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Decreasing water resources and a comprehensive approach to seawater reverse osmosis (SWRO): Case study—Cost analysis of a sample SWRO system

Rabia Seda Timur[a], Göksel Demir[b,*], Aslı Çoban[b], Adnan Çorum[c], Tunç Bozbura[c]

[a]*Teknik Arıtma, Necatibey Caddesi No: 65 34425 Karaköy/İstanbul*
[b]*Engineering Faculty, Department of Environmental Engineering, Bahçeşehir University, 34349 Beşiktaş/İstanbul-Turkey*
Tel. +90 212 381 05 48; email: goksel.demir@bahcesehir.edu.tr
[c]*Engineering Faculty, Department of Industrial EngineeringBahçeşehir University, 34349 Beşiktaş/İstanbul-Turkey*

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ABSTRACT

Water is used for a number of different purposes that are predicted to be affected by global warming. Good management of future water resources will become increasingly important as global warming takes its toll. The purpose of this study was to make a cost analysis of seawater desalination in Turkey for reverse osmosis systems, which would be filling a gap in the current literature. Investment costs, operating costs and total production costs of these systems were analyzed. Furthermore, the effects of varyingly priced consumption materials on operating and total production costs were determined. Due to the fact that energy costs constituted the greatest part of the operating costs (70%), the most discussed part of Seawater Reverse Osmosis systems, has been the energy recovery booster pumps. Thus leading to the utilization of energy recovery booster pumps as the decision criterion, as it was examined in detail in this study. It was concluded that implementation of the energy recovery system was beneficial both economically and environmentally.

Keywords: Desalination; Seawater reverse osmosis systems; Energy recovery; Cost analysis

1. Introduction

Water is essential for human life and development. Most of the world's agricultural production, hydroelectric power, and water supplies depend on the full water cycle. Water is already scarce and will be scarcer in future due to global warming. Today we can say that, the production of potable water has become a worldwide concern. Over 1 billion people do not have access to clean drinking water and approximately 2.3 billion people (41% of the world population) live in regions with water shortages [1]. Conserving drinking water resources is becoming an increasingly important task under the looming shadows of urban development, pollution and droughts [2]. Therefore, urgent and sustainable solutions are called for. Those solutions such as water conservation and water transfer or dam construction are not sufficient approaches to cope with increasing demand and, in many cases, decreasing supply. Traditional fresh water resources such as lakes, rivers, and groundwater are either overused or misused; as a result, these resources are either diminishing or becoming saline. As countries continue to develop and cities expand, few novel water resources are available to support daily fresh water needs. Water reuse and salt-water desalination are listed among the key methods to sustaining future generations across the globe. Water reuse

*Corresponding author.

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has been conducted to provide water for uses such as irrigation, power plant cooling water, industrial process water, and groundwater recharge and has been accepted as a method for indirect drinking water production. Desalination has become an important source for drinking water production, with thermal desalination processes developing over the past 60 y and membrane processes developing over the past 40 y [3]. Both water reuse and desalination have been incorporated successfully to provide additional fresh water production for communities using fresh water resources and conventional water treatment.

In this paper Seawater Reverse Osmosis (SWRO) system, a seawater desalination method, is presented in detail. Cost analysis of seawater desalination in Turkey for reverse osmosis systems was carried out along with the investment and total operating costs of the alternative systems. Besides, the effects of varyingly priced consumption materials on operating and total production costs were determined. Especially the effect of energy recovery booster pump usage in system was used as the decision criterion in different analyses. The significance of standard pre-treatment group was also investigated.

2. SWRO system in general

Desalination is the general term for the process of removing salt from water to produce fresh water. Desalination of seawater and brackish waters provides the main fresh water source for the regions suffering from the scarcity of natural water supplies [4]. Fresh water contains less than 1000 mg/l of salts or total dissolved solids (TDS) by definition [14]. Above that concentration, properties such as taste, color, corrosion propensity, and odor may be adversely affected. Many countries have adopted national drinking water standards by specifying certain parameters (TDS, color, odor, etc.), but the standard limits may vary from country to country or from region to region within the same country [1].

Reverse osmosis process is a general and widely applicable technique for the separation, concentration, or fractionation of inorganic or organic substances in aqueous or non-aqueous solutions in liquid or gaseous phases [5]. Basically water is forced through a membrane and while the water is passing through the membrane, dissolved solids, particles and organic materials cannot pass through the fine pores of the membrane. Rejects in the form of particulates are sent to the drainage as wastewater and thus dematerialized water is produced with 97–99% reduced salt concentration. In the last decade, applications of SWRO desalination have gained much momentum, and it is predicted to become the most important method to solve the problem of fresh water scarcity [6].

Pressure range for reverse osmosis systems is given as 7–70 bars. Pressure range for SWRO systems is at the upper end of that range with 60–70 bars. By the implementation of reverse osmosis systems in general, potable water production from brackish, surface or seawaters, distilled water production for industrial purposes, irrigation water production, pure water generation for hemodialysis units, and wastewater recovery can be accomplished. Membranes used in reverse osmosis systems are Thin Film Composite (TFC) membranes, which are typically made from polyamide. TFC membranes are composed of multiple layers and have a spiral wound shape (Fig. 1).

Pre-treatment, consisting of filtration and chemical dosing stages, is required to make reverse osmosis system function properly. Filtration is a physical process to remove turbidity and suspended solids from water with the aid of a filter media. Process is controlled by an automatic valve, which has a microprocessor control panel that remotely controls service and backwash periods. Following filtration process, system will continue with chemical dosing units if necessary. Additional pre-treatment steps to remove chloride must be taken before polyamide TFC membranes are exposed to feed water [7].

Acid Dosage Unit: It is used to reduce pH to more acidic values. System contains a dosing pump and a chemical solution tank.

Sodiummeta Bisulfite Dosage Unit: In order to prevent its degrading effects on membrane, this unit is used to remove chloride from water.

Anti-scalant Dosage Unit: With anti-scalant dosing Ca^{2+} and Mg^{2+} ions can be removed from raw water without causing any membrane fouling. It has a dosing pump with flow rate controlled by manual stroke grade.

Following the pretreatment processes, water enters the reverse osmosis unit. However, before entering the reverse osmosis unit, chloride values in water is controlled by an ORP Meter, which has a panel type 4–20 mA output current. Before entering the membranes, water initially passes through seven pieces of pre-filters

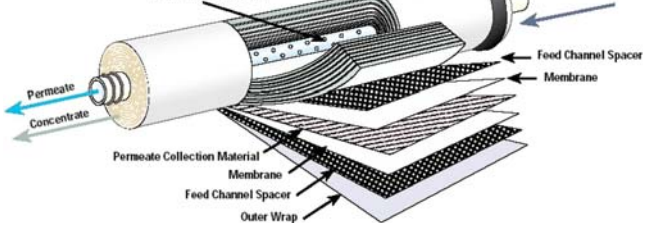

Fig. 1. Membrane composition. (*Source*: http://www.miraculewater.com/images/spiralmembrane.jpg)

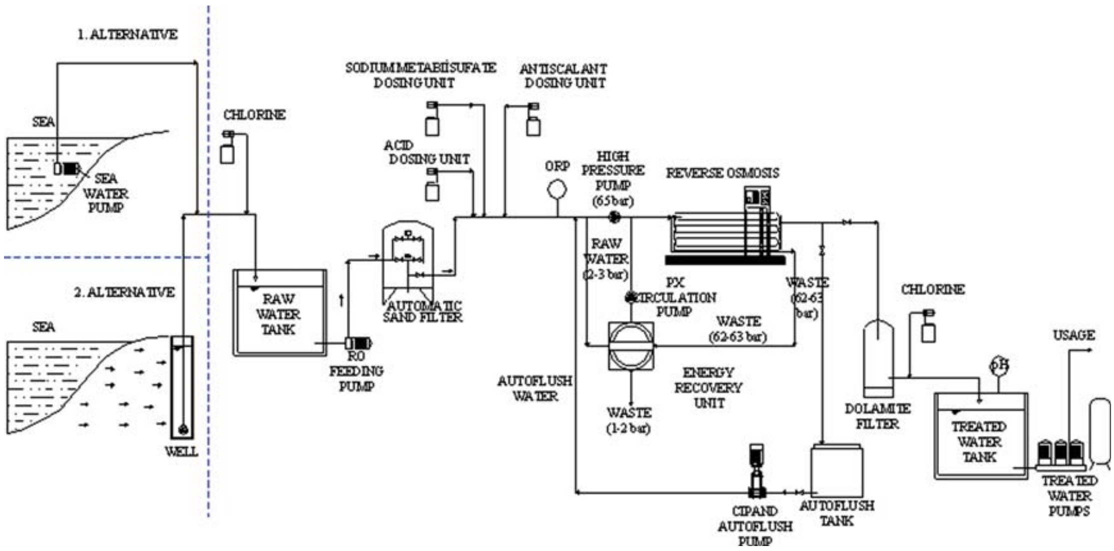

Fig. 2. Process diagram of SWRO.

with 1 µm pore size. Dimensions for the pre-filters are given as 20″, 30″, and 40″ of height and 2.5″ of diameter. Then a high-pressure pump pressurizes water to the needed pressure value (65–70 bar) and high-pressured water passes through membranes (Fig. 2). Membrane casings can be fiberglass or stainless steel with different membrane capacity in each. The PLC Control Unit controls the entire procedure in reverse osmosis unit. In certain periods, membrane cleaning unit is utilized to clean the system for more efficient membrane use and longer service life. Depending on the customer requirements, all equipments can be encased in an St 37 container and can be isolated from temperature effects.

3. Investment, operation and maintenance costs of an SWRO system

There is a common conception that seawater desalination is a very expensive technique. Main costs of SWRO plants are listed as initial system investment, energy consumption, and replacements including membrane and other equipment. Conduction of a detailed cost analysis not only produces useful data for economic feasibility point of view but also provides the most important tools for the consideration and selection processes of these systems that are getting more popular every day [8]. The economics of seawater desalting using reverse osmosis technology has been continuously improving with the reduction of production cost due to lower investment costs and decreased power consumption [9]. Increasing demand for more fresh water is pushing the industry towards improving the operational efficiency of SWRO desalination plants and increasing the lifetime of membranes [10].

For SWRO plants, power costs can account for up to 50% of the total plant operation and maintenance costs. Fixed costs, including capital investment, amortization, and insurance, by approximately 37% account for the second largest share in costs. Other costs include maintenance and parts (7%), membrane replacement (5%), labor (4%), and consumable chemicals (3%) [11]. As far as the energy consumption is concerned, energy recovery systems present themselves as crucial parts of the SWRO plant operations. Capacity of an SWRO plant and its energy consumption are positively correlated. In order to minimize energy consumption an equipment is used to convert hydraulic energy of rejected brine into rotational energy. The generated rotational energy is then delivered to the mechanical shaft that drives the motor of the high pressure pump (Fig. 3).

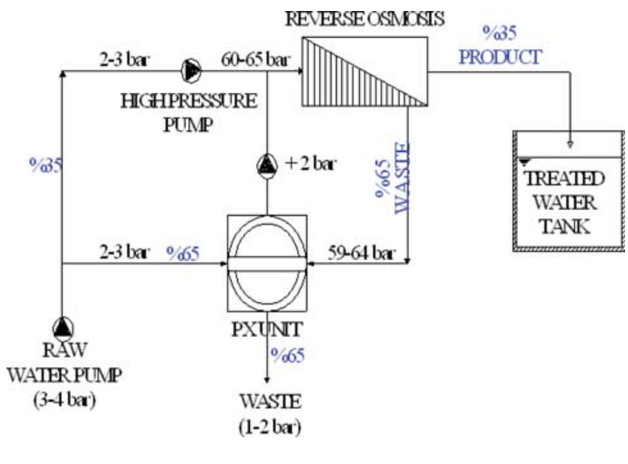

Fig. 3. Pressure exchange (PX) energy recovery system.

Table 1
Water analysis results from raw water sample and sample from SWRO outlet

Parameter	Unit	Raw water data	Reverse osmosis product data	TS-266 Standards	
				Class 1 and Class 2 Type 1	Class 2 Type 2
Turbidity*	NTU	–	–	max 5	max 5
Iron*	mg/l	<0.05	<0.05	max 0.05	max 0.2
Ammonium*	mg/l	<0.01	<0.01	max 0.05	max 0.5
Nitrite	mg/l	0.040	0–0.1	0.1	0.5
Nitrate	mg/l	0.49	0–0.1	25	50
Sodium*	mg/l	11,150	20–175	100	200
Chloride*	mg/l	20,800	25–600	max 30	max 250
Sulfate*	mg/l	462	25–250	max 25	max 250
Hardness	F	830	1–5	NA	
pH*	–	7.2	6.5–9.2	6.5–9.5	
TDS	mg/lt	35,000	<600	NA	
Conductivity*	µS/cm	63,000	<1250	max 650	max 2500

*Values for these parameters were listed in the standard TS-266 under the monitoring of compatibility section.
Corresponding values for parameters in the Turkish standard for human consumption waters, TS-266, were also given.

In this study ERI PX brand energy recovery booster pump is used due to its high efficiency and quality. It is one of the most efficient reverse osmosis energy recovery devices commercially available today. The device can handle operating pressures up to 83 bars (1200 psi) and have an efficiency curve that is virtually flat. Even if the feed salinity or temperature changes or the reverse osmosis recovery varies, the energy recovery device still runs at up to 97% efficiency levels [12].

4. A case study

In this case study, the investment and operating cost of a SWRO plant is examined with two different system alternatives, one with an energy recovery technology (System 1) and the other without (System 2). Both systems were constructed at a seaside resort of 200 houses in Bodrum, Turkey. Management of the resort drilled up a well for fresh water supply but as it was the case for water from most of the wells in Bodrum, it was highly mixed with seawater and this mixing created high concentrations of conductivity in water. Chemical analysis results for water samples from the well were shown in Table 1.

Evaluating the conductivity results, it was concluded that the water from the well was actually seawater and the design solution to that came up as an SWRO system. By constructing a seawater treatment plant, this resort would not need any drinking and usage water from other sources. It would produce its own water with high quality and health standards. There are some key features that form the investment cost. Due to its design the SWRO system included a pretreatment system with a sand filtration and chemical dosing units. Then water would pass through 8 pieces of GE Desal membranes with 99–99.5% ion rejection rate (Table 2).

As mentioned previously there were two different system alternatives, System 1 and System 2. In both systems, we have initial system investment, operational cost and equipment replacement cost. Initial system investment was defined as the first cost paid to purchase the system. Operational costs consisted of electrical energy consumption and chemical substances cost. Electrical energy consumption was decreased in System 1 by using an energy recovery booster pump, while it increased the capital investment. Chemicals used in the system were sodiummetabisulfate, antiscalant, chlorine, and acid. Equipments were 1 µm pore size cartridges with 20″ and 30″ height. Even though there was a multimedia sand filter unit on site, cartridge filters were placed at the inlet of reverse osmosis unit in

Table 2
System's total capacity and design data

System capacity	100 m^3/d
Working pressure	62 bar
Membrane	
Recovery	35%
Ion rejection	99–99.5%
Membrane type	AD8040TF DESAL–8 pcs
Membrane housing	Fiberglass–2 pcs

order to remove fine suspended solids. Even if a very small particle got into the membranes, it would tear the membrane layer and the membrane would become useless. Equipment replacement costs were due to periodic replacement of some of the equipments. Membranes made up for much of the equipment replacement costs, due to their approximately 3 y lifetime and pricing.

Initial investment for System 1 and System 2 were calculated to be €85,000 and €60,000, respectively. As it was expected initial investment for System 1 was higher than System 2. The difference was due to the inclusion of energy recovery equipment in System 1. In Tables 3 and 4 operational costs per cubic meter of water for System 1 and System 2 were presented. Referring to tables, total operational costs for System 1 and System 2 were €0.553/m^3 water and €1.065/m^3 water, respectively. Difference was due to the energy recovery system, which converted hydraulic energy into rotational energy. We could assume that each house consumed approximately 0.5 m^3 water/d. Therefore, for the project, daily water production amount was planned to be 100 m^3. Thus, daily operational cost for System 1 was €55.3, while it was €106.5 for System 2.

Table 3
Electrical energy consumption cost per m^3 water for System 1 and System 2

Eletricity	Number of units required	Working hours/d	System 1			System 2		
			Pomp power (kW)	Daily electricity consumption (kW h)	Cost (€/m^3 water)	Pomp power (kW)	Daily electricity consumption (kW h)	Cost (€/m^3 water)
Chlorine dosing pump	1	24	0.09	2.2	0.0019	0.09	2.2	0.0019
RO feeding pump	1	24	4	96	0.0854	4	96	0.0854
Acid dosing pump	1	24	0.09	2.2	0.0019	0.09	2.2	0.0019
Sodium metabisulfite dosing pump	1	24	0.09	2.2	0.0019	0.09	2.2	0.0019
Antiscalant dosing pump	1	24	0.09	2.2	0.0019	0.09	2.2	0.0019
RO high pressure pump	1	24	15	360	0.3203	40	960	0.8542
PX unit booster pump	1	24	1	24	0.0214			
Chlorine dosing pump	1	24	0.09	2.2	0.0019	0.09	2.2	0.0019
Total cost (Euro/m^3 water)					**0.437**			**0.9493**
Daily electricity consumption (kW h)					**490.8**			**1,066.80**

Table 4
Chemical substances cost per m^3 water for System 1 and System 2

Chemical	Dosage (mg/l ml/l)	Working hours/d	Daily consumption (kg)	Cost (€/m^3 water)
Chlorine (first) (15%)	1	24	1.9	0.00857
Acid (30–33%)	0.01	24	0.003	0.00001
Sodium metabisulfite (100%)	1.5	24	0.43	0.00321
Antiscalant (100%)	3.5	24	1	0.1
Chlorine (last) (15%)	0.5	24	0.95	0.00429
Total cost (€/m^3 water)				**0.11608**

Table 5
Equipment replacement cost for System 1 and System 2

Equipment	Amount	Replacement frequency (y)	Cost
Quartz, kg	700	3	131
Antracite, l	300	3	225
Cartridge Filter, pcs	7	1/13	58
RO Membranes, pcs	8	3	5200
Dolamite, kg	40	1	75

In Table 5, details of the equipment replacement cost and replacement periods for System 1 and System 2 is presented.

Presenting the three types of costs mentioned, we can now calculate the total system operating costs in periods and show them on the cash flow diagrams, for both alternative systems. The two systems had effective usage life of 10 y. After 10 y, the salinity level at the water would increase and the system was supposed to be upgraded due to the new conditions. Approximately the salvage values of the systems after 10 y were 30% of the initial system investments. That was €25,500 for System 1 and €18,000 for System 2. Considering the equipment replacement periods, it was reasonable to study on annual compounding period. Assuming 365 days a year, annual operational cost for System 1 and System 2 were €20,184.5 and €38,872.5, respectively. There was only problem for cartridge filter, which had a very short annual replacement frequency. We solved this problem by calculating the cumulative annual replacement cost (€58×13 = €754) for cartridge filter. Sales price of the water was €1/m^3 water. Daily revenue from the water was planned to be €100 thus yearly it was €36,500 (100×365). Cash flow diagrams for System 1 and System 2 were presented in Figs. 4 and 5, respectively. Values on the cash flow diagram was the cumulative costs for the corresponding periods (21013.5 = 20184.5 + 754 + 75; 39701.5 = 38872.5 + 754 + 75; 5556 = 131 + 225 + 5200).

In order to compare two systems present worth (PW) method was used. PW method was popular because future costs and revenue estimates were transformed into equivalent dollars in the present day. This made it easy to determine the economic advantage of one alternative over another [13]. PW of each alternative was calculated below, present worth being a function of both present value given future value (P/F) and present cost given annual cost (P/A). Annual interest rate (i) was accepted as 10%.

$$PW_1 = 36500\left(P/A, 10\%, 10\right) + 25500\left(P/F, 10\%, 10\right) - \left[85000 + 21013.5\left(P/A, 10\%, 10\right) + 5556\left(P/F, 10\%, 3\right) + 5556\left(P/F, 10\%, 6\right) + 5556\left(P/F, 10\%, 9\right)\right]$$

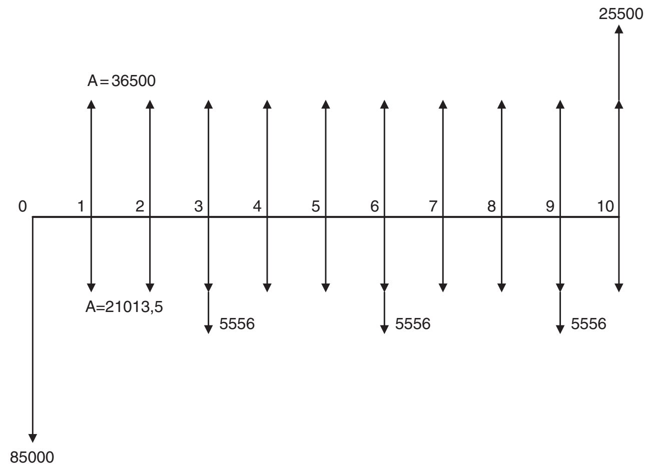

Fig. 4. Cash flow diagram for System 1.

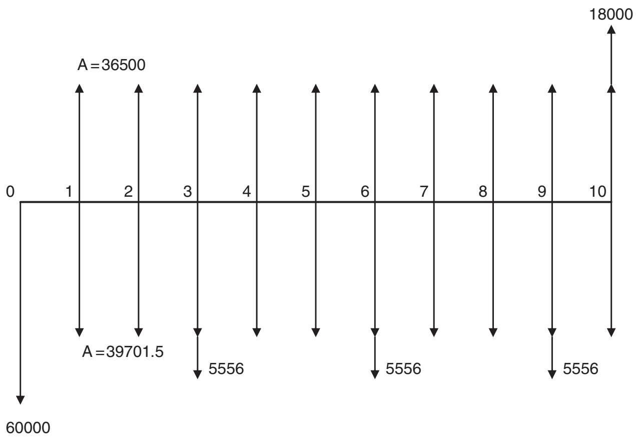

Fig. 5. Cash flow diagram for System 2.

$$PW_1 = 36500\left(6.1446\right) + 25500\left(0.3855\right) - \left[85000 + 21013.56.1446 + 5556\left(0.751 + 5556\left(0.5645\right) + 5556\left(0.4241\right)\right]$$

$$PW_1 = 234108.15 - 223786.4346 = 10321.7135$$

$$PW_2 = 36500\left(P/A, 10\%, 10\right) + 18000\left(P/F, 10\%, 10\right) - \left[60000 + 39701.5\left(P/A, 10\%, 10\right) + 5556\left(P/F, 10\%, 3\right) + 5556\left(P/F, 10\%, 6\right) + 5556\left(P/F, 10\%, 9\right)\right]$$

$$PW_2 = 36500\left(6.1446\right) + 180000.3855 - \left[60000 + 39701.5\left(6.1446\right) + 5556\left(0.7513\right) + 5556\left(0.5645\right) + 5556\left(0.4241\right)\right]$$

$$PW_2 = 231216.9 - 313616.7213 = -82399.8213$$

It was demonstrated that $PW_1 > PW_2$. Thus selecting and building System 1 was economically more advantageous. PW_2 was not even positive; it meant that it was not worth to build System 2 with current sales price of water.

6. Conclusion

The significant increase in reverse osmosis area showed us that the salinity level in well waters was increasing rapidly. The need for SWRO system in world pushed the technological improvements. Being initiated in the Middle East, this membrane technology started to claim a wider space in the fresh water production technologies field. Mediterranean coast of Turkey was the main area that used the SWRO technology in Turkey. Especially relatively arid regions such as Bodrum, Antalya etc. were the ones that most needed SWRO systems due to the inefficiency of brackish water reverse osmosis membranes or water softener units. Further improvements in membrane technology, energy use, and concentrate treatment allowed a wider application of reverse osmosis to inland and rural communities.

Cost analysis of a SWRO system, constructed in Bodrum to a summer resort with 200 luxury houses, was done in this study. With this system, each house would use high quality and healthy drinking and potable water safely with affordable prices. The most discussed part of SWRO systems, was the energy recovery booster pumps. Energy costs constituted the greatest part of the operating costs (70%). Thus it was also examined carefully by comparing two different alternative systems, "energy recovery technology used" (System1) and "not used" (System 2). To compare two systems present worth (PW) method was used. Results clearly showed us that selecting the energy recovery system would be economically advantageous. It provided more benefit to the user and environment at the same time. Upcoming changes and improvements in reverse osmosis technology would decrease the energy consumption rates and this way the SWRO systems would be used more effectively.

References

[1] L. Greenleea, D.F. Lawlerb, B. Freemana, B. Marrotc and P. Moulinc,"Reverse osmosis desalination, Water sources, technology, and today's challenges" (2009).

[2] A. Bick and G. Oron, "Post-treatment design of seawater reverse osmosis plants: boron removal technology selection for potable water production and environmental control," Desalination, 178 (2005) 233–246.

[3] P.H. Gleick,"The World's Water 2006–2007, The Biennial Report on Freshwater Resources," Island Press, Chicago (2006).

[4] Y. Lu, Y. Hu, X. Zhang, L. Wu and Q. Liu "Optimum design of reverse osmosis system under different feed concentration and product specification," J. Membrane. Sci., 287 (2007) 219–229.

[5] S. Sourirajan and J.P. Agrawal, "Reverse Osmosis," Ind. Eng. Chem., 61(11) (1969) 62–89.

[6] Y. Lu, Y. Hu, D. Xu and L. Wu, "Optimum design of reverse osmosis seawater desalination system considering membrane cleaning and replacing," J. Membrane. Sci., 282 (2006) 7–13.

[7] M. Shamel and O. Chung, "Drinking water from Desalination of seawater: optımızatıon of reverse osmosıs system operatıng parameters," J. Eng. Sci. Technol., 1(2) (2006) 203–211.

[8] D. Akgul, M. Cakmak, N. Kayaalp and I. Koyuncuc, "Cost analysis of seawater desalination with reverse osmosis in Turkey," Desalination, 220 (2008) 123–131.

[9] M. Will and K. Klinko, "Optimization of seawater RO systems design," Desalination, 138 (2001) 299–306.

[10] S.A. Avlonitis, K. Kouroumbas and N. Vlachakis, "Energy Consumption and membrane replacement costs of seawater reverse osmosis desalin plants," Desalination, 157 (2003) 151–158.

[11] P. Xu, J. Drewes and D. Heil,"Beneficial use of co-produced water through membrane treatment: technical-economic assessment", Desalination, 225 (2008) 139–155.

[12] R. Stover, "Energy Recovery Device Performance Analysis," Energy Recovery, Inc. (2005) http://www.energyrecovery.com/news/pdf/ERDPerformance.pdf

[13] L. Blank and A. Tarquin, "Eng Economy," 6th Ed., McGraw-Hill Inc. (2008).

[14] American Meteorological Society: "Glossary of Meteorology," URL: http://amsglossary.allenpress.com/glossary/browse?s = f&p = 41.