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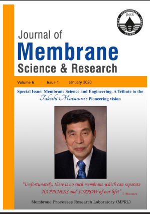

Engineering Advance

Sustainable Seawater Reverse Osmosis Desalination as Green Desalination in the 21st Century

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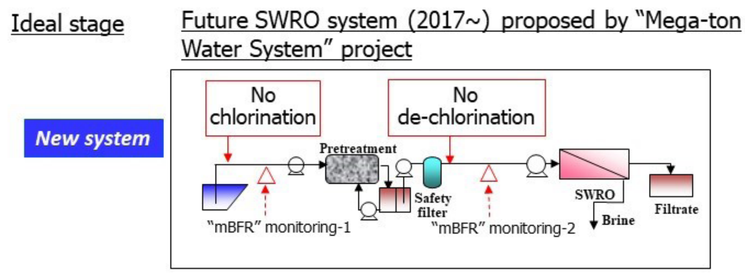
Renewable solar energy
Green desalination

Highlights

- Rapid growth of SWRO market
- "Mega-SWRO" plants in excess of half mega-ton/day or mega-ton/day size
- New system for future SWRO system as Green Desalination
- SWRO-PRO hybrid system allows 30% energy reduction

Graphical abstract



New system for future SWRO system as Green Desalination

Abstract

Seawater reverse osmosis desalination (SWRO) requires less energy compared with the distillation method and thus is an important technology except Middle Eastern countries where energy costs are higher. Recently, even Middle Eastern countries where the distillation method is still a major technology, have begun adopting the RO method in new desalination plants in line with government policy and the trend is for the development of larger (in excess of half mega-ton per day or mega-ton per day size) 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 summarized under three subjects: 1) Energy resources:

Renewable energy, 2) Seawater RO system: Advanced membrane and membrane system, 3) Reduction of marine pollution: Green desalination. The "Mega-ton Water System" project has been conducted to solve issues related to subjects 2) and 3) as Japanese national project.

a. By combining a low pressure SWRO membrane and a low pressure two-stage high recovery SWRO system, 20% energy reduction was possible. And 30% energy saving in total was also possible as the SWRO-PRO hybrid system.

b. For low environmental impact as green desalination, less chemical and less chemical cleaning for reliable operation have been established.

c. Low-cost renewable energy, particularly solar energy, is now available to solve issues related to subject 1. By combining these sophisticated technologies, the cost of seawater desalination will be \$ 0.50/ m^3/day or less.

1. Introduction

The United States began research and development of seawater desalination systems such as the distillation process and membrane process in the 1960s. The distillation process became major technology used in actual plants in the 1970s. Since 2000, transition of technology from the distillation to the reverse osmosis membrane process has occurred as shown in Figure 1. Now, the membrane process become major technology (Desal Data 2014/GWI/ Desalination Inventory) [1,2].

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 very 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 the trend of the establishment of "Mega-SWRO" in the Middle East became reality.

Considering the dramatic change from distillation to SWRO in Middle Eastern countries, the desalination market forecast for the Gulf and the rest of

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the world is shown in Figure 2 [3].

2018 and 2019 are major years for SWRO as shown in Figure 2 and Figure 3 [4]. More than 6 million m^3/d (1,585 MGD) of new production capacity is expected to be contracted over the next 12 months. Figure 3 shows that more than half of that new capacity is forecast for the six GCC countries as shown in Figure 3.

Trend of largest and the top 20 largest RO plants since 1970 are plotted in the desalination and the wastewater reclamation plants as shown on the left side of Figure 4 as reported in 2009 [5].

The scale of each desalination plants year by year has been increasing, 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 market by 2020. This prediction has been really realized now as shown on the right of Figure 4 [6]. Many large plants over the 500,000 m^3/day, the so-called "Mega-SWRO," started to construct them in 2018–2019 in Middle Eastern countries such as Saudi Arabia and the UAE.

2018/19 Tenders are shown on the right of Figure 4, presented at the Saudi Water Forum at 2019 by Mr. Altmann [6].

The rapid changes in the price of desalinated water since 2000 have been presented by Mr. Christopher A Gasson, as shown in Figure 5 [6,7].

The lowest prices of desalinated water in large size plants (Mega-SWRO) were as follows in 2018 [6,7].

- Rabihg3: 600,000㎥/d , \$0.53 /㎥
- Shuqaiq3: 380,000㎥/d , \$0.51 /㎥
- Taweelah: 909,200㎥/d , \$0.49 /㎥

Requirement for sustainable seawater desalination as green desalination for the 21st century must tackle issues related to: (1) Energy resources, (2) Seawater RO system, and (3) Reduction of marine pollution. The "Mega-ton Water System" project 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, (4) low water production cost as illustrated in Figure 6 [6,8,9].

The "Mega-ton Water System" project envisions green desalination.

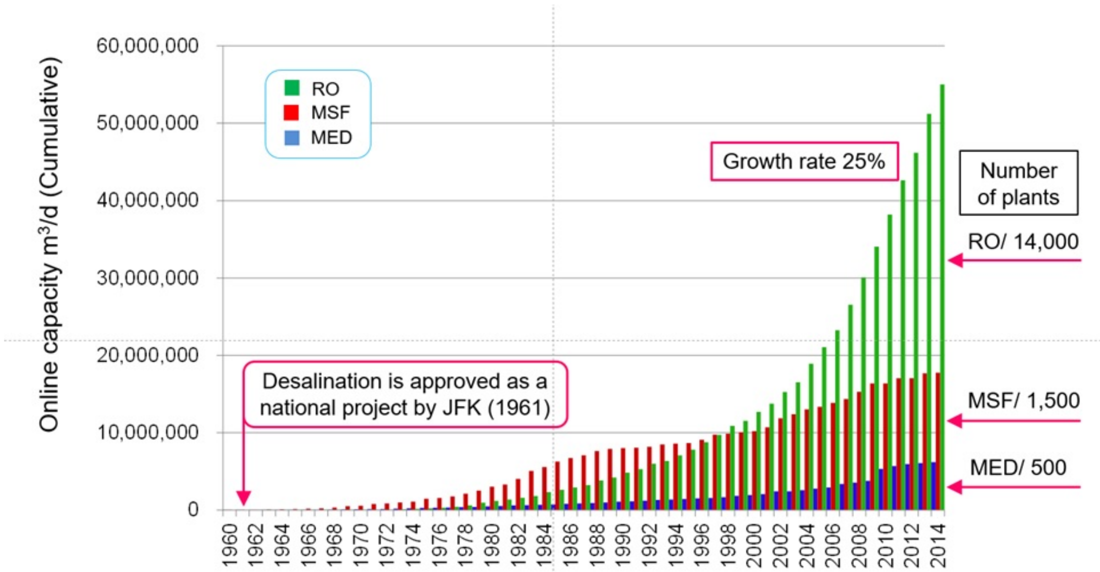


Fig. 1 Technology transition of from distillation to membrane [1,2].

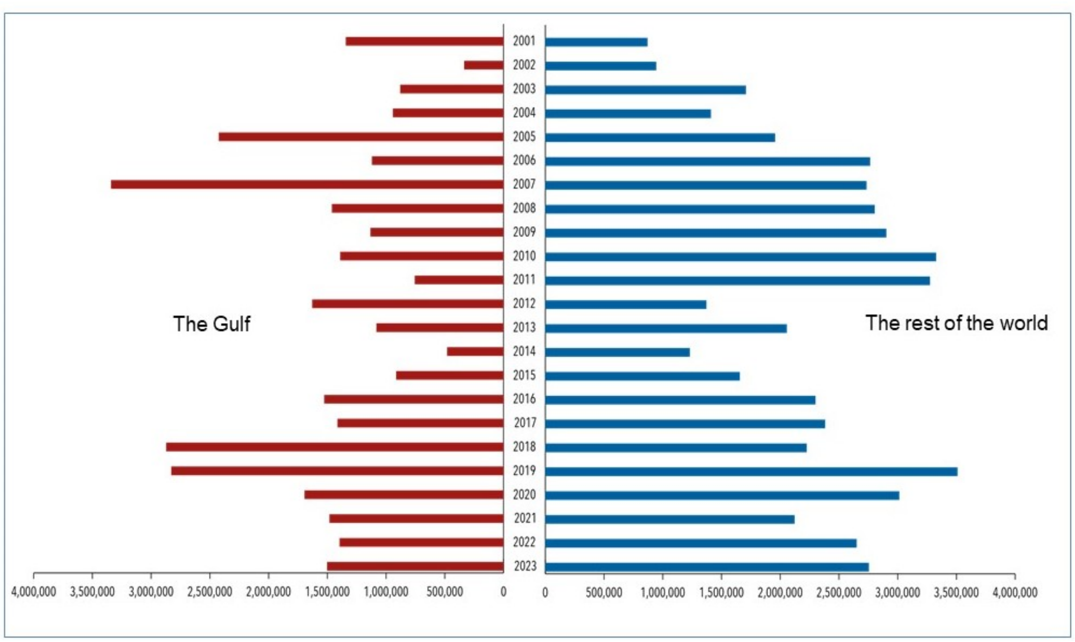


Fig. 2. Market forecast: the Gulf vs the rest of the world contracted desalination capacity [3].

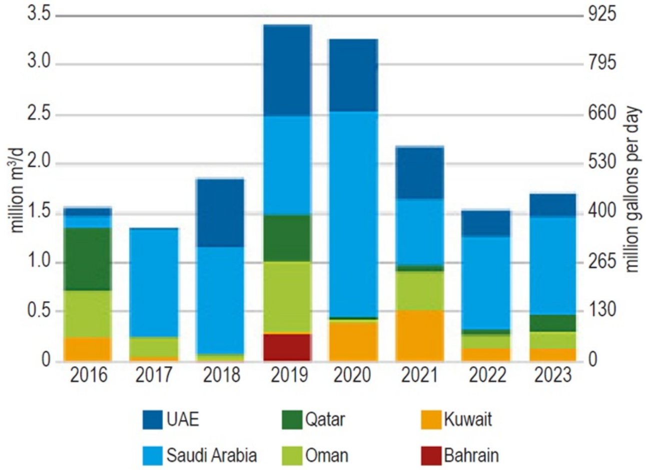


Fig. 3. Major years expected for SWRO [4].

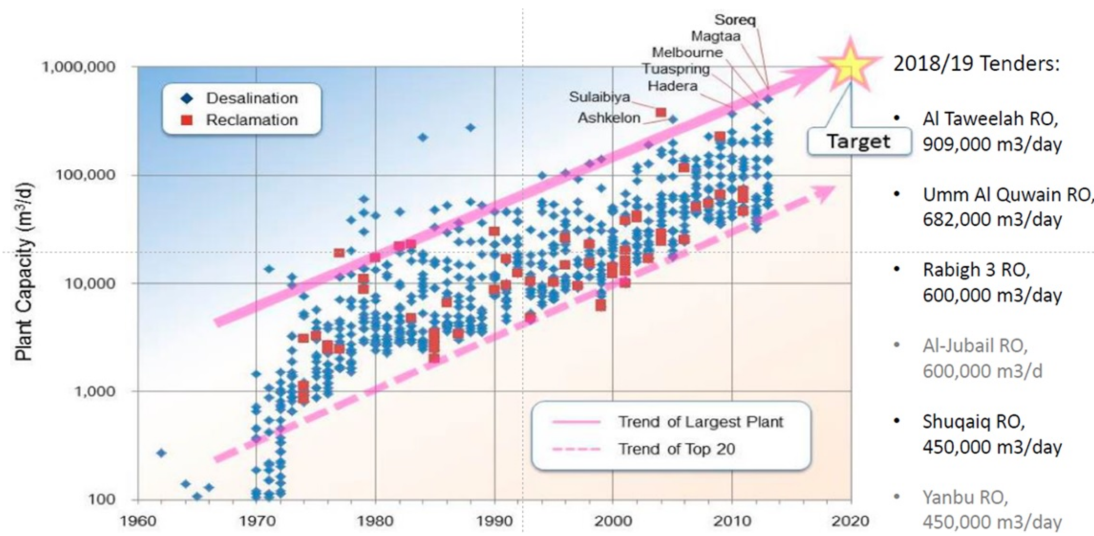


Fig. 4. Global SWRO desalination plant capacity development [5,6].

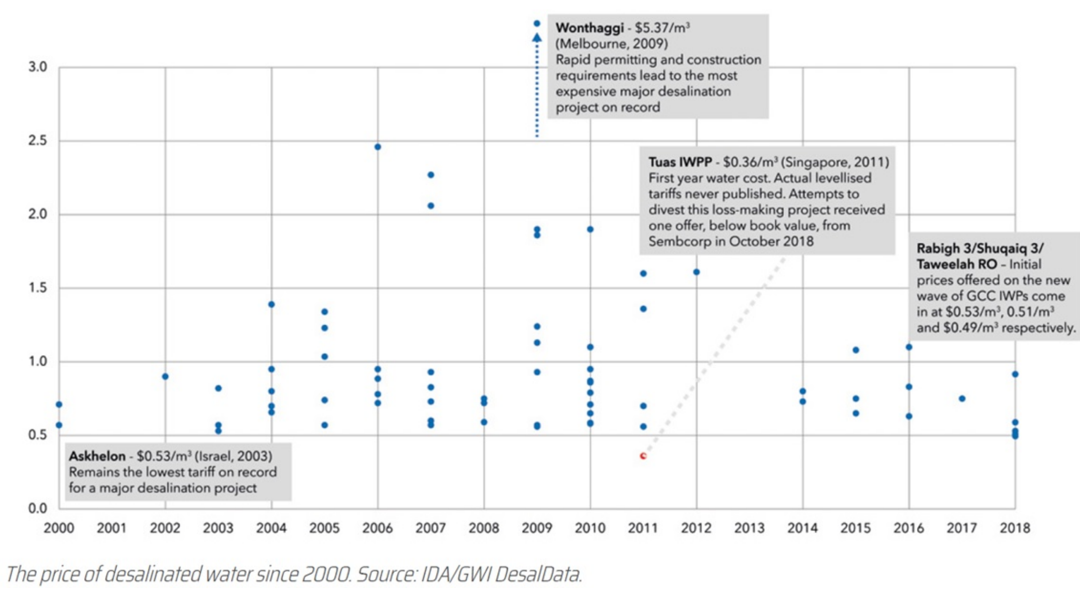


Fig. 5. Rapid change of the price of desalinated water since 2000 [6,7].

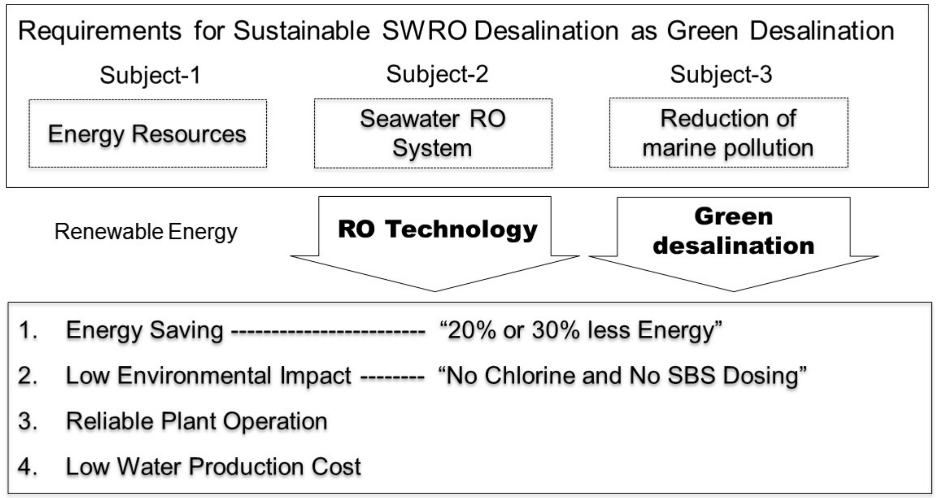


Fig. 6. Requirements for sustainable SWRO desalination as green desalination for the 21st century [6,8,9].

2. Results and discussion

As described in 1. Introduction, 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 of the plant systems (SEC: kwh/m³), followed by a reduction of the price of desalinated water.

This paradigm shift has occurred in the design and optimization of SWRO plants [6].

Another trend has been the continuous technological innovations such as the "Mega-ton Water System" considering of energy saving, low environmental impact and reliable plant operation for green desalination [6,8,9].

2.1. Subject 1: Energy resources - Renewable energy

This subject was not listed in the "Mega-ton Water System" project in 2009. Ten years ago, 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 ③ solar power energies were considered.

After ten years, solar power energy was considered the preferable renewable energy source [6].

2.2. Subject 2: Seawater RO system – RO technology

The subsequent progress of the "Mega-ton Water System" is shown in Figure 7 [6]. A national research project was conducted from 2010 to 2013 and pilot plant (500m³/d)verification was conducted from 2016 to 2018 in Al Jubail, Saudi Arabia to confirm the following three advanced technologies: ① The new advanced low pressure SWRO membrane ② low pressure two-stage, high recovery SWRO system and ③ biofouling monitoring "mBFR" technology.

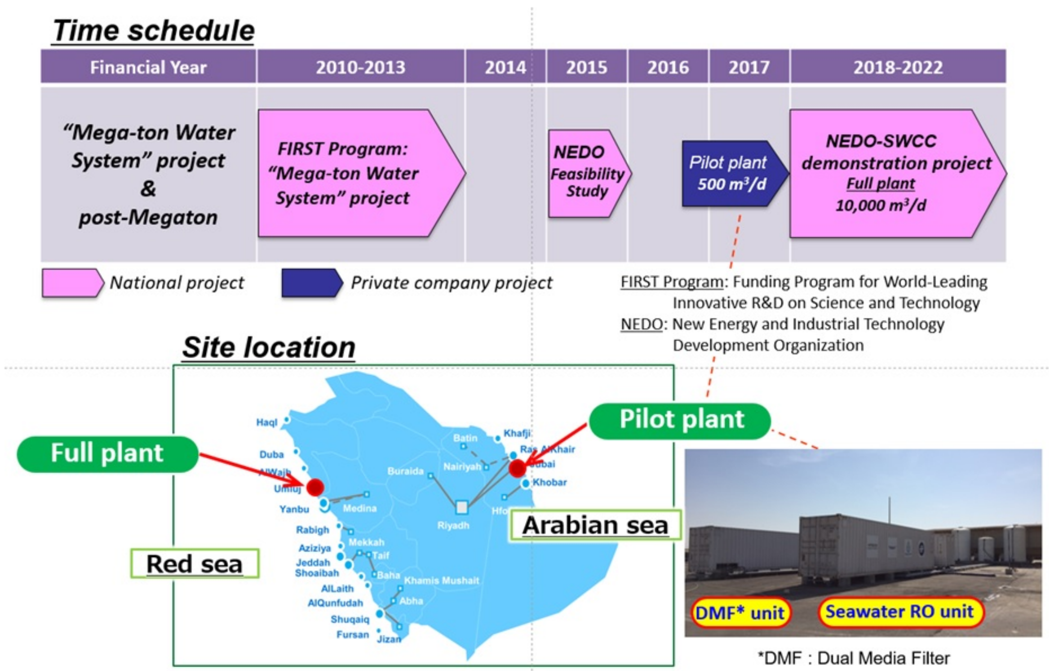


Fig. 7. Subsequent progress of the "Mega-ton Water System" [6].

a) Pilot plant verification

SWCC/DTRI, and Mega-ton Team as Toray Industries, Inc. and Hitachi Ltd. collaborated to evaluate advanced system designs and technologies developed by the "Mega-ton Water System" project. (Dec. 2016-Jan. 2018).

Al-Jubail, Saudi Arabia in the Gulf is considered to be the most heavy biofouling area due to high salinity (4.6%), high organics and large temperature variations (14 to 37 ºC). Stable operation and expected operation cost were verified over one year of operation, by complete no-chlorine and no-SBS dosing system [6]. The details were reported by Dr. Kuihara under the title "Further Progress of "Mega-ton Water System" Technology for Green Desalination" at the Saudi Water Forum, 18 March 2019 and also Dr. Kurihara and Dr. Kurokawa under the title "Further Progress of "Mega-ton Water System" at the 12th SWA-APDA Joint Conference, Singapore 11 July 2018.

b) NEDO-SWCC Demonstration Project

Hitachi and Toray have been commissioned by NEDO to implement the Demonstration Project for an Energy Saving Seawater RO System on an actual scale in Saudi Arabia as shown in Figure 8 [6].

- Partner : Saline Water Conversion Corporation ("SWCC")
- Demo : 10,000 ton/d Seawater RO System using "Mega-ton Water System" Technologies
- Location : Ummluji, Saudi Arabia
- Period : April 2018 – March 2023 (5 years)
- Targets :
  - 20% energy reduction.
  - Reduction of the construction cost by reducing the capacity of the pre-treatment facilities by high water recovery system.
  - Biofouling monitoring "mBFR" technology is implemented for low environmental impact and reliable plant operation as green desalination.

2.2.1. New advanced low pressure SWRO membrane

The history of the high-performance SWRO membrane and the new advanced low pressure SWRO membrane developed by Toray are shown in Figure 9 [6]. Since the 1980s, membrane performance of cross-linked fully aromatic polyamide composite membrane has been continuously improved both in salt rejection (%) and permeate quantity (m³/d as 8-inch element) as shown on the left side of Figure 9 [6]. The right side of Figure 9 [6] shows a comparison at the same flux base between the latest new advanced low pressure SWRO membrane (2018) and the 2010s membrane. About 15% decrease of operating pressure was confirmed as an advantage of the low pressure SWRO membrane.

2.2.2. Low pressure two-stage high recovery SWRO system

The experimental results of the high recovery SWRO system are shown in Figure 10 [6].

1) Flux equalization & high recovery
- Almost the same flux distribution as that of the conventional system was adjusted by applying back pressure to the first stage

2) Energy recovery
- The energy of permeate back pressure recovered by ERD and about 12% of the pump head could be reduced

3) Other feature: Lower membrane fouling
- Lower flow rate and flux at the first stage could reduce fouling potential significantly

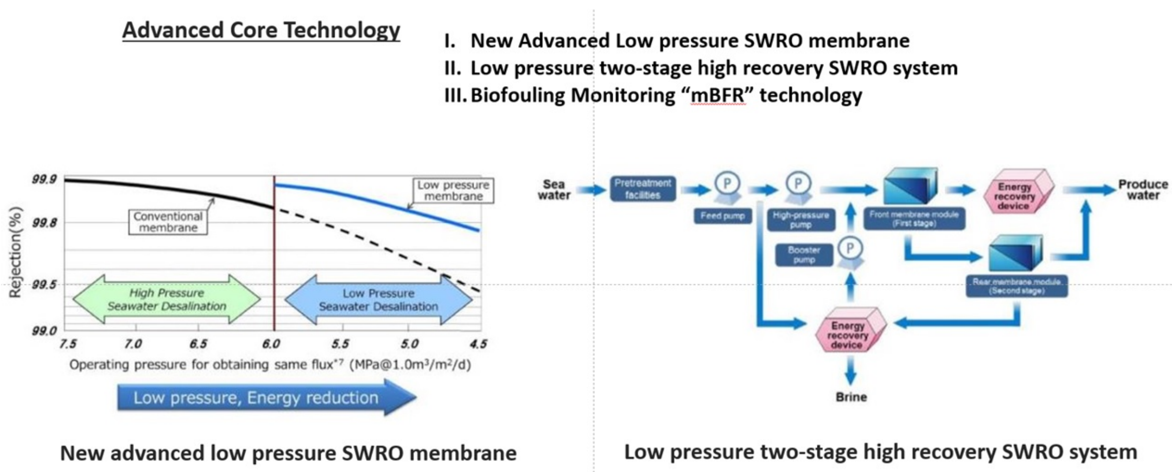


Fig. 8. Verification project for energy saving and low environmental impact seawater desalination system as green desalination in Saudi Arabia [6].

2.3. Reduction of marine pollution

2.3.1. SWRO-PRO hybrid process

The target of this research is 1) Energy recovery from concentrated brine by PRO system and 2) Reduce the concentration of brine discharged into the sea, in order to reduce environment impact. Thus Pressure Retarded Osmosis (PRO) technology (system) is to be added to the seawater desalination system as shown in Figure 11 [2,8,9].

The installation of a SWRO-PRO hybrid system reduces electricity consumption per unit necessary to produce water by 10% based on the calculation results of the demonstration plant.

30% energy savings in total, including energy savings of 20%, SWRO of the "Mega-ton Water System" are possible (Figure 12) [2,8,9].

2.3.2. Green desalination

10 years ago, there has been greater awareness of the need to preserve the environment, and there have been efforts to reduce the amount of chemically treated seawater discharged from desalination plants: the distillation and the membrane process, to lessen the ecological impact [10].

Background of "Green Desalination" is based on the study "The state of desalination and brine production: A global outlook which was recently published in the journal "Science of the Total Environment": Review: the state of desalination and brine production, and had a great impact on international media. The study was written by scientists from the Institute for Water, the Environment and Health from the United Nations University (UNU-INWEH), Wageningen University (Holland), and the Gwangju Institute of Science and Technology (South Korea) [11].

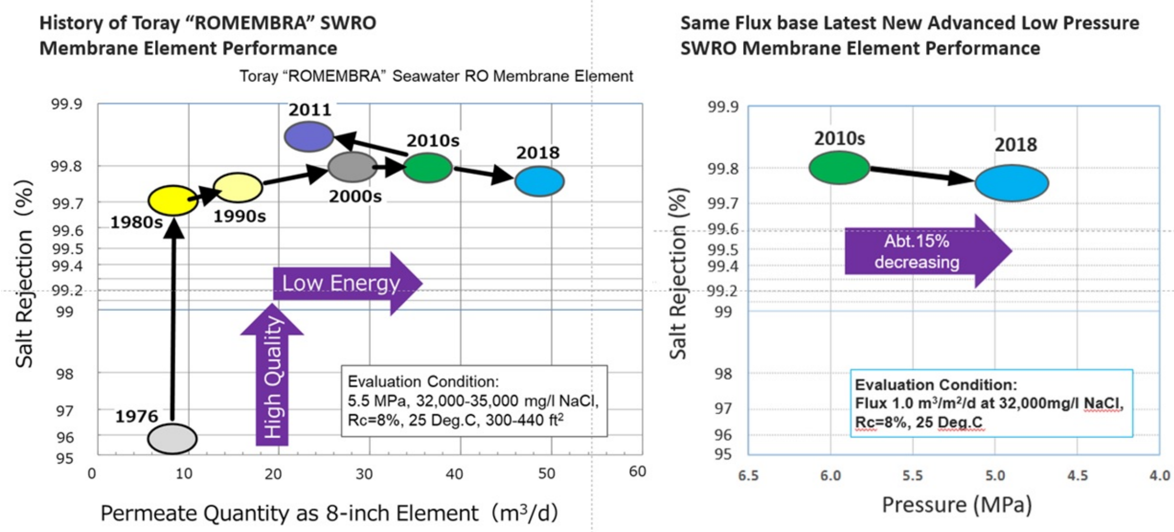


Fig. 9. History of the high-performance SWRO membrane and new advanced low pressure SWRO membrane [Reference 6].

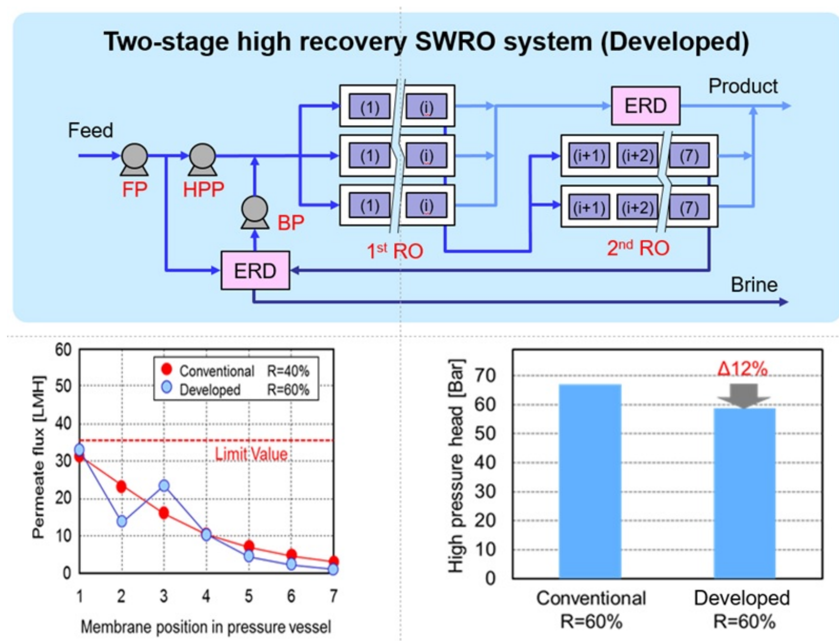


Fig. 10. Experimental results of high recovery SWRO system [6].

Study highlighted

・The need of unconventional water resources as key to supporting SDG 6 achievement.

・Water production by desalination is 95.37 million㎥/day.

・Brine production and energy consumption are key barriers to desalination expansion [11, 12].

About half of the world's desalinated seawater is produced in four countries in the Middle East. In order to reduce negative impacts on the environment and reduce the cost of water production, we have proposed innovative financial mechanisms and technological improvements (such as the development of commercial recovery and production systems for salts and metals). These solutions need to be affordable so they can be extended to low and middle income countries.

The purpose of this research is energy saving, cost saving and environmental impact reduction, which is the same direction as the "Mega-ton Water System" project as shown in Figure 6 [6, 8, 9].

The contents of the study by the United Nations University were announced through two international TV media. The first one was Bloomberg News/ 9 January - "Saudi thirst for water is creating a toxic brine problem". The second one was BBC News/ 14 January 2019 - "Concerns over increase in toxic brine from desalination plants". It is unknown why both TV programs used the expression "toxic brine," because the above study did not mention toxic brine.

Saudi Water Conversion Corporation (SWCC) responded sensitively to the above journal & TV News, using advanced technology and science, emphasizing that water environment management is carried out at all stages of project development and implementation from planning to design, construction and operation. Furthermore, the Desalination Technology Research Institute of SWCC (DTRI) has announced that it is promoting a green desalination initiative, which has already produced tangible results [13].

The International Desalination Association (IDA) also responded to this journal and TV News, and in an effort to publicize the IDA's response to the IDA Global Connections, conducted an opinion gathering survey on energy and environment experts regarding the environmental impact of seawater desalination [14].

2.3.3. Low environmental impact and reliable plant operation as green desalination.

History of anti-biofouling trials and new system for future SWRO system:

As shown in Figure 13 [6,8,9], anti-biofouling trials for the SWRO system were conducted as follows.

1) Initial stage: Conventional SWRO system since 1990.
   This system is still used in special cases such as when there is cooperation with the power plants.
   In this system, sterilization by chlorination was considered common sense, but frequent biofouling occurred and frequent chemical cleaning was performed. For example, two weeks of operation required one week of cleaning.

2) Intermediate stage: current SWRO system (2004~)
   Many global specialists on SWRO plant operation came together in Florida & San Diego in 2004, and discussed the matter of heavy biofouling of SWRO plants.
   As a solution, mild sterilization from continuous chlorination to intermittent chlorination has been adopted. However, biofouling has not been eliminated, and there are doubts concerning the efficacy of chlorine sterilization.

3) Ideal stage: Future SWRO system (2017~) presented by "Mega-ton Water System" project
   As the ideal stage, future SWRO system (2017~) has been presented by the "Mega-ton Water System" project based on the data [8,9].

This is a paradigm shift in understanding that chlorine sterilization and SBS dosing triggers biofouling. Thus, the new system has no chlorination and no de-chlorination. As a result, biofouling can be controlled even in highly saline seawater such as that of the Gulf Sea. Recommendation: this method optimized the pretreatment conditions by monitoring the "mBFR": membrane biofilm formation rate.

2.3.4. Chlorine sterilization has no effect on marine bacteria.

As shown in Figure 14, the effect of chlorine sterilization on marine bacteria was compared evaluated by the conventional method (Plate count method) and by fluorescence microscopic observation.

As already reported by the authors as shown in Figure 14 [15], the plate count method can be overestimated and Fluorescence microscopic observation shows that much higher numbers of marine bacteria survive after chlorination than expected.

Chlorine sterilization of seawater is not only ineffective, it is counterproductive.

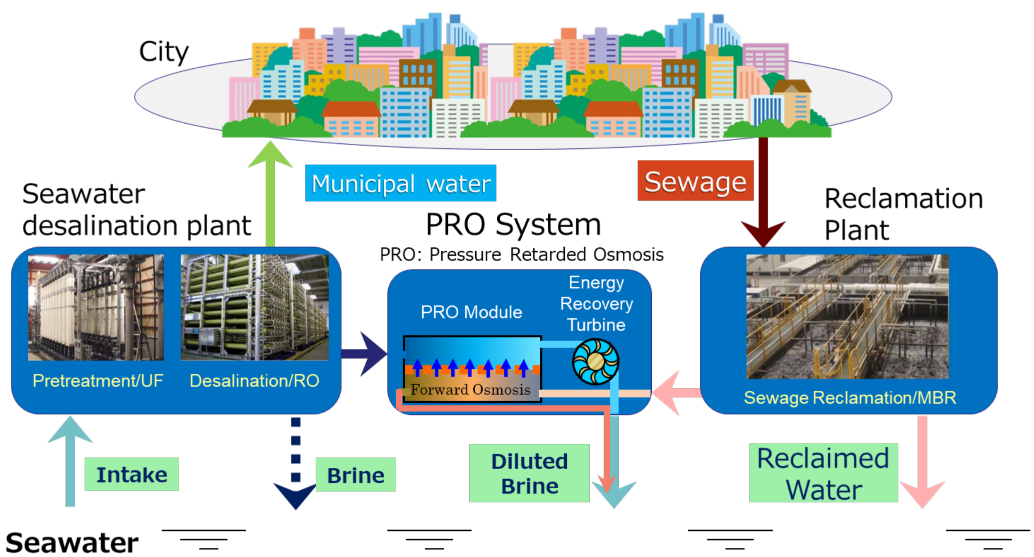
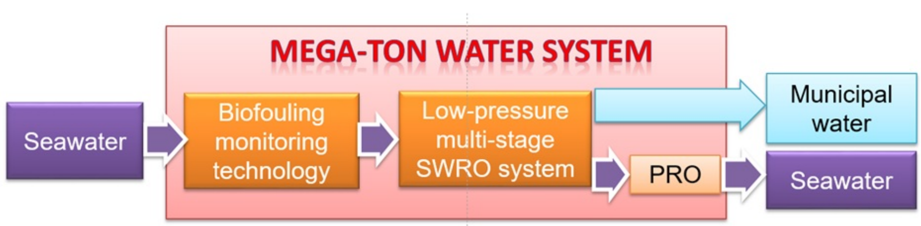


Fig. 11. SWRO-PRO hybrid process of "Mega-ton Water System" [2,8,9].



Process <Seawater conc. = 3.5%>	Membrane	ERD	Pump efficiency	PRO	SEC rate (%)
Conventional (R=45%)	Conventional	Turbo	70-85%	-	100
Mega-ton (R=60%)	Low-pressure SWRO membrane	New ERD	90%	-	80
Mega-ton (R=60%) with PRO				PRO	70

* Benchmark is conventional technologies in 2010.

Fig. 12. Energy consumption comparison as SEC (kwh/m^3) of 1) Conventional SWRO 2) Mega-ton SWRO 3) Mega-ton SWRO-PRO hybrid [2, 8,9].

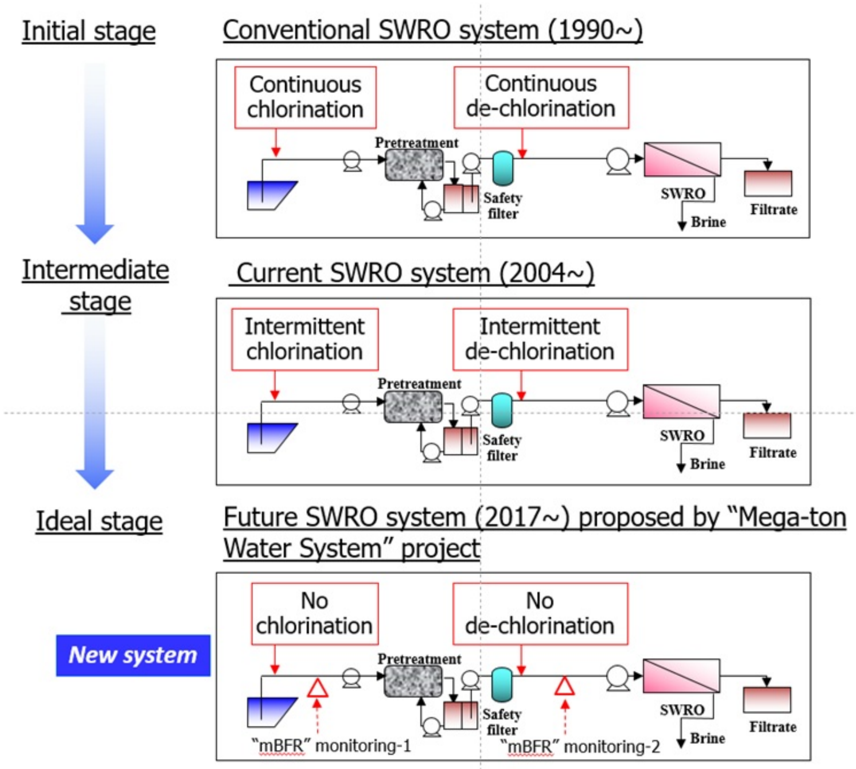


Fig. 13. History of anti-biofouling trials and new system for future SWRO system [6,8,9].

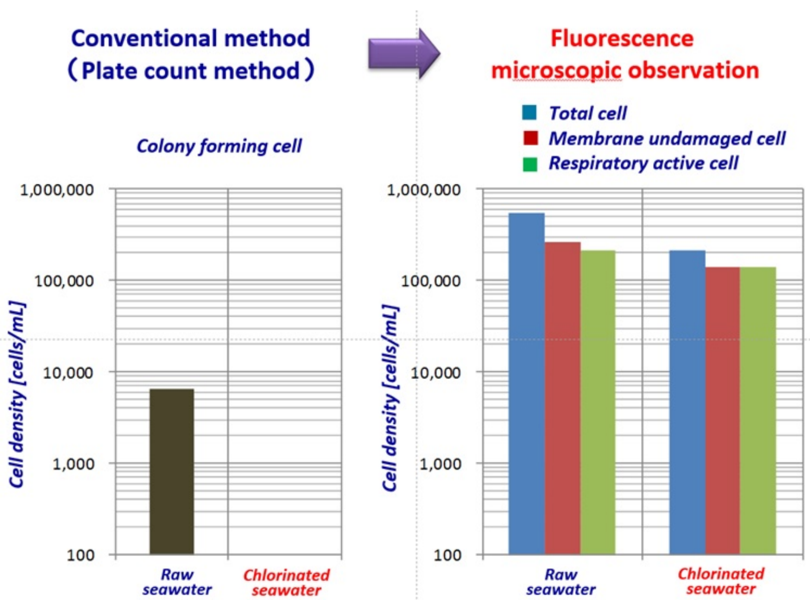


Fig. 14. Chlorine sterilization of seawater has no effect [6].

2.3.5. "mBFR": Membrane biofilm formation rate

The original "mBFR" measuring protocol was reported by the authors [15], after that, "mBFR" measurement were much improved the accuracy and reliability of the biofilm formation evaluation as shown in Figure 15 by Ito et al. [6].

"mBFR" was developed by Toray as an indicator of the seawater RO feed water.

2.3.7. Chlorine sterilization and SBS dosing triggers biofouling

In real SWRO system as shown in Figure 13, Initial stage: conventional SWRO system - continuous chlorination and continuous de-chlorination and Ideal stage: Future SWRO system –no chlorination and no de-chlorination were compared in pilot plant as shown in Figure 16 [6]. From this figure, no chlorination, no de-chlorination as Future SWRO system, show that no biofouling compared to the heavy biofouling of continuous chlorination, continues de-chlorination as Initial stage. Chlorine sterilization and SBS dosing triggers heavy biofouling.

2.3.8. Quantitative RO chemical cleaning interval due to biofouling

As shown on the left side of Figure 17, the points of "mBFR" are very important, especially the value of "mBFR" monitoring 2 [6] . The right side of Figure 17 shows the relationship between "mBFR" and the chemical cleaning interval. If the "mBFR" value at monitoring 2 is less than 10, the chemical cleaning interval will be once or twice a year. Low "mBFR" is necessary for reliable operation of a SWRO plant with less chemical cleaning. The chemical cleaning interval can be predicted with "mBFR" of RO feed water [6]. The details were presented by Mr. Y. Ito, S. Kitade and Y. Tanaka under the title "Clarification of Impact of Biofouling Triggered by Chemical Addition" at IDA World Congress, Tianjin, China 2013 and Mr. Y Ito, S. Kantani, T. Maeda, K.Okubo and M. Taniguchi under the title "Innovative Biofouling Monitoring Device and its Criteria for Reverse Osmosis plant Operation and Optimization" at IDA World Congress, San Diego, CA, U.S.A

3. Conclusions

1) SWRO has become major technology even in Middle Eastern countries and new large plants in excess of half mega-ton per day or mega-ton per day, so- called "Mega-SWRO" are expected to be contracted over the next 12 months.

2) Requirements for sustainable SWRO desalination as green desalination for 21st century are four key challenges as follows,

(1)Energy saving, (2) Low environment Impact, (3) Reliable Plant operation, (4) Low water production cost.

3) Solar power energy became promising candidate for energy resources as renewable energy.

4) Progress of innovative new advanced low pressure SWRO membrane and two-stage high recovery SWRO system are contributed to the 20% energy saving and 30% energy saving was confirmed by the SWRO-PRO hybrid system of the "Mega-ton Water System" project.

5) Future SWRO system as reliable plant operation was proposed by using no-chlorination and no-de chlorination system with mBFR monitoring technology.

6) Verification of this system was done in a pilot, located in Al Jubail over one year, and full scale plant verification will be conducted in Umluji, Saudi Arabia.

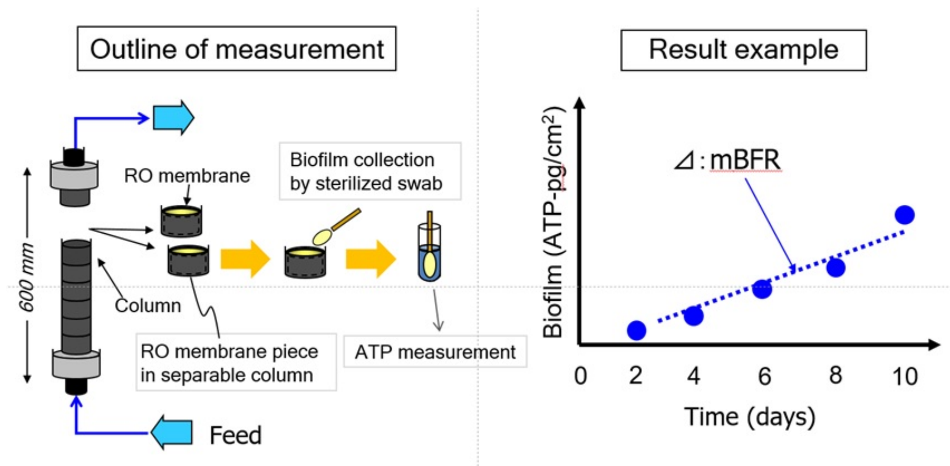


Fig. 15. "mBFR": Membrane biofilm formation rate [6].

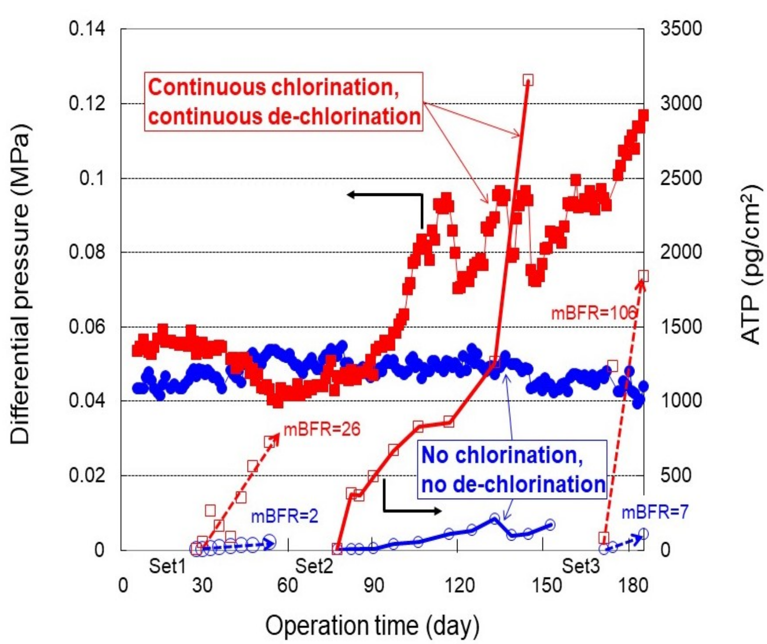


Fig. 16. Chlorine sterilization and SBS dosing triggers biofouling [6].

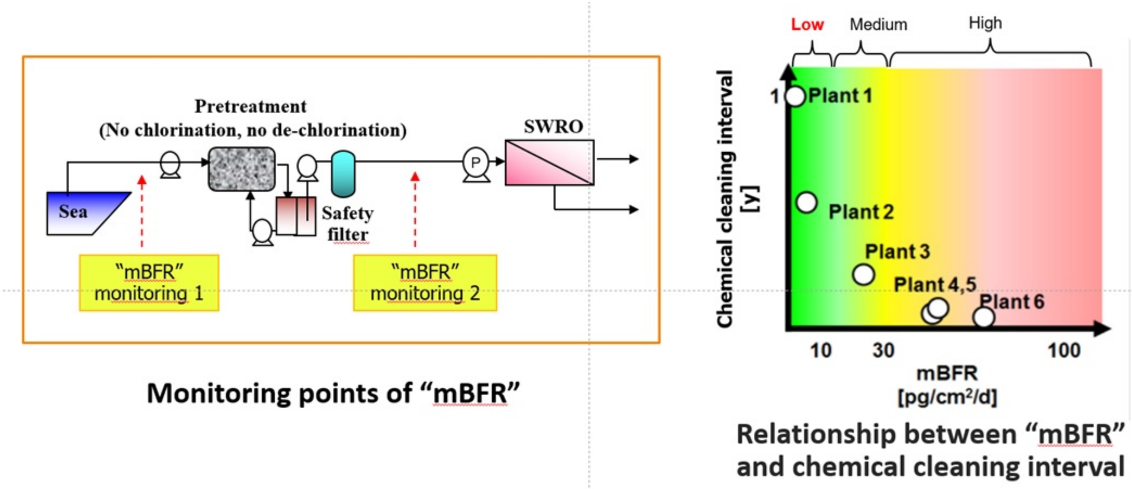


Fig. 17. Quantitative RO chemical cleaning interval due to biofouling [6].

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Part of this study is joint research of the Saline Water Conversion Corporation, Desalination Technologies Research Institute (SWCC/DTRI), Hitachi, Ltd. and Toray Industries, Inc.

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