PLANT AVAILABILITY OF SEAWATER DESALINATION ON MEMBRANE TECHNOLOGY AND BIOTECHNOLOGY

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Keywords: Seawater reverse osmosis, low pressure seawater reverse osmosis membrane, low pressure two-stage high recovery SWRO system, biofouling monitoring technology, pressure retarded osmosis (PRO), renewable solar energy, green desalination, brine concentration, and green hydrogen

Contents

Summary

President Kennedy's dream of obtaining fresh water from seawater seemed has been realized as a great scientific achievement and as Norihito Tambo predicted, seawater reverse osmosis desalination (SWRO) has become a major technology in Middle Eastern countries.

SWRO requires less energy compared with the distillation method and even Middle Eastern countries, where the distillation method is still a major technology, have started to adopt the RO method in new desalination plants in accordance with government policy and following the trend of developing larger (half mega-ton per day and larger) so-called Mega-SWRO plants. With these trends in the global market, the requirements of

sustainable SWRO desalination as green desalination for the 21st century are as follows: 1) Conservation of energy resources: Renewable energy, 2) Innovation of desalination technologies: New advanced membrane and membrane systems, 3) Reduction of marine pollution: Green desalination. The government-supported Mega-ton Water System project has been conducted to solve issues related to 2 and 3.

The combination of a low pressure SWRO membrane and a low-pressure, two-stage, and high-recovery SWRO system, also referred to as a SWRO-PRO hybrid system, it has enabled 20% energy reduction and 30% energy saving in total. Likewise, low environmental impact as green desalination has established a reliable operation using less chemical and chemical cleaning. Low-cost renewable energy, in particular, solar energy is now available to solve issues related to renewable energy. By combining these sophisticated technologies, desalinated water has become affordable at \$ 0.50/ m^3 or less (as low as \$0.28/ m^3).

SWCC has announced their future plans for SWRO. The main topic is directed to brine mining to obtain precious materials from the brine of SWRO. This plan will be connected to water and green hydrogen for a sustainable future.

The highlights of this chapter are as follows:

• Rapid growth of SWRO market
• Mega-SWRO plants in excess of half mega-ton/day or mega-ton/day size
• Low pressure SWRO membrane
• Low pressure two-stage high recovery SWRO system
• Biofouling monitoring technology
• Sustainable system for future SWRO system as Green Desalination
• SWRO-PRO hybrid system allows 30% energy reduction
• Brine concentration
• Green hydrogen

1. Introduction

1.1. President Kennedy's Speech

President Kennedy delivered a speech (1961) at a news conference on a desalination plan to see the deserts bloom on April 12, 1961. The desalination plan was as follows: *If we could ever competitively, at a cheap rate, get fresh water from salt water, that it would be in the long-range interests of humanity which could really dwarf any other scientific accomplishments. I am hopeful that we will intensify our efforts in that area*.

President Kennedy made this statement 17 times during his career in the Senate, 9 times before he was elected to the presidency, and 8 times after taking office.

1.2. Tambo's Prediction

Tambo's prediction (Tambo, 2002) of the increase in the world population and the development of water treatment technologies are shown in Figure 1. In this, we see that evaporation (Distillation) and membrane treatment is the newest technology in comparison with other conventional technology on a very long range of time frame. Membrane treatment technology, which enables highly precise control of water quality and high-speed treatment, is an essential countermeasure to the water shortages we face in the 21st century.

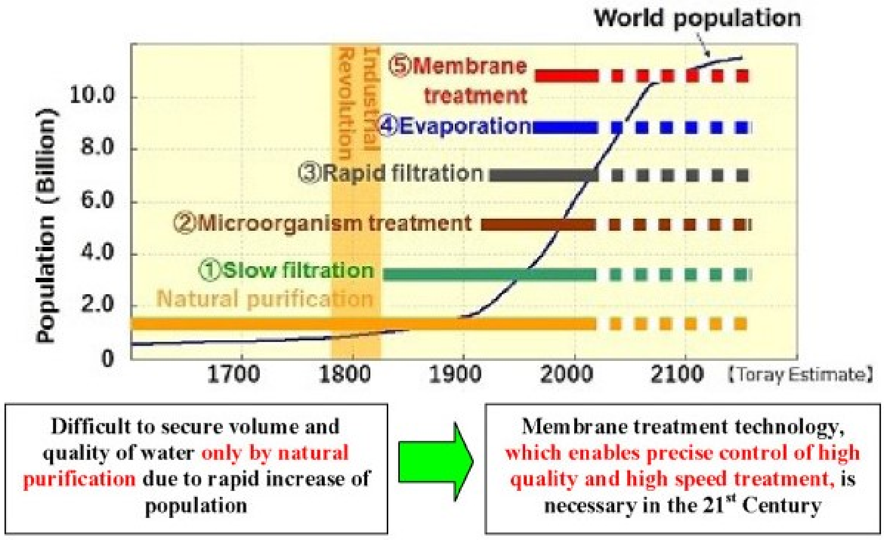


Figure 1. Increase of world population and development of water treatment technologies (Tambo, 2002)

2. Current Global Market Status of SWRO Plants

2.1. Technology Transition from the Distillation Method to Membrane Method

Research and development on seawater desalination systems such as the distillation process and membrane process began in the United States in the early 1960s. The distillation process became major technology used in actual plants in the 1970s. Around 2010, there has been a transition in the technology used from the distillation to the reverse osmosis membrane process, as shown in Figure 2.

Now, the membrane process has become the major technology (Global Water Intelligence: Desal Data, Desalination Projects, December 2020; Kurihara et al, 2016).

The cumulative online capacity (m^3/day) of RO is much higher than that of MSF and MED. And the growth rate of RO is also much higher than MSF and MED. The large number of RO plants means the average size of RO plants will still be small compared with MSF and MED. However, recently there have been moves towards developing Mega-SWRO in Middle Eastern countries became reality.

The comparison between RO and thermal desalination has a long history. In particular, in the early 1980s, we always had big discussions between two technologies in many academic conferences. One group showed support for thermal while the other group did for RO technology.

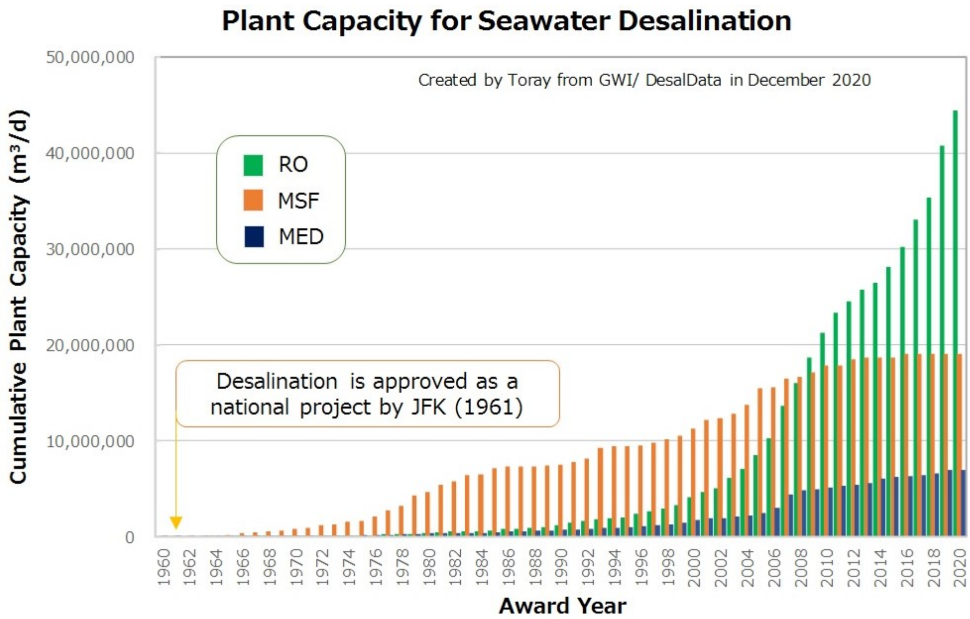


Figure 2. Technology transition from distillation to membrane (Global Water Intelligence; DesalData, 2020; Kurihara et al, 2016)

During the period of 1990 to 2000, RO technology was used in outside of Middle Eastern countries, however, Middle Eastern countries still preferred to use thermal desalination over RO technology.

This is a big mistake explained by the top personnel in Saudi Arabia. Many consultants associated with thermal process persuade the government without the correct comparison data.

Furthermore, another strong strategy was developed by SWCC's governors; H.E. Eng. Abdullah Bin Ibrahim Al-Abdulkareem. SWCC moves into the future, based on the energy and carbon footprint reduction originated from three SWCC initiatives:
(1) Replacement of our thermal desalination plants with state-of-the art RO plants and enhancement of existing plant operation
(2) Switching from hollow-fiber to spiral wound RO membranes at all our plants
(3) Developing new generation RO membranes, energy recovery devices and pump systems of enhanced energy efficiency and adopting green chemical and brine mining initiatives

There are many reports on the discussion between distillation and membrane process from the perspective of energy consumption. One of the typical reports is the review of M.W. Shahzad. et. al (2018). In this report, distillation and membrane process are compared on the standard primary energy approach and it concludes that there is no significant difference between the two methods. According to the author, there are two future roadmaps of desalination process. The current hybridization trends and the graphene-based membranes for possible next quantum jump in desalination efficiency.

The author states that it is possible to make 20-20% of improvement in the membranes and membrane processes. In the meantime, while the current hybridization such as

NF-RO, RO-PRO (pressure retarded osmosis), etc. are not identical with the graphene-based membranes.

The authors belong to the membrane manufacturing industry and noticed that there has been a big change in the global SWCC market, especially in the Middle Eastern countries

Considering the dramatic change from distillation to SWRO in Middle Eastern countries, the desalination market forecast for the Gulf and the rest of the world is shown in Figure 3 (Weaver, 2018). 2018 and 2019 are major years for SWRO as shown in Figure 3 and Figure 4 (Water Desalination Report, 2018). More than 6 million m^3/d (1,585 MGD) of new production capacity is expected to be contracted during 2019 to 2020. Figure 4 show that more than half of that new capacity is forecast for the six GCC countries.

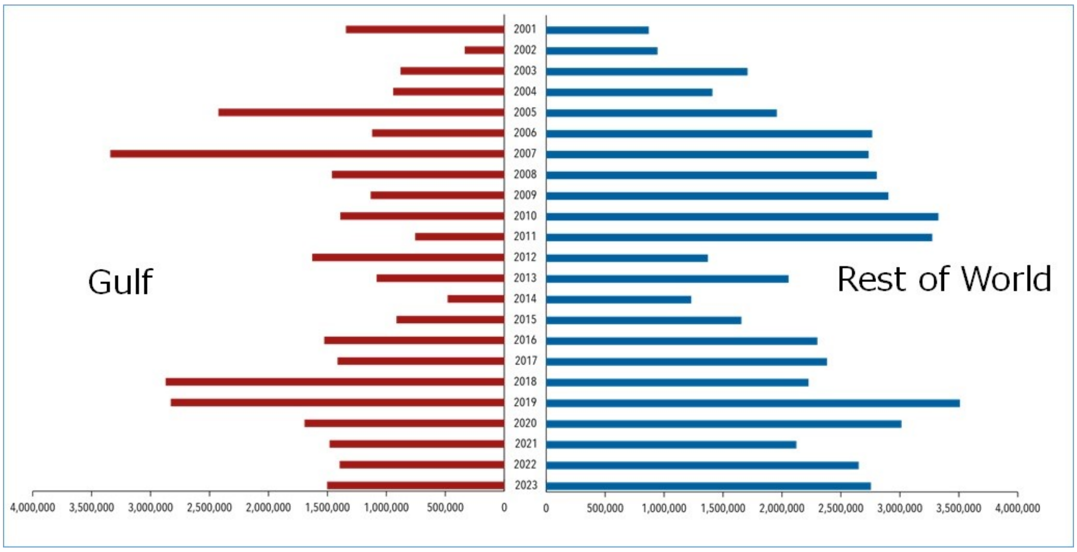


Figure 3. Market forecast: the Gulf vs the rest of the world contracted desalination capacity (Weaver, 2018)

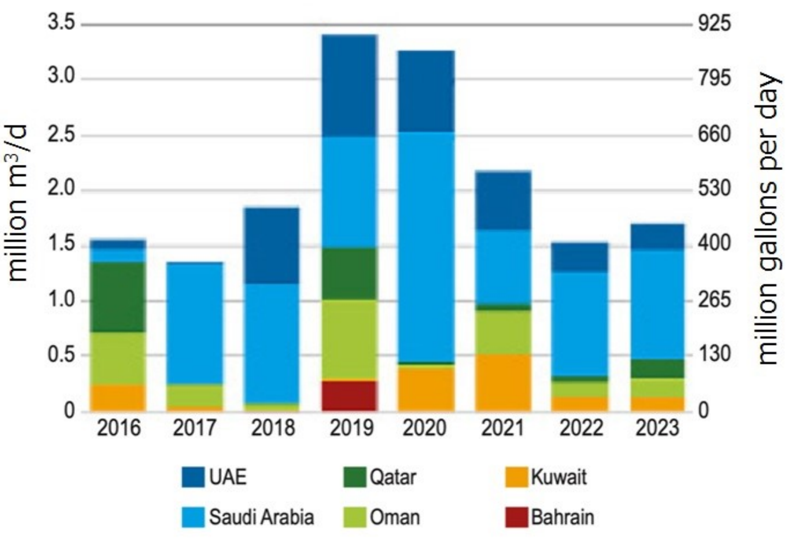


Figure 4. Major years expected for SWRO (Water Desalination Report, 2018)

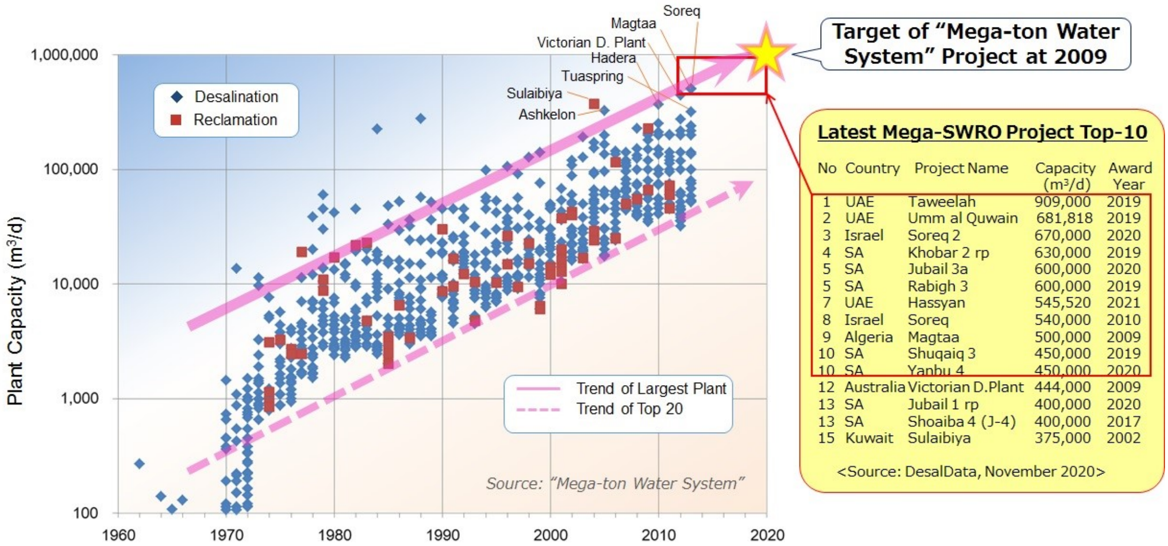
2.2. From Small Plants to Mega-size SWRO Plants

The trends since 1970 of the largest and the top 20 largest RO plants are plotted in the desalination and the wastewater reclamation plants as shown on the left side of Figure 5 as reported in 2009 (Kurihara and Hanakawa, 2013).

The scale of each desalination plant has been increasing year by year, thus we predicted in 2009 that Mega-SWRO: large plants of the mega-ton per day scale (1,000,000 m^3/day) would be required from the market by 2020.

This prediction has been realized as shown on the right of Figure 5 (Althman, 2019; Kurihara and Ito, 2020). Construction started on many large plants over the 500,000 m^3/day, the so-called Mega-SWRO, in 2018–2020 in Middle Eastern countries such as Saudi Arabia and the UAE.

2018/19 Tenders are shown on the right of Figure 5, presented at the Saudi Water Forum in 2019 by Mr. Altman (2019) and by the authors (Kurihara and Ito, 2019).



No	Country	Project Name	Capacity (m³/d)	Award Year
1	UAE	Taweelah	909,000	2019
2	UAE	Umm al Quwain	681,818	2019
3	Israel	Soreq 2	670,000	2020
4	SA	Khobar 2 rp	630,000	2019
5	SA	Jubail 3a	600,000	2020
5	SA	Rabigh 3	600,000	2019
7	UAE	Hassyan	545,520	2021
8	Israel	Soreq	540,000	2010
9	Algeria	Magtaa	500,000	2009
10	SA	Shuqaiq 3	450,000	2019
10	SA	Yanbu 4	450,000	2020
12	Australia	Victorian D.Plant	444,000	2009
13	SA	Jubail 1 rp	400,000	2020
13	SA	Shoaiba 4 (J-4)	400,000	2017
15	Kuwait	Sulaibiya	375,000	2002

<Source: DesalData, November 2020>

Figure 5. Global SWRO desalination plant capacity development (Kurihara and Hanakawa, 2013; Althman, 2019; Kurihara and Ito, 2020)

2.3. Affordable Price of Desalinated Water

The rapid changes in the price of desalinated water since 2000 have been presented by Mr. Christopher A Gasson, as shown in Figure 6 (Water Desalination Report, 2018). The price of desalinated water in large-size plants (Mega-SWRO) has rapidly decreased since 2018 (Kurihara and Ito, 2020).

- Rabihg 3 (Saudi Arabia):600,000 m^3 /d , \$0.53/m^3
- Shuqaiq 3 (Saudi Arabia): 380,000 m^3 /d , \$0.51/m^3
- Taweelah(UAE): 909,200 m3/d , \$0.49/m^3
- Jubail 3A (Saudi Arabia): 600,000 m^3 /d, \$0.41/m^3

- Soreq 2 (Israel): 672,000 m3/day, $0.40/m^3
- Hassyan (UAE) (Saudi Arabia): 545,000 m^3 /d, $0.28/m^3 (Water Desalination Report, 2020).

The price has dropped to $0.28/m^3 in Dec. 2020

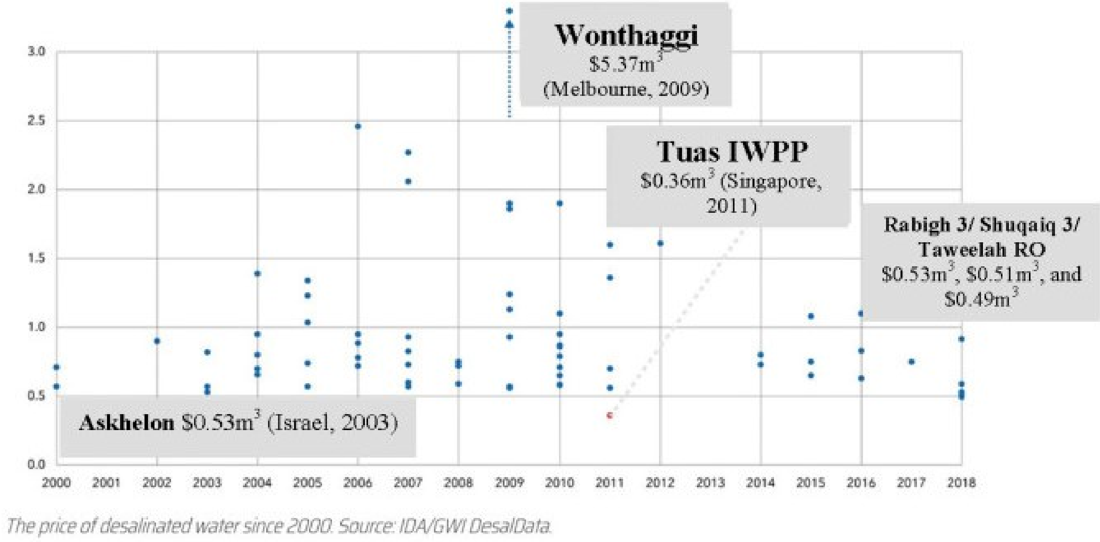


Figure 6. Rapid change of the price of desalinated water since 2000 (Gasson, 2019) (Askhelon: $0.53m3 (Israel, 2003) Remains the lowest tariff on record for a major desalination project; Tuas IWPP: $0.36m3 (Singapore, 2011) First year water cost, actual levelized tariffs never published. Attempts to divest this loss-making project received, one offer, below book value from Sembcorp in October 2018; Wonthaggi:$5.37m3 (Melbourne, 2009) Rapid permitting and construction requirements lead to the most expensive major desalination project on record; Rabigh 3/Shuqaiq 3/ Taweelah RO: Initial prices offered on the new wave of GCC IWPs come in at $0.53m3, $0.51m3, and $0.49m3 respectively)

3. Results and Discussion

3.1. Sustainable SWRO Desalination as Green Desalination

To realize sustainable seawater desalination as green desalination for the 21st century, the following issues must be tackled: (1) Energy resources, (2) Seawater RO system, and (3) Reduction of marine pollution.

The Mega-ton Water System project (Kurihara et al, 2016; Kurihara and Hanakawa, 2013; Kurihara and Ito, 2020) was conducted with the aim of developing sustainable water treatment core technologies. The missions of the seawater RO system were: (1) energy saving (20% or 30%), (2) low environmental impact, (3) reliable plant operation, and (4) low water production cost as illustrated in Figure7 (Kurihara and Ito, 2020).

The Mega-ton Water System project envisions green desalination.

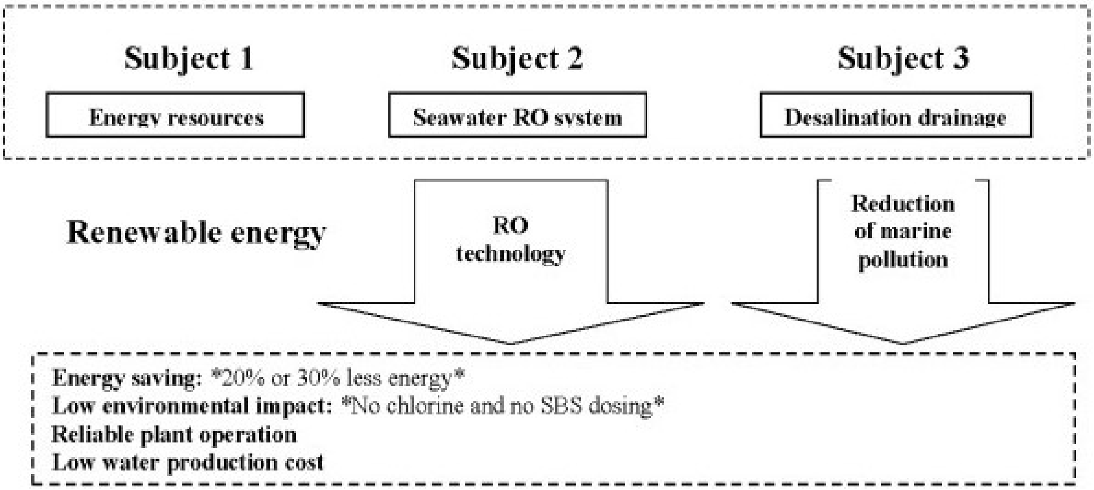


Figure 7. Requirements for sustainable SWRO desalination as green desalination for the 21st century (Kurihara and Ito, 2020)

As described in Section 1, the global market for SWRO, especially in Middle Eastern countries, has changed with increases in plant size (Mega-SWRO) and decreases of Specific Energy Consumption (SEC: kWh /m^3) of the plant systems followed by a reduction of the price for desalinated water.

This paradigm shift has occurred in the design and optimization of SWRO plants (Sanz, 2013).Another trend was the continuous technological innovations such as the Mega-ton Water System as energy reduction, low environmental impact, and reliable plant operation for green desalination.

3.1.1. Subject 1: Energy Resources: Renewable Energy

This subject was not listed by the Mega-ton Water System project in 2009. In 2010, the International Desalination Association (IDA) launched the industry's first Environmental Task Force-now called the IDA Energy and Environmental Committee (EEC). Through many discussions on promising candidates, 1) nuclear, 2) wind power and 3) solar power energies were considered.

In 2019, solar power energy had remarkably progressed and for Mega-SWRO, it was considered to be the preferable renewable energy source (Althman, 2019).

3.1.2. Subject 2: Seawater RO System-RO Technology

3.1.2.1 Requirement for Energy-Saving

Energy reduction and improvement of water quality are two major subjects in SWRO desalination. The average energy consumption in SWRO plants had been reduced to 40% as a total plant and one fourth in the case of 1st RO pass consumption over the last 40 years by 2012, as shown in Figure 8 (Sanz, 2013). This is a result of the remarkable technical advances in membranes, pumps, and energy recovery devices. Technical progress to reduce energy consumption further, (for example, low-pressure operation membranes and high permeability at low temperature) and efficient energy recovery devices are still required.

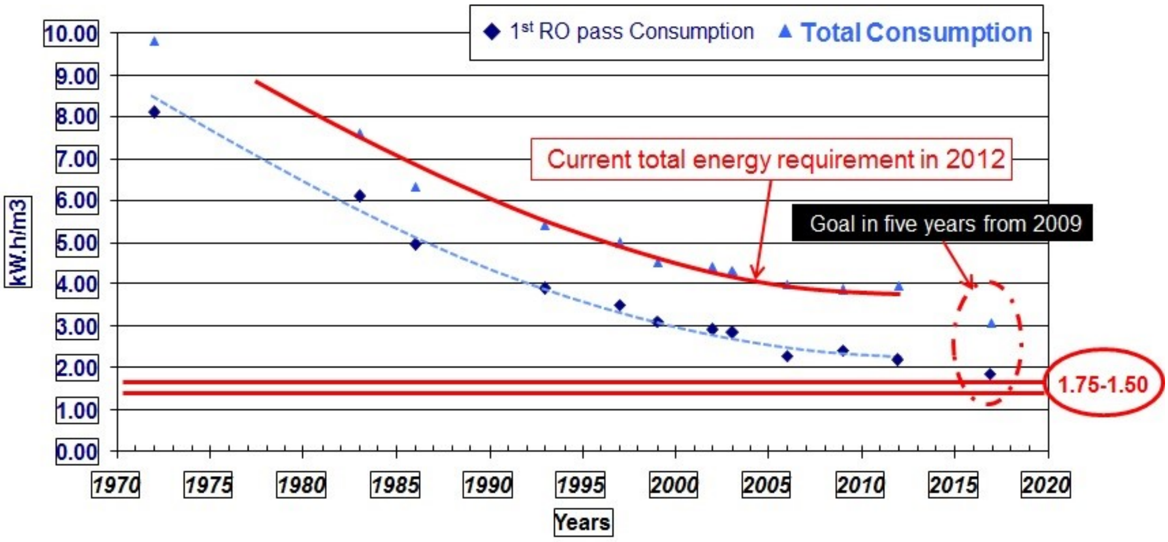


Figure 8. Trends of energy reduction in SWRO (Sanz, 2013)

The Mega-ton water system project achieved a 20% reduction to 2.80 kWh/m^3 as total consumption by 2014 (Kurihara and Takeuchi, 2018).

According to Sommaria, the maximum of 3.5 kWh/m^3 as SEC had been necessary since 2017 (Sommaria, 2014). As for water quality, the regulation value of salt disinfection by-products (DBPs) and boron concentration depend on whether the water is for drinking or irrigation use.

3.1.2.2 Requirement for Water Quality Improvement

Although the ideal cross-linked fully aromatic polyamide SWRO membrane should have both high water permeability and high solute removal performance, there is usually a trade-off between an increased water permeability and decreased solute rejection rate. However, the performance of an RO membrane is controlled by altering the size and quantity of the pores in the membrane, which are spaces within polymers. Namely, solutes in the water are excluded by pore size, and the water permeability depends on the quantity of pores. To enhance performance, scientific research on the molecular structure and solute transport mechanism in an RO membrane is necessary. A schematic diagram of water permeation through the protuberance of the RO membrane is shown in Figure 9 (Kurihara et al, 2015).

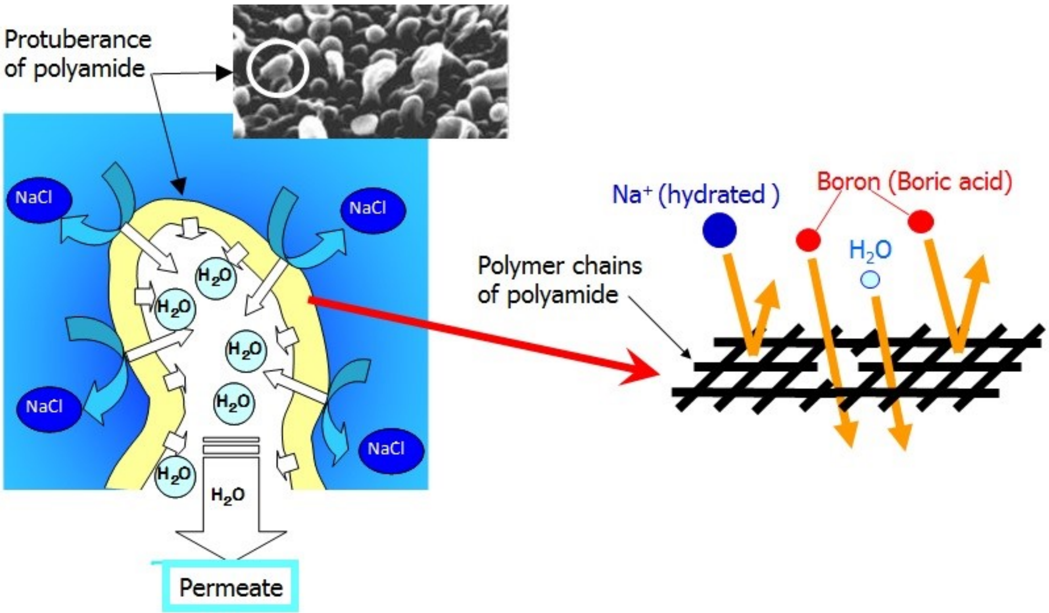


Figure 9. Schematic diagram of salt removal and water permeation through the protuberance (Kurihara et al, 2015)

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Biographical Sketches

Masaru Kurihara, Adviser at Toray Industries, Inc. Senior Scientific Director, Mega-ton Water System in Funding program for World-Leading Innovative R&D on Science and Technology during FY 2009-FY2013. He is now promoting the verifications of the technology collaboration with Saline Water Conversion Corporation in Saudi Arabia, 1) Pilot plant verification at Al Jubail, the Arabian Gulf during 2016-2018 and 2) Full plant verification of NEDO-SWCC Demonstration Project at Duba, the Rea Sea during 2018-2022. He received the B.S. in 1963 at Gunma University, Japan and Dr. Engineering 1970 at the University of Tokyo, Japan. He studied the membrane under the fund of the Office Saline Water Conversion (OSW) at University of Iowa as post doctorate. He joined Toray in 1963. Over 50 years, his research activities have primarily focused on membrane-based desalination and water reuse by RO/NF/UF/MF and MBR membranes. He has published more than 100 articles and 300 patents on the membranes and membrane processes. He has received numerous awards from national and international academic societies and foundations: Technical Award Development of Cross-linked Aromatic Polyamide Composite Reverse Osmosis Membrane from the Chemical Society of Japan, Production Award from Okouchi Memorial Foundation, Lifetime Achievement Award , Outstanding Professional in Water Reuse and Conservation Award from International Desalination Association (IDA), Award for International Communication and Cooperation in Membrane Technology from Membrane Industrial Association of China (MIAC), and others. He is a Board Member of IDA, a member of IDA Honorary Council, President of Asia Pacific Desalination Association (APDA), Fellow of The Chemical Society of Japan and The Society of Polymer Science, Japan with Lifetime Achievement Award.

Hiromu Takeuchi, Senior Engineer of Water Treatment & Environment at Toray Industries, Inc., and was Coordinator of technology management of “Mega-ton Water System” project in Funding program for world-leading Innovative R&D on Science and Technology during FY2009-FY2013. He obtained a master's degree in engineering from Keio University in 1971 and joined Toray Industries, Inc. After working at the Engineering Research Laboratories, he was seconded to the Water Production Promotion Center at Chigasaki for three years from 1977, where he developed the operation technology for the first seawater desalination pilot plant in Japan at that time. After returning to Toray in 1980, he was in charge of the development of production technology for reverse osmosis membrane elements for seawater desalination and the development of process technology for seawater desalination plants. Since 1992, he has been appointed as the technical manager for launching Japan's first large-scale seawater desalination plant in Okinawa Prefecture. Although he retired from Toray in March 2015, he continued to work in the water treatment department under a business consignment contract with Toray. He is providing technical support for a large-scale full-plant demonstration project for Energy Saving Seawater Desalination Technology in Saudi Arabia, jointly undertaken by Saline Water Conversion Corporation and New Energy and Industrial Technology Development Organization from 2018. In addition to the above, he is currently a member of the board of directors of the Japan Desalination Association, which is a regional affiliate of IDA as an activity of the water treatment industry in Japan and is also appointed as its secretary general.

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