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More than 30% energy saving seawater desalination system by combining with sewage reclamation

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ABSTRACT

Although seawater reverse osmosis (RO) system has been applied commonly in the world, there are still remaining two key issues for further expansion; (1) High energy consumption and (2) Marine environmental impact attributing to high salt concentration of brine water. Herein, new seawater RO system that enables us to overcome the issues has been proposed. The key feature of this system is to reduce salt concentration of seawater by dilution using the water derived from wastewater treatment or reclamation system to achieve the extreme energy reduction of high pressure pump and to make salt concentration of brine water to the same level as the seawater. In order to demonstrate this system, a demo plant designed "water plaza" was built up and operated in Kitakyushu, Japan, where 1,500 m^3/d of sewage and 500 m^3/d of seawater are used as raw water, and product water is supplied and used as a boiler feed raw water in the Shin-Kokura Thermal Power Plant of Kyushu Electric Co., Inc. During the plant operation, the pressure of high pressure pump for seawater desalination, which is normally 5–6 MPa, has been kept at approximately 3.5–4.0 MPa. It shows that the proposed system can realize more than 30% of energy saving for seawater desalination.

Keywords: Energy saving; Low environmental impact; Seawater desalination; Membrane; RO

1. Introduction

Seawater desalination was just a human dream in the 1960's, but now, has already established a firm position in the world as one of the key technologies to overcome the current severe water scarcity. The distillation and reverse osmosis (RO) membrane are the representative seawater desalination technologies, and they have been practically installed and operated in many places to play an important role to secure water resources. Especially, RO membrane became a main stream of seawater desalination because of the high reliability of membrane technology as well as extreme cost reduction by the development of system and device technologies. But it still has mainly the following two challenges for further expansion: (1) water production cost and energy reduction, which are still relatively high compared with surface water treatment and wastewater reclamation, (2) reduction of marine environmental impact caused by high salt concentration of brine water.

In order to achieve such challenges, we established the new research association, Global Water Recycling and Reuse Solution Technology Research Association

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(GWSTA), and progressed the national project in Japan named as "Water Plaza" with the foundation from New Energy and Industrial Technology Development Organization (NEDO, Japan). Herein, the new seawater desalination RO system to realize more than 30% of energy saving was proposed and demonstrated by construction and operation of full-scale "demo plant". This paper introduces a brief summary of this project "Water Plaza", the concept of how to achieve extreme energy saving efficiency, operation results of "demo plant", and case study to estimate the energy saving.

2. Project of "Water Plaza"

2.1. Project purposes

There are mainly three purposes in this project as follows [1]:

(1) To provide energy-saving and environment-friendly solutions that combine various water resources effectively.

GWSTA aims to provide sustainable solutions that can address each region's local characteristics using our technologies of seawater desalination and of sewage and industrial wastewater reclamation. A typical solution is the "integrated membrane system for seawater desalination and sewage reclamation" enabling us to achieve extreme energy saving for seawater desalination system as described in detail later.

(2) To showcase the water recycling technologies mainly composed of made-in-Japan proven membranes.

As described later, the full-scale "demo plant" was built up in Kitakyushu, Japan which includes membrane bioreactor (MBR), ultra-filtration (UF) and RO systems, and opened for visitors.

(3) To provide the test bed to develop cutting-edge technologies for the effective use of various water resources.

2.2. Integrated membrane system of seawater desalination and wastewater reclamation

In order to achieve significant energy saving in seawater RO (SWRO) system for seawater desalination, the authors focused on the reduction of seawater salt concentration. In the SWRO system, energy consumption of high pressure pump (HPP) occupies the most in total, and it is significantly influenced by the osmotic pressure between feed water and product water.

Therefore, a seawater dilution is considered as a promising way to achieve significant energy saving. Any types of dilution water, if it has low salt concentration, is a candidate for dilution water, and especially the treated wastewater such as the effluent of treatment plant of sewage and industrial wastewater is a strong candidate because it is usually discharged into the environmental field. Therefore, when MBR is employed as a wastewater treatment facility, MBR effluent can be directly applied as the dilution water (shown as Fig. 1a), because it is theoretically free of solid. In this system, RO membrane treatment of the mixed water with low salt concentration requires relatively lower HPP pressure, which is named as medium pressure RO (MPRO). Moreover, it is effective and contributes to energy saving further that once MBR effluent is treated by low pressure RO (LPRO) and then LPRO brine are mixed with seawater and simultaneously RO permeates are obtained as product water (shown as Fig. 1b).

In these systems, seawater intake volume can be reduced because the dilution water plays a role as water resources for seawater desalination. So, the integrated system can reduce both cost and energy consumption for seawater intake and pretreatment. Moreover, use of the diluted seawater can control the salt concentration of MPRO brine which is normally discharged to the ocean, by the adjustment of dilution ratio and MPRO recovery ratio. It means that it is possible to control the salt concentration of brine water at the same level as the ocean, contributing to the significant reduction of marine environmental impact.

Because the product water in this integrated system is permeated through RO, it can be of potable-quality but not be used for direct potable water because it derives from wastewater as well as seawater. For indirect potable reuse, "NEWater" in Singapore and "Groundwater Replenishment System" in California, USA are famous. They treat sewage and remove micro-pollutants from it by RO. Recently, direct potable reuse (DPR) of wastewater gathers the

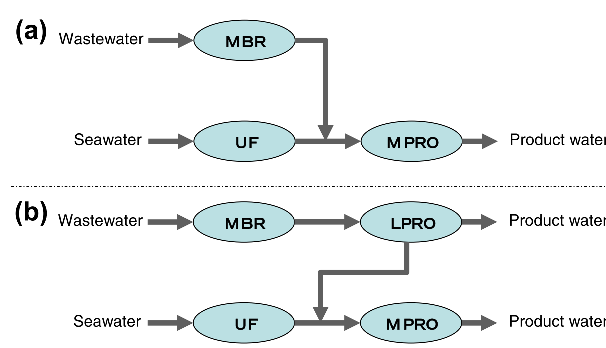

Fig. 1. Flow examples of integrated membrane system of seawater desalination and wastewater reclamation.

strong attention to secure water resources economically. In January 2012, NWRI (National Water Research Institute) released the white paper for DPR and showed that DPR can reduce cost and energy consumption through case studies in California [2]. It may raise the momentum of DPR expansion. In any case, the product water in the integrated system is not currently available for drinking water, though available for non-drinking such as industrial, agricultural and recreational use. Actually, there are several regions where seawater desalination plants are established for industrial water production such as at Dahej in India [3] and at Tianjin in China [4,5].

2.3. Configuration of "demo plant"

In Kitakyushu, Japan, the full scale "demo plant" of integrated membrane system of seawater desalination and wastewater reclamation was established in December 2010 in cooperation with Kitakyushu City, an environmental model city that vigorously engages in the promotion of energy saving and international technological cooperation in the sewage and other water treatment fields. Herein, around 1,500 m^3/d of raw sewage and 500 m^3/d of seawater are taken, and 1,400 m^3/d of product water is produced and 300 m^3/d of several types of water is supplied to the test bed. The schematic flow is summarized in Fig. 2.

In the "demo plant", MBR + RO system was employed for sewage reclamation. In MBR, raw sewage is biologically treated through the UCT process that enables us to achieve simultaneous biological nitrogen and phosphorus removal, and then solid-free treated water is obtained through membrane filtration (Fig. 3). Herein, three types of membrane modules are employed, two of them are flat sheet type (Hitachi Plant Technologies, Ltd. and Toray Industries, Inc.) and another is hollow fiber type (Asahi Kasei Cooperation). All membrane material is Polyvinylidene fluoride (PVDF), and detailed feature of each membrane module is listed in Table 1. For the flat sheet types of membrane, double-deck type of membrane modules where membrane units are set up vertically to use effectively air scrubbing for membrane scouring and gravity filtration (no pump use) are employed to promote energy saving. Furthermore, fine bubble diffusers for air scouring are applied for one train to increase oxygen transfer efficiency, excess air supply is prevented by adjusting the flow rate of aeration depending on residual NH_4-N concentration in the aerobic tank, and gravidity filtration is applied to cut filtration pump energy in the case of flat sheet membrane.

LPRO treatment of MBR effluent removes ions and micro-pollutants to make high quality product water, which is the same level as drinking water. Herein, MBR effluent generally includes slight amount of organic compounds enhancing microorganism growth in RO elements. In such a case, RO performance would sometimes decrease significantly due to so called "bio-fouling". So, "low-fouling RO membrane" suppressing microorganism attachment on membrane surface is employed for LPRO treatment. The configuration of LPRO unit is shown in Table 2.

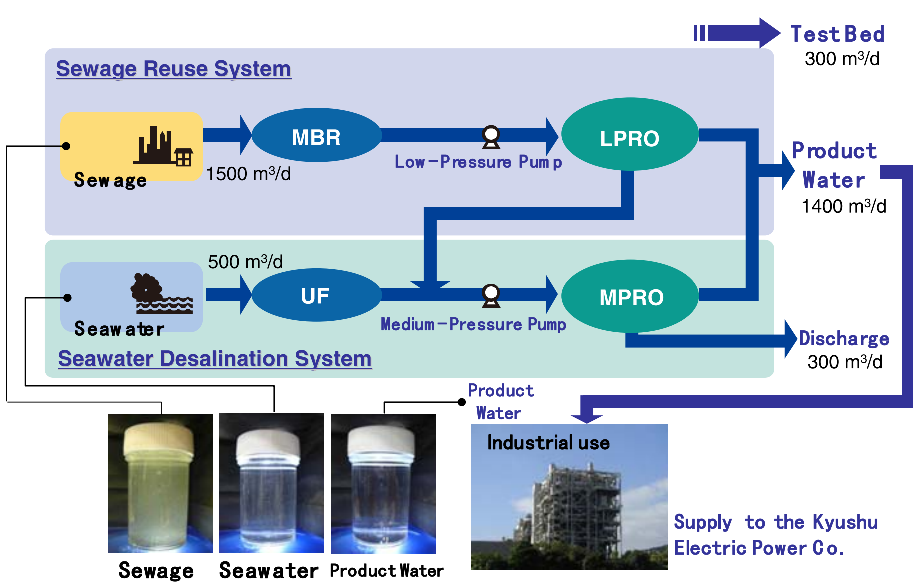

Fig. 2. The schematic flow of "domo plant" built in Kitakyushu, Japan.

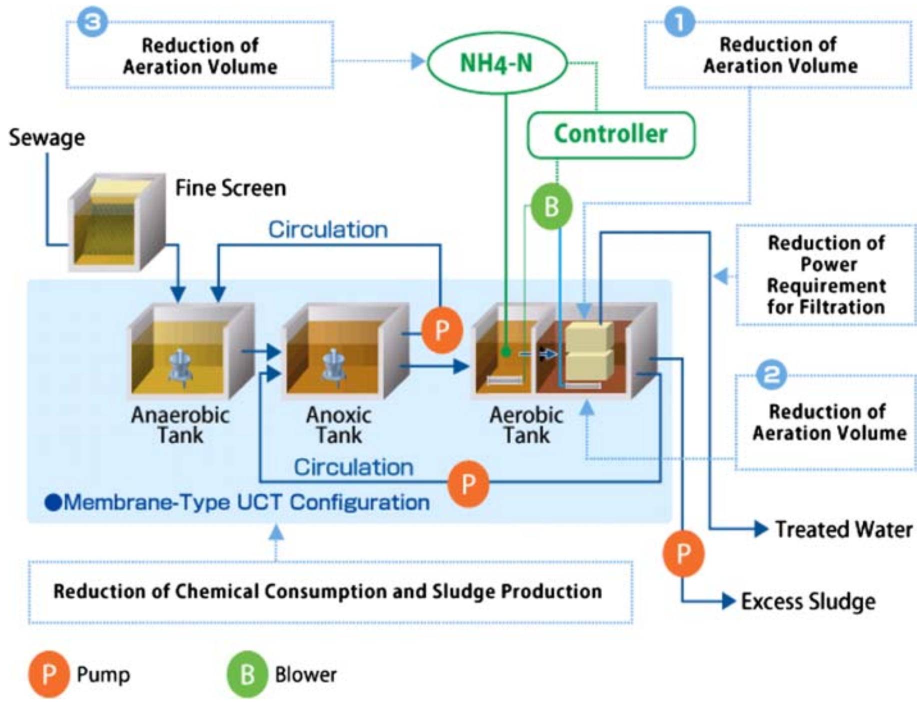

Fig. 3. Basic configuration of MBR and points to realize energy saving.

Table 1
MBR modules installed in "demo plant"

Configuration	No. 1-1 Train Submerged flat sheet membrane	No. 1-2 Train	No. 2. Train Submerged hollow fiber membrane
Pore size	0.1 μm	0.08 μm	0.1 μm
Membrane		PVDF	
Side view			
Membrane area	800 m^2/module	280 m^2/module	300 m^2/module
Module number	1	3	3
Manufacturer	Hitachi Plant Technologies, Ltd.	Toray Industries, Inc.	Asahi Kasei Corporation

Approximately 500 m^3/d of seawater is taken from Kanmon strait, and flowed into UF membrane as shown as Table 3 to remove solid substances from seawater. And then UF treated water is mixed with LPRO brine at 1:1 ratio. Mixed water is fed to MPRO unit, which configuration is shown in Table 2. For the first stage of MPRO, 16-inch RO element is employed, which reduces significantly water producing cost and

Table 2
Configuration of LPRO and MPRO units

	LPRO unit	MPRO unit
Element (EL) type	Spiral type	
Membrane material	Aromatic Polyamide	
EL configuration	2 stage 7 EL/vessel × (6 + 3) vessel 63EL (8 in.)	2 stage 6 EL/vessel × (1 + 3) vessel 6EL (16 inch: 1st bank) + 18EL (8 in.: 2nd bank)
Unit appearance		
RO manufacturer	Toray Industries, Inc.	

Table 3
Configuration of UF unit

	UF unit
Module type	Pressurized hollow fiber membrane (outside–in)
Membrane material	PVDF
Pore size	0.01 μm
Membrane area	72 m^2/module
Module configuration	4 modules/trains × 2 train
Unit appearance	
Manufacturer	Toray Industries, Inc.

energy especially for large-scale plants. In order to enhance energy saving, pressure recovery device is employed to reuse the pressure of brine water.

The permeate water of LPRO and MPRO are produced at 1,400 m^3/d, and most of them are flowed and used in the Shin-Kokura Thermal Power Plant of Kyushu Electric Co., Inc. since April in 2011.

3. Operation results

Before starting continuous plant operation, test operations of MPRO was carried out to acquire energy consumption data under various conditions of mixed ratio of seawater and LPRO brine (mixing ratio of LPRO brine was 40–80%) and MPRO recovery ratio (50 or 60%) as shown in Table 4. Mixing ratio of LPRO brine significantly affected feed water electrical conductivity (EC) as well. A test operation for one condition lasted for around 2 h, and average data during stable period was selected as the representative data of each condition.

Relationship between HPP pressure and feed water EC is summarized in Fig. 4, indicating that both feed water EC and MPRO recovery ratio significantly

Table 4
Test conditions for the effect of mixing ratio of LPRO brine water and SWRO ratio on HPP pressure of MPRO unit

Case	Mixing ratio of LPRO brine water (%)	MPRO recovery ratio (%)	Feed water EC (μS/cm)	HPP pressure (MPa)
Case 1	80	60	12,350	2.1
Case 2	70	60	17,610	2.7
Case 3	60	60	22,700	3.2
Case 4	50	60	27,700	3.7
Case 5	40	60	32,200	4.3
Case 6	70	50	17,780	2.4
Case 7	60	50	22,400	2.8
Case 8	50	50	27,000	3.2
Case 9	40	50	31,500	3.7

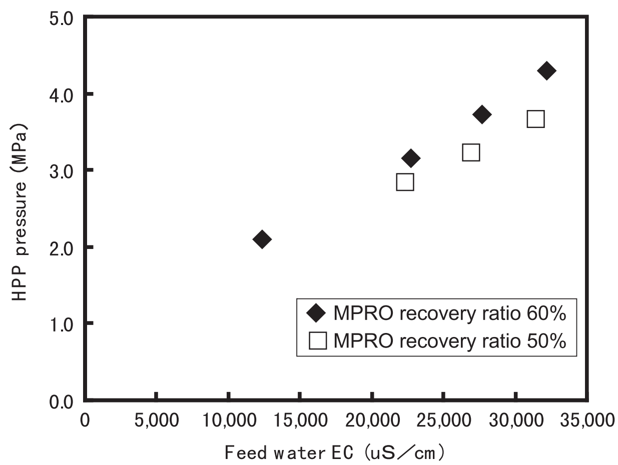

Fig. 4. Relationship between HPP pressure and feed water EC.

affected HPP pressure as theoretically estimated. Average EC of seawater in "demo plant" was around 47,480 μS/cm, meaning that around 5.1–5.9 MPa of HPP pressure would be required if seawater is directly applied as feed water. And around 37% of energy saving is expected when compared with the case of 50% of mixing ratio of LPRO brine.

A technical key point of the integrated membrane system of seawater desalination and sewage reclamation is stability of MPRO operation because feed water includes the organic matter derived from sewage treatment system. Time course of feed pressure, water temperature, feed water EC and permeate EC are shown in Fig. 5. Feed pressure was very stable and permeate EC was gradually increased as temperature increased, whose behavior is theoretically reasonable. As above, MPRO operation kept uneventfully stable even if sewage reclamation LPRO brine was applied as dilution water.

Time course of product water volume is shown in Fig. 6. The full operation of "demo-plant" has started since the end of August in 2011 as shown in this figure. As water quality of raw sewage, seawater,

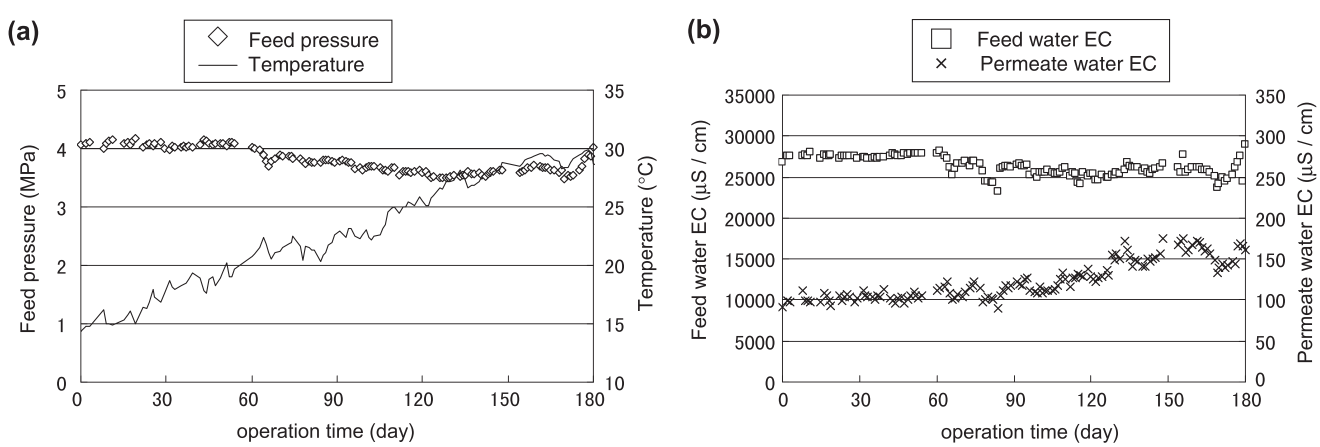

Fig. 5. Time course of feed pressure and water temperature (a), feed water EC and permeate water EC (b).

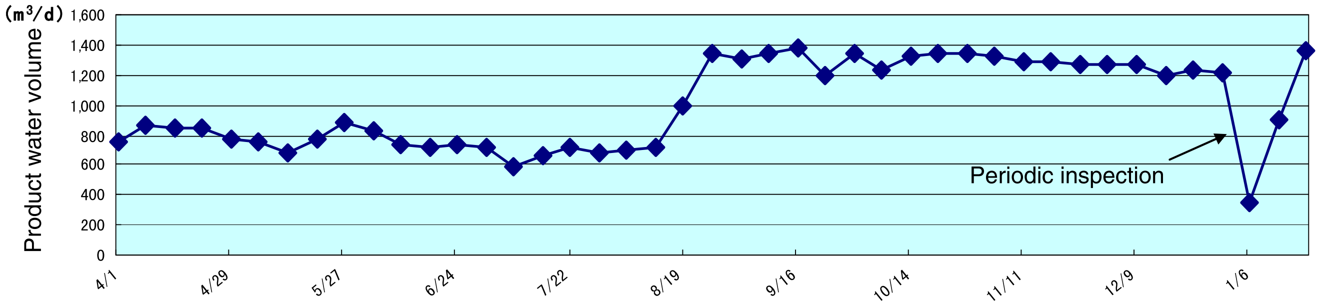

Fig. 6. Time course of product water volume.

MBR effluent, and product water were summarized in Table 5, product water quality was extremely higher than designed value, which was determined based on the water quality utilized by the Shin-Kokura Thermal Power Plant before plant establishment. In the Shin-Kokura Thermal Power Plant, product water and industrial water were blended and supplied to purification process to make boiler water for electric generation, which includes ion exchange process. Since plant product water supply started, frequency of regeneration of ion-exchange resin was significantly decreased to almost at half because EC of product water (RO permeates) was around 50–70 µS/cm, significantly lower than that of industrial water, which was around 200–300 µS/cm (shown as Fig. 7). According to the relationship between inlet water EC of purification process and monthly frequency of regeneration of ion-exchange resin in Fig. 7, the frequency of regeneration of ion-exchange resin would be reduced down to 1 time/month if product water alone were used for inlet water of purification process. Anyway, product water supply contributed to extreme cost reduction of regeneration of ion-exchange resin.

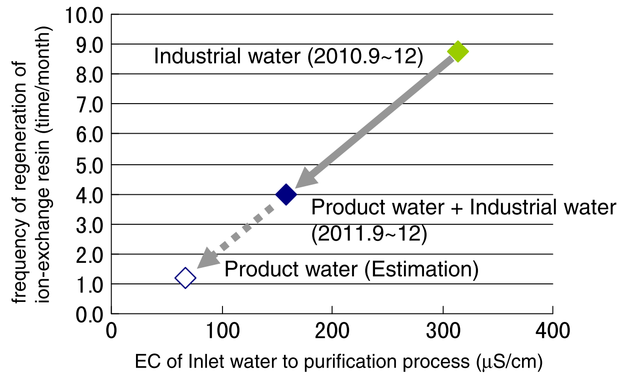

Fig. 7. Relationship between inlet water EC of purification process and monthly frequency of regeneration of ion-exchange resin.

Table 5
Water quality of "demo plant"

Items	Unit	Sewage	MBR effluent	Seawater	Mixed water	Product water	(Design)	Tap water criteria
Turbidity	degree	–	<0.1	–	–	<0.1	<2	≦2
pH	–	7.3 (6.81–7.64)	6.9 (6.5–7.2)	8.2 (8.0–8.4)	7.4 (7.1–7.8)	6.7 (6.5–6.9)	5.8–8.6	5.8–8.6
EC	µS/cm	1,520 (793–2,640)	1,450 (651–1,980)	47,480 (43,500–56,300)	26, 800 (24,800–31,100)	69 (51–98)	<250	–
TDS	mg/l	824 (460–1,332)	705 (525–875)	33,936 (31,800–36,000)	16,980 (14,710–18,600)	–		≦500
Cl^-	mg/l	285 (170–445)	274 (155–388)	18,970 (16,685–21,000)	10,050 (8,680–11,100)	16.3 (9.9–26)	<80	≦200
TOC	mg/l	38 (24–63)	3.9 (1.9–6.3)	3.0 (0.9–13)	7.3 (4.5–11.0)	0.3 (0.1–1.1)	<2	≦3
Total hardness	mg/l	183 (135–243)	186 (163–218)	6,400 (5,170–6,932)	3,350 (3,122–3,478)	1.4 (0.5–2.4)	<100	≦300

*Average value (minimum – maximum).

4. Case study for energy saving estimation

A technical feature of the integrated membrane system of seawater desalination and sewage reclamation is seawater dilution by discharged water from sewage treatment plant to reduce energy consumption of HPP of MPRO feed water as described above. Therefore, it is an appropriate scenario to compare energy consumption in the part of seawater desalination process between with and without seawater dilution to evaluate energy saving efficiency. That is, in the comparative controlled flow (Case 1), seawater alone is taken as a water resource, pretreated by UF membrane, and then flowed into SWRO membrane (Fig. 8a). On the other hand, in the integrated system (Case 2), seawater and LPRO brine water from a sewage reclamation process are utilized as water resources, seawater alone pretreated by UF membrane, then mixed with the LPRO brine, finally treated by MPRO membrane (Fig. 8b).

To compare between them, product water volume was equally assumed at 18,000 m^3/d. Energy consumption of seawater intake (Case 1 and 2), UF pretreatment (Case 1 and 2) and MPRO treatment (Case 2) were calculated by actual energy consumption data in "demo plant" multiplied by scale up factor at 0.74, where this value was determined by the comparison of energy consumption of HPP between in "demo plant" scale and in 18,000 m^3/d scale. Though it was considered that energy consumption for the LPRO brine transportation (Case 2) depends on the place such as distance and height, it was assumed equivalent specific energy consumption with seawater intake. For energy consumption of SWRO treatment in Case 1, pressure of HPP was estimated by the calculation tool provided by Toray, and residual energy consumption was calculated based on actual data of "demo plant". Herein, the effect of energy recovery device was also taken into account.

Firstly, recovery ratio in SWRO in Case 1 was determined because it affects energy consumption significantly. High recovery ratio would reduce intake and pretreatment volume, but would increase energy consumption of HPP. In normal case, recovery ratio of SWRO seawater desalination is in the range from 40 to 60%. Because calculation results under the range of recovery ratio showed that energy consumption under 40% of it was the lowest, 40% of recovery ratio was adopted here. Calculation results showed energy consumption of water intake, UF pretreatment and RO treatment based on the unit amount of product water were 0.81, 0.28 and 3.23 kWh/m^3 respectively, in total 4.31 kWh/m^3 (Table 6).

As recovery ratio in Case 2, the same value (60%) as "demo plant" was adopted here. Calculation results showed energy consumption of water intake, UF pretreatment and RO treatment were 0.54, 0.09 and 2.29 kWh/m^3 respectively, in total 2.92 kWh/m^3 (Table 6).

These results indicate that installation of the integrated system reduce 1.39 kWh/m^3 of energy consumption, meaning 32.4% of energy saving efficiency. This energy reduction was attributed largely to water volume reduction of water intake and pretreatment, and HPP energy reduction.

The above energy calculation results depend on water quality and situation, especially strongly affected

Table 6
Calculation results of energy consumption in case study

Energy consumption (kWh/m^3)	Case 1 (controlled flow)	Case 2 (integrated system)
Water intake	0.81	0.54
UF pretreatment	0.28	0.09
SWRO or MPRO	3.23	2.29
Total	4.31	2.92

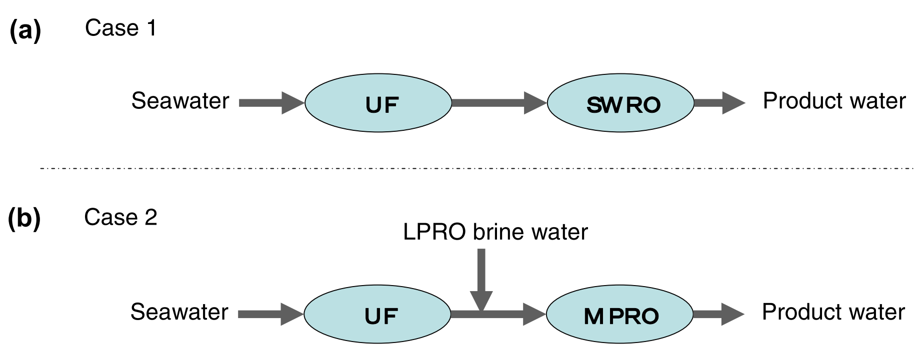

Fig. 8. Basic flow of case study to estimate energy saving; (a) Case 1: the comparative controlled flow, (b) Case 2: the integrated system of seawater desalination and sewage reclamation.

the situation of dilution water acceptance. For example, the case that seawater desalination plant is located very far from a wastewater treatment plant supplying dilution water may cancel out energy saving effect by dilution water transportation. Anyway, the integrated system can contribute to more than 30% of energy saving, and play the important role as one of the attractive candidates to supply adequate water solutions.

5. Conclusions

Advanced seawater desalination system that enables us to realize more than 30% of energy saving was proposed here. Key feature of this system is to reduce salt concentration of seawater by dilution with the water derived from a wastewater treatment system, such as brine water from MBR + RO sewage reclamation system.

In order to demonstrate this system, a "demo plant" was built up and operated in Kitakyushu, Japan, where 1,500 m^3/d of sewage and 500 m^3/d of seawater are treated, and product water is supplied and effectively used in the Shin-Kokura Thermal Power Plant of Kyushu Electric Co., Inc. since April 2011. The plant has reached full operation potential since the end of August 2011. During the plant operation, HPP pressure for seawater desalination was very stable at approximately 3.5 MPa.

Case study based on the actual "demo plant" operation revealed that energy consumption of the proposed integrated membrane system was 2.92 kWh/m^3 whereas that of the UF + RO system was 4.31 kWh/m^3, meaning 32.4% of energy saving efficiency.

Acknowledgments

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