. Clean, drinkable water is not available to anywhere between 1.4 and 1.8 billion people globally [8]. Sustainable and long-term access to clean water resources is

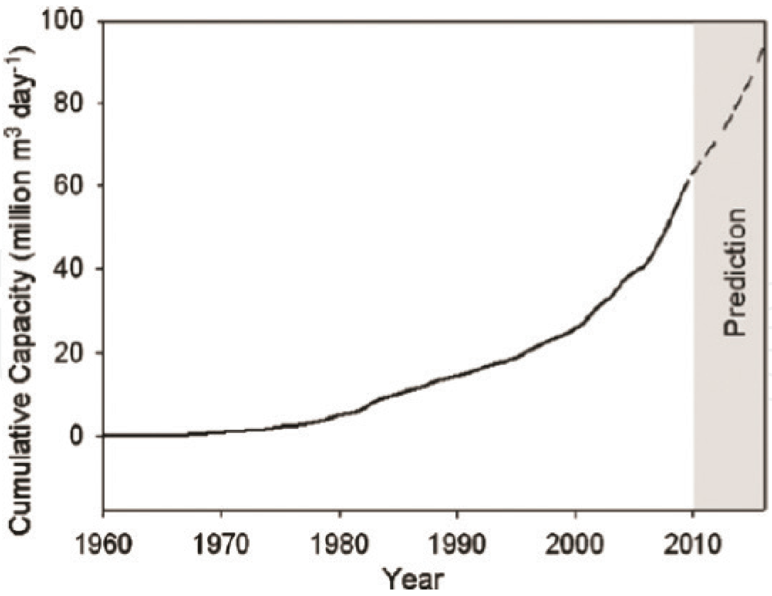

Figure 1. Cumulative desalination capacity from 1960 to 2016 [12, 13].

critical to all global economies and populations. The shift to biofuels may add further substantial water demands when it comes to crop irrigation, product manufacturing, and biorefining processes [9]. One of the primary reasons for the decrease in natural water supplies is the ongoing climate change and overexploitation of resources. The available remediation methods, including, water conservation, water transportation, and the construction of new dams, are insufficient for addressing or partially subduing with the exponentially growing demands. The most pressing global challenges include the production of potable water from salty or seawater as the world's largest water resource remaining, and the recycling or treatment of wastewater.

Desalination process is a technology that can convert saline water into usable water and can offer one of the most accessible solutions to the global water concerns [10]. A significant 75% of the Earth is covered with water and 97.5% of this water is located in the oceans. As indicated in **Figure 1**, the cumulative production capacity in desalination plants increased by 50% in 2010 to 60 million cubic meters per day, up from 40 million m^3 per day in 2006. In the first half of 2008, the growth in contract capacity was 39%, and the total global desalination production capacity was at around 50 million m^3 in 2009 [11–13].

3. Current state-of-the-art RO technology

The desalination membranes and their filtration potential are essential for the successful treatment of unconventional water sources such as seawater and wastewater. Arguably, desalination membranes can be the key to solving the concerns associated with water scarcity. There are multiple ways in which the process of seawater or brackish water desalination can be attained, and some of these ways, primarily rely on either thermal energy or the mechanical/electrical types of energy [14]. Because of its reliance on energy consumption, the process of seawater desalination is usually more costly than the process of filtering freshwater from rivers, groundwater, water recycling, and water conservation. **Table 1** outlines a summary of the technical and cost-related parameters for the major types of commercial and industrial desalination processes. The thermal processes for water filtration may include multistage flash (MSF), multiple effect distillation (MED), and thermal vapor compression (TVC) processes. The thermal-based filtration approaches have a record of high reliability accompanied by very high-energy consumption expectations. Processes that depend on mechanical/electrical energy include the mechanical vapor compression (MVC) and the reverse osmosis (RO) processes. The RO-based filtration process has the lowest energy consumption demands in comparison to other processes; however, its positives are undermined by a relatively lower reliability if compared to the other process types. In order for the seawater desalination to successfully occur, it is necessary to lower the total amount of the dissolved solids (TDS) content from 35,000–47,000 mg/L down to less than 500 mg/L [15].

Contemporary RO membrane technology is used as the primary methodology for desalination processes. RO membranes are introduced in a range of research and industrial applications that require desalination of saltwater and wastewater. Emerging shifts in energy recovery potential and innovations in pretreatment technology have dramatically enhanced the reliability and energy consumption demands in RO membrane technology. The expansive research and production efforts in RO desalination processes over the past four decades have

Energy used	**Thermal**		**Mechanical**	
Process	MSF	MED/TVC	MVC	RO
State of the art	Commercial	Commercial	Commercial	Commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0.6	6
Heat consumption (kJ/kg)	250–330	145–390	–	–
Electricity consumption (kWh/m^3)	3–5	1.5–2.5	8–15	2.5–7
Plant cost ($/$m^3$/d)	1500–2000	900–1700	1500–2000	900–1500
Time of commissioning (months)	24	18–24	12	18
Production unit capacity (m^3/d)	<76,000	<36,000	<3000	<20,000
Conversion freshwater/seawater	10–25%	23–33%	23–41%	20–50%
Maximum top brine temperature (°C)	90–120	55–70	70	45 (max)
Reliability	Very high	Very high	High	Moderate (for seawater)
Maintenance (cleaning per year)	0.5–1	1–2	1–2	Several times
Pretreatment of water	Simple	Simple	Very simple	Demanding
Operation requirements	Simple	Simple	Simple	Demanding
Product water quality (ppm)	<10	<10	<10	200–500

Source: AQUA-CSP, DLR 2007.

Table 1. Major commercial desalination processes.

accounted for the 44% of the global desalination production capacity and for the 80% of the total number of desalination plants installed worldwide [16].

RO desalination has displaced the more conventional thermal types of technology, including the multistage flash (MSF) [17]. Furthermore, RO desalination technology is expected to maintain its dominance despite the arrivals and the proposals of new alternative technologies like membrane distillation [18], electrodialysis [19], capacitive deionization [20], and forward osmosis [21]. The commercial focus on RO technology is growing globally because of the constant improvement of the process and the respective cost reduction opportunities that arise from it. Some of the RO membrane advances feature innovation in membrane materials, membrane module design, feed pretreatment, process design, energy recovery, and reduction in energy consumption. Some of these improvements are quantitatively outlined in **Figure 2(a), (b)** and **(c)**. The significant sevenfold decrease in salt passage over the course of 30 years of development has greatly extended the potential range of saline feeds that can be treated to adhere the strict potable water standards. By improving mechanical, chemical, and biological strength of RO membranes, and by increasing their permeability, the developments have lowered the membrane cost per unit volume of water produced by more than 10 times since 1978. Combined efforts to lower fouling and concentration polarization, and to maximizing permeate flux and energy recovery potential, have decreased the energy consumption from 12 $kWhm^{-3}$ in the 1970s to less than 2 $kWhm^{-3}$ in 2006 [22].

The most extensive advantages to the water filtration process have come directly from the improvement of the membranes themselves. The key structural parameters, materials used, and morphology of RO membranes have been actively modified in order to advance membrane functionality, such as permeability and selectivity, and applicability, such as mechanical, chemical, and biological stability. The current RO membrane market is controlled by the thin film composite (TFC) polyamide membranes. These membranes consist of three layers that include a polyester web acting as a structural support (120–150 μm thick), a microporous interlayer (about 40 μm), and an ultrathin barrier layer located on its upper surface (0.2 μm) [23]. One of the possible concerns is that the polyester support web cannot itself provide the necessary support for the barrier layer since it is too porous and irregular. As a result, a microporous interlayer of polysulfonic polymer is added between the barrier layer and the support layer to enable the ultrathin barrier layer to endure the high-pressure compression. The barrier layer's thickness is lowered to minimize the opposition to the permeate transport process. The membrane pore size generally required to attain salt rejection higher than 99% on a consistent basis is less than 0.6 nm. This selective barrier layer is frequently created out of aromatic polyamide, for instance using interfacial polymerization of 1,3-phenylenediamine (also known as 1,3-benzenediamine) and the tri-acid chloride of benzene (trimesoyl chloride) [24]. Membrane featuring an improved chemical resistance and structural sturdiness can provide enhanced tolerance to impurities, better durability, and improved cleaning parameters [25, 26].

The most extensively used designs in RO desalination are the spiral wound membrane module configuration. This type of configuration allows for greater specificity of membrane's surface area, better scale-up operations, interchangeability, and low replacement costs. It is likewise the least expensive module configuration that can be used for production based on flat sheet TFC membranes [27, 28]. The spiral wound configuration was originally developed

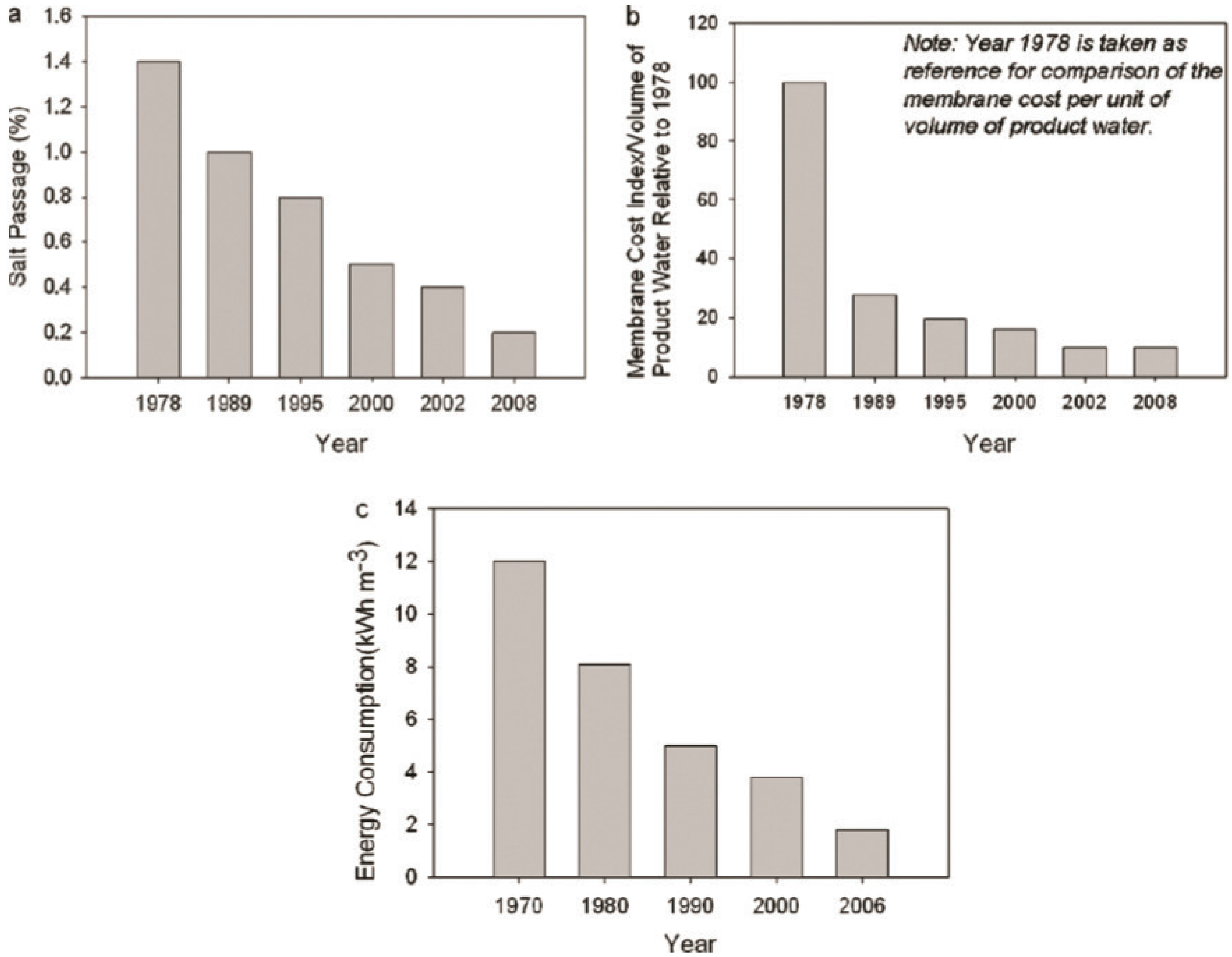

Figure 2. (a) Salt rejection enhancement potential, (b) membrane cost reduction, and (c) energy consumption minimization of RO [22].

over several decades ago and there has been extensive progress in the dimensions of spacers, feed channels, vessels, and the construction materials. These enhancements have helped to optimize the interconnection between module design and fluidic transport characteristics, which in turn decreased fouling and pressure losses. Polyamide spiral wound membranes control RO/Nanofiltration (NF) market sales with a 91% share majority, while the asymmetric cellulose acetate (CA) hollow fiber membranes in the far removed second spot [29]. CA membrane has a high chlorine resistance; hence, chlorine can be injected in the CA membrane unit to deter the growth of microorganisms and algae. On the other hand, RO/Nanofiltration (NF) has significantly higher salt rejection capacity and net pressure driving force potential [30]. Within the industrial sector, there are four primary membrane module suppliers that provide RO membranes to large-scale desalination plants, and these include DOW, Toray, Hydranautics, and Toyobo. State-of-the-art seawater desalination RO membrane modules from each respective supplier are shown in **Table 2** to provide a benchmark of current SWRO performance parameters. A more extensive comparison of these products has not been included since the research data corresponds to varying test or operating conditions [31–38]. Ongoing research on modular element design is currently concentrating on the optimization

http://dx.doi.org/10.5772/intechopen.71716

Membrane module brand name	Material & module	Permeate flux ($m^3\ day^{-1}$)	Salt rejection (%)	Specific energy consumption[d] ($kWh\ m^{-3}$)
DOW FILMTEC™ 8-in. SW30HRLE	TFC cross-linked fully aromatic polyamide spiral wound	28.0[a]	99.60–99.75[a]	3.40 (2.32)[e] at Perth SWRO Plant, Australia [32]
Hydranautics 8-in. SWC4+	TFC cross-linked fully aromatic polyamide spiral wound	24.6[b]	99.70–99.80[b]	4.17 (2.88)[e] at Llobregat SWRO Plant, Spain [32, 35]
Toray 8-in. TM820C	TFC cross-linked fully aromatic polyamide spiral wound	19.7–24.6[a]	99.50–99.75[a]	4.35 at the Tuas SWRO Plant, Singapore [33]
Toyobo 16-in. HB10255	Asymmetric cellulose tri-acetate hollow fiber	60.0–67.0[c]	99.40–99.60[c]	5.00 at Fukuoka SWRO Plant, Japan [34]

[a]Operating condition: 32 g L^{-1} NaCl solution, 55 bar, 25°C, pH 8 and 8% recovery [29, 35].

[b]Operating condition: 32 g L^{-1} NaCl solution, 55 bar, 25°C, pH 7 and 10% recovery [34].

[c]Operating condition: 35 g L^{-1} NaCl solution, 54 bar, 25°C and 30% recovery [36].

[d]These numbers are parameter specific and should not be compared to different desalination plants because of the different operating parameters (e.g., feed water quality, recovery, pretreatment processes, process design, etc.).

[e]The number in brackets is the energy consumption value of the RO membrane unit.

Table 2. Some of the state-of-the-art SWRO membrane modules in current application.

of hydrodynamics and the minimization of the concentration polarization effects. Further research directions have likewise focused on larger modular elements that are necessary for an improved desalination capacity.

One of the recent developments at Koch Membrane Systems includes a release of the 18-in. spiral wound modules featuring the MegaMagnum® trade name. Hydranautics and DOW (FILMTECTM) have 16-in. Modules piloted in cooperation with the Singapore National Water Agency. Research studies on the effects of the ongoing improvements indicate that such module designs can offer effective solutions when it comes to lowering the costs of desalination by up to 20% [39, 40].

4. RO desalination technology development and challenges

Research conducted by Sheikholeslami suggests that the upcoming challenges that the desalination industry will have to address are related to feed water characterization, process development, renewable energy source, materials development, stringent water standards, and brine management [41]. For instance, the largest SWRO plant in the world is located in Ashkelon, Israel, and features a production capacity of about 110 million m^3/year. If researchers consider the global average water consumption per capita of 1243 m^3/year (5% for domestic use, 85% for agricultural irrigation, and 10% for industrial use) [42], then even this plant can supply fresh drinkable water to less than 100,000 people. What this discrepancy in demands and expectations suggests is that mega-sized desalination plants are necessary and they need to be built within the foreseeable future if global multibillion populations are to be supplied with sufficient clean water.

From the perspective of global industrial complex, the greatest concern is how making RO desalination affordable in low-income countries with limited access to RO technology. Arguably, the capital investment and operating costs of RO plants must be further reduced in order to make this feasible. Electric energy, chemicals, and labor make up about 87% of the total RO cost [14]. Further advancement in membrane material and module optimization can dramatically contribute to the improvement of these aspects. The rejection of low-molecular weight compounds, especially boron species, is likewise necessary and would strongly contribute to lowering operational and production costs.

The membrane with the highest boron rejection potential currently available on the market can only achieve 93% boron rejection at optimum conditions. However, it has been reported that 99% of boron rejection is required in the Middle Eastern region for the one-pass RO process to comply with the WHO water drinking standards [43]. Higher salt rejection can potentially reduce the number of RO passes needed to achieve the desirable water quality. As a result, the decline in fouling, especially through the development of chlorine-tolerant membranes, is crucial since it reduces the costs of membrane replacement, backwashing chemicals, and energy needed to overcome the additional osmotic pressure. The operating pressure in many of the current systems is already nearing the thermodynamic limit and an additional reduction would have a relatively modest effect on the overall performance [44]. Nonetheless, a decrease in energy consumption would be substantial, as the energy costs signify half of the total water production costs. Higher permeability would further reduce the membrane area, which in turn will lead to a decrease in membrane replacement costs, smaller plant footprint, and a reduced use of harsh cleaning chemicals. From the perspective of industrial application, research potential, and commercial interest, all emerging membrane innovations need to outperform the materials and modules available on the market and are listed in **Table 2**.

Author details

Amira Abdelrasoul[1]*, Huu Doan[2] and Ali Lohi[2]

*Address all correspondence to: amira.abdelrasoul@usask.ca

1 Department of Chemical and Biological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

2 Department of Chemical Engineering, Ryerson University, Toronto, Ontario, Canada

References

[1] Werber JR, Deshmukh A, Elimelech M. The critical need for increased selectivity, not increased water permeability, for desalination membranes. Environmental Science & Technology Letters. 2016;**3**:112–120

[2] Comprehensive Assessment of the Freshwater Resources of the World. World Meteorological Organization-Geneva, CH, WMO; 1997. p. 9

[3] Fry LM, Mihelcic JR, Watkins DW. Water and nonwater-related challenges of achieving global sanitation coverage. Environmental Science & Technology. 2008;**42**:4298-4304

[4] Montgomery MA, Elimelech M. Water and sanitation in developing countries: Including health in the equation. Environmental Science & Technology. 2007;**41**:17-24

[5] Health and Environment in Sustainable Development: Five Years after the Earth Summit 1997;54-55

[6] Progress on Drinking Water and Sanitation: Special Focus on Sanitation; World Health Organization Report (WHO). 2008

[7] Global Water Security, Intelligence Community Assessment. 2012 ICA 2012-08, 2 February 2012

[8] Hanneke H. Water in Canada, A Resource in Crisis. Canada: Lone Pine Publishing. ISBN 10: 1926736044 2011

[9] Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, Mayes AM. Science and technology for water purification in the coming decades. Nature. 2008;**452**:301-310

[10] Gleick PH. The World's Water 2008-2009 the Biennal Report on Freshwater Resources. Chicago: Island Press; 2008

[11] New Desalination Capacity, 1980-2009-Chart. United States: Global Water Intelligence; 2009. p. 10

[12] Desalination: A National Perspective. Washington, DC: National Academies Press; 2009

[13] The Big Dipper: Contracted Desalination Capacity Forecast-Chart. United States: Global Water Intelligence; 2009. p. 10

[14] Fritzmann C, Löwenberg J, Melin T, Wintgens T. State-of-the-art of reverse osmosis desalination. Desalination. 2007;**216**:1-76

[15] El-Nashar AM. Water and wastewater treatment technology—History and current status of membrane desalination process. Paris, France: Encyclopedia of Life Support Systems (EOLSS); 2010

[16] Greenlee LF, Lawler DF, Marrot BD, Mouli BP. Reverse osmosis desalination: water resources, and today's challenges. Water Research. 2009;**43**:2317-2348

[17] Energy Makes All the Difference: Desalination Operating Costs Compared Chart. Global Water Intelligence; 2007. p. 8

[18] Hsu ST, Cheng KT, Chiou JS. Seawater desalination by direct contact membrane distillation. Desalination. 2002;**143**:279-287

[19] Sadrzadeh M, Mohammadi T. Sea water desalination using electrodialysis. Desalination. 2008;**221**:440-447

[20] Oren Y. Capacitive deionization (Cdi) for desalination and water treatment past, present and future (a review). Desalination. 2008;**228**:10-29

[21] McGinnis RL, Elimelech M. Energy requirements of ammonia-carbon dioxide forward osmosis desalination. Desalination. 2007;**207**:370-382

[22] The International Desalination and Water Reuse Quarterly. Boca Raton, Fl: Lineal Pub. 2006;**16**:10-22

[23] Petersen RJ, Cadott JE. Thin film composite reverse osmosis membrane. In: Porter MC, editor. Handbook of Industrial Membrane Technology. New Jersey: Noyes Publication; 1990

[24] Cadotte JE. Reverse Osmosis Membrane. Patent Application No. 4039440. p. 1977

[25] Tarboush BJA, Rana D, Matsuura T, Arafat HA, Narbaitz RM. Preparation of thin-film-composite polyamide membranes for desalination using novel hydrophilic surface modifying macromolecules. Journal of Membrane Science. 2008;**325**:166-175

[26] Li L, Zhang S, Zhang X, Zheng G. Polyamide thin film composite membranes prepared from 3,4′,5-biphenyl triacyl chloride, 3,3′,5,5′-biphenyl tetraacyl chloride and M-phenylenediamine. Journal of Membrane Science. 2007;**289**:258-267

[27] Pearce G. Water and wastewater filtration: membrane module format. Filtration & Separation. 2007;**44**:31-33

[28] Polasek V, Talo S, Sharif T. Conversion from hollow fiber to spiral technology in large seawater RO systems—Process design and economics. Desalination. 2003;**156**:239-247

[29] Market Outlook for RO/NF and UF/MF Membranes Used for Large-Volume Applications. In: Water Executive. 2004. p. 9-11

[30] Kumano A, Fujiwara N. Cellulose triacetate membranes for reverse osmosis. In: Normam AGF, Li N, Ho WSW, Matsuura T, editors. Advanced Membrane Technology and Application. New Jersey: John Wiley & Sons; 2008. p. 21-43

[31] FilmtecTM Membranes—Filmtec Sw30hr Le-400 Seawater Reverse Osmosis Element. Dow Chemical Company.

[32] Laine JM. Design & Operation Considerations: Two Large-Scale Case Studies. Suez Environment; 2009

[33] Stover RL. Low Energy Consumption SWRO. in: Clean Technology 2008, Boston, Massachusetts, 2008

[34] Shimokawa A. Desalination plant with unique methods in Fukuoka, in: Japan-U.S. Governmental Conference on Drinking Water Quality Management and Wastewater Control, Las Vegas 2009

[35] Europe's Largest SWRO Plant Opens. Water Desalination Report 2009. p. 45

[36] Hydranautics introduces desalination membranes, Membrane Technology. 2003; **2003**(11):2-3

[37] Lee KP, Arnot TC, Mattia D. A review of reverse osmosis membrane materials for desalination-development to date and future potential. Journal of Membrane Science. 2011;**370**(1-2):1-22

[38] Kumano A, Fujiwara N. Cellulose triacetate membranes for reverse osmosis. In: Li NN, Fane AG, Ho WSW, Matsuura T, editors. Advanced Membrane Technology and Application. New Jersey: John Wiley & Sons; 2008. p. 39

[39] Yun TI, Gabelich CJ, Cox MR, Mofidi AA, Lesan R. Reducing costs for largescale desalting plants using large-diameter, reverse osmosis membranes. Desalination. 2006;**189**:141-154

[40] Ng HY, Tay KG, Chua SC, Seah H. Novel 16-inch spiral-wound RO systems for water reclamation—A quantum leap in water reclamation technology. Desalination. 2008;**225**:274-287

[41] Sheikholeslami R. Strategies for future research and development in desalination—Challenges ahead. Desalination. 2009;**248**:218-224

[42] Hoekstra AY, Chapagain AK. Globalization of Water: Sharing the Planet's Freshwater Resources. Oxford: Blackwell Publishing; 2008

[43] Li NN, Fane AG, Ho WSW, Matsuura T, editors. Advanced Membrane Technology Applications. New Jersey: John Wiley and Sons, Inc.; 2008. p. 3

[44] Zhu A, Christofides PD, Cohen Y. On RO membrane and energy costs and associated incentives for future enhancements of membrane permeability. Journal of Membrane Science. 2009;**344**:1-5